PRESSURE TRANSDUCER HANDBOOK

NATIONAL
SEMICONDUCTOR

1977
PRESSURE TRANSDUCER HANDBOOK
National Semiconductor

THE PRESSURE TRANSDUCER HANDBOOK

Table of Contents

SECTION 1 – PRESSURE TRANSDUCER PRODUCTS

SECTION 2 – PRODUCT DESCRIPTIONS

SECTION 3 – ACCURACY AND SPECIFICATIONS

SECTION 4 – CONFIGURATIONS, PACKAGING AND ENVIRONMENT

SECTION 5 – INSTALLATION

SECTION 6 – FLUID FLOW

SECTION 7 – AUTO-REFERENCING

SECTION 8 – SIGNAL CONDITIONING

Table of Contents (Continued)

SECTION 9 – MEDICAL APPLICATIONS (NON LIFE SUPPORT)

SECTION 10 – ACCELEROMETERS AND LOAD CELLS

SECTION 11 – SWITCH CONTROL

SECTION 12 – ACOUSTIC APPLICATIONS

SECTION 13 – TEMPERATURE MEASUREMENT

SECTION 14 – AUTOMOTIVE APPLICATIONS

SECTION 15 – QUICK SELECTION AND ORDERING GUIDE

SECTION 16 – DEFINITION OF TERMS

SECTION 17 – CONVERSION CONSTANTS

This book is dedicated to the man whose endeavors made it possible, but who will not see it in print –

Richard J. Billette

PREFACE

Here is your new catalog and handbook of integrated-circuit pressure transducers from National Semiconductor. In addition to complete specifications and a quick selection guide for National's IC transducer products, this edition includes comprehensive discussions of transducer theory, device structure, reliability and in-depth application data including circuits for the new easy-to-use *auto-reference* compensation technique for improving accuracy in any application.

Because IC transducers are finding use in many and diverse disciplines, the breadth of application information includes traditional, non-traditional and state-of-the-art fields as well. National hopes this catalog/handbook provides the requisite insight and data for your own special applications.

For information on devices introduced since this printing, or for more information on listed devices or applications, contact your local National representative or regional office.

This edition supersedes all previous catalogs, specifications and application notes.

NATIONAL SEMICONDUCTOR CORPORATION LIFE SUPPORT POLICY

National Semiconductor Corporation general policy does not recommend the use of its components of any type in "life support applications". National interprets "life support application" to mean a situation wherein failure or malfunction of the National component threatens life or makes injury probable.

We fully recognize that component application within a life support system is not necessarily a "life support application" of that component. In fact, many well designed life support systems have no single component in a "life support application".

When National is aware of the use of our commercial grade components within a life support system, we are required to determine whether or not our policy relative to component application is in jeopardy. In such cases we require a written statement, from an officer of the company bearing system responsibility, assuring that a malfunction of our component does not pose direct or indirect threat of injury or death.

WARNING: DO NOT
USE IN LIFE SUPPORT

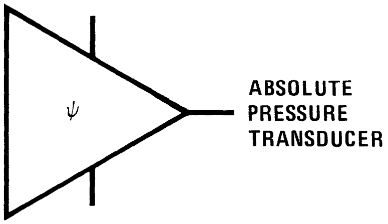
2900 Semiconductor Drive, Santa Clara, California 95051,
(408) 737-5000/TWX (910) 339-9240

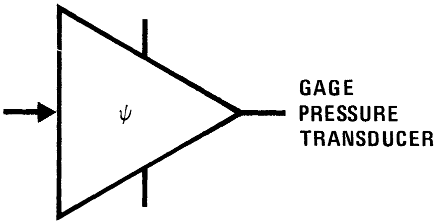
Manufactured under one or more of the following U.S. patents: 3083262, 3189758, 3231797, 3303356, 3317671, 3323071, 3381071, 3408542, 3421025, 3426423, 3440498, 3518750, 3519897, 3557431, 3560765, 3566218, 3571630, 3575609, 3579059, 3593069, 3597640, 3607469, 3617859, 3631312, 3633052, 3638131, 3648071, 3651565, 3693248.
Recent patents applicable to pressure transducers: 3836796, 3886799, 3899695, 3909924, 4006634.

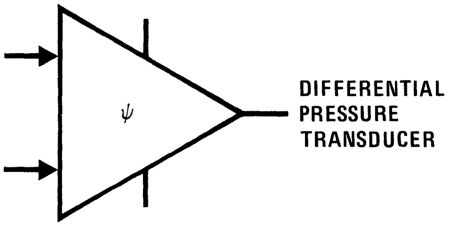
THE NEW JOHN McTAKEGAMI SYMBOLS

Symbolic Meaning: The new IC pressure transducer symbols combine the Greek letter psi, which it measures, with the standard symbol for an operational amplifier, which it includes. The input arrows indicate that the *differential* device has two inputs (two arrows); that the *gage* device has an ambient input (one arrow); and that the *absolute* device has a closed vacuum reference (no arrow).

Symbolic Justice: In a contest for the new symbols, among National IC pressure transducer representatives, Yoshiyuki Takegami of Japan submitted entries based on the op amp symbol, and John McKenzie of ACS entered a symbol featuring the Greek letter ψ. We combined them into the John McTakegami symbols. (Yoshiyuki received $50; John received 50 yen.)







Section 1

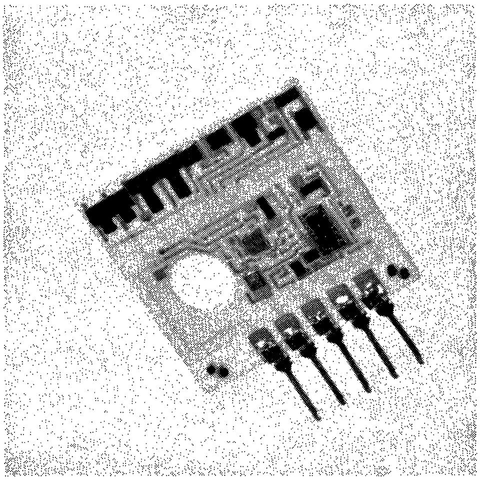
Pressure Transducer Products

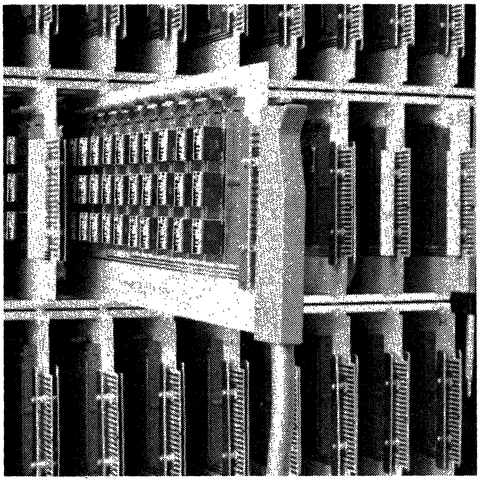
THE TRUE IC TRANSDUCER

Like many other fields of endeavor, the methodology of pressure transduction has advanced through progress in solid-state electronics. While traditional mechanical transducers have served well in the past, electronic sensors — particularly hybrid IC pressure transducers — now offer lower cost, higher accuracy and greater flexibility. And, like other hybrid IC's, the IC pressure transducer is inherently compact, rugged and reliable — fully capable of performing its function in tough industrial, consumer, medical, military and automotive environments.

Since the IC pressure transducer produces an electrical signal — a voltage that is linear with pressure — it is simple to use and easy to interface with electronic activators, displays and control systems. With the growing trend toward automation of commonly used mechanical or manually operated devices — now including automotive engine controls, home appliances, environmental control of home, office and factory, even measurements on the human body — the IC pressure transducer is finding an ever-widening horizon of applications. While for many of these applications full automation is still in the future, the critical sensor element — the IC pressure transducer — is here today.

Pressure Transducer Products





BENEFITS

- Low cost
- High accuracy
- Fast response
- Compact
- Rugged
- Reliable
- Versatile

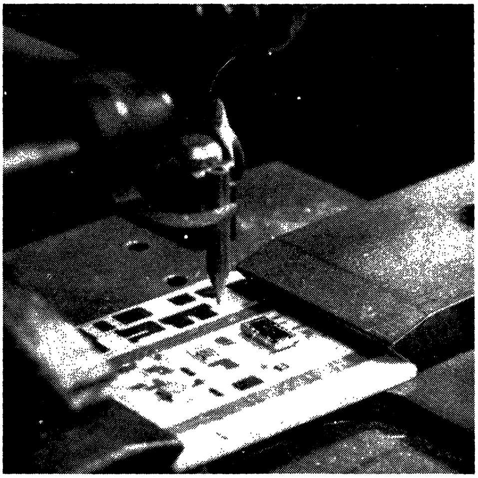
Because National's pressure transducers are true integrated-circuit transducers, they offer the designer all the benefits of the hybrid IC with its low cost, high volume production technology. Inherently fast, accurate, compact and rugged, National's IC pressure transducers are manufactured with the same stringent quality controls as other IC's, with additional in-process testing to ensure that each transducer meets the strict performance specifications and reliability standards expected of all National products.

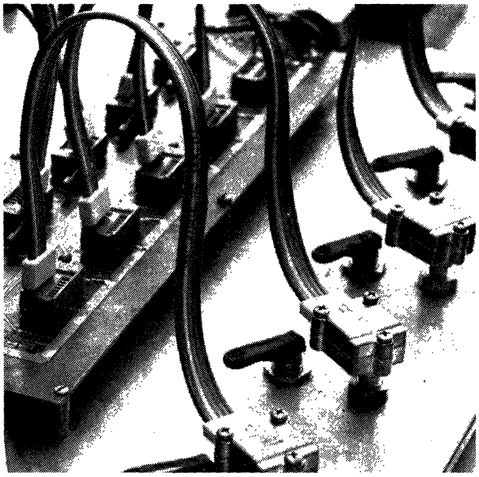
PERFORMANCE

- Field interchangeable
- Temperature compensated
- Easy interface with *auto-reference*
- High signal level – low impedance
- Insensitive to supply voltage variations
- Low volumetric displacement
- *Absolute, gage* or *differential* versions
- 10 to 5000 psi ranges

To maintain its high accuracy under various operating conditions, each transducer includes signal amplification, voltage regulation and temperature compensation. Each transducer is laser trimmed to match its response characteristic to a secondary standard transducer. This ensures field interchangeability without costly tweeking and allows even higher accuracy to be achieved by using the *auto-reference* technique to compensate all common-mode errors.

A further improvement in accuracy is provided by the low internal volume (~1/3cc) and low volumetric displacement (~10^{-3}cc) of the transducer cavity. This virtually eliminates transducer feedback, even in micro-measurement systems, and provides a highspeed response, (greater than 10 kHz) that enables the transducer to accurately measure audio frequency pressure variations.





ENVIRONMENT

- Insensitive to vibration
- High natural frequency
- Storage corrosive protection
- Optional operating corrosive protection
- Hi-Rel programs
- Hybrid IC with port for PCB mounting
- Ruggedly packaged units with NPT fittings
- Stainless steel, brass, nylon or zinc packages

Because of their high natural frequency and durable construction, National's IC pressure transducers are insensitive to vibration and capable of surviving rough handling. Corrosive effects are virtually eliminated in storage by a conformal parylene coating. The *backward gage* or *fluid-filled* versions provide similar protection for operation in corrosive pressure systems. A special MIL qualification program is available for the standard *backward gage* versions.

APPLICATIONS

- Industrial, commercial and residential controls
- Environmental systems
- Machine tool control
- Fluid distribution
- Instrumentation
- Non-life support medical
- Automotive diagnostic and control
- Military systems

Capable of meeting a wide range of application requirements with 10 to 5000 psi pressure ranges, National's standard IC pressure transducer line includes single-port versions for *absolute* or *gage* pressure and dual-port versions for *differential* applications. Package configurations include the compact ceramic IC with port, ready for PC board installation, and fully plumbed units with stainless steel, brass, molded nylon or cast zinc housing options, for integral system installations.

Section 2

Product Descriptions

2

THE TRANSDUCER NEEDLE

Finding the pressure transducer you need may at times seem like searching for the proverbial needle in a stack of pressure transducers. To help you zero in, we've separated National's IC pressure transducers into neat groups, with the features, applications, specifications and package configurations given for each series. So forget the needle. The transducer product descriptions start on the next page.

National Semiconductor

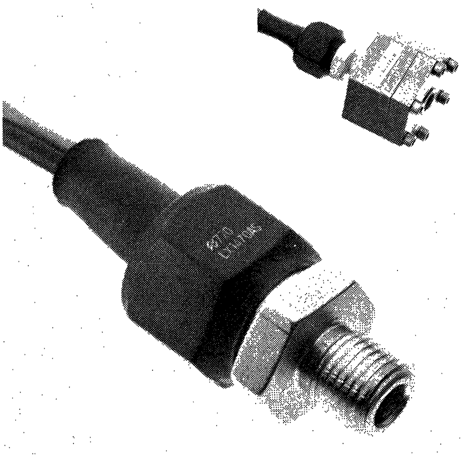
Absolute Pressure Transducers

LX14XXA, LX14XXAF, LX14XXAS, LX14XXAFS SERIES

DESCRIPTION

The LX14XX Series provides a selection of ruggedly packaged absolute transducers with operating pressure ranges of 0–100 psia to 0–5000 psia. These devices feature the compact concentric PX4 brass or PX4S stainless steel housing for easy installation with a crescent wrench and 10″ flying leads for easy soldering and secure electrical connection. The leads are epoxy-sealed to provide fully hermetic protection against hostile exterior environments. Fluid-filled housings PX4F and PX4FS are also available for systems using corrosive or conductive working fluids.

Like other National IC pressure transducers, the LX14XXA units are designed to provide high accuracy and excellent stability. They are field interchangeable and can be easily interfaced with auto-reference, control and display systems. Each device includes internal temperature compensation, voltage regulation and full signal conditioning by an operational amplifier with a low-impedance 10V output.



LX14XXA (LX14XXAFS Inset)

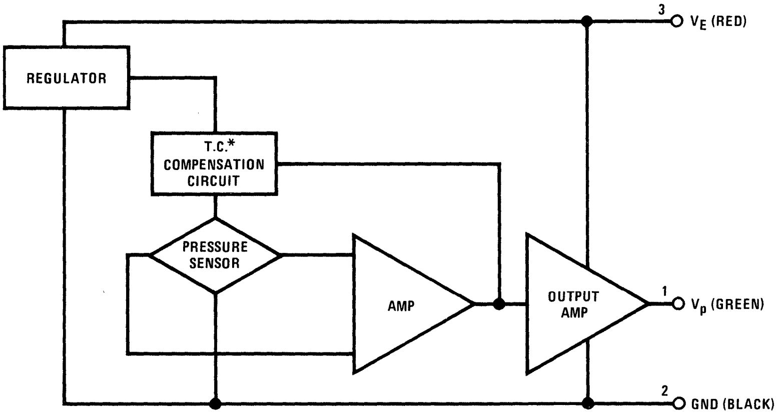
FEATURES

- 0–100 psia to 0–5000 psia
- Rugged concentric housing
- Flying leads
- Hermetic package
- Fluid-filled version
- High accuracy
- Temperature compensation
- High stability
- Field interchangeability
- Available from National distributors

APPLICATIONS

- Engine diagnostics
- Machine tools
- Hydraulics
- Off-road vehicles
- Pneumatics
- Pressurized tanks and lines
- Pressure vessels
- Deep well pumps
- Oceanography
- Welding machines

BLOCK DIAGRAM



*National patents 3836796, 3886799, 3899695

MAXIMUM RATINGS

Excitation Voltage	30V
Output Current	
Source	20 mA
Sink	10 mA
Transducer Bias Current	20 mA
Operating Temperature Range	0°C to 85°C
Storage Temperature Range	−40°C to +105°C
Lead Soldering Temperature (10 seconds)	260°C

TYPICAL CHARACTERISTICS

Output Voltage Sensitivity to Excitation Voltage	0.5%
Output Impedance	<50Ω
Electrical Noise Equivalent ($0 \leq f \leq 1$ kHz)	0.04% Span
Natural Frequency of Sensor Diaphragm	> 50 kHz
Transducer Bias Current	7–10 mA

ABSOLUTE PRESSURE DEVICES—GUARANTEED SPECIFICATIONS*

DEVICE TYPE (NOTE 1)	OPERATING PRESSURE RANGE	MAXIMUM OVER PRESSURE	REFERENCE TEMPERATURE = 25°C REFERENCE PRESSURE = 0 psi				EXCITATION VOLTAGE, V_E = 15 V_{DC} (NOTE 3) OPERATING TEMPERATURE = 0°C to 85°C			
			OFFSET SPECIFICATIONS				SPAN SPECIFICATIONS			
			OFFSET CALIBRATION V	TEMP. COEFFICIENT ± psi/°C	REPEATABILITY ± psi	STABILITY ± psi	SENSITIVITY CALIBRATION mV/psi	TEMP. COEFFICIENT ± psi/°C	L-H-R (NOTE 2) ± psi	STABILITY ± psi
LX1420A	0 to 100 psia	150 psia	2.5 ±0.25	0.030	0.4	1.0	100 ±2	0.03	0.60	0.40
LX1430A	0 to 300 psia	450 psia	2.5 ±0.25	0.090	1.0	2.0	33.3 ±0.67	0.09	2.0	1.0
LX1440A	0 to 1000 psia	1500 psia	2.5 ±0.25	0.3	3.5	7.0	10 ±0.2	0.3	6.0	3.0
LX1450A	0 to 2000 psia	3000 psia	2.5 ±0.25	0.6	7.0	14	5 ±0.1	0.6	20.0	7.0
LX1460A	0 to 3000 psia	4500 psia	2.5 ±0.25	0.9	10.0	20.0	3.33 ±0.067	0.9	30.0	10.0
LX1470A	0 to 5000 psia	5000 psia	2.5 ±0.25	1.5	17.0	35.0	2 ±0.04	1.5	75.0	17.0

Note 1: Add suffixes for standard options: S = stainless steel, F = fluid-filled. Standard options: LX14XXAS, LX14XXAF, LX14XXAFS.

Note 2: L-H-R combines linearity, hysteresis and repeatability of span.

Note 3: Operation is possible with excitation voltage as low as 10V. Output voltage will saturate at excitation voltage less 2V.

*See Section 3 for definition of specifications

National Semiconductor

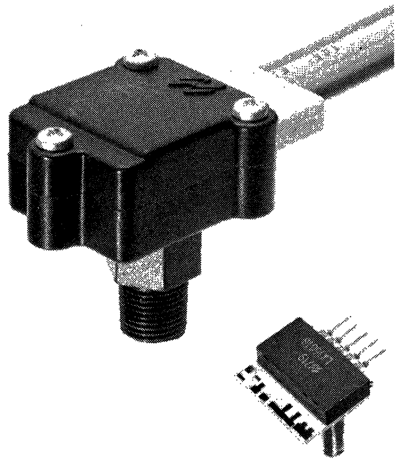
Absolute and Gage Pressure Transducers

LX16XXA, LX16XXG, LX16XXAF; LX17XXA, LX17XXG, LX17XXAF; LX17XXAN, LX17XXGN, LX17XXAFN SERIES

DESCRIPTION

This series provides a wide selection of absolute and gage pressure transducers with operating pressure ranges of ±5 psig to 0–300 psia or psig. For each operating pressure range, the transducer can be provided either in the basic PX6 hybrid IC package for easy PC board mounting or in the compact, rugged PX7 housing with 1/8" NPT fitting. This housing is available in tough diecast zinc (PX7) or in lightweight molded nylon (PX7N) for ultra-clean applications, both of which provide excellent mechanical isolation. The absolute transducers can also be provided with fluidic isolation to protect against corrosive or conductive working fluids.

Like other National IC pressure transducers, these devices are designed to provide high accuracy and excellent stability. They are field interchangeable and can be easily interfaced with auto-reference, control and display systems. Each device includes internal temperature compensation, voltage regulation and full signal conditioning by an operational amplifier with a low-impedance 10V output.



LX17XX (LX16XX Inset)

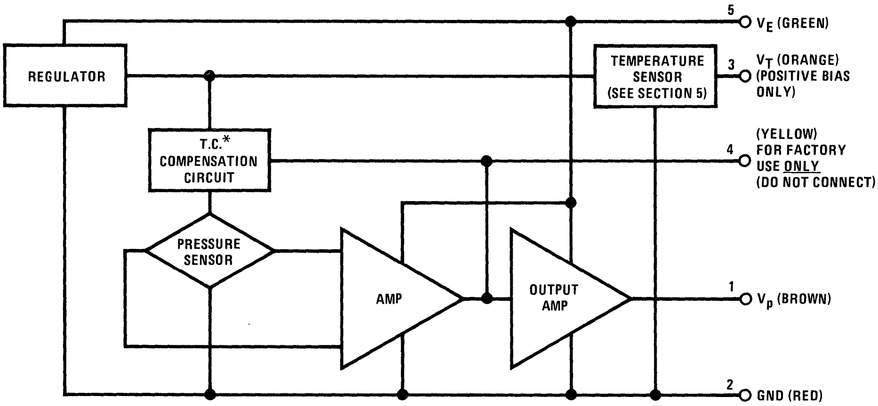
FEATURES

- ±5 psig to 0–300 psig or psia
- Hybrid IC package for PC board mounting
- Rugged diecast zinc or molded nylon housing
- Fluid-filled absolute versions
- Temperature sensor
- Easy auto-reference interface
- High accuracy
- Temperature compensation
- High stability
- Field interchangeability
- Available from National distributors

APPLICATIONS

- Food and beverage processing
- Medical electronics
- Computer and peripheral pneumatics
- Hot bulb thermometry
- Hydraulic and pneumatic control
- Heating, ventilation, air conditioning and refrigeration controls
- Automotive-diagnostics, safety, control
- Low pressure and vacuum systems
- Barometry

BLOCK DIAGRAM



*National patents 3836796, 3886799, 3899695

MAXIMUM RATINGS

Excitation Voltage	30V
Output Current	
Source	20 mA
Sink	10 mA
Transducer Bias Current	20 mA
Operating Temperature Range	0°C to 85°C
Storage Temperature Range	–40°C to +105°C
Lead Soldering Temperature (10 seconds)	260°C

TYPICAL CHARACTERISTICS

Output Voltage Sensitivity to Excitation Voltage	0.5%
Output Impedance	<50Ω
Electrical Noise Equivalent ($0 \leq f \leq 1$ kHz)	0.04% Span
Natural Frequency of Sensor Diaphragm	> 50 kHz
Transducer Bias Current	11–15 mA

GUARANTEED SPECIFICATIONS*

DEVICE TYPE (NOTE 1)	OPERATING PRESSURE RANGE	MAXIMUM OVER PRESSURE	REFERENCE TEMPERATURE = 25°C REFERENCE PRESSURE = 0 psi (NOTE 3)				EXCITATION VOLTAGE, V_E = 15 V_{DC} (NOTE 4) OPERATING TEMPERATURE = 0°C to 85°C			
			OFFSET SPECIFICATIONS				SPAN SPECIFICATIONS			
			OFFSET CALIBRATION V	TEMP. COEFFICIENT ± psi/°C	REPEATABILITY ± psi	STABILITY ± psi	SENSITIVITY CALIBRATION mV/psi	TEMP. COEFFICIENT ± psi/°C	L-H-R (NOTE 2) ± psi	STABILITY ± psi
ABSOLUTE PRESSURE DEVICES										
LX1601A, LX1701A	10 to 20 psia	40 psia	2.5 ±0.5	0.0054	0.05	0.3	1,000 ±20	0.0054	0.05	0.05
LX1602A, LX1702A	0 to 15 psia	40 psia	2.5 ±0.3	0.0072	0.06	0.3	670 ±13	0.0072	0.07	0.06
LX1603A, LX1703A	0 to 30 psia	60 psia	2.5 ±0.25	0.009	0.1	0.3	333 ±6	0.009	0.16	0.10
LX1610A, LX1710A	0 to 60 psia	100 psia	2.5 ±0.25	0.018	0.2	0.6	167 ±3.3	0.018	0.36	0.24
LX1620A, LX1720A	0 to 100 psia	150 psia	2.5 ±0.2	0.0216	0.4	1.0	100 ±2	0.0216	0.60	0.40
LX1730A	0 to 300 psia	450 psia	2.5 ±0.2	0.063	1.0	2.0	33.3 ±0.67	0.063	2.0	1.0
GAGE PRESSURE DEVICES										
LX1601G, LX1701G	–5 to +5 psig	40 psig	7.5 ±0.5	0.0054	0.05	0.3	1,000 ±20	0.0054	0.05	0.05
LX1611G, LX1711G	–5 to +5 psig	100 psig	7.5 ±0.5	0.0054	0.05	0.3	1,000 ±20	0.0054	0.05	0.05
LX1602G, LX1702G	0 to 15 psig	40 psig	2.5 ±0.3	0.0072	0.06	0.3	670 ±13	0.0072	0.07	0.06
LX1603G, LX1703G	0 to 30 psig	60 psig	2.5 ±0.25	0.009	0.1	0.3	333 ±6	0.009	0.16	0.10
LX1604G, LX1704G	–15 to +15 psig	40 psig	7.5 ±0.25	0.009	0.1	0.3	333 ±6	0.009	0.16	0.10
LX1610G, LX1710G	0 to 60 psig	100 psig	2.5 ±0.25	0.018	0.2	0.6	167 ±3.3	0.018	0.36	0.24
LX1620G, LX1720G	0 to 100 psig	150 psig	2.5 ±0.2	0.0216	0.4	1.0	100 ±2	0.0216	0.60	0.40
LX1730G	0 to 300 psig	450 psig	2.5 ±0.2	0.063	1.0	2.0	33.3 ±0.67	0.063	2.0	1.0

Note 1: Add suffixes for standard options: N = nylon, F = fluid-filled. Standard options: LX16XXAF; LX17XXAF, GN, AFN.

Note 2: L-H-R combines linearity, hysteresis and repeatability of span.

Note 3: Offset pressure for LX1601A and LX1701A is 10 psia.

Note 4: Operation is possible with excitation voltage as low as 10V. Output voltage will saturate at excitation voltage less 2V.

*See Section 3 for definition of specifications

National Semiconductor

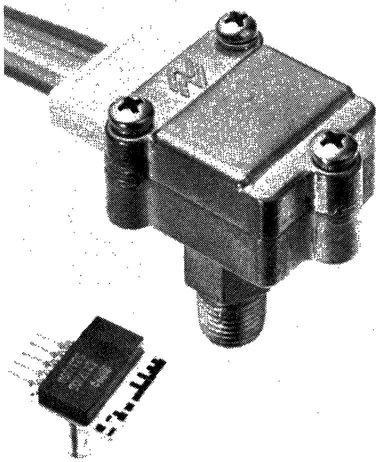
Backward Gage Pressure Transducers

LX16XXGB, LX17XXGB SERIES

DESCRIPTION

The LX16XXGB and LX17XXGB Series are backward gage pressure transducers with operating pressure ranges of ±5 psig to 0–300 psig. These units provide superior protection against corrosive and conductive working fluids by applying the pressure to the back side of the sensor diaphragm. For each operating pressure range, the transducer is available either in the basic PX6B hybrid IC package for easy PC board mounting or in the compact, rugged PX7B zinc alloy housing with 1/8" NPT fitting for systems requiring mechanical isolation from extraneous forces.

Like other National IC pressure transducers, these units are designed to provide high accuracy and excellent stability. They are field interchangeable and can be easily interfaced with auto-reference, control and display systems. Each device includes internal temperature compensation, voltage regulation and full signal conditioning by an operational amplifier with a low-impedance 10V output.



LX17XXGB (LX16XXGB Inset)

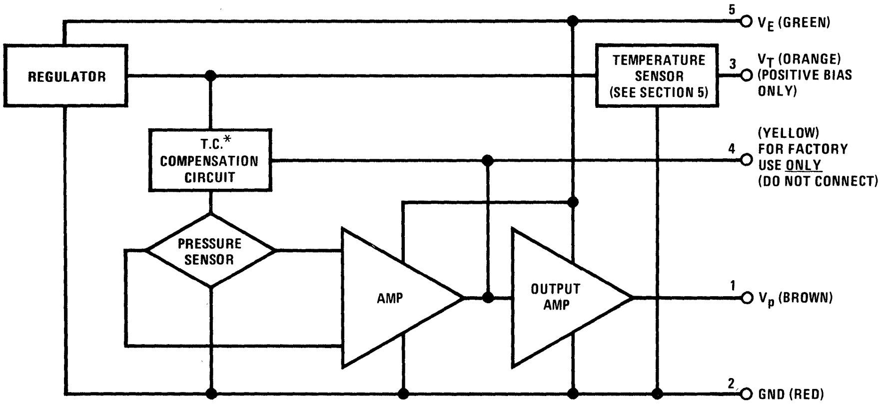
FEATURES

- ±5 psig to 0–300 psig
- Backward gage construction
- Hostile working fluid protection
- Hybrid IC package for PC board mounting
- Ruggedly housed versions
- Temperature sensor
- High accuracy
- Easy auto-reference interface
- Temperature compensation
- Excellent stability
- Field interchangeability
- Available from National distributors

APPLICATIONS

- Saline solutions
- Sewage
- Petro-chemical systems
- Aqueous solutions
- Process fluids
- Medical dialysis
- Water management
- Cooling systems
- Fuel management
- Liquid head

BLOCK DIAGRAM



*National patents 3836796, 3886799, 3899695

MAXIMUM RATINGS

Excitation Voltage	30V
Output Current	
Source	20 mA
Sink	10 mA
Transducer Bias Current	20 mA
Operating Temperature Range	0°C to 85°C
Storage Temperature Range	−40°C to +105°C
Lead Soldering Temperature (10 seconds)	260°C

TYPICAL CHARACTERISTICS

Output Voltage Sensitivity to Excitation Voltage	0.5%
Output Impedance	<50Ω
Electrical Noise Equivalent ($0 \leq f \leq 1$ kHz)	0.04% Span
Natural Frequency of Sensor Diaphragm	> 50 kHz
Transducer Bias Current	11–15 mA

BACKWARD GAGE PRESSURE DEVICES– GUARANTEED SPECIFICATIONS*

DEVICE TYPE	OPERATING PRESSURE RANGE	MAXIMUM OVER PRESSURE	REFERENCE TEMPERATURE = 25°C REFERENCE PRESSURE = 0 psi				EXCITATION VOLTAGE, V_E = 15 V_{DC} (NOTE 2) OPERATING TEMPERATURE = 0°C to 85°C			
			OFFSET SPECIFICATIONS				SPAN SPECIFICATIONS			
			OFFSET CALIBRATION V	TEMP. COEFFICIENT ± psi/°C	REPEATABILITY ± psi	STABILITY ± psi	SENSITIVITY CALIBRATION mV/psi	TEMP. COEFFICIENT ± psi/°C	L-H-R (NOTE 1) ± psi	STABILITY ± psi
LX1601GB, LX1701GB	−5 to +5 psig	40 psig	7.5 ±0.5	0.0054	0.05	0.3	1,000 ±20	0.0054	0.05	0.05
LX1611GB, LX1711GB	−5 to +5 psig	100 psig	7.5 ±0.5	0.0054	0.05	0.3	1,000 ±20	0.0054	0.05	0.05
LX1602GB, LX1702GB	0 to 15 psig	40 psig	2.5 ±0.3	0.0072	0.06	0.3	670 ±13	0.0072	0.07	0.06
LX1603GB, LX1703GB	0 to 30 psig	60 psig	2.5 ±0.25	0.009	0.1	0.3	333 ±6	0.009	0.16	0.10
LX1604GB, LX1704GB	−15 to +15 psig	40 psig	7.5 ±0.25	0.009	0.1	0.3	333 ±6	0.009	0.16	0.10
LX1610GB, LX1710GB	0 to 60 psig	100 psig	2.5 ±0.25	0.018	0.2	0.6	167 ±3.3	0.018	0.36	0.24
LX1620GB, LX1720GB	0 to 100 psig	150 psig	2.5 ±0.2	0.0216	0.4	1.0	100 ±2	0.0216	0.60	0.40
LX1730GB	0 to 300 psig	450 psig	2.5 ±0.2	0.063	1.0	2.0	33.3 ±0.67	0.063	2.0	1.0

Note 1: L-H-R combines linearity, hysteresis and repeatability of span.

Note 2: Operation is possible with excitation voltage as low as 10V. Output voltage will saturate at excitation voltage less 2V.

*See Section 3 for definition of specifications

National Semiconductor

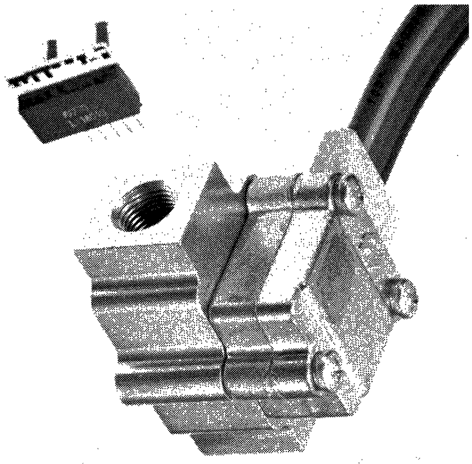
Differential Pressure Transducers

LX16XXD, LX16XXDF; LX17XXDD, LX17XXDDF SERIES

DESCRIPTION

The LX16XXD and LX17XXDD Series provides an excellent selection of differential transducers with operating pressure ranges of ±5 psid to 0—100 psid. Because of its dual-port input, a single differential transducer can be used to measure fluid flow rate or flow totalization. For each operating pressure range, the transducer is available in the basic PX6D hybrid IC package for easy PC board mounting or in the compact, rugged PX7D brass housing with rigidly held 1/8″ NPT female fittings for isolation from high common-mode pressures. Either unit can also be provided with fluidic isolation for systems using corrosive or conductive working fluids.

Like other National IC pressure transducers, these units are designed to provide high accuracy and excellent stability. They are field interchangeable and can easily be interfaced with auto-reference, control and display systems. Each device includes internal temperature compensation, voltage regulation and full signal conditioning by an operational amplifier with a low-impedance 10V output.



LX17XXDD (LX16XXD Inset)

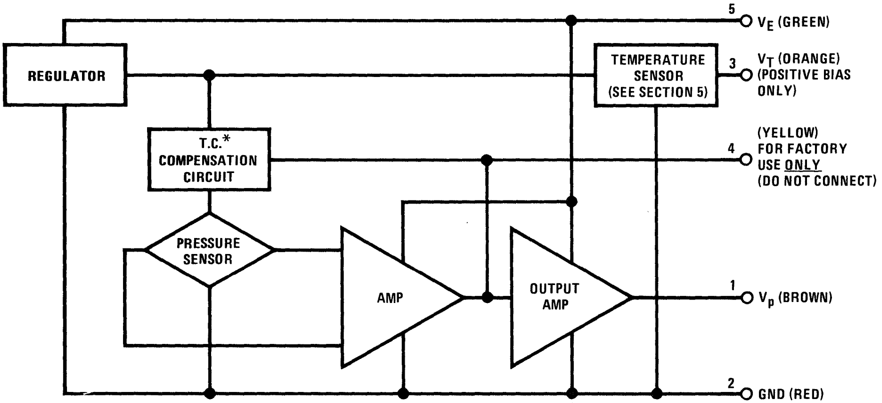
FEATURES

- ±5 psid to 0—100 psid
- Easy one-transducer flow meter
- Hybrid IC package for PC board mounting
- Rugged brass housings
- Rigid dual-port structure
- Fluid-filled versions
- Temperature sensor
- Easy auto-reference interface
- High accuracy
- Excellent stability
- Field interchangeability
- Available from National distributors

APPLICATIONS

- Fluid velocity
- Volumetric flow control
- Flow totalization
- Fuel management
- Fluid dispensing
- Wind speed
- Water management
- Process fluid flow

BLOCK DIAGRAM



*National patents 3836796, 3886799, 3899695

MAXIMUM RATINGS

Excitation Voltage	30V
Output Current	
Source	20 mA
Sink	10 mA
Transducer Bias Current	20 mA
Operating Temperature Range	0°C to 85°C
Storage Temperature Range	−40°C to +105°C
Lead Soldering Temperature (10 seconds)	260°C

TYPICAL CHARACTERISTCS

Output Voltage Sensitivity to Excitation Voltage	0.5%
Output Impedance	<50Ω
Electrical Noise Equivalent ($0 \leq f \leq 1$ kHz)	0.04% Span
Natural Frequency of Sensor Diaphragm	> 50 kHz
Transducer Bias Current	11–15 mA

DIFFERENTIAL PRESSURE DEVICES–GUARANTEED SPECIFICATIONS*

DEVICE TYPE (NOTE 1)	OPERATING PRESSURE RANGE	MAXIMUM OVER PRESSURE	REFERENCE TEMPERATURE = 25°C REFERENCE PRESSURE = 0 psi				EXCITATION VOLTAGE, V_E = 15 V_{DC} (NOTE 3) OPERATING TEMPERATURE = 0°C to 85°C			
			OFFSET SPECIFICATIONS				SPAN SPECIFICATIONS			
			OFFSET CALIBRATION V	TEMP. COEFFICIENT ± psi/°C	REPEATABILITY ± psi	STABILITY ± psi	SENSITIVITY CALIBRATION mV/psi	TEMP. COEFFICIENT ± psi/°C	L-H-R (NOTE 2) ± psi	STABILITY ± psi
LX1601D, LX1701DD	−5 to +5 psid	40 psid	7.5 ±0.5	0.0054	0.05	0.3	1,000 ±20	0.0054	0.05	0.05
LX1611D, LX1711DD	−5 to +5 psid	100 psid	7.5 ±0.5	0.0054	0.05	0.3	1,000 ±20	0.0054	0.05	0.05
LX1602D, LX1702DD	0 to 15 psid	40 psid	2.5 ±0.35	0.0072	0.06	0.3	670 ±13	0.0072	0.07	0.06
LX1603D, LX1703DD	0 to 30 psid	60 psid	2.5 ±0.3	0.009	0.1	0.3	333 ±6	0.009	0.16	0.10
LX1604D, LX1704DD	−15 to +15 psid	40 psid	7.5 ±0.3	0.009	0.1	0.3	333 ±6	0.009	0.16	0.10
LX1610D, LX1710DD	0 to 60 psid	100 psid	2.5 ±0.25	0.018	0.2	0.6	167 ±3.3	0.018	0.36	0.24
LX1620D, LX1720DD	0 to 100 psid	150 psid	2.5 ±0.2	0.0216	0.4	1.0	100 ±2	0.0216	0.60	0.40

Note 1: Add suffix F for standard fluid-filled options.

Note 2: L-H-R combines linearity, hysteresis and repeatability of span.

Note 3: Operation is possible with excitation voltage as low as 10V. Output voltage will saturate at excitation voltage less 2V.

*See Section 3 for definition of specifications

HIGH RELIABILITY PRESSURE TRANSDUCER

Thanks to continued improvement in our device packaging, testing and failure analysis, National's standard isolated backward gage pressure transducers are now available for high reliability applications. With a substantial quantity order we can provide any of the LX17XXGB Series as type LX17XXGB/883 with Class B or Class C qualification as per MIL-STD-883A, with test modifications for IC pressure transducers as recommended by National and currently under consideration by RADC.

The recommended screening procedures, as shown in the table, are the same procedures we use for testing our standard transducer devices. The continued use of these tests, in conjunction with intensive failure mode analysis, have resulted in minor packaging modifications that have greatly improved device reliability. Our comprehensively documented test results have been correlated with long term reliability data to establish the device structural integrity and testing technology requisite for a Hi Rel pressure transducer program.

SCREEN		CLASS B		CLASS C	
		METHOD	REQUIREMENT	METHOD	REQUIREMENT
3.1.1	Internal visual	2017	100%	2017	100%
3.1.2	Pressurebake*	24 hrs., 125°C, 90% of proof pressure.	100%	24 hrs., 125°C, 90% of proof pressure.	100%
3.1.3	Pressure Cycle*	5 psig to 90% of proof pressure, 6 Hz for 1.5 hrs.	100%	5 psig to 90% of proof pressure, 6 Hz for 1.5 hrs.	100%
3.1.5	Temperature cycling	1010, test condition B min	100%	1010, test condition B min	100%
3.1.7	Constant acceleration	2001, test condition A (min) Y_1 plane	100%	2001, test condition A (min) Y_1 plane	100%
3.1.8	Hermeticity*	Pressurized package integrity method	100%	Pressurized package integrity method	100%
3.1.9	Interim (pre-burn-in) electrical parameters	Per applicable procurement document			
3.1.10	Burn-in test	1015 160 hrs @ 125°C min	100%		
3.1.11	Final electrical test	Per applicable procurement document		Per applicable procurement document	
	(a) Static tests				
	(1) 25°C (subgroup 1, table I, 5005)		100%		100%
	(2) Maximum and minimum rated operating temp. (subgroups 2, 3, table I, 5005)		100%		–
	(b) Dynamic tests and switching tests 25°C (subgroups 4 and 9, table I, 5005)		100%		–
	(c) Functional test 25°C (subgroup 7, table I, 5005)		100%		100%
3.1.12	Radiographic		–		–
3.1.13	Qualification or quality conformance inspection test sample selection, see Method 5005				
3.1.14	External visual	2009	100%	2009	100%

*Tests modified for pressure transducer IC's.

Note. Method 5014 (proposed)

Section 3

Accuracy and Specifications

THE GNAT'S EYEBROW

Not many engineers have ever seen a gnat's eyebrow, but the accuracy they require is often better than one. We're still not sure whether our pressure transducers can meet that requirement, but we do know how to calculate overall accuracy in a well-defined pressure-flow system. And, to make it easy for you to do, we've provided simple, easy-to-use formulas and system-defined specifications that plug right in.

With these formulas you can determine the effect of system parameters and transducer error compensation techniques, such as auto-referencing and periodic calibration, to get the accuracy you need. This means you don't have to settle for our specified worst-case errors when your application calls for something better—as long as it isn't better than a gnat's eyebrow. We're still not sure whether a gnat has eyebrows, but we're working on his cardio-vascular system.

Accuracy and Specifications

ERROR ANALYSIS FOR PRESSURE TRANSDUCERS

The main function of a pressure transducer is to make accurate pressure measurements. The main question is, how accurate? The answer for National transducers is simple. We don't just make convenient measurements and give you the puzzle to decipher. Our pressure transducer parameters are measured under well-defined user conditions, and the parameters are related directly to system performance. By knowing these parameters and a few simple formulas you can easily calculate the overall accuracy under any given set of conditions. You can also isolate error-causing factors and maximize accuracy in systems where such factors can be controlled or compensated.

TRANSDUCER RESPONSE AND LINEARITY

No device is perfectly linear, but National's pressure transducers approach the ideal straight line response with a deviation that is small as compared with other errors in most applications. But more importantly, as shown in *Figure 1*, the response is fitted to a *best straight line* (BSL) that intersects the true response at the reference pressure. This is called a *BSL with forced reference.* It places the largest linearity error where it belongs, at the maximum applied pressure. And since there is zero linearity error at the reference pressure, it also simplifies the use of *auto-reference* techniques to compensate for offset errors in any application and *curve-fitting* to compensate for linearity errors in ultra-high accuracy applications.

A SYSTEM MODEL

To see how transducer performance parameters are related to system accuracy, consider the hybrid IC pressure transducer system shown in *Figure 2*. The problem is to determine the magnitude of error for given values of the *major input* (applied pressure) and the *minor inputs* (temperature and supply voltage). The *error sources* are inherent to the transducer, but the magnitude of error from each one may depend on the major and minor inputs to the transducer system. The voltage and temperature coefficients, for example, produce errors that are respectively proportional to supply voltage deviation and temperature. But the error they produce is only partially dependent on applied pressure. Linearity and hysteresis are both proportional to applied pressure, while repeatability, stability and calibration errors are only partially pressure dependent.

To simplify our model, we first divide the error sources into 2 groups: those that are dependent on applied pressure and those that are not. The inherent linearity (and clever design) of National's hybrid IC transducers allows us to do this very simply. As a result, the output signal V_S is given by:

$$V_S = V_O + S \cdot P$$

where V_O is the offset voltage (obtained at reference pressure), S is the sensitivity and P is the applied pressure. As a further result, the error in output signal ΔV_S can be expressed as:

$$\Delta V_S = \Delta V_O + s \cdot P$$

where ΔV_O is the *offset* error, which is independent of applied pressure, and $s \cdot P$ is the *span* error, which is proportional to applied pressure, with s as the span error coefficient.

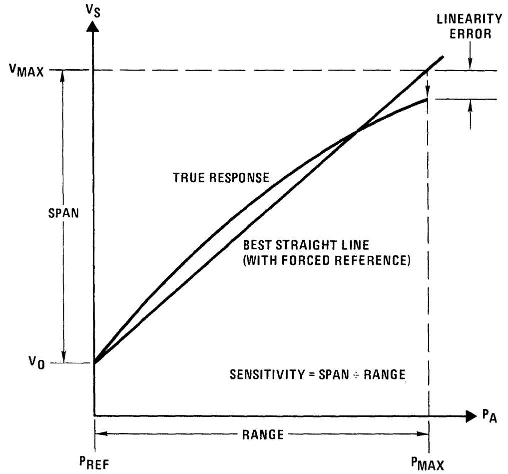


FIGURE 1.

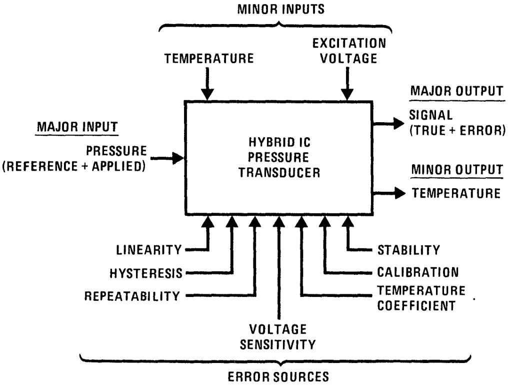


FIGURE 2.

The *offset* errors, being independent of the major input variable (applied pressure), are equivalent to system *common-mode* errors. As shown in the *error band* representation in *Figure 3*, the offset error is the same, regardless of pressure. It has the effect of translating the response line up or down, while the slope or sensitivity remains constant.

The *span* errors, being proportional to the major input variable, are equivalent to sytem *normal mode* error. As shown in the *error band* representation in *Figure 4*, the span error increases linearly with the applied pressure. It has the effect of rotating the response line around the offset-reference pressure point.

While mutually independent, the *offset* and *span* error groups both contain errors that are dependent on the minor input variables. As shown in Table I, each group includes a temperature coefficient, a supply voltage coefficient and 3 time dependent coefficients. These coefficients are used to specify the errors in National's hybrid IC pressure transducers and to calculate overall accuracy.

TABLE I. Offset and Span Errors

OFFSET (COMMON-MODE)	SPAN (NORMAL MODE)
Calibration	Sensitivity Calibration
Temperature Coefficient	Temperature Coefficient
Repeatability	Linearity-Hysteresis-Repeatability
Stability	Stability
Voltage Coefficient	Voltage Coefficient

SYSTEM ACCURACY

With the errors divided into 2 groups of mutually independent coefficients defined by their dependence (or non-dependence) on the system input variables, we can now compute either the worst-case error or the most probable error for any hybrid IC pressure transducer system.

Worst-Case Error: The worst-case overall error E_{WC} is obtained by simple addition of all applicable errors:

$$E_{WC} = \sum_{1}^{n} e_x$$

Where e_x is the error resulting from the n^{th} error coefficient.

Most Probable Error: The most probable error E_{MP} is obtained by computing the square root of the sum of the squares:

$$E_{MP} = \sqrt{\sum_{1}^{n} e_x^2}$$

We can now select the applicable error coefficients and evaluate the error terms e_x from the specifications given for any individual pressure transducer.

ACCURACY SPECIFICATIONS

By convention, system accuracy is calculated in terms of the major input variable, in this case, applied pressure. A moment's thought will show the common sense wisdom of using input pressure rather than the major output variable, response voltage. While important to system

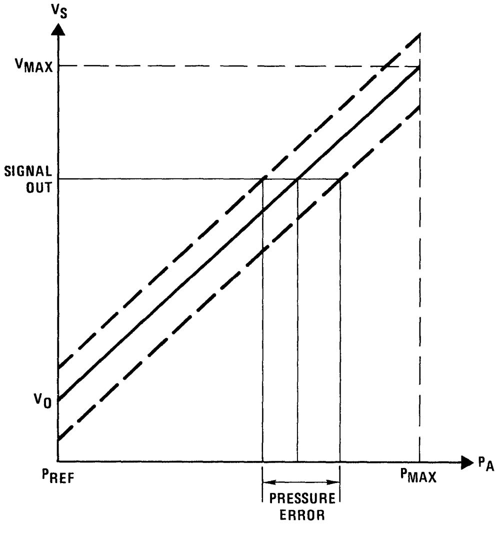


FIGURE 3.

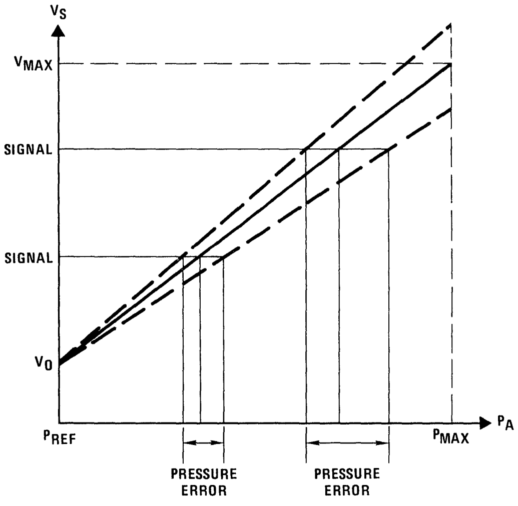


FIGURE 4.

component design and interfacing, the response voltage is only an interim variable with the sole purpose of telling the user or other parts of the system the value of input pressure. It is uniquely related to input pressure only for a given supply voltage, the value of which may change as system design proceeds. The psi accuracy of a National hybrid IC transducer is independent of supply voltage (within the specified range) and, if necessary, can easily be converted to output variance (voltage) by multiplying by the sensitivity.

In line with this convention, each transducer error coefficient is measured in volts or V/°C then divided by sensitivity to express the error specification in psi. This convention excludes calibration and supply voltage sensitivity specifications, both of which are used for transducer interfacing as well as error calculation and must be converted to psi for system accuracy calculations.

OFFSET SPECIFICATIONS

The offset characteristics are measured at 25°C with 15V excitation and with the reference pressure applied. The reference pressure is 0 psi for all but the LX1601A and LX1701A, both of which have a 10 psia reference. Although measured at the reference pressure, the offset errors are the same regardless of pressure and can be substituted directly into the overall accuracy formulas. They are measured and defined as follows.

Offset Calibration: Defines the offset voltage and its maximum deviation from unit to unit, including long-term stability (1 year, shelf or operating). The deviation is measured and specified in volts and must be divided by sensitivity to express the error band in psi for accuracy calculations.

Offset Temperature Coefficient (TC_O): Defines the maximum deviation in offset voltage as the temperature is varied from 25°C to any other temperature between 0°C and +85°C. It is specified in psi/°C and must be multiplied by the temperature difference to obtain the error in psi. The maximum error is (85°C–25°C). $TC_O = (60°C) \cdot TC_O$.

Offset Repeatability: Defines the maximum deviation in offset voltage when applied pressure is cycled through its full range 50 times in a 1 minute period. It is measured in volts and divided by sensitivity to express the specified error in psi.

Offset Stability: Defines the maximum deviation in offset voltage over a 1000 hour period during which the pressure and temperature are cycled over their specified operating ranges with power applied, and over the storage temperature range without power. The stability is the same whether the transducer is operating or not. The deviation is measured in volts and divided by sensitivity to express the specified error in psi.

SPAN SPECIFICATIONS

The span characteristics are measured at 25°C with 15V excitation and with the applied pressure set first at maximum, then at reference to obtain the span voltage. Since the span errors are proportional to pressure and specified at maximum pressure P_{MAX}, they define the maximum span or full scale error. To determine the span error at any intermediate pressure P, multiply by the ratio $(P - P_{REF})/(P_{MAX} - P_{REF})$. The span errors are measured and specified as follows:

Sensitivity Calibration: Defines the slope of the best straight line fitted to the response curve with forced reference at the reference pressure output voltage. Also defines the sensitivity deviation from unit to unit, including long-term stability (1 year, shelf or operating). The deviation is measured in mV/psi and must be divided by the sensitivity and multiplied by the applied pressure range [$(P - P_{REF})$ for any pressure of interest or $(P_{MAX} - P_{REF})$ for the maximum error] to express the error in psi.

Span Temperature Coefficient (TC_S): Defines the maximum deviation in span voltage as temperature is varied from 25°C to any temperature from 0°C to +85°C. It is specified for P_{MAX} in psi/°C and must be multiplied by the temperature difference to obtain the error in psi. The maximum error is $(85°C-25°C) \cdot TC_S = (60°C) \cdot TC_S$.

Linearity-Hysteresis-Span Repeatability: Defines the maximum deviation in span voltage when the pressure is cycled from P_{REF} to P_{MAX} 50 times in a 1 minute period. Specified at P_{MAX} in psi.

Span Stability: Defines the maximum deviation in span voltage over a 1000 hour period during which the pressure and temperature are cycled over their specified operating ranges with power applied, or over the storage temperature range without power. The span stability is the same whether the transducer is operating or not. The deviation is specified at P_{MAX} in psi.

ACCURACY CALCULATIONS

As discussed above, the error coefficients are specified in a form that allows them to be used directly in overall accuracy calculations. To show how the specifications apply for various use conditions, we will perform calculations for a typical absolute pressure transducer, the LX1610A, with specifications given in Table 2. Analogous procedures will apply to any National hybrid IC pressure transducer.

In the calculations that follow, we will assume that excitation voltage is sufficiently regulated to keep its effect nil. The regulation required to satisfy this condition is derived as follows. The psi error E_{VR} resulting from output sensitivity to excitation voltage is given by:

$$E_{VR} = \frac{0.5\% \cdot \Delta V_e}{\text{Sensitivity}}$$

where 0.5% is the sensitivity to excitation voltage, ΔV_e is excitation voltage deviation and Sensitivity is the device sensitivity. For example, to keep the error below 0.06 psi (0.1% of the pressure range) for the LX1610A:

$$\frac{\Delta V_e}{V_e} = \frac{E_{VR} \cdot \text{Sensitivity} \cdot 100\%}{V_e \cdot (0.005)}$$

$$\frac{\Delta V_e}{V_e} = \frac{(0.06\text{ psi})(0.167\text{ V/psi})\ 100\%}{15\text{V}\ (0.005)} = 13\%\text{ Regulation}$$

which holds for any National pressure transducer. This degree of voltage regulation essentially eliminates voltage regulation error in all but ultra-high accuracy applications.

Referring to Table 2, the specified errors are first converted to *maximum error* (at T_{MAX} or 85°C for offset, at T_{MAX}, P_{MAX} for span), and the calibration tolerances are divided by the sensitivity. This converts the offset calibration error to psi, but the span calibration error must also be multiplied by P_{MAX}. The resulting errors, listed in the second row, are the maximum errors that can occur for each of the listed error coefficients. The span error at any pressure P can be obtained by multiplying these span errors by P/P_{MAX}. The third row lists the maximum errors that can occur at T_{REF} or 25°C. These are the same for all except TC_O and TC_S, which are both zero at T_{REF}. The fourth row under *span* shows the error at P_{REF}, which is zero for all span errors.

CALIBRATED VS INTERCHANGEABLE ACCURACY

In calculating overall accuracy, the first question is whether each pressure transducer device will be calibrated upon installation or replacement. If so, you will want to use the *calibrated accuracy,* which holds only for one specific transducer unit. The calibrated overall accuracy excludes National's calibration errors but includes all other applicable specified errors:

Calibrated Accuracy: E_C = Stability + (TC + Linearity + Hysteresis + Repeatability). But if you're going to just plug it in with no adjustments, you'll need the *interchangeable accuracy,* which allows for unit-to-unit calibration errors. In this case you include National's calibration errors but exclude stability error (the specified calibration error includes both calibration and stability errors):

TABLE 2. LX1610A Absolute Pressure Transducer Specifications

OPERATING PARAMETERS

Excitation Voltage	15V
Output Voltage Span	10V
Pressure Range	0 to 60 psia
Temperature Range	0°C to +85°C

GENERAL NOISE PARAMETERS

Output Sensitivity to Excitation	0.5%
Electrical Noise (0 ≤ f ≤ 1 kHz)	0.04% of Span

OFFSET ERRORS

COEFFICIENT	CALIBRATION	TEMPERATURE COEFFICIENT (25°C REF.)	REPEATABILITY	STABILITY
Specified Error	2.5 ±0.25V	±0.018 psia/°C	±0.2 psia	±0.6 psia
Maximum Error (at 85°C)	±1.5 psia	±1.08 psia	±0.2 psia	±0.6 psia
Error at 25°C	±1.5 psia	0	±0.2 psia	±0.6 psia

SPAN ERRORS

COEFFICIENT	SENSITIVITY CALIBRATION	TEMPERATURE COEFFICIENT (25°C REF.)	REPEATABILITY	STABILITY
Specified Error	167 ±3.3 mV/psia	±0.018 psia/°C	±0.36 psia	±0.24 psia
Maximum Error (85°C, P_{MAX})	±1.2 psia	±1.08 psia	±0.36 psia	±0.24 psia
Error at 25°C	±1.2 psia	0	±0.36 psia	±0.24 psia
Error at P_{REF}	0	0	0	0

Interchangeable Accuracy: E_I = Calibration + (TC + Linearity + Hysteresis + Repeatability) where E_I is the overall error allowing for direct exchange of transducers of the same type, with the same operating conditions.

Of course, either of these errors can be calculated as worst-case (simple linear addition, as shown) or most probable errors. To keep it simple, we will work mainly with worst-case error, remembering that the most probable error is always smaller and easily calculable via the square root of the sum of the squares.

MAXIMUM ERROR

Referring again to Table 2, the maximum possible error occurs at T_{MAX} with P_{MAX} applied. Under these conditions, the *calibrated overall error* E_C is:

$$E_C = \underbrace{(1.08 + 0.2 + 0.6)}_{\text{Offset}} + \underbrace{(1.08 + 0.36 + 0.24)}_{\text{Span}}$$

Worst-Case: $E_{WCC} = 1.88 + 1.68 = 3.56$ psia

Most Probable: $E_{MPC} = \sqrt{1.57 + 1.35} = 1.71$ psia

which represent, respectively, 5.9% and 2.9% of the operating pressure range. The corresponding *interchangeable overall error* is:

$$E_I = \underbrace{(1.5 + 1.08 + 0.2)}_{\text{Offset}} + \underbrace{(1.2 + 1.08 + 0.36)}_{\text{Span}}$$

Worst-Case: $E_{WCI} = 2.78 + 2.64 = 5.42$ psia

Most Probable: $E_{MPI} = \sqrt{3.46 + 2.74} = 2.49$ psia

which represent, respectively, 9.0% and 4.1% of the operating pressure range.

REDUCING TEMPERATURE ERRORS

Since the temperature coefficients are two of the main error components, a reduced temperature range or some form of external temperature compensation can greatly reduce overall error. Considering the previous example, a 50% to 80% effective temperature compensation is sufficient to bring TC errors into line with other errors. The TC error is usually monotonic and measured and compensated using the minor output for temperature. For 80% effective temperature compensation (reducing effective range from 60°C to 12°C):

$$E_C = (\underline{0.22} + 0.2 + 0.6) + (\underline{0.22} + 0.36 + 0.24)$$

Reduced TC Errors

Worst-Case: $E_{WCC} = 1.02 + 0.82 = 1.84$ psia

Most Probable: $E_{WCI} = \sqrt{0.45 + 0.24} = 0.83$ psia

which results in 3.1% and 1.4% overall errors, reduced from 5.9% and 2.9% by 80%-effective temperature compensation. A corresponding improvement is achieved for the interchangeability accuracy:

$$E_I = (1.5 + \underline{0.22} + 0.2) + (1.2 + \underline{0.22} + 0.36)$$

Reduced TC Errors

Worst-Case: $E_{WCI} = 1.92 + 1.78 = 3.70$ psia

Most Probable: $E_{MPI} = \sqrt{2.34 + 1.62} = 1.99$ psia

which results in 6.2% and 3.3% overall errors, reduced from 9.0% and 4.1%, respectively.

AUTO-REFERENCE COMPENSATION

A more powerful, easier to use, and generally applicable method, the auto-reference technique can often eliminate all offset errors by periodic sampling of the offset voltage at reference pressure. With this technique, (see Section 7), only the span errors apply. Again, using the LX1610A specifications, the calibrated accuracy is:

$$E_C = \underbrace{(1.08 + 0.36 + 0.24)}_{\text{Span}}$$

Worst-Case: $E_{WCC} = 1.68$ psia

Most Probable: $E_{MPC} = \sqrt{1.35} = 1.16$ psia

which reduces the error to 2.8% or 1.9%, as compared with 5.9% and 2.9%. For interchangeable accuracy it is even more effective:

$$E_I = \underbrace{(1.2 + 1.08 + 0.36)}_{\text{Span}}$$

Worst-Case: $E_{WCI} = 2.64$ psia

Most Probable: $E_{MPI} = \sqrt{2.74} = 1.65$ psia

resulting in 4.4% and 2.8% overall error as compared with 9.0% and 4.1% without auto-reference compensation.

AUTO-REFERENCE + TEMPERATURE CONTROL

For very high accuracy applications, both auto-reference and temperature range reduction may prove valuable. In these cases, the temperature may take the form of a temperature-controlled chamber designed to hold temperature within a few degrees of T_{REF} (which may be shifted to a higher temperature to allow use of an oven). In such a case, the only errors included are linearity-hysteresis-span repeatability and span stability. For calibrated accuracy:

$$E_C = \underbrace{(0.36 + 0.24)}_{\text{Span (without TC error)}}$$

Worst-Case: $E_{WCC} = 0.6$ psia

Most Probable: $E_{MPC} = \sqrt{0.1872} = 0.43$ psia which reduces error to 1% and 0.72%. For interchangeable accuracy, calibration error is included:

$$E_I = \underbrace{(1.2 + 0.36)}_{\text{Span (without TC error)}}$$

Worst-Case: $E_{WCI} = 1.56$ psia

Most Probable: $E_{MPI} = \sqrt{1.57} = 1.25$ psia

resulting in 2.6% and 2.1% overall interchangeable errors.

STABILITY COMPENSATION

With calibrated overall error down to a fraction of a psi, resulting from auto-reference and temperature control, the periodic recalibration of span may become worthwhile. Since the span stability error is a slow aging variation of span voltage and specified for one year, operating or not, a weekly recalibration may well reduce this error by an order of magnitude. Such a recalibration also eliminates the calibration errors so that only calibrated accuracy applies.

$$E_C = (0.36 + \underbrace{0.04}_{\text{Reduced Stability Error}})$$

Worst-Case: $E_{WCC} = 0.4$ psia

Most Probable: $E_{MPC} = \sqrt{0.1312} = 0.36$ psia

resulting in 0.67% and 0.6% overall calibrated accuracy.

LINEARITY COMPENSATION

For ultra-high accuracy applications, the remaining error, linearity-hysteresis-span repeatability must be reckoned with. The hysteresis and repeatability components of this coefficient are so small as to approach the noise in the operational amplifier included in the hybrid IC pressure transducer. (In a 1 kHz bandwidth, this noise is about 0.04% of full scale for a 1 kHz bandwidth and may require narrow band techniques if ultra-high accuracy is to be achieved). We do know, however, that the linearity error is a large fraction of the remaining error, perhaps as high as 90%, and that it can be successfully compensated via curve-fitting techniques to reduce overall calibrated error to about 0.1%, worst-case.

SUMMING IT UP

As can be seen by these examples, the errors specified for National's transducers are the worst-case errors within the specified operating range. You can obtain higher levels of accuracy by system-error analysis, restriction of operating parameter ranges and error compensation. The main error-causing parameters are time and temperature, and the most effective compensation technique is auto-referencing. For higher system-accuracy requirements, a finer degree of error control can be provided by periodic calibration and linearization.

Section 4

Configurations, Packaging and Environment

MERELY TOUGH ENVIRONMENTS

The operating environment for a pressure transducer can vary from merely tough to really tough. That's why National hybrid transducers are provided in a variety of configurations, ruggedly packaged to withstand the hard knocks of reality, resist corrosive operating fluids, and prevent extraneous mechanical coupling with the pressure sensor. By selecting the right configuration for the right job, you will avoid the undue cost of *over-qualified* versions and the reliability problems of *under-qualified* versions. You will also reduce the transducer's task from really tough to merely tough. (And, your boss will give you a raise).

Configurations, Packaging and Environment

PRESSURE-FLOW ENVIRONMENTS

The basic IC pressure transducer is a rugged, corrosion resistant device, but its operating environment often presents some special problems. Because it is connected directly into a pressure-flow system, the transducer may be required to withstand unusual vibration and stress levels and the attack of corrosive working fluids. To meet this wide range of operating environments, National's basic IC pressure transducer is provided in a variety of functional and package configurations.

BASIC TRANSDUCER STRUCTURE*

The basic IC transducer comprises a single-crystal silicon sensor with supportive circuit components mounted on a ceramic substrate like a conventional hybrid IC *(Figure 1).* The silicon sensor, which responds to either positive or negative pressure, includes a reference pressure cavity which encloses a vacuum in *absolute* transducers or is open (via the alternate inlet) in *gage* or *differential* transducers. With minor circuit modifications for the *differential* and *backward gage* versions and inclusion of appropriate pressure ports, the same basic transducer device can serve for all three basic pressure measurements.

THE SHOCK AND VIBRATION PROBLEM

While vibration is a serious problem for most pressure transducers, it is no problem at all for the hybrid IC pressure transducer. Like other hybrid IC's, the IC transducer is reliable in extreme shock and vibration environments, and the high natural frequency (>50 kHz) of its low-mass sensor diaphragm is far above normal equipment vibration frequencies. In a liquid system, the natural diaphragm frequency is typically reduced by more than an order of magnitude, but it is also heavily damped by the working fluid.

THE STRESS PROBLEM

Since the sensor diaphragm responds to direct stress from applied pressure, it is also sensitive to indirect stress due to substrate deformation. To help prevent this parasitic stress, the sensor chip is mounted upon the substrate via a stress attenuating pedestal. This mount is adequate for low external stress environments, but additional mechanical isolation is required for higher accuracy or in systems where extraneous forces are encountered. The required isolation can be provided by flexible cables and rugged housing and plumbing, all of which are available in National's standard pressure transducer products, as discussed later in this section. To prevent stress-related errors, a maximum degree of stress prevention is strongly recommended for most applications.

THE CORROSION PROBLEM

While standard IC devices can be protected from corrosive environments by simple hermetic enclosure, the IC pressure transducer circuit must be mechanically coupled with the working fluid. Depending on the nature of the fluid, the coupling can be either direct or via an intermediate fluid. To allow direct coupling with some fluids and protect the transducer in storage, the circuit is

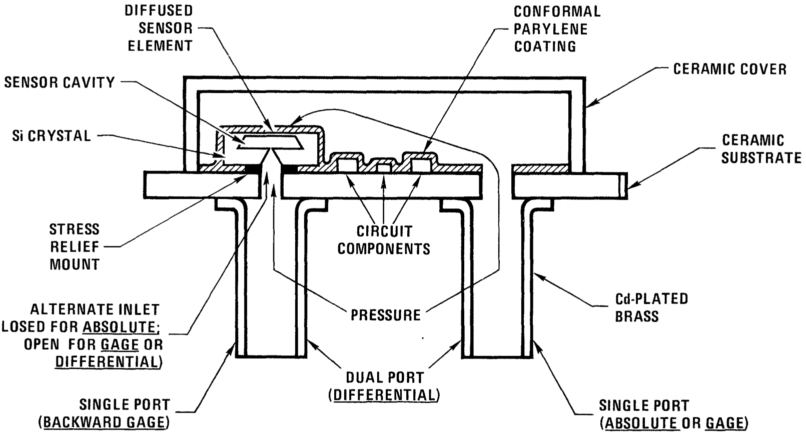


FIGURE 1. Basic Hybrid IC Pressure Transducer Structure

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*National Patent 3,909,924

coated with a thin compliant layer of parylene. When the transducer is not operating, this protects against virtually all corrosive, ionic and conductive fluids (Table I). In operation, however, it protects only against non-ionic and non-conductive fluids such as air, oil and alcohol. Additional protection is required for operation with ionic or conductive fluids such as water and aqueous solutions. The required protection can be provided by fluidic isolation, available as the "F" option for *absolute* or *differential* versions; or by using the *backward gage* version, which applies the pressure to the back side of the sensor diaphragm.

THE FLUID-FILLED "F" OPTION

For systems with corrosive or conductive working fluids, additional protection for the circuit can be provided by the "F" option. As shown in *Figure 2,* the transducer interior is filled with a carefully de-gassed silicone oil that is isolated from the working fluid by a silicone "sock". This sock provides a highly compliant barrier that correctly transmits pressure to the silicon sensor diaphragm yet protects the circuit from corrosion by the working fluid. Transducers with the "F" option meet all guaranteed specifications, but typical performance characteristics may be affected in some applications.

Frequency Response: The damping effect of the oil on the sensor diaphragm reduces frequency response from the normal 50 kHz to less than 1 kHz. Hence the fluid-filled versions are not recommended for audio frequency applications.

g-Load Errors: The fluid-filled transducer acts as a very insensitive liquid accelerometer. The resulting errors are very small, less than 0.1% of span in the most sensitive transducer (LX1601), for 1g.

Low Pressure: At very low pressures approaching vacuum, a small residual gas bubble may expand and limit signal output.

"Sock" Reliability: In most applications, the silicone sock has a life of a few hundred thousand full pressure cycles. Its life may be reduced by working fluids that attack the membrane or by very fast high pressure pulses (water hammer effect).

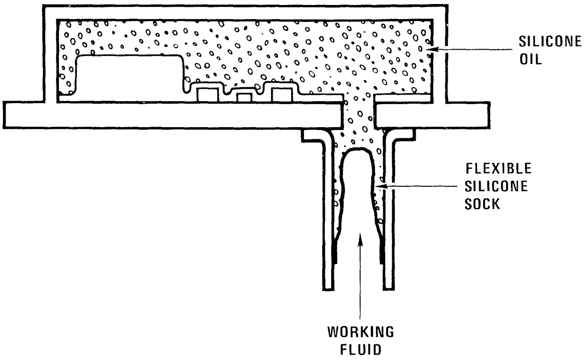


FIGURE 2. Basic Fluid-Filled Configuration PX6F

TABLE I. PROPERTIES OF PARYLENE

MATERIALS	EFFECT	TRANSDUCER
Alcohols, ketones, acetic acids and oxygenated solvents including brake fluid, Aliphatic hydrocarbons such as hexane, octane, cyclohexine and gasoline.	Zero Effect	Safe for Operation or Storage
Aromatic hydrocarbons such as toluene and xylene, and water.	Slow Penetration	Safe for Storage only
Chlorinated hydrocarbons such as carbon tetrachloride and chlorobenzene.	Slight Temporary Swelling	Not Safe for Operation or Storage
All organic solvents.	Insoluble below 150°C	
Inorganic solvents such as strong alkaline solutions, concentrated salt solutions and strong acids such as HCl.	Insoluble below 125°C	

Chemical Resistance: The silicone sock is highly resistant to most working fluids, as shown in Table II.

BACKWARD GAGE ISOLATION

In the backward gage transducer, the primary pressure input is applied to the back side of the sensor diaphragm as shown in *Figure 3.* This fully protects the circuit elements from the working fluid but exposes it to the ambient environment. While the parylene coating protects against "normal" atmospheric moisture, extremely high humidity sufficient to condense moisture on the parylene can cause long term degradation. In such cases, the fluid-filled differential transducer can be used, combining the advantages of fluidic and backward gage isolation.

TABLE II. PROPERTIES OF SILICONE SOCKS

Weather and Sunlight Resistance Ozone Resistance Oxidation Resistance Alkali Resistance Animal and Vegetable Oil Resistance	Excellent
Electrical Resistance Flame Resistance Compression Set Resistance Water Resistance Acid Resistance Dilute Hydraulic Fluids: Water-Glycol Lubricating Oils: (petrol base) High Anilene	Good
Radiation Resistance Steam Resistance Acid Resistance Concentrated Alcohols Oxygenated Solvents: Acetone MEK Hydraulic Fluids: Phospate Ester Lubricating Oils: (petrol base) Low Anilene	Fair
Tear Resistance Abrasion Resistance Brake Fluids (non-petroleum base) E. P. Gear Lubricant Gas Permeability	Poor
Chlorinated Hydrocarbons: Chloroform Carbon Tet Trichlor, Perclor Diester Synthetic Lubricants Gasoline Synthetic Lubricants Aliphatic Hydrocarbon Resistance Hexane Isooctane Aromatic Hydrocarbon Resistance Toluene Benzene Hydraulic Fluids: Petroleum Silicate Ester	Not Recommended

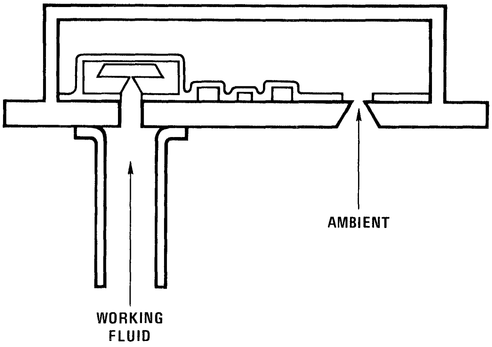


FIGURE 3. Backward Gage Configuration PX6B

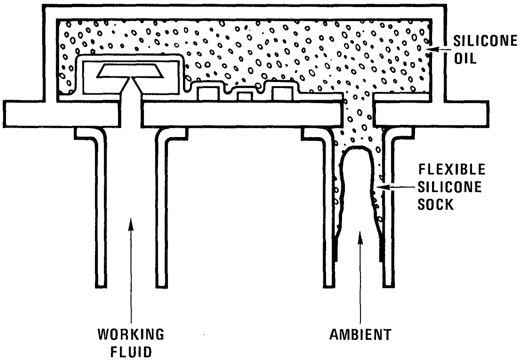


FIGURE 4. Fluid-Filled Differential Configuration PX6DF

HOUSING AND PLUMBING OPTIONS

The PX6 Hybrid IC Package

The basic PX6 package is used for the LX16XX Series transducers and is available in absolute, gage, backward gage and differential configurations, with or without fluidic isolation. As shown in *Figure 5,* the PX6 hybrid IC package series is ideal for PC board mounting and for systems requiring a definitive electrical/plumbing interface to facilitate separate maintenance domains. Because the PX6 doesn't include a protective housing or rigidly held fittings, it is subject to stress produced by extraneous forces (especially the differential version) and should not be used where such stress could interfere with the required system accuracy. In such cases, the user should perform a simulated or actual system-mechanical test to evaluate stress-related errors or consider use of a more rugged package before final selection.

The PX4 "Absolute" Housings

The PX4 housing provides a rugged, compact and fully plumbed package for the LX14XXA Series of absolute pressure transducers. As shown in *Figure 6,* it is concentric for easy installation and includes hermetically sealed flying leads for safe, easy soldering and secure wiring connections. It is available in standard brass or optional stainless steel (PX4S),with or without fluidic isolation. The fluid-filled version (PX4F) includes an extension to the basic PX4 package, as shown in *Figure 7,* and provides a package that is totally submersible in hostile fluids.

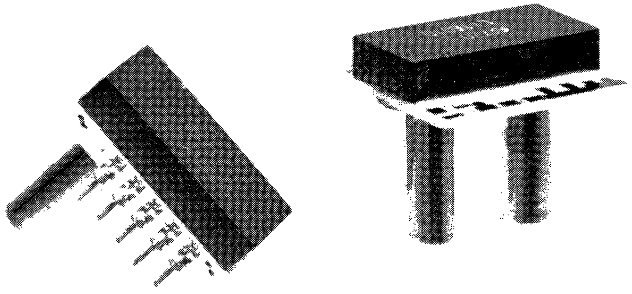


FIGURE 5. PX6 and PX6D Packages

FIGURE 6. PX4(S) Housing for LX14XXA(S) Absolute Transducers

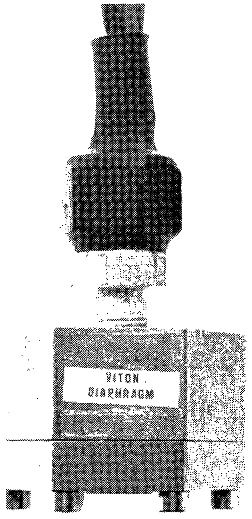


FIGURE 7. PX4F(S) Stainless Steel Housing for LX14XXAF(S) Transducer, Fluid-Filled

The PX7 Series Housings

Like the PX6 package, the PX7 is available in any functional configuration (absolute, gage, backward gage or differential), with or without fluidic isolation. But as the basic package for the LX17XX series transducers, the PX7 also includes a rugged, fully plumbed housing for mechanical and environmental isolation. To meet various functional requirements, it is available in a variety of materials.

Absolute and Gage Configurations: As shown in *Figure 8,* the PX7 absolute, gage and backward gage versions all include a rugged housing with a 1/8" NPT fitting to isolate the transducer from extraneous forces in the system. Both the absolute and gage versions are available in molded nylon (PX7N), which provides a lightweight package that is low in cost yet rugged. The nylon is ideal for food process, medical and other "clean" applications. The most rugged LX17XXA and LX17XXG housings are also available in cast zinc (PX7). The backward gage version (PX7B) is available only in zinc.

PX7D Differential Housing: In a differential transducer, a high common-mode line pressure at the two ports applies an extraneous force to the transducer. To isolate the transducer from this force, the two ports must be rigidly held. As shown in *Figures 9 and 10,* the PX7D version holds the ports in a rugged brass housing with 1/8" NPT female fittings to provide the required isolation.

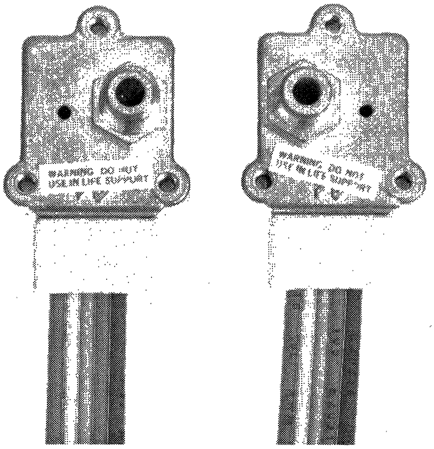


FIGURE 8. PX7(N) Housing for LX17XXA(N) Absolute or LX17XXG(N) Gage Transducers and PX7B Housing for LX17XXGB Backward Gage Transducers

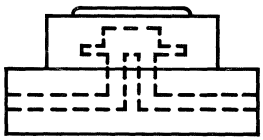


FIGURE 9. PX7D Housing with Port Structure

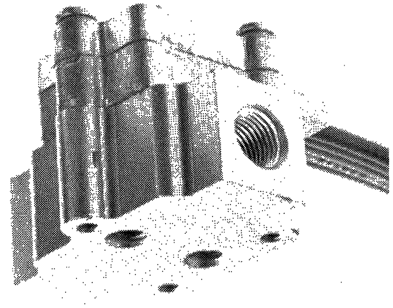


FIGURE 10. PX7D High Common-Mode Differential Housing for LX17XXDD Transducers

Section 5

Installation

"GOODBYE, RUBE GOLDBERG"

As fellow inventors we are awed by Rube Goldberg's genius for lashing up incompatible components, but National's standardized pressure transducers simply don't need that kind of genius. What they do need is a simple electromechanical interface with adherence to a few simple rules, like: "Anchor by pressure port or NPT fitting only", "Don't stress the ceramic or pins", and "Bypass V_E to prevent oscillation". If Rube Goldberg was on your staff, he would probably say the same thing, maybe more. But since he isn't, say, "Goodbye, Rube Goldberg", and use the methods given in this section and your own ingenuity for a simple, reliable pressure transducer installation.

Installation

PRESSURE TRANSDUCER INSTALLATION

Although National's pressure transducers are ruggedly built for high performance and reliability, they require reasonable care in electromechanical interface design and assembly to ensure high accuracy and trouble-free service in a pressure flow system. To ensure interface integrity, this section provides recommended methods for mechanical mounting and electrical connection plus assembly tips for a wide range of applications. The interface requirements are generally different for each package type, but the following rules apply to all National IC pressure transducers.

"ANCHOR BY PRESSURE PORT OR NPT FITTING ONLY"

National pressure transducers are designed to be anchored by the pressure port or NPT fitting threads and should *not* be supported by gripping the transducer housing. The only exception to this rule is the PX7D housing which includes two female screw fittings for panel mounting as well as two female 1/8" NPT pressure ports. The port is rigidly connected on all models and fully capable of supporting the transducer weight without causing stress. Gripping the transducer body *causes* stress. For specific mounting methods see discussions for individual package types.

"DON'T STRESS THE CERAMIC OR PINS"

As with any integrated circuit package, the basic ceramic package and pins should be protected from mechanical abuse in assembly and in final use. This can cause inaccuracy and premature failure. The ceramic is especially vulnerable in the PX6 since it is not protected by an external housing. To avoid stress in the PX6, use only flexible tubing mounted firmly in a "stress-relief" bracket near the transducer and carefully aligned with it. The PX7 package prevents ceramic stress internally, but its cable must be firmly anchored near the transducer to avoid stress on the pins. Only the PX4 fully protects both the ceramic and the leads from stress. However, it is still good practice to tie down the leads near the PX4 housing. For specific stress prevention methods see discussion of individual package types.

"BYPASS V_E TO PREVENT OSCILLATION"

As with any device containing operational amplifiers, the IC pressure transducer requires a power supply bypass capacitor to prevent oscillation in electrically noisy environments. The only exception is the LX16XX and only when it is connected to a nearby active device on the same PC board. An unbypassed transducer may oscillate at 1 to 20 MHz, which causes anomalous behavior of its low frequency response, as shown in *Figure 1*. To prevent oscillation, a 0.22 μF ceramic or 1 μF tantalum capacitor is usually sufficient *(Figure 2)*. The capacitor should be connected as near the transducer as possible and must be within 4 inches of the transducer connector pins. For specific capacitor mounting and connection, see discussions of individual package types.

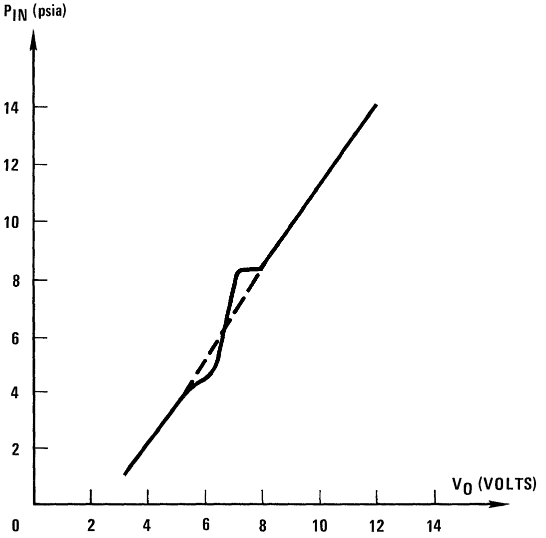
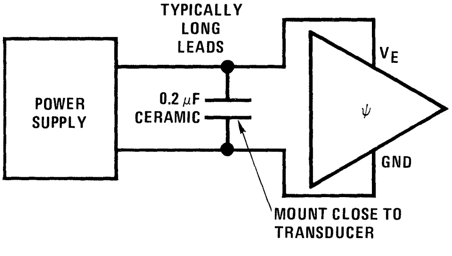
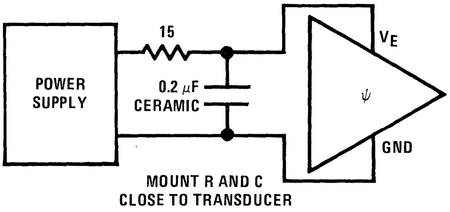


FIGURE 1. Typical Response Anomaly Caused by Unbypassed Transducer



(a) Simple Capacitor Bypass



(b) RC Supply Bypass for Long Inductive Cables

FIGURE 2. Power Supply Bypass for IC Pressure Transducers

TESTING THE TRANSDUCER

In testing the transducer be sure to stay within its maximum specifications and avoid tests in which moisture may enter the pressure port.

> **Important:** *Do not* blow in the port to see if the transducer is working. This can cause moisture to condense on the circuit or leads and cause performance degradation.

For high accuracy applications (~1%), each transducer must be tested and calibrated, since calibration and linearity errors may vary from one transducer to another by a considerable magnitude.

The test set-up should provide a simple electromechanical interface that doesn't mistreat or stress the transducer and which generally adheres to the rules outlined above and those that apply to the specific transducer under test. The test jig should use an appropriate connector rather than solder for electrical contact. For the LX16XX series a standard dual-in-line socket can be used. The LX17XX series transducer cable end connector is designed to mate with a zero-insertion-force connector for incoming inspection, calibration or other testing. This connector is cut off before final installation and hence cannot be used for field recalibration. For the LX14XX Series use alligator clips or similar connector devices.

THE PX6 SERIES—PC BOARD MOUNT

The LX16XX Series pressure transducer is provided in the basic PX6 hybrid IC package for PC board mounting only. This package must be supported only by the pressure port and connected only to flexible tubing. The PX6 can be mounted either horizontally or vertically on the PC board as shown in *Figures 3 through 6.* The horizontal mount is preferred since it is less sensitive to alignment and provides a stress-free mount with a simpler assembly procedure.

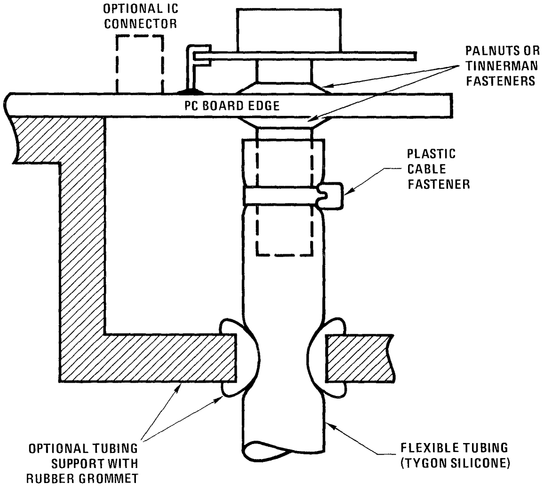


FIGURE 3. Preferred Horizontal PX6 Installation (Single Port)

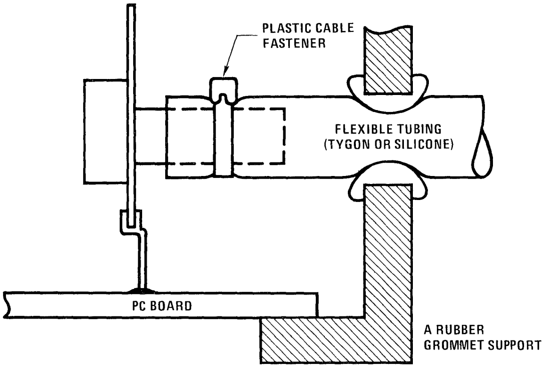


FIGURE 4a. Rubber Grommet Support

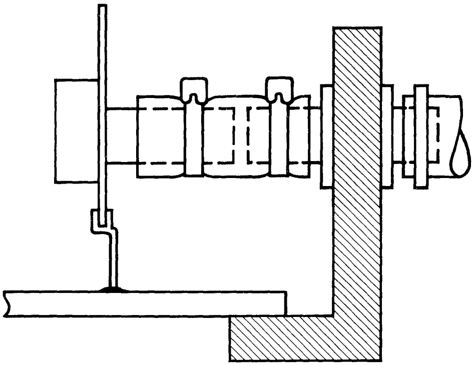


FIGURE 4b. Quick Disconnect Support (Recommended for Dual-Port (PX6D) Packages)

PC BOARD ASSEMBLY TIPS

The assembly procedure will depend on whether the PX6 is to be mounted horizontally or vertically and whether dip or spot soldering is to be used. In either case, ensure that the soldering profile is not exceeded (260°C for 10 seconds) and that the flexible tube is aligned with the pressure port and does not cause stress on the ceramic package or leads once final mechanical connection is made.

DIP OR WAVE SOLDERING

To avoid soldering the pressure port or tube bracket, the transducer is first inserted in the PC board as shown in *Figure 7* then dip soldered before final mechanical connection.

Horizontal Mount—Preferred: After soldering, the transducer is tilted from its vertical soldered position into its final horizontal position with its port inserted through the slot in the PC board and held securely with two Palnuts or Tinnerman fasteners (only one port fastened if dual-port PX6D). The support bracket for the flexible tube can then be added and the port-tube connection made. For the single port PX6 package this mount is not sensitive to tube-port alignment and easily results in a stress-free mount. However, with the dual-port PX6D version, great care is required in maintaining port-tube alignment to prevent stress in the ceramic package.

Vertical Mount—Acceptable: After soldering, the tube support bracket is added and connection made between the pressure port and flexible tubing. To prevent stress (especially for the dual-port version), a spacer should be used to accurately position the transducer before soldering.

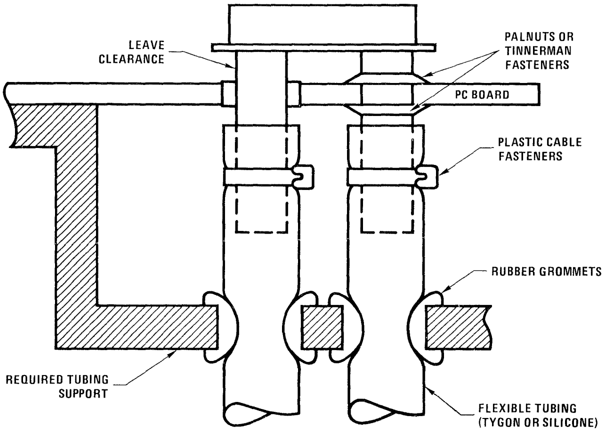


FIGURE 5. Preferred Horizontal PX6D Installation

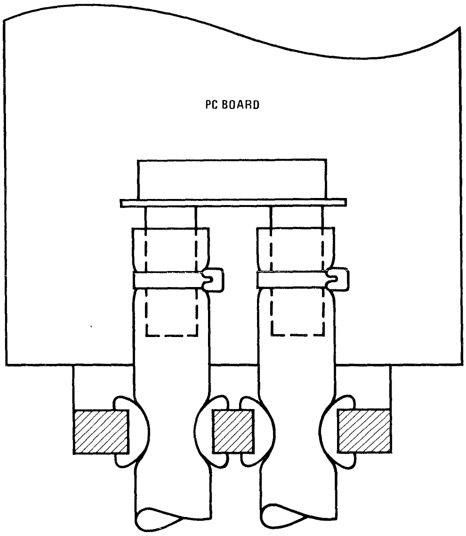


FIGURE 6. Optional Vertical PX6D Installation (Top View)

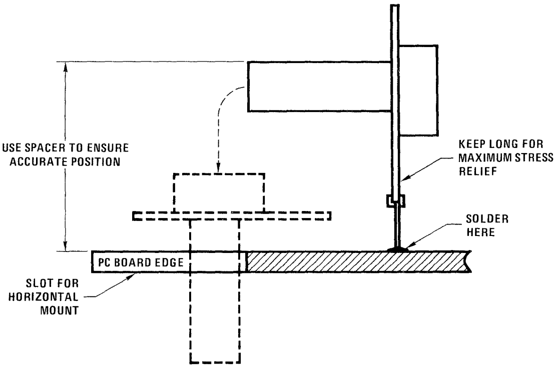
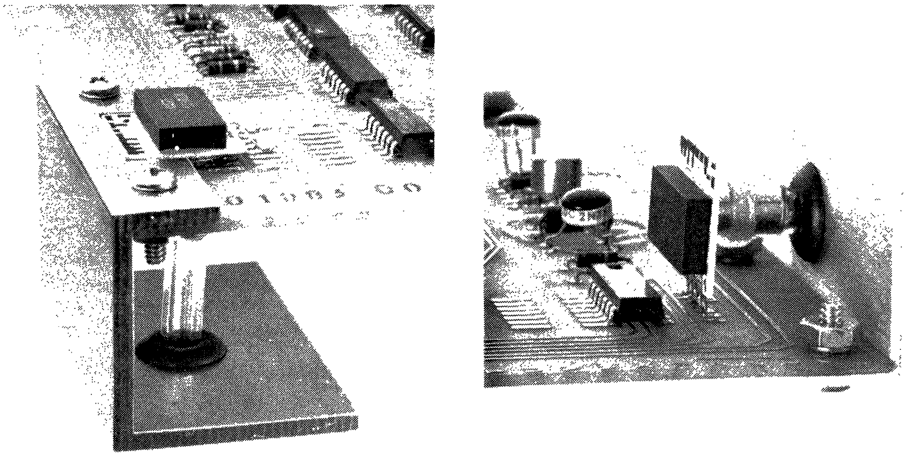


FIGURE 7. PX6(D) in PC Board for Dip Soldering



(a) Horizontal (b) Vertical

FIGURE 8. PX6 in Horizontal and Vertical Mount

SPOT SOLDERING

If the transducer leads are to be spot soldered the transducer can be inserted in the PC board and final mechanical connection made before soldering. To prevent damage to the package apply solder only to the tip of the lead and keep solder and heat of soldering away from the lead-ceramic interface. Before soldering, be sure that the pressure port and flexible tubing are aligned and securely fastened with the transducer in its final vertical or horizontal position.

SPECIAL ELECTROMECHANICAL PRECAUTIONS

The LX16XX transducer provides reliable service when properly installed, but its performance or service life can be impaired with an improper electromechanical interface. To ensure reliable service, adhere to the following additional rules:

Mechanical: The ceramic package should never be potted or allowed to touch or be constrained by another hard surface. Either of these can severely damage the ceramic base or lid.

Electrical: Pins 3 and 4 should never be grounded, and no connection at all should be made to pin 4. Pin 3 is the temperature sensor output and, if used, should only be connected to a high impedance amplifier (see temperature sensor discussion below). The transducer output signal (pin 1) should *never* be connected to an impedance of less than 1k. Unless the output signal is connected to another active device nearby on the same PC board, a bypass capacitor (0.22 μF ceramic or 1 μF tantalum) should be connected between pin 5 (V_E) and pin 2 (ground), to prevent oscillation in noisy electrical environments. The capacitor should be mounted on the PC board as near the transducer as possible (within 4 inches trace length). The power supply leads must never be reversed, and the operating voltage, V_E should *always* be at least 10V. With this voltage the maximum output signal is 8V. The recommended minimum normal operating voltage, V_E is 15V. This provides the full signal output of 13V maximum.

PX6(D) "DO'S AND DON'T'S"

DO

- Insert transducer in PC board and *dip solder* before mechanical connection.
- Insert transducer in PC board and make mechanical connection before *spot soldering.*
- Use flexible tubing (tygon or silicone) and anchor to PC board for stress relief.
- Use plastic cable wraps to clamp tube to pressure port.
- Anchor port to PC board in *horizontal mount* with two Palnuts or Tinnerman fasteners or with adhesive, without directly supporting the ceramic package.
- Install capacitor for V_E-to-ground bypass, within 4 inches trace length on PC board (0.22 μF ceramic or 1 μF tantalum).
- Take special care to align pressure ports with flexible tubes with PX6D and PX6DF versions.

DON'T

- Anchor both ports of PX6D.
- Pot the ceramic.
- Submerge in water.
- Block gage port.
- Allow ceramic base or lid to touch other mechanical constraints.
- Misalign pressure port with flexible tube.
- Leave long catenary tube between bracket and port.
- Expect connector pins to take much punishment.
- Attempt to measure water or other corrosive fluid without backward gage or fluidic isolation.
- Ground pins 3 and 4.
- Make connection to pin 4.
- Reverse power supply leads or allow V_E below 10V.
- Operate with V_E higher than 30V
- Connect signal output to less than 1k impedance.

PX7 SERIES HOUSINGS

The LX17XX series transducer is provided in a rugged outer housing with 1/8" NPT fitting(s) and a 10-inch ribbon cable with a connector for use with a zero-insertion-force mating connector. This connector can be used for incoming inspection, calibration and testing but should be cut off for permanent installation (since there is no mating connector suitable for field installation).

PX7 SERIES MECHANICAL INTERFACE

Single-Port: The single-port housings (PX7, PX7F, PX7N, PX7FN) each have a single 1/8" NPT male fitting. The housing must be anchored by this fitting and the connection sealed with teflon tape as shown in *Figure 9.* It is especially important to use teflon tape between the two fittings when the zinc housing (PX7) is fit to a dissimilar metal. The nylon NPTS fitting (PX7N) should be used for a gasket or O-ring seal when it is inserted in a metallic female fitting and the system must work over a large temperature range. In either case, the female fitting must be rigidly held to minimize vibration. A typical PX7 installation is shown in *Figure 10.*

Dual-Port: The dual-port housings (PX7D and PX7DF) each have 2 in-line 1/8" NPT female fittings for pipe mounting and 2 1/4-20 threaded female screw holes for optional panel mounting. The housing is made of brass for extra strength and can be mounted either in-line as shown in *Figure 11* or on a panel as shown in *Figure 12.* As with the single-port versions, it is good practice to seal the PX7D pressure connections with teflon tape and use a rigidly held mount to minimize vibration.

Cable Support: The cable is connected directly to the transducer pins and must be secured near the transducer to minimize stress on the pins *(Figures 9 through 12).* The section of cable between the cable support and the transducer should be short and firm.

Moisture Protection: The PX7 housing is environmental, not hermetic, and must be protected from moisture seepage into the cable-transducer interface. Moisture on the leads causes metallic plating while power is applied to the transducer. *Do not pot the transducer.* For operation in humid environments a separate hermetic outer enclosure should be used.

PX7 ELECTRICAL INTERFACE

Pins 3 and 4 should never be grounded, and no connection at all should be made to pin 4. Pin 3 is the temperature sensor output and, if used, should only be connected to a high impedance amplifier (see temperature sensor discussion). The transducer output signal (pin 1) should be connected only to an impedance of not less than 1k. A V_E-to-ground bypass capacitor (0.22 μF ceramic or 1 μF tantalum) must be connected on the cable to prevent oscillation in noisy electrical environments. As shown in *Figure 13,* the capacitor is connected between the green (V_E) and red (ground) wires no more than 4 inches from the transducer. The power supply leads must never be reversed, and the operating voltage V_E should *always* be at least 10V. With this voltage the maximum output signal is 8V. The recommended minimum normal operating voltage V_E is 15V. This provides the full signal output of up to 13V.

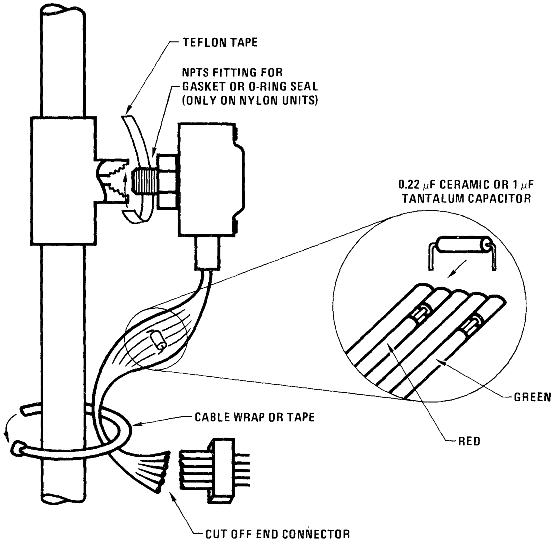


FIGURE 9. PX7 Housing Interface

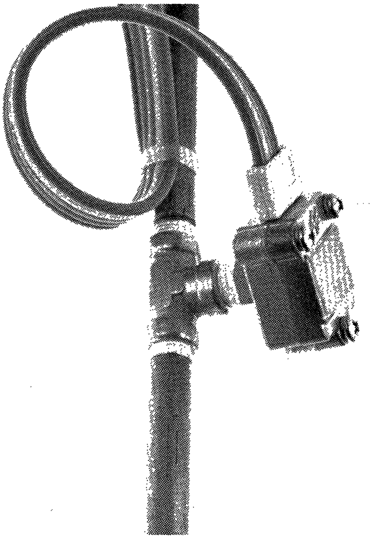


FIGURE 10. Typical Single-Port PX7 Installation

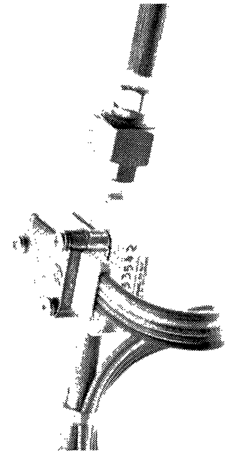


FIGURE 11. Typical PX7D In-Line Pipe Mounting with Rotary Unit

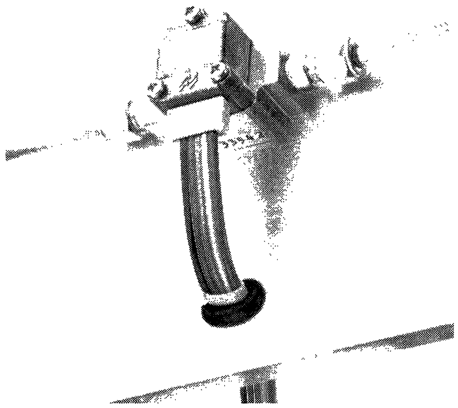


FIGURE 12. Typical PX7D Panel Mounting

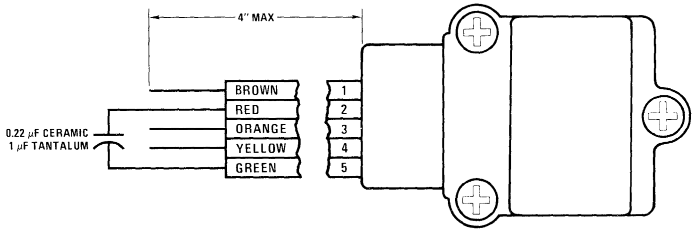


FIGURE 13. Capacitor Connection for PX7 (LX17XX) Series Packages

PX7 SERIES "DO'S AND DON'T'S"

DO

- Anchor by pipe threads into a rigid fitting.
- Use teflon tape to seal connection.
- Use NPTS thread on nylon PX7N package to make gasket or O-ring seal when metal fitting is used and system has wide temperature range.
- Use threaded holes for optional panel mounting of PX7D or PX7DF.
- Use separate outer hermetic enclosure in humid environments.
- Anchor cable close to transducer for stress relief.
- Use cable end connector with zero-insertion-force connector for incoming inspection and other testing.
- Cut off end connector for permanent installation.
- Install V_E-to-ground bypass capacitor (0.22 µF ceramic or 1 µF tantalum) in noisy electrical environments.

DON'T

- Screw zinc housing into dissimilar metal fitting unless teflon tape is used for chemical isolation.
- Allow catenary loop in cable.
- Seek mating connector for permanent installation (doesn't exist).
- Allow moisture to enter cable-transducer interface (seal is environmental, not hermetic).
- Submerge transducer in water.
- Pot the cable-transducer interface.
- Attempt to measure water or other corrosive fluid without backward gage or fluidic isolation.
- Connect pin 3 and 4 to ground.
- Make connection to pin 4.
- Connect signal output to less than 1k impedance.
- Reverse power supply leads or allow V_E below 10V.
- Operate with V_E higher than 30V.

PX4 SERIES HOUSINGS

The LX14XX Series transducer is provided in a concentric brass (PX4) or stainless steel (PX4S) housing with a 1/4" NPTS male fitting (female on PX4F or PX4FS) and three flying leads. The lead-transducer interface is epoxy-sealed for hermetic protection, which allows the PX4 to be used in extremely humid environments. With fluidic isolation (PX4F or PX4FS) the LX14XX Series transducer can be submerged in water without damage, but an outer hermetic enclosure is recommended if it is to be submerged in a saline solution or in water for an extended period (see next section). The PX4 series housing is ruggedly built for easy interfacing in any pressure-flow system, and it will provide high performance and reliable, trouble-free service if the following simple rules are adhered to in its electromechanical interface.

PX4 MECHANICAL INTERFACE

The PX4 Series housing is designed to be supported by its 1/4" NPTS fitting and must *not* be anchored by gripping the housing body. As shown in *Figure 14,* the PX4 (or PX4S) must be installed by applying a crescent wrench to the 0.94" hex nut immediately above the NPT fitting.

> **Important:** The wrench must never be applied to the larger, rubber-covered hex section, especially when backing the transducer out of a fitting, since this will disassemble the transducer and render it useless.

The pressure connection should be sealed with teflon tape between the fittings for low pressure fluids and with an additional gasket or axial O-ring seal in high pressure (especially gaseous) systems. The NPTS thread allows such an axial seal against the hex shoulder. Although the flying leads are secured by epoxy, it is good practice to fasten them to the transducer body with a plastic cable wrap or tape, leaving a loop for stress relief, to prevent long-term wire fatigue. Typical installation of the basic PX4 housing is shown in *Figures 14* and *15.*

PX4 ELECTRICAL INTERFACE

A V_E-to-ground bypass capacitor (0.22 μF ceramic or 1 μF tantalum) must be connected to the wires near the transducer to prevent oscillation in noisy electrical environments. As shown in *Figure 14,* the capacitor is connected between V_E (pin 3, red) and ground (pin 2, black) not more than 4 inches from the lead-transducer interface. The power supply leads must never be reversed, and V_E should always be at least 10V. With this voltage, the maximum signal output is 8V. The minimum recommended normal operating voltage is 15V, which provides the full signal output of 13V maximum. The signal output (pin 1, green) should be connected only to an impedance of at least 1k.

PX4 SERIES "DO'S AND DON'T'S"

DO

- Anchor by pipe threads in a rigid fitting.
- Use teflon tape to seal pressure connection.
- Use NPTS threads for a gasket or O-ring seal in high pressure systems.
- Apply crescent wrench only to 0.94" hex nut.
- Use separate outer hermetic enclosure for submersion in water.
- Secure leads to housing with plastic cable wrap or tape.
- Install V_E-to-ground bypass capacitor (0.22 μF ceramic or 1 μF tantalum) in noisy electrical environments.

DON'T

- Anchor transducer by gripping the housing.
- Submerge PX4 or PX4S in water.
- Submerge PX4F or PX4FS fluid-filled housing in water for extended periods.
- Apply wrench to housing.
- Reverse power supply leads or allow V_E below 10V.
- Connect signal output to less than 1k impedance.
- Operate with V_E higher than 30V.
- Attempt to measure water or other corrosive fluid without fluidic isolation.

EXTERNAL HERMETIC ENCLOSURES

The Submersion Problem

As with any electromechanical device, direct submergence in water or other corrosive fluid can cause immediate or long-term damage to the transducer, depending on the hermeticity of its package. The parts most vulnerable to moisture are the circuit components and connector leads. Although the circuit components can be fully protected by fluidic isolation with the "F" option, the leads are protected in various degrees, depending on the package type, all of which fall short of full hermetic protection against very corrosive liquids. For such applications, a hermetic outer enclosure such as described in this section is recommended.

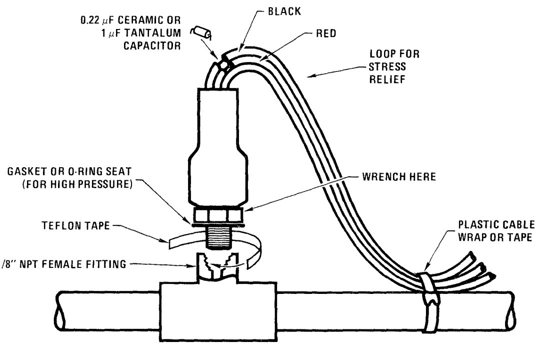


FIGURE 14. PX4 Housing Interface

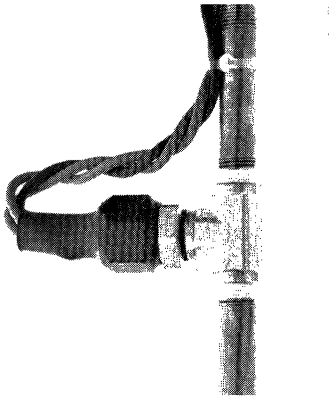


FIGURE 15. Typical PX4 Installation

TRANSDUCER SUBMERSION SUITABILITY

Only the fluid-filled "F" version of any transducer should be considered for full submergence. The lead protection and, hence, suitability for full submergence, varies with the package type:

PX6F Series: Since the PX6F leads have no hermetic or mechanical protection, the PX6F can be submersed only with a hermetic outer enclosure and only if the transducer is securely mounted to prevent stress on the leads.

PX7F Series: The PX7F leads are environmentally protected but vulnerable to moisture seepage into the lead-transducer interface. The fluid-filled versions (PX7F, PX7FN) are recommended for submersion only with an external hermetic enclosure.

PX4F Series: The PX4F leads are hermetically protected by an epoxy seal at the lead-housing interface. This allows the PX7F to be submerged in water for short periods, but an external hermetic enclosure is required for submergence in more corrosive fluids, such as saline solutions, or for extended periods in water.

SUBMERSIBLE ENCLOSURES

A submersible enclosure for a pressure transducer must normally provide four utilities:

1. Pressure port interface.
2. Electrical interface.
3. Suspension or mounting.
4. Maintenance access.

Standard hermetic enclosures normally provide for these needs using a rigid housing with machined O-ring seals and costly hermetic electrical feed-through connections. A hermetic pipe-section enclosure for the PX4D is shown in *Figure 16.* While providing the necessary utilities, this enclosure is unnecessarily complex and expensive for most transducer submergence applications.

COMPLIANT HOUSINGS—THE "RUBBER GLOVE"

Since the basic pressure transducer interface requires only pressure coupling and electrical connection, a simple, low-cost submersible pressure transducer assembly can be affected by inserting the transducer in a fluid-filled compliant bag. The ideal "bags" for this application are rubber gloves, inner tubes, football bladders and beachballs. These enclosures are similar to those used for marine submergence of pressure transducers and other electronics. The main advantage of this approach is that flexibility eliminates the requirement of strength in the outer enclosure. It is only a fluid separation membrane.

As shown in *Figure 17,* the rubber glove provides fluidic protection and pressure coupling similar to the "sock" used in the fluid-filled versions. Like the sock, it has a high surface-to-volume ratio and high resistance to corrosive fluids. Since the glove is low in cost and easy to assemble, it can merely be discarded when no longer needed.

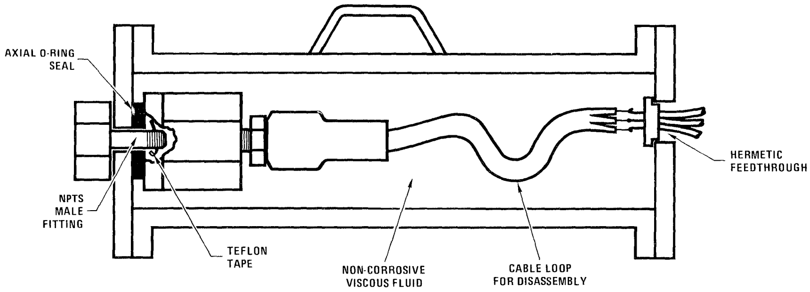


FIGURE 16. LX14XXF Transducer in Rigid Hermetic Housing

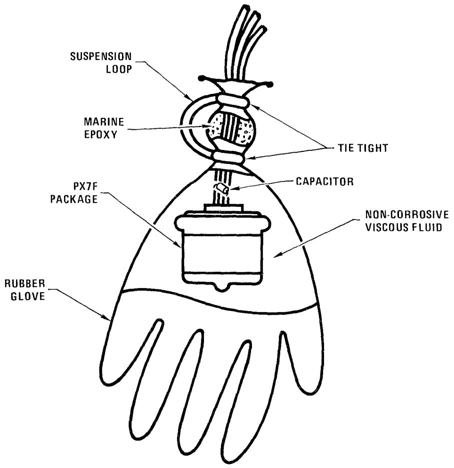


FIGURE 17. LX17XXF Transducer in Rubber Glove Assembly

GLOVE BUOYANCY

The glove assembly is lightweight for easy suspension, and its buoyancy can be controlled by the density of the enclosed fluid. The fluids normally used in marine applications have a density similar to plastic, about 2g/cc. The silicone fluids have a density of 0.7 g/cc and may be useful for submergence in low-density industrial fluids such as gasoline. Note that the density of the transducer and enclosed wire must be included in the buoyancy determination.

GLOVE ASSEMBLY

Assembly of the glove enclosure is simple but slightly more difficult if air bubbles are to be minimized as shown in *Figure 18.* Since the epoxy is slightly permeable to air, the air will eventually escape under pressure of deep submergence. This is of little consequence for most applications and only reduces buoyancy by a small amount. As shown in *Figure 19,* the PX6F must be firmly mounted on a small PC board for use in the rubber glove.

THE TEMPERATURE SENSOR

The internal temperature sensor (pin 3) of the LX16XX and LX17XX pressure transducers currently provides a near-linear response sensitivity of 2 to 4 mV/°C. This sensitivity can vary for each transducer and may change as improvements are made in National's pressure transducer circuits. It should therefore be calibrated for each transducer when the temperature sensor output is used.

As shown in *Figure 20,* the currently used temperature sensing element is a zener diode. To prevent excessive heating, current through the diode must be limited to 150 µA by a resistor connected between V_E (pin 5) and the temperature sensor output (pin 3). Pin 3 should be connected only to a high impedance amplifier.

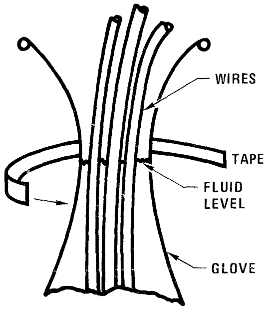


FIGURE 18. Assembling Glove with Minimum Air Content

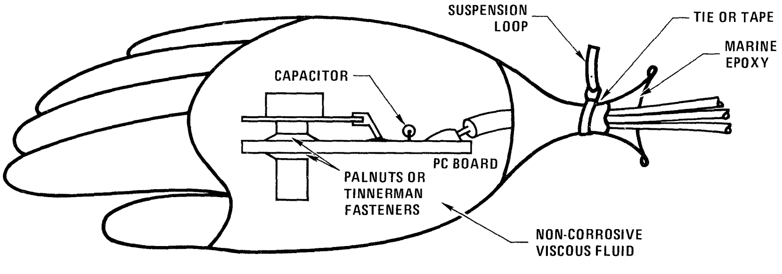
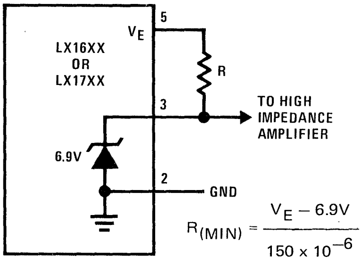


FIGURE 19. LX16XXF Installed in Rubber Glove Assembly



$$R_{(MIN)} = \frac{V_E - 6.9V}{150 \times 10^{-6}}$$

FIGURE 20. Temperature Sensor Connection

Section 6

Fluid Flow

THE GREAT HOW-DONE-IT?

The feats of great magicians have always mystified people, but as with any other technology, even fluid flow, the mysteries of magic can easily be unraveled if you know the secrets of the great How-done-it?. Of course, How-done-it? doesn't give up secrets easily, but with the help of other great magicians, such as Bernoulli, Joule and Clapeyron, we've managed to weasel out of him most of the simple truths relating the application of IC pressure transducers to pressure vessels, open flow, closed flow, and acoustics, along with the solution to one of the most elusive mysteries in the history of fluid flow: how to build a simple precision flowmeter with a linear output. The deeper mysteries of auto-referencing, signal conditioning, switch control theory, and specific IC pressure transducer applications are unveiled in later sections.

Transducers in Fluid Flow Applications

INTRODUCTION

People have been building fluid systems for many millenia and the knowledge of how to measure pressure in fluids is centuries old. So what's so special about the line of transducers introduced by National Semiconductor? In a nutshell, the solid state transducer allows much better sensing and, therefore, much better control of fluid systems for a given amount of money spent on system control.

To give the electrical engineer a better understanding of the strange worlds of mechanical, chemical, aeronautical, civil, and acoustical engineers we will describe the three basic classes of transducer applications. All transducer usages will fit into one of the following categories:

1. Pressure Vessel
2. Open Flow
3. Closed Flow

Each is thoroughly described and the key equations of each class are derived.

For a mental model think of "open flow" as represented by the flow of a fluid in which the main energy involved is simply kinetic. Water in an aqueduct or a long pipe where the potential energy at the dam up in the mountains or the compressive energy of the pump has long since been converted to the kinetic energy of the flowing stream.

For "closed flow," think of a compressor as used for example in refrigeration systems. Here the fluid density is changing and thus significantly contributing to the energy of the system, still primarily kinetic.

In a "pressure vessel" a stationary fluid is assumed.

Now on to the system modeling.

"PRESSURE VESSEL" APPLICATION

The simplest application of an absolute pressure transducer is the direct measurement of absolute pressure of a fluid at rest within a pressure vessel.

The concept of a pressure vessel is very general here . . . it merely represents that container of fluid which keeps the fluid free of dynamics. Thus, using this broad view, on a calm day . . . the world is a pressure vessel. Likewise, a vacuum chamber is a pressure vessel.

As indicated in *Figure 1,* the LX Series can be plumbed into the pressure vessel, thus adding its own package volume and that of the plumbing to the volume of the pressure vessel. Where the pressure vessel is small, this additional volume must be considered if the measurement or control function involved seeks some relationship between pressure and volume.* It is important to recognize that the change in volume of the transducer package with pressure change is entirely negligible.

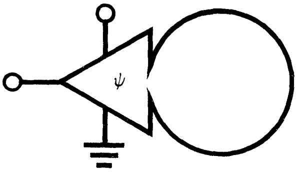


FIGURE 1

As indicated in *Figure 2,* the LX Series can be totally enclosed within the pressure vessel, working fluid chemistry allowing, so that little volume change in the system is experienced. When the volume of the vessel is large compared to that of the LX Series package, as is usually the case, the two alternative hook-ups are equivalent.

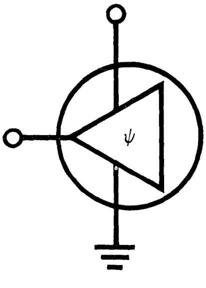


FIGURE 2

Finally, when the walls of the pressure vessel disappear, we have a barometer . . . a very good application of the LX1602A.

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*Care must be taken to avoid any temperature gradients between the pressure vessel and the transducer.

Pressure — Temperature Measurements

Another important family of "pressure vessel" applications for the LX16XX and LX17XX Series involves the measurement of temperature used in conjunction with an absolute pressure reading. The integrated temperature sensing diode reads the temperature of the silicon diaphragm in the transducer package. This temperature signal may be used for the additional temperature compensation of the pressure signal.

The accuracy of the transducer depends primarily upon the temperature coefficients of the pressure signal. This is typically one to two orders of magnitude looser than the precision, which depends upon hysteresis and deadband. Therefore, for such devices, if one were to calibrate the pressure signal temperature error in terms of the temperature signal, then a correction table could be established to increase its accuracy to the same order as its precision.

Other Fluid Functions

By suitably combining the temperature with the pressure signal other fluid variables within the pressure vessel can be formulated. Two important fluid variables are density and heat content.

Density of a known gaseous fluid can be calculated without knowledge of the fluidic thermodynamic process going on simply by measuring simultaneously the pressure and temperature at the same point as described in equation 1.

Equation 1:

$$\rho = C_2 \frac{P}{T} \;;$$

where

ρ = density

P = pressure

T = temperature

C_2 = inverse gas constant

Knowing the pressure, temperature and the density of the fluid at one or more points simultaneously, much can be learned about the nature of the processes causing change in the fluid. In a bounded pressure vessel, one variable often of concern is the heat transfer or energy exchange within some portion of a cycle or during some specific period. The change in heat content at a specific point in the system can be traced most easily in the bounded pressure vessel by tracking the fractional change in pressure as shown in equation 2.

Equation 2:

$$dh = C_3 \frac{P}{\rho}\left(\frac{dp}{P}\right) \;;$$

where: dh = change in heat content

$\left(\frac{dp}{P}\right)$ = fractional change in pressure with time

C_3 = inverse Joule's constant

If one were willing to track the fractional change of temperature and density as well as that of pressure, then complete knowledge of the state of the enclosed fluid as well as a complete characterization of the changing process results. Expressing equation 1 in terms of fractional changes yields equation 3.

Equation 3:

$$\left(\frac{dp}{P}\right) - \left(\frac{dT}{T}\right) = \left(\frac{d\rho}{\rho}\right) \;;$$

where

$\frac{dT}{T}, \frac{d\rho}{\rho}$ = functional change of temperature and density with time

Define a process characterization constant C_4 as shown in equation 4 and substitute in equation 3.

Equation 4:

$$C_4 \equiv \frac{\left(\frac{dp}{P}\right)}{\left(\frac{d\rho}{\rho}\right)} = 1 + \frac{\left(\frac{dT}{T}\right)}{\left(\frac{d\rho}{\rho}\right)}$$

Figure 3 is a table of this characterization constant under a number of important practical conditions.

So, by measuring absolute pressure changes and absolute temperature changes in an enclosed fluid system, one is able to characterize the process which caused the change of fluid properties. The process characterization constant (C_4) relates original oil changes in system energy to changes in fluid state defined by pressure, temperature, and density.

C_4	FLUID STATE	FLUID THERMODYNAMIC PROCESS	
0	$\left(\frac{dp}{P}\right) = 0$	P = constant	ISOBARIC
1	$\left(\frac{dT}{T}\right) = 0$	T = constant	ISOTHERMIC
$1 < n < k$	$\left(\frac{dp}{P}\right) = n\left(\frac{d\rho}{\rho}\right)$	$\frac{P}{\rho n}$ = constant	POLYTROPIC (Adiabatic and Irreversible)
k	$\left(\frac{dp}{p}\right) = k\left(\frac{d\rho}{\rho}\right)$	$\frac{P}{\rho k}$ = constant	ISENTROPIC (Adiabatic and Reversible)
∞	$\left(\frac{d\rho}{\rho}\right) = 0$	ρ = constant	INCOMPRESSIBLE (If bounded fluid gaseous, then process is ISENTHALPIC)

Note: In all cases dP dT, dρ represent changes with time of the absolute values of P, T, and ρ

FIGURE 3. State and Process Characterization

Phase Change

The process characterization constant poorly defines thermodynamic processes where changes of phase are involved. Where a phase change from gaseous to liquid fluid is involved, a characteristic energy transfer called latent heat (H_{LATENT}) occurs in accordance with expression given by Clapeyron, shown as equation 5.

Equation 5:

$$H_{LATENT} = \frac{T}{C_2} \cdot \frac{\left(\frac{dp}{P}\right)}{\left(\frac{dT}{T}\right)};$$

where

C_2 = inverse gas constant

For various fluids entering phase change, a new process characterization constant (C_5) given by Clausius/Clapeyron, shown in equation 6.

Equation 6:

$$C_5 = \text{LOG}_e\ P + \frac{C_2}{T} \cdot H_{LATENT}$$

$$\text{or} \quad C_5 = \text{LOG}_e\ P + \frac{\left(\frac{dp}{P}\right)}{\left(\frac{dT}{T}\right)}$$

Thus, we have developed the equations of state for fluids undergoing thermodynamic processes with and without phase changes so as to characterize these processes via measurement of pressure and temperature within a pressure vessel using the absolute transducer.

Generally, measurements of pressure and temperature in a multiphase system are difficult. Often for the purpose of measurement, a small parallel tap is made into the main flow channel so as to divert a negligible portion of the fluid flowing; then a sudden expansion is performed in the tap, and a small tap is led back into the main flow channel. This type of device is called a flash chamber and is shown in *Figure 4.*

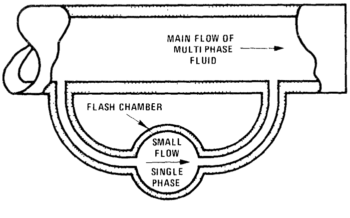


FIGURE 4

The flash chamber accomplishes the conversion of multiphase system (liquid and gas) to a single phase system (gas).

Such a chamber is simply a pressure vessel susceptible to analysis by the aforementioned modeling techniques.

OPEN FLOW APPLICATIONS

Just as pressure vessel processes were characterized by thermodynamic changes in fluid media rather than kinetic or spacial changes, open flow conditions and processes are best characterized as those in which we are primarily concerned with the kinetic properties of a fluid system and their changes, rather than the state and changes of state of a controlled volume of fluid. Whereas in the pressure vessel measurements involve absolute pressure, the kinetic state of an open flow system most often requires gage and differential pressure transducers.

The form of Bernoulli's flow equations most applicable to open flow conditions is given in equation 7.

Equation 7:

$$\left.\frac{P}{\rho}\right)_{STAGNATION} = \left.\frac{P}{\rho}\right)_{STATIC} + \frac{V^2}{2g} + y;$$

where:

$\left.\frac{P}{\rho}\right)_{STAGNATION}$ = Stagnation pressure head

$\left.\frac{P}{\rho}\right)_{STATIC}$ = Static pressure head

$\left.\frac{V^2}{2g}\right)$ = Kinetic flow head

y = Potential flow head

This particular form of Bernoulli's equation is valid where fluid density remains reasonably constant. As seen in the definition of terms (equation 7), the concept of a head is key to open flow applications. Easiest to conceive is the potential head, wherein a particle of fluid at a different height than at some other location has some potential to flow to that other location. That potential is proportional to the height difference. It is small wonder, therefore, that dimensions of a head are those of a column of fluid; inches of mercury, feet of water, millimeters of mercury or torr. If that particle of fluid were to fall, so as to change location or flow, without changing pressure within that particle, then that potential flow head would convert to a kinetic flow head. Another useful concept in equation 7 is that of stagnation. If you were waiting with a catcher's mit at a fixed location and a particle of fluid at a given pressure flowed into the mit, in order to stop that particle with your mit you would have to bring it to rest. In doing so, assuming the fluid particle remained at the same density and temperature, the particle's pressure head would increase by the absorbed kinetic head. If you were then to pull the mit down to ground level, the stagnation head would in addition increase by the potential head. Therefore, the stagnation head of a given fluid particle is an expression of that particle's pressure were it suddenly brought to rest and dragged to the bottom. Bernoulli's equation indicates that however that particle may meander under open flow conditions, the sum of its static pressure head, its kinetic flow head, and its potential flow head remains constant. In most open flow situations the variable of major interest is flow velocity. In situations where it is convenient to measure both stagnation pressure and static pressure at essentially the same point (y is constant) a differential pressure transducer can be used in a method similar to that of a pitot-tube as shown in *Figure 5.* Equation 7 can then be rearranged as shown in equation 8.

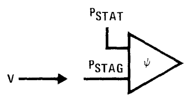


FIGURE 5. Flow Rate Pressure Square Law Relationship

Equation 8:

$$V_y = \sqrt{2g\left[\left.\frac{P}{\rho}\right)_{STAGNATION} - \left.\frac{P}{\rho}\right)_{STATIC}\right]}$$

Applications where this type of measurement is common are air speed indication for airplanes and weather balloons, water speed for boats and aqueducts and irrigation ditches, ventilation control, sewage processing, industrial mixing, and others. More generally, where y varies in open flow conditions, changes in flow conditions due to geometric changes in the flow boundaries are monitored by measurements of fluid level changes and fluid pressure changes. Equation 9 gives the applicable form of Bernoulli's equation.

Equation 9:

$$\frac{dv}{g} + \frac{dp}{\rho} + dy = 0,$$

where dv, dp, dy are changes with distance

Figure 6 shows this general case of open flow boundary condition monitoring. Notice that both the fluid level and each of the gage transducers used are vented to atmosphere for reference. In this particular case, the use of a differential

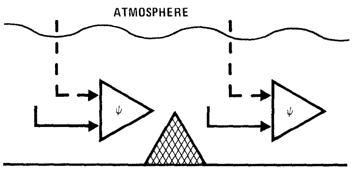


FIGURE 6. Flowmeter Output with Exaggerated Pressure Transducer Common-Mode Inaccuracy

transducer is not practical due to the physical separation of the points of interest. Two transducers must be used. Examples of applications include weir and dam flow and level control, oceanographic measurements, and for the special cases of near zero velocities . . . general level control.

The schemes of both *Figures 5 and 6* are ideal for accuracy improvement via auto-referencing (see auto-referencing section).

Once again there are some cautions that must be respected in the application of transducers in open flow conditions. Perhaps the most often overlooked and frustrating caution involves temperature gradient. As was explained in the pressure vessel section, although good transducers are temperature compensated, temperature gradients within the transducer are deadly enemies producing errors that defy all compensation techniques. If the temperature signal from the LX Series transducers is used in determining the density of the working fluid, then the transducer wants to be thermally well-coupled. However, if the atmospheric environmental temperature is significantly different from that of the working fluid, a severe gradient of temperature can occur within the transducer unless the transducer is totally immersed in the working fluid (a condition usually impractical). Fortunately, in most open flow applications, the temperature reading is not needed to determine density and the dynamics of the flow do not prohibit fairly long tube lengths from the transducer to the point of measurement. The result is that it is practical to provide a situation wherein the working fluid within the transducer is at the same temperature as the surrounding environment.

One extremely useful feature of the LX Series pressure transducers comes into play in applications of the type shown in Figure 6. In many such open flow applications the distance between points one and two is measured in miles. In such cases the system accuracy is not simply dependent upon the accuracies of measurements of pressure point one and point two but rather the difference calculation dp. Obviously that accuracy depends on the transmission of information over several miles. In general, maintaining accuracies under these conditions requires healthy signal to noise ratio at each transducer output as well as a hefty pre-transmission signal and easy interface with the transmitter.

The IC pressure transducers are ideally suited for coupling to VCOs for FM transmission (see Signal Conditioning section) the method favored by all modern trends in instrumentation. Among the many advantages are extremely low noise susceptibility even when bundled with many other signal carrying cables, ease of conversion to digital signals to facilitate interface with modern control logic or input to general purpose digital computers, and ease of combination with other analog FM signals to form a composite system variable.

ACOUSTICS

One special form of open flow application is the case where the pressure wave velocity is high compared to the fluid flow velocity. Such applications are called acoustic. The acoustic energy of a sound wave is directly proportional to the sound pressure as shown in equation 10.

Equation 10:

$$dh = C_3 \frac{dp}{\rho}$$

For acoustics, the open flow approximation of an "incompressible, isothermic medium" must be replaced by the model of a "stationary, isentropic medium." That is, the propagating pressure wave shakes each fluid particle about its stationary location proportional to the sound pressure constituting a dynamic change in density (dp). As shown in equation 11, the proportionality constant between the change in the fluid density and the sound pressure is the inverse squared speed of sound in that medium.

Equation 11:

$$d\rho = C_7 \; dp; \; C_7 = \frac{1}{a^2} \; ;$$

where "a" is the speed of sound.

Sound pressure measurements should be made with differential transducers in which the reference point monitors the quiescent pressure level. Usually sound pressures are very low, so as to require the LX1601G or LX1701G (see Acoustic Applications section).

High frequency response can be severely limited by bounded chambers. In fact just the tube and lid can limit response normally in the tens of kilo Hertz to the low kilo Hertz region. However, the silicon pressure diaphragm response alone with the tube and lid removed or when liquid coupled is such that calibrated sound pressure measurements can be achieved at frequencies well above 50 kilo Hertz. Thus, the LX Series pressure transducers are capable of calibrated pressure measurements in open flow conditions ranging in dynamics from static to ultrasonic frequency.

CLOSED FLOW APPLICATIONS

Pressure vessel applications require the investigation of time dependent variables at one point. Open flow applications require the investigation of time independent variables at many points. In closed flow applications, we need to investigate both kinds of variables. That is, the processes at work within the fluid system involve state change energies of like order of magnitude as kinetic energies. Perhaps the most obvious examples of systems reliant on such processes are engines of all kinds, as well as refrigerators and air conditioners, compressors, gas pipelines, fire extinguishers, gun cartridges and explosives.

In closed flow the equation used to model the flow between two locations must be altered to include the change of state.

Equation 12:

$$h_{STAGNATION} - h =$$

$$C_3\left[\left(\frac{P}{\rho}\right)_{STAGNATION} - \frac{P}{\rho}\right] = C_3\left(y + \frac{V^2}{2g}\right)$$

In equation 12, $h_{STAGNATION}$ represents the total equivalent heat energy of the system and is constant; h is the heat content of a fluid particle at a particular location such that ($h_{STAG} - h$) represents the kinetic and potential flow energy.

In open flow the density of the fluid is assumed to be known and constant. Consider a working fluid that is gaseous and whose density variation may be described by equation 1 of the pressure vessel applications section. Equation 13 shows the substitution of equation 1 in equation 12.

Equation 13:

$$h_{STAGNATION} - h =$$

$$\left(\frac{C_3}{C_2}\right) T \left[\frac{P_{STAGNATION}}{P} - 1\right] = C_3\left(y + \frac{V^2}{2g}\right)$$

In the same manner in which equation 8 was derived from equation 7 in the section on open flow applications, equation 14 is derived from equation 13 to show flow velocity.

Equation 14:

$$V_y = \sqrt{2g\left[\frac{T}{C_2}\left(\frac{P_{STAGNATION}}{P} - 1\right)\right]}$$

Thus, where the system allows a Pitot tube measurement of the two absolute pressures and temperatures at one point, the closed flow can be modeled by equation 14 and two LX Series transducers. Common applications include high velocity air flow as in compressors, and engine manifold gas flow.

To measure closed flow in small flow channels, it is usual to insert an obstruction in the passage between two points at which fluid properties can be sensed. Again, rather than the incompressible and isothermic conditions applicable to liquids in open flow, heat transfer and in fact heat loss due to flow conditions is experienced. Equation 15 presents Bernoulli's equation for this situation with the energy loss due to obstruction indicated in terms of change in heat content. For extremely long, thin, rough-walled, closed-flow vessels, the fractional loss can actually approach unity.

Equation 15:

$$\left[\frac{Y_2 + \frac{V_2^2}{2g}}{Y_1 + \frac{V_1^2}{2g}}\right] = 1 - \left(\frac{h_1 - h_2}{h_{STAGNATION} - h_1}\right);$$

where

$$\left(\frac{h_1 - h_2}{h_{STAGNATION} - h_1}\right) = \text{Loss of energy}$$

Structures are used that tend to minimize the distance between sensing points as well as minimize the fractional loss of energy. Commonly used structures range from orifices where losses are up to half of the total energy and sensing points are very closely spaced, to Venturi's where losses are negligible but sensing points are widely spaced. Equation 16, derived from equation 15 shows a typical calibration equation for a specific obstruction over a specific range of flow.

Equation 16:

$$\left(\frac{V_2}{V_1}\right)_y = \sqrt{1 - \left\{\frac{h_1 - h_2}{h_{STAGNATION} - h_1}\right\}}$$

Figure 7 shows some typical flow measurement obstructions.

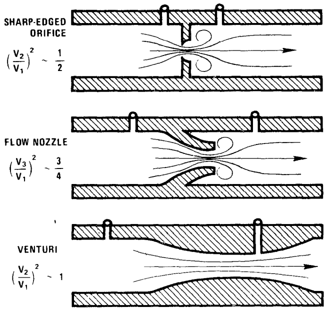


FIGURE 7

It must be remembered that these are rule of thumb examples and fluids undergoing drastic thermodynamic changes will not approximate these processes for these flow conditions. For example, the nearly lossless Venturi of streamlined flow conditions forms a roaring energy loser when turbulent hot gases are pushed through so as to become the converging-diverging nozzle of rocketry fame.

OPEN VS CLOSED FLOW

Conventionally, differential pressure transducers rather than absolute transducers are used for flow measurement. Three arguments are popular for maintaining this convention . . . one of them very good and the other two rather weak.

In low flow rate applications the dynamic head is most often small compared to the static head. The incompressible isothermic model, expressed in the equations of the open flow applications section, is often appropriate under such low flow conditions. The resulting simple expression of Bernoulli's equation that leads to the use of differential pressure transducer is given by equation 17.

Equation 17:

$$d\,(V^2) = C_8 \left(\frac{dp}{\rho}\right); \quad \rho \neq \rho\,(p, t)$$

In addition to being the analytically obvious best choice when equation 17 is an appropriate model of flow conditions, a single differential transducer can be made to perform with much greater accuracy than a pair of gage or absolute transducers of comparable quality because the differential transducer need only range both the dynamic and static heads. Since the static head is not called for in equation 17, the added ranging requirement merely adds common mode error to the measurement. Under these conditions the differential pressure transducer convention for flow measurement is justified and the differential transducers are highly recommended . . . particularly with auto-referencing.

Equation 18:

$$d\,(V^2) = C_9\, d\left(\frac{p}{\rho}\right); \quad \rho = \rho\,(p, t)$$

Traditionally, even in cases where more complex Bernoulli models (equation 18) should be used, the simple incompressible model is substituted. One argument claims that one can always make up for errors in the modeling equation by specifying greater accuracy in the differential pressure transducer. Proponents of this argument consider the alternate use of two absolute pressure transducers along with two temperature transducers (to achieve a more accurate modeling equation) too sophisticated. The tradition of simple single variable models using few highly accurate transducers to achieve moderate system accuracy is so well founded in the measurement and control industries that until recently only manufacturers of low volume, high accuracy, high cost transducers existed. The low cost LX Series devices are first and foremost integrated circuits (that happen to be transducers as well) rather than conventional transducers (that happen to utilize integrated circuits). In electronics in general, and specifically within the integrated circuits business, adding functions is easy . . . but measuring to a tight spec is difficult.

In most closed flow applications the variables of interest are functions of absolute pressure, differential pressure, and temperature, with respect to time and location. If the system modeler desires a certain tolerance on this complex function he may either gather single variable data at multiple locations or multivariable data at few locations.

In either case, auto-referencing techniques can greatly improve system accuracy.

Approaches to Flowmetering

TRADITIONAL PRESSURE TRANSDUCER FLOWMETERS

The simplest form of pressure transducer flowmeter is called a Pitot Tube. It measures the difference between stagnation pressure and static pressure at a point and in a specific direction within a fluid stream. Static pressure (P_o) is the pressure measured perpendicular to the flow velocity so as to be free of kinetic effects. Stagnation pressure (P_{oo}) is the pressure measured facing directly into the flow velocity so that the measured fluid is brought to rest against the pressure port. Thus the stagnation pressure is the sum of static pressure and the total effects of kinetic energy. In an adiabatic stream, stagnation pressure is a measure of total system energy and can be assumed constant at any point in the stream. *Figure 1* shows a Pitot Tube. Equation 1 defines stagnation pressure.

$$P_{oo} = P_o + \rho\frac{v^2}{2g} \tag{1}$$

where:
P_{oo} = Stagnation pressure [#/in^2]
P_o = Static pressure [#/in^2]
ρ = Fluid density [#/in^3]
v = Stream velocity [in/sec]
g = Gravitational constant [in/sec^2]

The Pitot Tube's differential pressure (ΔP) input to the pressure transducer is given by equation 2.

$$\Delta P = P_{oo} - P_o = \rho\frac{v^2}{2g} \tag{2}$$

Pitot Tubes are used almost exclusively in fluid streams that are much larger in cross section than the tube itself. For example, Pitot Tubes are often used for air speed determination in the open atmosphere and in large ventilation ducts. In most closed fluid stream systems, such as flow in pipes, the fluid velocities of interest are too small for measurement with a Pitot Tube. That is, the velocity of the fluid moving through the full inside diameter of the enclosing pipe is too small to give rise to a large enough differential pressure for accurate measurement. Fortunately, most systems also can tolerate more flow impedance than required by a Pitot Tube. An obstruction in the stream that amplifies the fluid velocity is just what is needed. Consider a Venturi section of pipe as shown in *Figure 2*. Consider area one (A_1) to be the cross section intersected by pressure tap one (P_1) and area two (A_2) to be the cross section intersected by pressure tap two (P_2). Consider also that for a low flow velocity through a short section, fluids are incompressible (ρ = constant). This means that the volumetric flow rate (Q) through area one and area two are equal as is expressed by equation 3.

$$Q = A_1 v_1 = A_2 v_2 \tag{3}$$

In addition, consider the flow to be adiabatic through the short section, such that stagnation pressures at area one and area two are equal as is expressed by equation 4.

$$P_{oo} = P_1 + \rho\frac{v_1^2}{2g} = P_2 + \rho\frac{v_2^2}{2g} \tag{4}$$

The differential pressure input to the pressure transducer ($\Delta P = P_1 - P_2$) is derived by substituting equation 3 into equation 4 and is given by equation 5.

$$\Delta P = \frac{\rho}{2g}\left(\frac{Q}{A_1 A_2}\right)^2 (A_1^2 - A_2^2) \tag{5}$$

A sharp edged orifice of equivalent area ratio (A_2/A_1) to a Venturi section has the disadvantages of higher flow impedance, some compressibility, and some heat loss. It has the advantages of lower cost and great standardization. Though not obvious, if the area two pressure tap is placed immediately downstream of the orifice, equation 5 very closely approximates the differential pressure input to the pressure transducer shown in *Figure 3.*

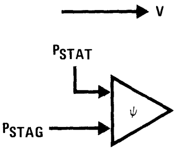


FIGURE 1. Pitot Tube

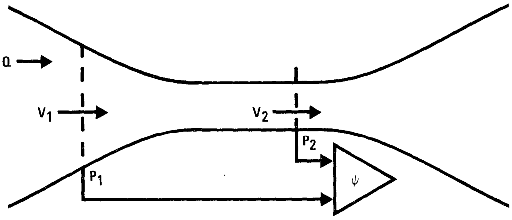


FIGURE 2. Venturi Section

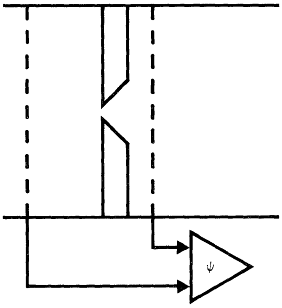


FIGURE 3. Sharp Edged Orifice

THE SQUARE LAW PROBLEM

Equation 5 clearly indicates that flowmetering methods based upon the creation of a calibrated obstruction in the flow stream involve a square law relationship. That is, the output which is simply proportional to differential pressure (ΔP) is in turn proportional to the square of the flow rate (Q). Many schemes have been devised for linearizing the output signal relationship to flow rate in the electronic domain. This involves creating a square root relationship between the output voltage from the pressure transducer and its conditioning electronics (V_p) and the differential pressure across the calibrated obstruction (ΔP). That is, if (V_p) is made proportional to the square root of (ΔP), and (ΔP) is proportional to the square of (Q); then (V_p) is proportional to (Q). An analog circuit approach to square rooting makes use of the logarithmic relationship that exists between the voltage drop across a diode junction and the current through it. Over a limited range of values, the ratio of a number's natural log to its square root is nearly constant. Section 8 gives details of this method. Digital approaches to such linearization are far more powerful because no specific algebraic relationship is required. That is, any single-valued relationship can be linearized by digital techniques. One such approach digitizes the transducer output and feeds that value into a read-only-memory (ROM). The ROM simply does a code conversion that yields an output code representing the flow rate corresponding with that pressure. The problem with that approach is that a gigantic ROM is required for reasonable flow rate resolution. Another digital approach trades conversion speed for ROM size (and thus resolution) by having the ROM store deltas. In this case only the increments between successive differential pressure values ($\delta\Delta P$) corresponding to the increments of flow rate (δQ) to be resolved are stored. This technique has been used in the construction of accurate aneroid altimeters. Section 8 gives details of this digital approach to linearization useful with inexpensive techniques of analog to digital conversion and output display (see Section 7).

Unfortunately, circuit techniques of linearization do not linearize inaccuracies. To examine this revelation, allow some simplifying (albeit erroneous) assumptions to be corrected later. First, assume that calibrated obstruction and the fluidic phenomena that give rise to the square law relationship between (ΔP) and (Q) are error free. Second, assume that the pressure transducer's inaccuracy is common-mode or pressure independent. This means the error can be expressed as a constant uncertainty in units of pressure regardless of what pressure is applied. Third, assume that all circuitry within and outboard of the pressure transducer to yield (V_p) contributes no error. Fourth, assume that the required flowmeter's inaccuracy is common-mode or flow rate independent. This means it is desired that the error in (V_p) as a function of (Q) can be expressed as a constant uncertainty in units of flow rate regardless of what flow rate is applied. Since all inaccuracy is assumed to be due to the pressure transducer, it would be well to examine the effect of the inaccuracy on the output signal, both as a function of (ΔP) and as a function of (Q). *Figure 4* shows the pressure transducer output characteristic, (V_p) vs (ΔP), with a highly exaggerated common-mode inaccuracy indicated as an error band. *Figure 5* shows the flow rate vs pressure square law relationship. *Figure 6* shows the flowmeter output characteristic with the

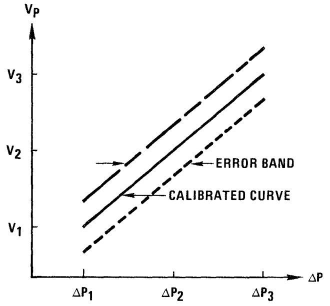


FIGURE 4. Pressure Transducer Output With Exaggerated Common-Mode Inaccuracy

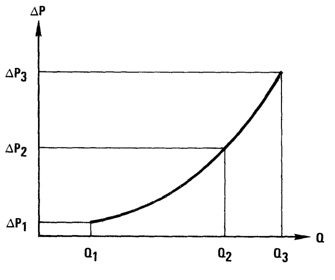


FIGURE 5. Flow Rate Pressure Square Law Relationship

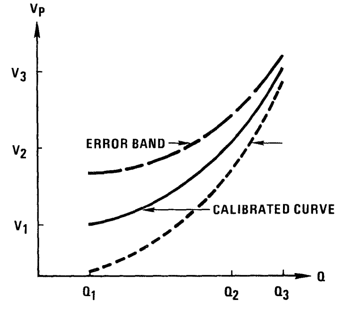


FIGURE 6. Flowmeter Output With Exaggerated Pressure Transducer Common-Mode Inaccuracy

pressure transducer error band superimposed. Since an increment pressure change corresponds with a very large flow rate change at the low end of the flow rate range, the output inaccuracy is also very large at the low end. At the high end of the flow rate range an increment of pressure change corresponds with a small flow rate change, yielding a small output inaccuracy. When electronic signal shaping is used for linearization, the basic cause of inaccuracy is unaltered. *Figure 7* shows the result of electronic linearization with respect to accuracy. Clearly, the inaccuracy is not common-mode per our assumed requirement. Electronic linearization is generally useful and will be useful to the approach described later in this text. . .but it has little or no effect on square law inaccuracy.

FLOWMETER ACCURACY REQUIREMENTS

The simplifying assumption that the optimum flowmeter inaccuracy is common-mode (flow rate independent), though sometimes true, is not generally the case. To better understand flowmeter accuracy requirements, it is necessary to understand how a flowmeter is applied. Most often, the process of interest involves moving one or more fluids from one location to another. Depending upon how important the fluid state variables are to the process, there may or may not be interest in measuring and controlling the exact flow rate during the fluid transfer. If such measurement is of primary importance, then common-mode accuracy is of primary importance. But, almost always, the most important requirement is accurate knowledge of how much total fluid has transferred at any time. Consider a process wherein the fluid flow rate can vary over a wide range and where the variable of interest is instantaneous accumulated volume. Examples of such a process are residential gas and water metering, fuel metering, pumping gasoline, pipeline control, irrigation, etc. In this case, the requirement is for a certain accuracy of accumulated volume whether all the fluid transfer occurred at low or high flow rate. Unlike the common-mode assumption where the required accuracy could be expressed as a constant percent of flow rate range, the required accuracy in this case can be expressed as a constant percent of flow rate value throughout the flow rate range (not including zero flow). *Figure 8* shows the desired shape of inaccuracy of a linearized flowmeter output for optimum flow totalization. The electronic accumulation function via integrating the flow rate output signal is simply a digital counting job, and is assumed to be error free. Comparison of *Figure 8* with *Figure 7* shows the real square law problem. The flowmeter needs best accuracy at the lowest flow rates, and is forgiving at the highest flow rates. The square law problem causes the flowmeter to have maximum error at the lowest flow rates and best performance at the highest flow rates. In short, accuracy is out of phase.

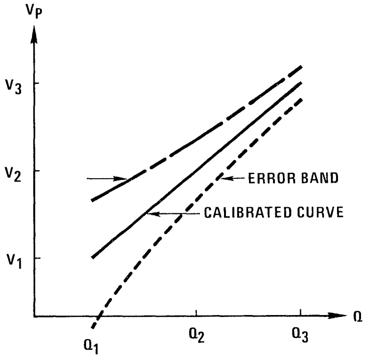


FIGURE 7. Electronically Linearized Flowmeter Output With Exaggerated Inaccuracy

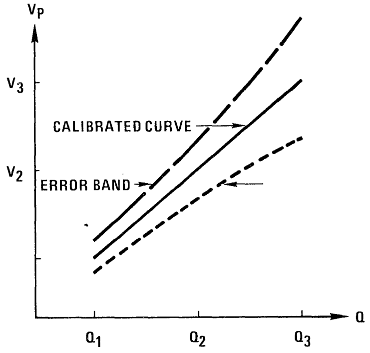


FIGURE 8. Linearized Flowmeter Output With Exaggerated Desirable Inaccuracy

A NEW APPROACH TO FLOWMETERING—THE FLEXURAL IRIS ORIFICE

Certainly the best way to remove the inaccuracy problem associated with the square law relationship between the differential pressure across an orifice and the flow rate through the orifice is to alter that algorithm right at its source. . .at the orifice. In addition to showing that (ΔP) is proportional to (Q^2), equation 5 indicates that (ΔP) is a function of areas (A_1) and (A_2). Most usually, the pipe cross sectional area (A_1) is much larger than the orifice area (A_2). For this case equation 5 can be simplified to equation 6.

$$\Delta P = \frac{\rho}{2g}\left(\frac{Q}{A_2}\right)^2 \qquad (6)$$

The trick, then, is to make (A2) a variable function of (Q) such that (ΔP) is proportional to (Q^n); where (n) is much less than two (2). This can be accomplished using a virtually no-moving-part modification of a simple orifice that operates as a flexural iris.* Suppose the orifice of *Figure 3* were composed of cantilever beam sections rather than a single rigid plate. *Figure 9* shows such a flexural iris orifice with four cantilever beam sections. Also depicted is an exaggerated flexure of one cantilever element due to dynamic pressure. Appendix I gives an analysis of the dynamic pressure gradient acting upon such a cantilever, the beam flexure, and the resulting orifice area as expressed in equation 7.

$$A = \left[b_o + 2\left\{ L - \frac{h}{\Delta P}\left(\frac{E}{2}\right)\left(\frac{h}{L}\right)^2 \left(\frac{b_o + L}{3b_o + 2L}\right) \text{sine}\, \Delta P \left(\frac{2}{E}\right)\left(\frac{L}{h}\right)^3 \left(\frac{3b_o + 2L}{b_o + L}\right) \right\} \right]^2 \qquad (7)$$

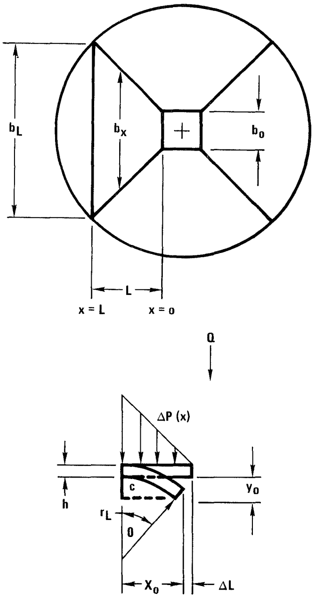


FIGURE 9. Flexural Iris Orifice

Consider a specific flexural iris orifice of easy to achieve dimensions and properties given in Table I, designed to fit within a 1-inch inside diameter pipe. Equation 8 is the result of substituting the values of Table I into equation 7 and converting units such that (ΔP) is expressed in atmospheres (atm) and the angle whose sine is represented is expressed in degrees.

$$A = \left[0.708 - \left(\frac{1.067}{\Delta P}\right) \text{sine}\ 36.43\Delta P\right]^2 \qquad (8)$$

TABLE I. Flexural Iris Orifice Example Design Values

b_o	0.030 inches
b_L	0.707 inches
L	0.339 inches
h	0.005 inches
E	3×10^7 psi

Equation 9 is the result of substituting a value of density typical of gasoline and many oils into equation 6 as well as converting units such that (Q) is expressed in gallons per minute (gpm) and (ΔP) is expressed in atmospheres.

$$Q = 182\sqrt{\Delta P}\ A;\ \rho = 0.7\ \rho_{water} \qquad (9)$$

It will quickly become obvious that the dimensions chosen, though easy to achieve and otherwise appropriate, were not arbitrary. It happens that a flow rate of one (gpm) through the flexural iris yields a pressure drop of one (atm). This allows easy comparison of simple pressure to flow rate relationships that represent various conditions with that of the flexural iris. Equation 10 gives the relationship for an ordinary orifice of fixed area which yields the square law accuracy problem.

$$Q = \sqrt{\Delta P}\ ;\ A = \text{const.} \qquad (10)$$

Equation 11 gives the relationship for a hypothetical structure of variable area which yields uniformly distributed accuracy.

$$Q = \Delta P;\ A \propto \sqrt{\Delta P} \qquad (11)$$

Equation 12 gives the relationship for a hypothetical structure of variable area which yields the ideal flowmeter accuracy distribution.

$$Q = (\Delta P)^2;\ A \propto (\Delta P)^{3/2} \qquad (12)$$

---

*National Patent No. 4006634.

Table II tabulates the results of equations 8 through 12 for various values of (ΔP). Since the flowmeter output signal before linearization is proportional to the differential pressure, a plot of Table II values expressed as (V_p) vs (Q) immediately reveals the effects of the flexural iris. *Figure 10* is the plot of Table II values. Clearly, the flexural iris output shown in *Figure 10* most closely approximates the output for ideal accuracy. The value of the digital techniques of linearization rather than a square root analog is also apparent from *Figure 10.* This consideration points up a preferred embodiment of the flexural iris for volume production of flowmeters. That is, it is far more important to have an output characteristic that is very reproducible in production than one that closely approximates some analytic expression.

One technique that favors flexural iris reproducibility is the stamping or molding of both the cantilever spring sections of the iris and spring constraints together in one piece. *Figure 11* is a sketch of a stamped flexural iris with cylindrical (jar-lid style) integral constraint.

AUTO-REFERENCING

During discussion of the square law problem, it was assumed that the major inaccuracies were common-mode. Continuing that assumption, auto-referencing yields the optimum accuracy for the lowest cost (see Section 7).

TABLE II. Pressure/Flow Rate Relationship for Various Structures

ΔP[atm]	FLEXURAL IRIS		FIXED AREA	VARIABLE AREA	
	$A[10^{-4}$ inches$^2]$	Q[gpm]	$Q = \sqrt{\Delta P}$ [gpm]	$Q = \Delta P$[gpm]	$Q = (\Delta P)^2$ [gpm]
0.1	8	0.05	0.32	0.1	0.01
0.2	9	0.07	0.45	0.2	0.04
0.3	10	0.10	0.55	0.3	0.09
0.4	12	0.14	0.63	0.4	0.16
0.5	15	0.20	0.71	0.5	0.25
0.6	19	0.27	0.77	0.6	0.36
0.7	25	0.38	0.84	0.7	0.49
0.8	32	0.52	0.89	0.8	0.64
0.9	43	0.73	0.95	0.9	0.81
1.0	55	1.00	1.00	1.0	1.00

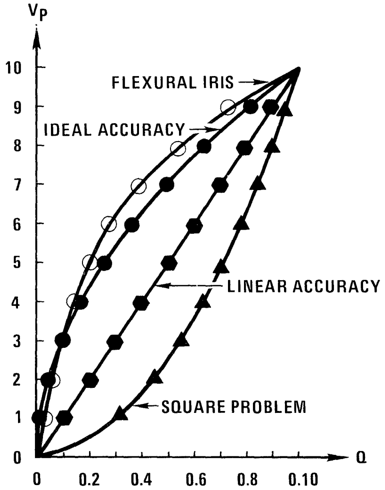


FIGURE 10. Flowmeter Output Signals for Various Configurations

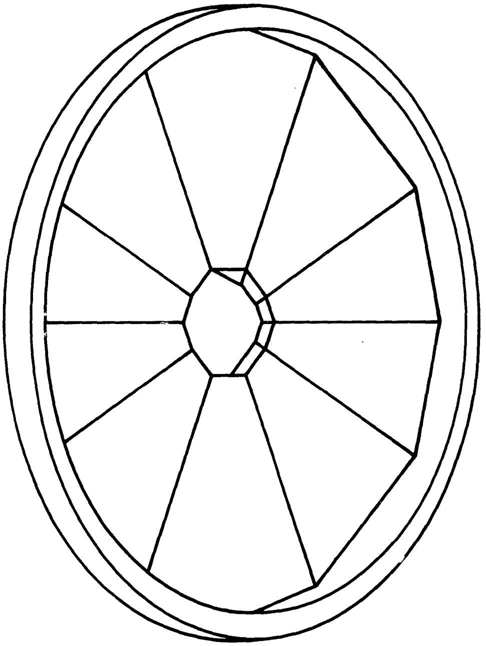


FIGURE 11. Stamped Flexural Iris With Integral Cantilevered Spring Sections And Jar-Lid Constraint

THE NEW FLOWMETER

The new flowmeter is not all new. The most advantageous features of the traditional flowmeter approach have been kept intact. The device remains essentially a dynamically responsive, low volumetric displacement, no-moving-parts system. A sharp edged orifice is replaced by a flexural iris orifice. Some errors normally handled by expensive transducers coupled with meticulously tweeked linear circuitry are instead handled by a solenoid valve coupled with well proven digital circuits using inexpensive standard solid state components. The craft of tool-and-die makers, delicately and expensively balanced within a many socket-head-capscrewed coat of armor, is replaced by an elegantly simple hybrid IC performing as a pressure transducer. The composite flowmeter system given by *Figure 12* is the new flowmeter.

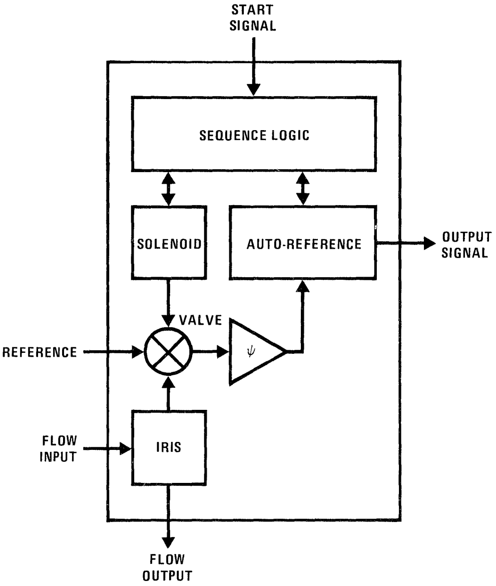


FIGURE 12. Composite Flowmeter

APPENDIX I

Analysis of Trapezoidal Cantilever Dynamic Pressure Gradient, the Resulting Flexure and Orifice Area:

The trapezoidal cantilever width of *Figure 9* is given by:

$$b_x = b_o + x$$

The dynamic head (ΔP), is given by equation 6:

$$\Delta P = \frac{\rho}{2g} \left(\frac{Q}{A_2}\right)^2$$

$$A_2 = b_o{}^2$$

$$\therefore \Delta P = \frac{\rho}{2g} \left(\frac{Q}{b_o{}^2}\right)^2$$

The full (ΔP) occurs at ($x = L$), whereas ($\Delta P = o$) at ($x = 0$). Since the flow rate radial profile in a pipe is essentially parabolic, the radial pressure gradient is roughly linear:

$$\Delta P_x = \left(\frac{x}{L}\right) \Delta P$$

Therefore the beam loading (F):

$$dF_x = \Delta P_x \, dA_z = \Delta P_x b_x dx$$

$$F_x = \int_o^x \Delta P_x b_x dx = \frac{\Delta P}{L} \left[b_o \int_o^x x dx + \int_o^x x^2 dx\right]$$

$$F_x = \frac{\Delta P}{L} \left[\frac{b_o x^2}{2} + \frac{x^3}{3}\right]$$

The beam moment (M):

$$M_x = xF_x$$

The beam stiffness (D):

$$D_x = \frac{Eh^3}{12} b_x \text{ ; } E = \text{Young's Modulus}$$

The beam radius of curvature (r):

$$r_x = \frac{D_x}{M_x}$$

$$\therefore r_L = \frac{1}{\Delta P} \left(\frac{Eh^3}{2L^2}\right) \left(\frac{b_o + L}{3b_o + 2L}\right)$$

The angle of curvature (ϕ):

$$\phi = \frac{L}{r_L}$$

The axially projected beam length (x_o):

$$x_o = r_L \sin \phi$$

The change in projected beam length (ΔL):

$$\Delta L = L - x_o$$

The orifice area (A):

$$A = (b_o + 2\Delta L)^2$$

$$\therefore A = \left[b_o + 2\left(L - r_L \text{ sine } \frac{L}{r_L}\right)\right]^2$$

substituting the entire expression of (r_L):

$$A = \left[b_o + 2 \left\{ L - \frac{h}{\Delta P} \left(\frac{E}{2}\right) \left(\frac{h}{L}\right)^2 \left(\frac{b_o + L}{3b_o + 2L}\right) \text{ sine } \Delta P \left(\frac{2}{E}\right) \left(\frac{L}{h}\right)^3 \left(\frac{3b_o + 2L}{b_o + L}\right) \right\}\right]^2$$

Section 7

Auto-Referencing

COFFEE, TEA OR AUTO-REFERENCING?

Whether you're measuring coffee, tea or any other fluid, getting maximum accuracy for minimum cost is top priority. That's why National's IC pressure transducers are designed for easy automatic calibration at reference pressure—better known as *auto-referencing*, which eliminates all offset errors and gives you more accuracy for the dollar than any other method. So, if you're into dispensing coffee and tea, the answer of course is, "All three". And if you're not, use auto-referencing anyway. It's the only way to fly.

Basics of Auto-Referencing

IT'S COST-EFFECTIVE

Auto-referencing is a family of powerful techniques used to compensate time and temperature errors by periodic correction of the output signal with respect to one or more reference pressure levels. The error correction circuits are usually simple and low in cost, and at least one pressure level suitable for referencing is usually accessible or can be easily produced. So, it's natural to want to use auto-referencing, since the alternative (an expensive precision pressure transducer) is usually more trouble than it's worth and definitely more expensive than an auto-referenced pressure transducer with comparable accuracy.

IT'S SIMPLE

To simplify auto-referencing, National's IC pressure transducers are linear, and their response errors are conveniently divided into common-mode errors (invariant with pressure) and normal mode errors (proportional to pressure), as shown in *Figure 1*. These two error groups are mutually independent (Section 3) so that either one or both can be corrected by auto-referencing depending on the accuracy desired.

COMMON-MODE AUTO-REFERENCING—EASY AND EFFECTIVE

Common-mode errors are generally the largest (especially at lower pressures, where it really counts in some applications) and therefore give way to the greatest accuracy improvement when auto-referenced. They are also the easiest to auto-reference, as shown in *Figure 2*, since all that's required is to sample the signal at reference pressure and subtract the error from the signal at any "measure" pressure. This is expressed by the formula.

$$V_{SCM} = V - \Delta V_{REF} \qquad (1)$$

Where V is any measure pressure signal, ΔV_{REF} is the error pressure signal and V_{SCM} is the output signal corrected for common-mode error by subtracting the error from the measure signal. As seen in *Figure 2*, no slope correction is involved.

The basic auto-reference functions required to implement this formula are shown in *Figure 3*. They include a switch, a sample-and-hold, and interconnecting logic for synchronizing with the measure-reference cycle.

NORMAL MODE AUTO-REFERENCING—ADDED PRECISION

With most of the error removed by auto-referencing the offset error, a further improvement that places the transducer in the "high precision" class can be achieved

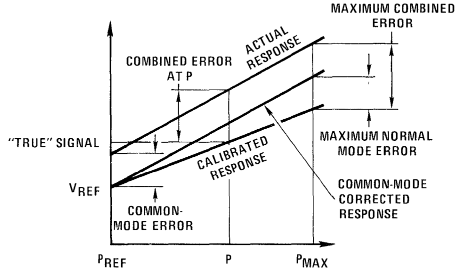


FIGURE 1. Transducer Errors

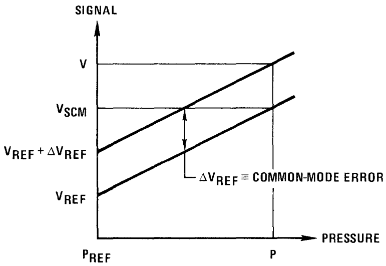


FIGURE 2. Common-Mode Error Correction

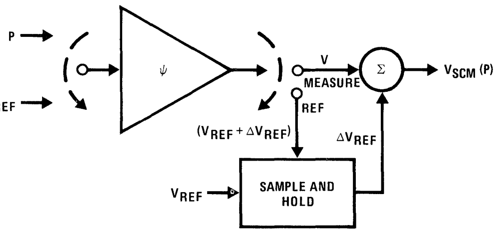


FIGURE 3. Basic Common-Mode Auto-Reference Functions

by normal mode error correction. Normal mode auto-referencing is a bit more complex but may be well worth it if high accuracy is required and the temperature range is unwieldy. As shown in *Figure 4,* auto-referencing normal mode requires an additional reference pressure point (preferably at P_{MAX}), and since the error is proportional to pressure, the expression for error includes the slope of the responsivity line.

By similar triangles *(Figure 4),* the exact expression for ΔV (normal mode) is given by:

$$\Delta V = \frac{(V_M - V_{MAX})}{(V_M - V_{REF})} \cdot (V_{SCM} - V_{REF}) \qquad (2)$$

where: $\Delta V = \Delta V(P)$, $V_{SCM} = V_{SCM}\ (P)$ is the signal corrected for common-mode error (equation 1)

let: $V_M - V_{MAX} = \Delta V_M$, the sampled normal mode error at P_{MAX};

$V_M - V_{REF}$ = span voltage + ΔV_M, approximately equal to span voltage.

Equation 3 reflects these substitutions.

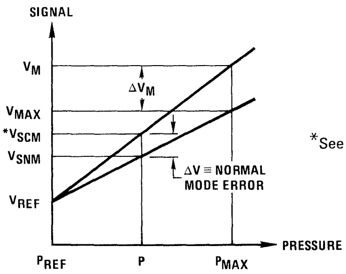
$$\Delta V \approx (\Delta V_M/\text{Span Voltage})(V_{SCM} - V_{REF}) \qquad (3)$$

To correct for normal mode error we merely subtract ΔV from V_{SCM}, the signal corrected for common-mode error. This rotates the common-mode corrected response *(Figure 1)* clockwise to cause coincidence with the desired calibrated response. The formula for normal mode auto-referencing is therefore:

$$V_{SNM} = V_{SCM} - (\Delta V_M/\text{Span Voltage}) \cdot (V_{SCM} - V_{REF}) \qquad (4)$$

Where V_{SNM} is the output signal corrected for normal mode error.

Because of our simplifying assumption (span = constant), the added functions required for normal mode auto-referencing are significantly reduced by elimination of division by a measured variable. As shown in *Figure 5,* an additional switch pole, three additional subtractors, a multiplier and another sample-and-hold are sufficient. Since the two reference pressures, P_{REF} and P_{MAX}, are applied in sequence, the sample-and-hold function can be shared for normal mode and common-mode errors in many applications.



*See *Figure 2*

FIGURE 4. Normal Mode Error Correction

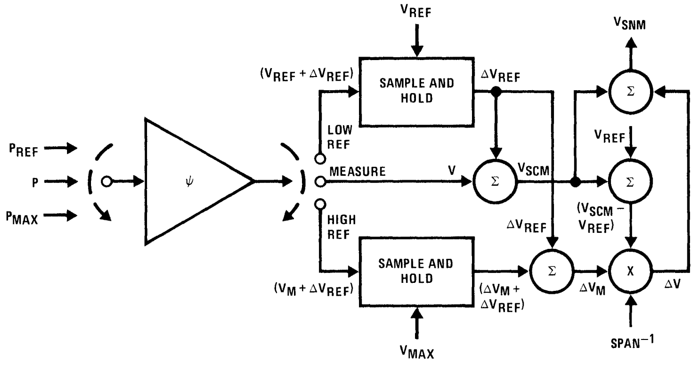


FIGURE 5. Combined Common-Mode and Normal Mode Auto-Reference Functions

COMMON-MODE

It's Good For Everybody

As discussed before, common-mode auto-referencing is a universal method for eliminating virtually all time and temperature induced offset error. While it's never wise to declare that a technique is "universal", some techniques are so powerful that it becomes easier to cite instances wherein the technique should not be used than where it should. Auto-referencing is just such an "almost universal" technique. Why then is this technique not more widely used with transducers? Traditionally, transducer users and producers are "linear/analog" oriented people, to whom "digital" people are those other guys in the soft world. Factually, analog approaches to auto-referencing are less cost effective. So, there's a natural reluctance for analog people to employ digital circuitry for an analog function. Yet, all mensuration theorists and educators highly recommend the technique. Therefore, the message is . . . get on board, fellow analogers, digital auto-referencing is good for you.

Which pressure transducer users should *not* use a common-mode auto-referencing circuit? In applications involving a short measurement cycle, where the zero point is either read or manually adjusted at the start of the cycle, an auto-referencing circuit is of no value. In acoustic measurements where the transducer is AC coupled such that DC or steady state response is of little value, common-mode auto-referencing won't help. In all other applications common-mode auto-referencing yields the optimum accuracy for the lowest cost.

SIMPLEST CASE—"NATURALLY WELL SUITED"

What's the best way to use auto-referencing? The correct, but imprecise, answer is . . . as often as you can. The object is to have those measurements of greatest interest closest in time to an auto-reference command. The kind of duty cycle naturally best suited to auto-referencing is "short repeated cycles", each containing a reference point. Another almost as well suited kind of duty is a short interest period immediately preceded by a referencing point, but followed by a long no-interest period. In either case, a measurement point of interest is within several hours of the preceding reference point. Most applications have duty cycles that are in one of the two aforementioned "naturally well suited for auto-referencing" categories. Equally important, many applications that have duty cycles not naturally well suited can be converted to the short repeated cycle situation with relative ease if the value of doing so is recognized by the designer early enough. The simplest of the best suited applications involve things that go up, then go down, and then rest awhile. Ideally, the pressure increases rapidly to the range of interest, hovers at the measurement condition, decreases quickly, and hovers at the reference condition.

Some applications very closely resemble the ideal description. For example, a weighing scale is ideal (Section 10, Load Cells). Also ideal are filling washing machines, beer bottles, and toilet tanks. Another ideal category is pressure sumps such as tire pressure, oil pressure, and blood pressure (Section 9, Sphygmomanometers).

In these cases, the measurement apparatus is usually turned-on at a reference condition before experiencing the measurement condition of interest. Less ideal, but certainly improved by auto-referencing, are flow measurement and control applications. Examples are fuel pumps, pulmonometers, and even machines that smoke cigarettes. In these cases, the flow rate is zero at some point in a relatively short cycle . . . usually at turn-on.

The trick is to cause the command signal at the right time. The best time is after the transducer is warmed up and when the application is hovering at a reference condition. All the previous examples were of a type wherein the reference condition exists at and shortly after turn-on. This makes life easy. If the warm-up error is of little concern, then the turn-on signal can be used directly as the command signal, as shown in *Figure 1.*

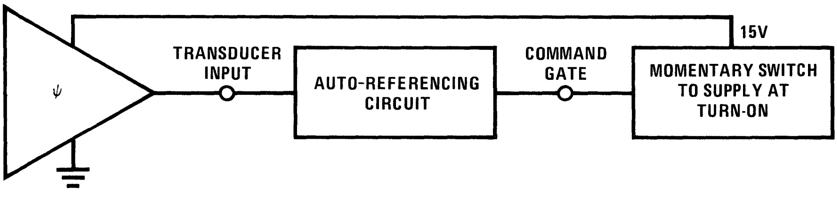


FIGURE 1. Auto-Reference Commanded by Turn-ON

Other ways of getting the required momentary command signals often present themselves as appropriate to the application. For example, in weighing systems, some displacement is inherent just as the load is applied to the scale pan barely before pressure build-up, an invitation to use a mechanical switch.

SIMPLE CIRCUIT FOR SIMPLEST CASE

The momentary switch referred to for the simplest case forms an enable signal for input to the command gate, *Figure 2.*

The basic functions of an auto-reference circuit are shown in *Figure 3.*

The leading edge, negative transition of the enable signal resets the control latch and resets the counter to zero. While in the low state, the enable signal inhibits the counter from accepting input pulses to allow time for stabilization of pressure. The referencing sequence is initiated on the trailing edge, positive transition of the enable signal. The D to A converter is used as an infinite sample-and-hold as well as a programmable voltage source, supplying and maintaining the desired correction voltage. The output of the transducer is summed with the auto-reference correction voltage at the summing junction of the first amplifier. The circuit is shown in *Figure 4.*

The "bit" rating of the (D/A) determines the resolution of the output signal. The quality of regulation of the reference voltage applied to the (D/A) determines the system stability. Thus, these easily attained circuit parameters take control of the transducer system's key accuracies. The control logic resets the (D/A), steers clock pulses into the (D/A) until the system output is at reference voltage and sends a busy signal to the sequence logic *(Figure 4).*

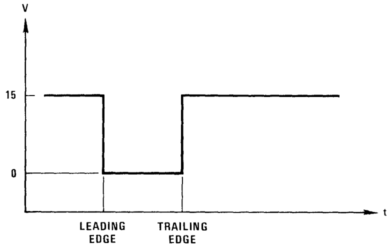


FIGURE 2. Typical Auto-Reference Enable Signal

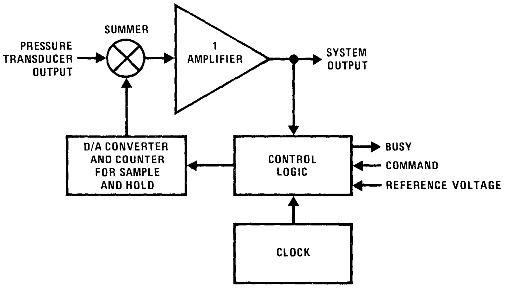
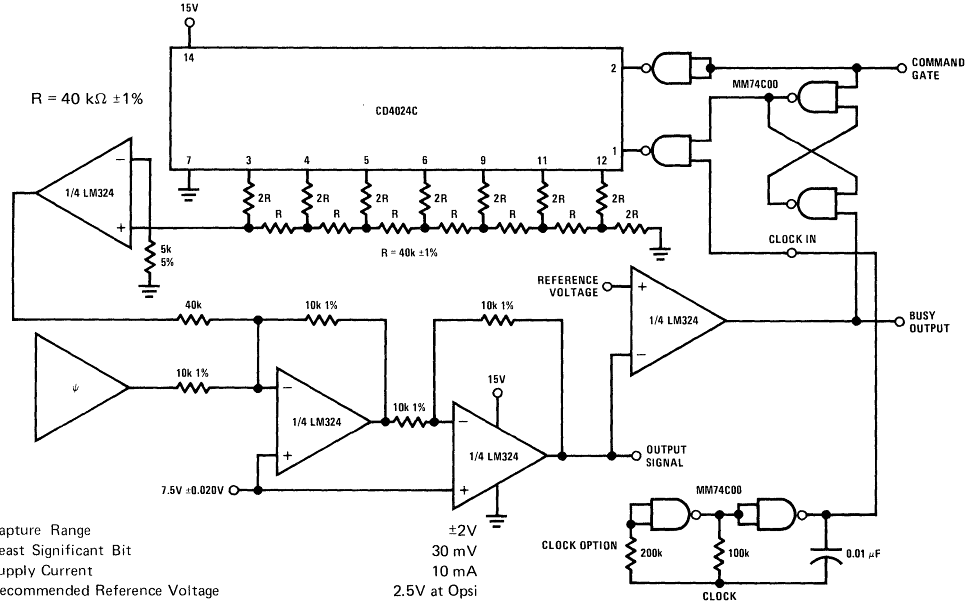


FIGURE 3. Basic Functions of Digital Auto-Reference Circuit



Capture Range	±2V
Least Significant Bit	30 mV
Supply Current	10 mA
Recommended Reference Voltage	2.5V at Opsi
Signal Input Impedance	10 kΩ
Busy Output	
Conversion in Process	0V
Conversion Complete	15V
Command Gate Should be Kept at	15V
Momentary Grounding Initiates Auto-Reference Command	

FIGURE 4. Auto-Reference Circuit with D/A Converter

SIMPLE PLUMBING FOR TOUGHER CASE

Duty cycles fall into two main categories . . . *batch process* and *continuous process*. In batch process, the reference condition generally exists right at process turn-on. For example, a weighing scale would be turned on before the load is applied and would be at reference conditions before and after loading. Similarly, the washing machine water level is zero both before and after the duty cycle and turn-on coincides with zero level. A sphygmomanometer is inflated during blood pressure measurement and is deflated both before and after duty cycle and in particular at turn-on. Whether at turn-on or not, at some point in a batch process, there is an obvious reference condition. In continuous process, the reference condition generally doesn't exist at all unless plumbed. In these cases, a solenoid is actuated as often as application allows. Generally, a cyclic pattern is developed. A clock circuit is often involved. In all cases, solenoid actuation causes reference pressure, so that auto-reference command is in sync with solenoid actuation.

Suppose you needed to know the flow rate of a river at various locations along its length. You'd need to know the cross sectional area, of which depth is a variable factor . . . and you'd need to know the flow velocity. Pressure transducers are likely choices for sensing both variables. Clearly, this application lacks features of the "naturally well suited for auto-referencing" kind. Unlike the toilet tank, there is no time at which the depth and velocity are known. In the previously described applications, there was always a known reference condition at which the user consciously or inadvertently gave the command signal immediately preceding a measurement condition. In more officious terms, the user knew when the measurand was at reference condition . . . thereby commanding autoreferencing at the reference condition and reading or controlling at the measurement condition. In this new breed of application, we need to access the reference condition rather than lay in wait. That is, there is a reference condition available. It won't walk up and attach itself to our pressure tube—but it is accessible if plumbed.

ACCESS PLUMBING AND ACTUATION

In addition to the "transducer/auto-reference/enable" system for the simple case, a reference condition actuator is required. The actuator can be turned-on by the user, or by some usage condition (like power-up), or by a timer circuit (clock). Some actuators are self-limiting in duration . . . others must be turned-off after auto-referencing, as shown in *Figure 5.*

Busy signal duration is substantially longer than is enable signal duration so as to allow reference pressure stabilization and time to reach reference signal, as shown in *Figure 6.*

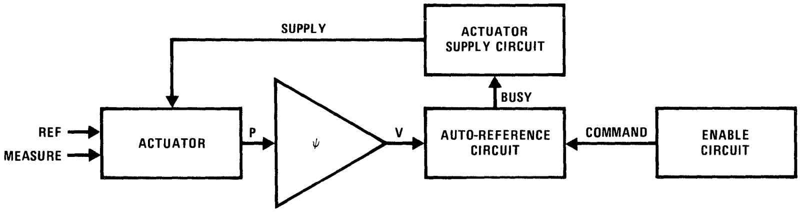


FIGURE 5. Auto-Reference with Reference Condition Actuators

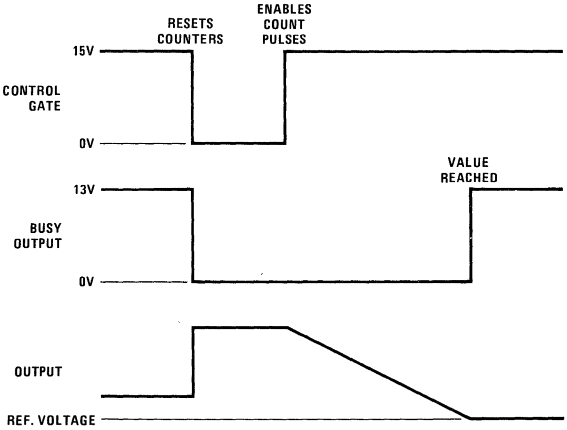


FIGURE 6. Timing Pulses for Reference Condition Actuator Circuit

Consider the depth measurement in our river. Suppose we use either a gage or absolute pressure transducer near the bottom with a vent tube to the surface (along with the bundle of wires). A 3-way solenoid valve plumbed between the transducer inlet port, the water, and the vent tube . . . serves as the reference actuator. A timer circuit acts as enabler *(Figure 7)*.

Consider the velocity measurement in that river. This requires a differential pressure transducer. A 2-way solenoid valve plumbed between the two inlet ports of the transducer serves as reference actuator, as shown in *Figure 8*.

COMMANDING AUTO-REFERENCING: STARTING

Now that we know when to auto-reference, how do we command it? Electrically, the command gate of the auto-reference circuit must see a positive voltage transient exceeding a threshold voltage and a return to a voltage below the threshold. The model of a momentary switch from ground to supply, as shown in *Figure 9*, is practical, but overly restrictive. There are three levels of sophistication that can be used to command auto-reference.

The simplest way is *manual command.* A momentary contact pushbutton switch can be used that turns on auto-reference alone or in conjunction with display or even with total electronics. If the switch function used approximates a step, as would be the case for bias turn-on, then the signal must be differentiated by the command circuit to initiate the zeroing sequence.

More elegant is the *semiautomatic command.* Consider a stepping switch. It could be manually initiated in a manner described for manual command. But, it could then sequence through such steps as solenoid actuation, followed by auto-reference command, followed by return to measurement mode. A shift register or a sequence counter would be a more electronic and less expensive substitute for the stepping switch.

Most sophisticated is the *automatic command.* Consider now a stepping switch that actuates the solenoid, commands the auto-reference, then triggers the timing circuit that upon expiration will restart the sequence, and finally returns to measurement mode. Again, the register or counter can substitute for the switch. However, consider a stepping switch that also contains both the timing circuit and the autoreference circuit and even drives the display. This, of course, is a microprocessor. (Section 7, Microprocessor Auto-Referencing).

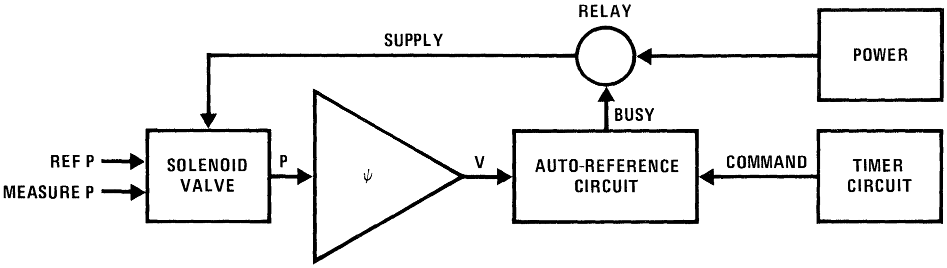


FIGURE 7. Timer-Actuated Circuit—Single-Port Transducer

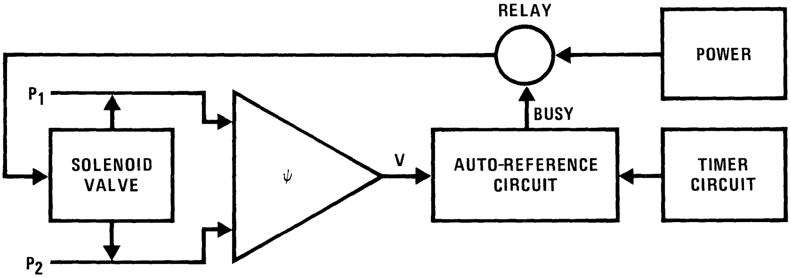


FIGURE 8. Timer-Actuated Circuit—Dual-Port Transducer

SEQUENCING

The actuation and auto-reference command block diagram is shown in *Figure 10.* Within the sequence function, coincidence logic assures that the start signal and reference conditions occur simultaneously. Coincidence detection is commonly provided by an "exclusive OR" circuit like an NSC MM74C86 CMOS. Steering logic receives the coincidence signal and the autoreference completion (end busy) signal and instigates stepping. Steering commonly employs "NAND gates" and "Flip Flops" like NSC MM74C00 CMOS and NSC MM74C74 CMOS respectively. Stepping logic takes signals from the steering logic and directs the output function. If a timer is controlling the start function, the stepper may also be used to reset the timer, thereby directing sequence. Stepping commonly uses "shift registers" like NSC MM74C164 CMOS or "counter/dividers" like NSC MM5622A CMOS. The entire sequence function controls the output function.

ACCURACY

The beauty of the auto-reference technique can now be examined in terms of system accuracy and resolution. The common-mode errors contributed by the pressure transducer, which appear as a reference drift due to various effects and a lack of reference resolution, are totally replaced by the accuracy limits of the auto-reference circuit. Reference drift is solely a function of voltage regulation since it is as stable as is the reference voltage. That error can be made virtually zero. Resolution is a function of the "bit" rating of the D/A converter. Auto-reference circuits can vary greatly in cost depending on such application requirements as offset capture range and resolution. If the pressure transducer is properly chosen, the circuit can reduce offset (common-mode) error to from 1/4% span to 1/2% span, leaving only the substantially less severe sensitivity based (normal mode) transducer errors to contribute to system error . . . not a bad trick for the price of an inexpensive circuit and possibly a solenoid valve. Needless to say, we at National recommend auto-referencing for everybody.

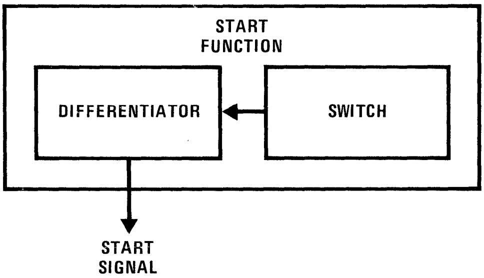


FIGURE 9. Momentary Switch Start Signal

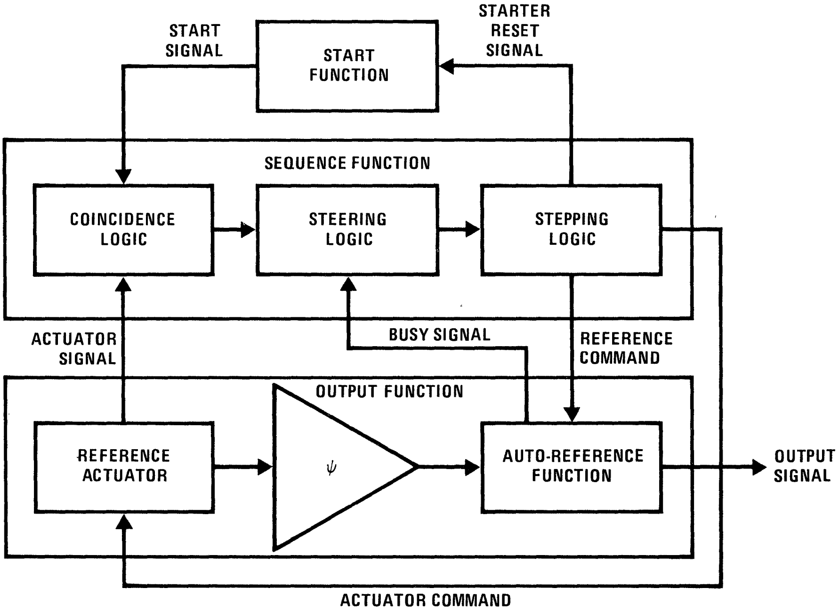


FIGURE 10. Auto-Reference Sequencing Logic

Advanced Auto-Referencing for the Sophisticated User

REFERENCE CREATION*

In our previous discussion, we dealt with situations requiring auto-referencing in two ways. If the duty cycle were such that the reference pressure appeared at the measurand port on a known schedule, we merely commanded auto-referencing at the appropriate moment. These "naturally well suited for auto-referencing" situations were best characterized by applications involving "batch processes". Typical applications in this category are blood pressure measurement (sphygmomanometry), weight measurement (scales), and liquid dispensers (gasoline pumps).

If the duty cycle did not offer a known schedule. . .but the reference pressure was available to the measurand port via plumbing and valving, then we created an appropriate duty cycle, so as to access the reference pressure. These tougher situations were characterized by applications involving "continuous processes". Typical applications in this category include liquid level height measurement (head), fluid flow (water metering), and fluid velocity (wind speed). Such applications require a reference actuator (a valve) and some plumbing to access the reference pressure.

However, what do we do when the duty cycle is unscheduled and a known reference pressure isn't available? Then, of course, we need schedule a duty cycle and *create a reference pressure* at the appropriate moment.

Perhaps the best example of an application requiring the creation of a scheduled reference pressure is that of an accurate barometer. The best choice of reference pressure is none at all. . .that is, a vacuum. The principle involved is that of a syringe. A quick pull on a syringe easily produces pressures less than ten torr. A reasonable solenoid actuation scheme should be able to reproduce that pressure to within one or two torr. A system using this method is shown in *Figure 1.*

Another application that is almost as well suited as a barometer is an accurate altimeter. The ten torr reference corresponds to about 90,000 feet altitude reference, and the two torr reproducibility would correspond with a sea level error of about 15 feet altitude. A trade-in of common-mode errors like offset temperature effects and offset drift against a 15 or 20 foot altitude error is certainly a good trade (you win by a factor of ten in accuracy and probably much more in cost). Other applications that could benefit by the "make-your-own-reference" technique are those that would otherwise require awkward plumbing. For example, in liquid depth sensing (particularly in the ocean) referencing to surface pressure requires a long vent tube. *Figure 1* shows a scheme for creating a vacuum reference.

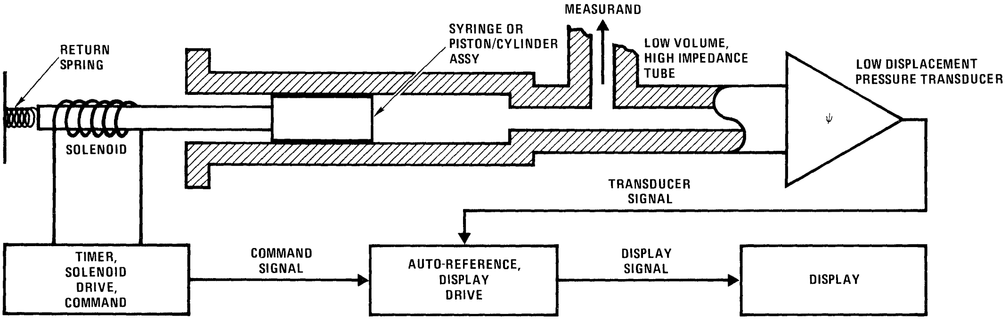


FIGURE 1. Vacuum Reference Pressure Produced by Piston and Cylinder

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*Patent pending

INEXPENSIVE DIGITAL DISPLAY

Since the auto-referencing circuits contain the major functions of a counting A/D converter, a display can be driven by the auto-reference circuit without the addition of another A/D converter. Thus, a usually expensive component addition is avoided. The additional and altered circuitry using the clock pulses is shown in *Figure 2.*

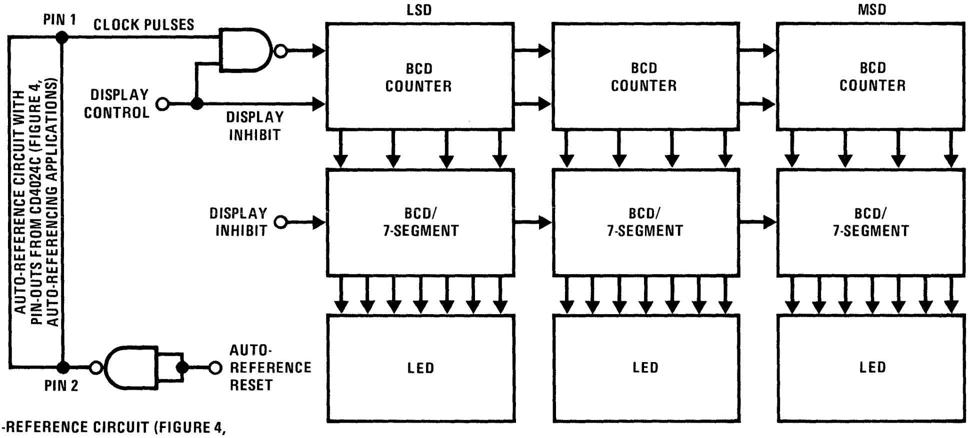
The simplest sequence begins with an auto-reference reset pulse, followed by an auto-reference command. At this point, common-mode error is removed and display indicates zero. Next, the measurement condition is applied to the transducer. . .thus changing the analog output. Then the state of the display control gate is changed so as to allow clock pulses into the counters and remove the counter inhibit function. A second auto-reference command nulls the analog signal while the clock pulses are counted by the BCD counters. The display rolls up to the final value.

A more elegant sequence involves the use of BCD/7-segment converters with holding registers. The optional display inhibit is pulsed at each final null condition, updating the readout. In this sequence, extraneous zero display and rolling digits are eliminated.

Pressure gaging, flowmetering, weight scales, and blood pressure meters (sphygmomanometers), are good applications for these display systems.

MICROPROCESSOR AUTO-REFERENCING

The machinations of auto-referencing can be accomplished with hardware or with software. In a microprocessor based system, auto-referencing is better implemented with a subroutine than with extraneous circuit components—and it's less expensive at no loss in accuracy. A microprocessor based auto-reference system in its simplest form is shown in *Figure 3.*



CHANGE AUTO-REFERENCE CIRCUIT (FIGURE 4,
AUTO-REFERENCING APPLICATIONS):
REMOVE PIN 2 CONNECTION TO COMMAND GATE

FIGURE 2. Inexpensive Digital Display Circuit

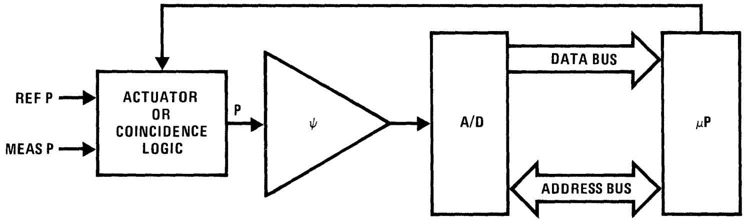


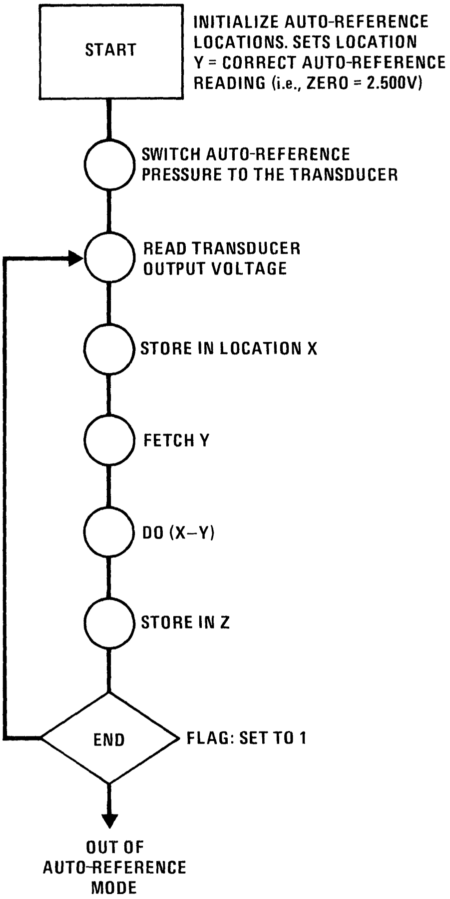
FIGURE 3. Microprocessor-Controlled Auto-Referencing

Only two permanent storage locations are required of the microprocessor to achieve auto-referencing. One location houses the desired output value at reference pressure. The other location stores the difference between actual transducer output at reference pressure and the desired output value at reference pressure. This difference is added to the transducer output at measurement pressure when in the measurement mode—thus arithmetically removing all offset based transducer errors. A general format for a microprocessor based auto-referencing subroutine is shown in *Figure 4*.

DUO-AUTO-REFERENCING OF MULTI-PNEUMA-POTENTIOMETRIC SYSTEMS (NORMAL MODE, TOO) FOR SOPHISTICATES

Since we can always auto-reference one pressure measurand plumbed into one transducer, we should easily perceive auto-referencing many pressure measurands plumbed into many transducers (just perceive it—don't do it). Now also conceive the existence of scanning multi-pressure input, single-pressure output valves. Such scanning valves are common in pneumatic systems. In principle, these are pneumatic "MUXES"—we'll call them "pneuma-mux". We may now simply extrapolate to conceive auto-referencing many pressure measurands plumbed into one transducer.

Many commercial control systems utilize the pneumatic equivalent of potentiometric input signals. Let's call these "multi-pneuma-potentiometric" signals. Systems taking inputs from pneumatic thermostats in the "heating, ventilation, air conditioning, refrigeration" field follow this model. Pneumatic thermostats are potentiometric temperature to pressure converters. A desired temperature is chosen as well as a temperature control range about the desired temperature. The change in output pressure is proportional to changes of input temperature within the control range. Typically available to such systems is a controlled low pressure reference line (usually at 3 psig) and a high pressure reference line (usually at 15 psig). The "pneuma-pots" proportion temperature input signals between the high and low pressure reference values.



Location Z contains number to be added to all future transducer readings

FIGURE 4. Auto-Reference Subroutine (Normal Mode)

This situation presents a new opportunity—not only for auto-referencing multiple inputs to a transducer for the usual purpose of eliminating offset based errors (single reference auto-referencing); but also for auto-referencing multiple inputs to a transducer for eliminating both normal mode and common-mode errors (except linearity and hysteresis errors). *Figure 5* shows a microprocessor based system for "duo-auto-referencing, multi-pneuma-pot" signals.

Figure 6 shows a typical transducer output plot for the i^{th} pressure input relative to the reference pressures. Both the actual and desired output characteristics are shown.

Some simple definitions will help in the development of software for auto-referencing using a microprocessor:

$\Delta V_{LO} \equiv V_{LO\ ACT} - V_{LO\ DES}$; common-mode error

$\Delta V_i \equiv V_{i\ ACT} - \Delta V_{LO}$; common-mode corrected signal

$V_{S\ ACT} \equiv V_{HI\ ACT} - V_{LO\ ACT}$; uncorrected span

$V_{S\ DES} \equiv V_{HI\ DES} - V_{LO\ DES}$; desired span

$R \equiv V_{S\ ACT}/V_{S\ DES}$; normal mode correction coefficient

$V_{Si} \equiv R(\Delta V_i - V_{LO\ DES})$; normal mode corrected partial span

$V_{i\ DES} \equiv V_{Si} + V_{LO\ DES}$; desired signal at P_i

The microprocessor must permanently store $V_{LO\ DES}$ and $V_{S\ DES}$. After each scan, it must measure and store $V_{HI\ ACT}$ and $V_{LO\ ACT}$. At each scan position, it must measure and store $V_{i\ ACT}$. Then the programming need calculate in order ΔV_{LO}, $V_{S\ ACT}$; ΔV_i, R; V_{Si}; $V_{i\ DES}$. An example is shown below.

EXAMPLE:

$V_{LO\ DES} \equiv 2.5V$, $V_{S\ DES} \equiv 10V$

let: $V_{HI\ ACT} = 12.8V$, $V_{LO\ ACT} = 2.2V$

$V_{i\ ACT} = 6V$

then: $\Delta V_{LO} = -0.3V$, $V_{S\ ACT} = 10.6V$;

$\Delta V_i = 6.3V$, $R = 1.06$;

$V_{Si} = 4.028V$

$V_{i\ DES} = 6.528V$

Successful implementation of this kind of approach should yield system accuracy of better than 1/2% span with cost effectiveness far better than achievable via traditional approaches. Most often, the corrected microprocessor output $V_{i\ DES}$ is used to initiate switch control of compressors in an HVACR system (see Section 11).

The message—get with auto-referencing, it's the choice of sophisticates.

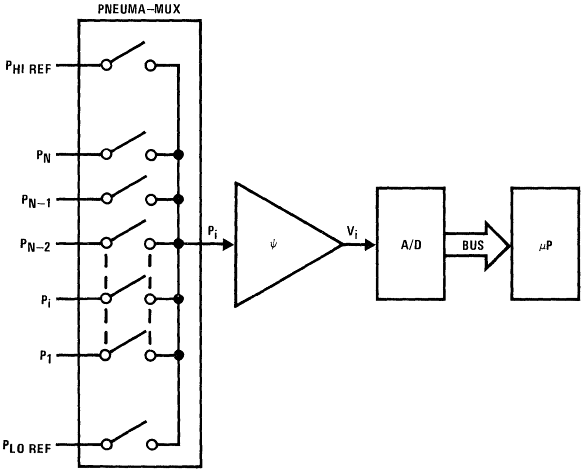


FIGURE 5. Duo-Auto-Referencing, Multi-Pneuma-Potentiometer System using Microprocessor

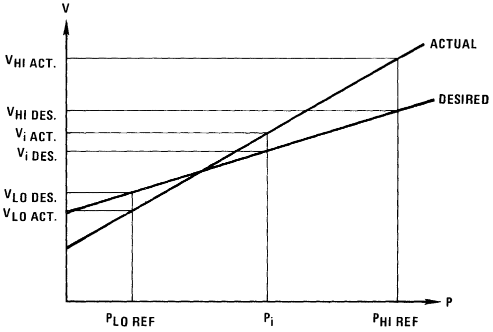


FIGURE 6. Transducer Response Plot for i^{th} Pressure Input Relative to High and Low Reference Pressures

Section 8

Signal Conditioning

SAMSON AND DELIGHTFUL

When Samson found a shape that didn't suit him, he could easily bend it or beat it into a shape that did. Of course, that kind of brute force approach seldom gets results in signal shaping and, in fact, is never even needed with National's IC pressure transducers, since they have a nice linear 2.5V to 12.5V output signal that can easily be auto-referenced, scaled, converted to digital words, or used to drive a VCO. But there are some curvaceous pressure input functions, such as those picked up by altimeters and flowmeters, that definitely need to be straightened, or at least translated into something meaningful. For these cases, we still don't recommend the brute force of Samson, but rather the delightful subleties of analog and digital curve-fitting techniques described herein.

Scaling Transducer Output Voltage

INTRODUCTION

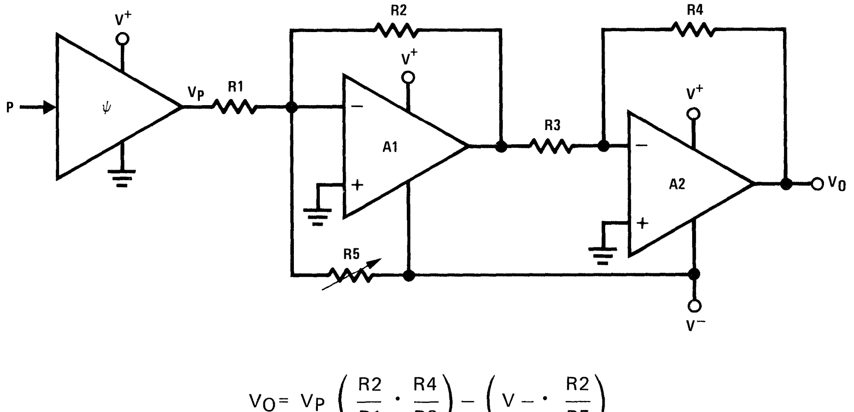
Most of National Semiconductor's pressure transducers have standardized curves where an output of 2.5V represents the minimum pressure input and an output of 12.5V represents the maximum pressure input. This is true throughout the range of zero to 5000 psi. Rescaling for specific applications is often required.

Since the most common requirement calls for zero volts out when pressure input is zero that case will be dealt with in detail. The assumption will be made that the user has access to plus and minus supplies (relative to ground). Most op amps will not operate linearly near their supply voltages; thus a single ended supply system (0 to 15V for example) will introduce errors near zero.

The circuit shown in *Figure 1* will allow the user to level shift the transducer output and adjust the gain as desired.

By using two operational amplifiers in the standard inverting configuration, gain and offset can be adjusted independently. Amplifier A1 is always set for unity gain (R1 = R2) and R5 is adjusted to set the offset voltage (usually zero volts). Amplifier A2 will control the gain without changing the offset.

To illustrate the versatility of the circuit, two devices will be compared. The LX1603G is a single ended pressure transducer while the LX1604G is a double ended type. Table I shows their output voltage vs pressure input characteristics. In addition, Table I shows the resulting voltages after shifting to zero volts out for zero pressure in.



$$V_O = V_P\left(\frac{R2}{R1}\cdot\frac{R4}{R3}\right) - \left(V^- \cdot \frac{R2}{R5}\right)$$

If R1 = R2 and R3 = R4, then $\Delta V_P = \Delta V_O$.

FIGURE 1

TABLE I

INPUT PRESSURE (PSIG)		OUTPUT VOLTAGE		
LX1603G	LX1604G	STANDARD TRANSDUCER	MODIFIED LX1603G	MODIFIED LX1604G
0	−15	2.5	0	−5.0
15	0	7.5	5.0	0
30	+15	12.5	10	+5.0

Example 1

If the desired output of an LX1603A is 0V for 0 psia and 10V for 15 psia, R1–R4 = 10k, V^+ = 15V and V^- = −15V. Equation 1 indicates the proper determination of R5.

$$R5 = \frac{R2 \cdot V^-}{V_P\ (0\ \text{psia})} = \frac{10k \cdot 15}{2.5} = 60k \qquad (1)$$

Example 2

If the desired output for an LX1604G is −5V for −15 psig, 0V for 0 psig and 5V for 15 psig, R1–R4 = 10k, V^+ = 15V and V^- = −15V. Equation 2 indicates the proper determination of R5.

$$R5 = \frac{R2 \cdot V^-}{V_P\ (0\ \text{psig})} = \frac{10k \cdot 15}{7.5} = 20k \qquad (2)$$

If a gain other than unity is desired, R4 can be adjusted and not affect the offset. Equation 3 indicates the independence of R4 for gain setting.

$$R4 = A \cdot R3 \text{ and } R1 = R2 = R3, \qquad (3)$$

where A is desired gain.

It is possible to design a single op amp circuit to dependently adjust offset and gain. However, the dual op amp approach shown above eliminates trial and error tweaking with minor cost addition.

Solid-State Barometers

As an example of how you can scale a transducer's output to suit your needs, consider a do-it-yourself barometer. Either an LX1701A or an LX1702A is candidate. Let's take a standard LX1701A with a 2.5V to 12.5V output swing (for 10–20 psia) and externally scale the output. *Figure 1* shows you the necessary circuit and its equation. Let R1 = R2 = R3 = 10 kΩ. Let's derive appropriate values of R4 and R5 to provide output voltages in common barometric units.

Consider output in millibars (mb). At 11 psia, we wish the output to be 7.584V, corresponding to 758.41 mb. The normal output would be 3.5 ±0.5V. Suppose the particular transducer chosen had the mean output of 3.5V. Then the output at 11 psia need be increased by 4.084V. Equation 1 shows the selection of R5.

$$R5 = \left(\frac{6.9}{\Delta V_O}\right) R2 = \frac{6.9\ R2}{4.084} = 16.895\ k\Omega$$

Similarly, at 19 psia, we wish the output to be 13.1V, corresponding to 1309.98 mb. Suppose the particular transducer chosen exhibits the perfect nominal output for 19 psia, 11.5V. Thus, the transducer span between 11 psia and 19 psia is 8V. The desired span is 5.516V, corresponding to 551.6 mb (1309.98 mb – 758.41 mb). Equation 2 shows the selection of R4.

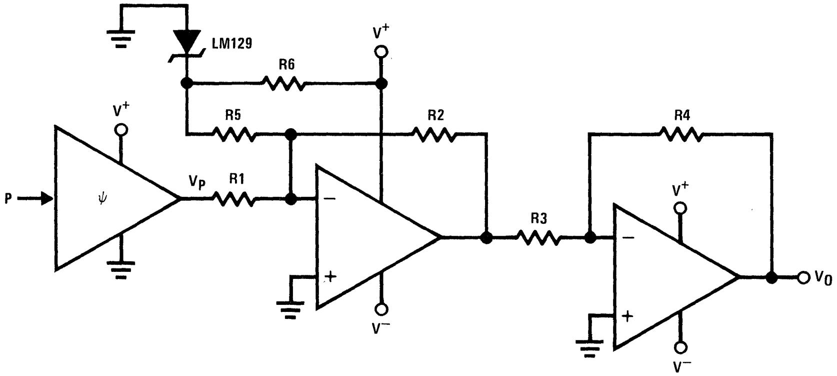
$$R4 = \left(\frac{\text{Desired Span}}{\text{Span}}\right) R3 = \frac{5.516}{8} \cdot 10 = 6.895\ k\Omega$$

In like fashion, the values of R4 and R5 can be calculated for output in units of mm Hg. Table I tabulates values of R4 and R5 for outputs in mb and mm Hg.

We have been considering ideal transducers. But a production LX1701A could have ±500 mV offset error. Resistor tweaking may be necessary to correct for such an error. In fact, probably the best way to build the barometer is to use 15 kΩ, 5% resistors with 5 kΩ series pots, measure actual slope and offset for your circuit, then—you guessed it—diddle.

TABLE I. LX1701A

V_P	psia	mb	R4	R5	mm Hg	R4	R5
3.5V	11	758.41		16.895 kΩ	568.87		31.526 kΩ
11.5V	19	1309.98	6.895 kΩ		982.59	5.171 kΩ	



$$V_O = V_P\left(\frac{R2}{R1} \cdot \frac{R4}{R3}\right) + \left(6.9 \cdot \frac{R2}{R5}\right);$$

where $V^+ = 15\ V$ and $V^- = -15V$

FIGURE 1

Pressurized-Cable Fault Detection and Location – Example of Frequency Output

The underground and surface cables used in wire transmission of data are often pressurized. The pressurization protects the cable against its environment. Any leakage, or a break in the external layer, exposes the cable's interior to possibly destructive environmental conditions. Thus it is necessary to detect a leak as quickly as possible and to localize it with a maximum of precision. *Figure 1* shows a basic pressurized-cable control system that uses mechanical transducers (designated as "M" in the figure).

A long-distance transmission cable usually has a certain number of conductors designated for control and supervisory purposes (six are shown in *Figure 1*). Such wires are placed in pairs so as to form (three) independent loops—B1, B2 and B3— of a known resistivity per mile for a given wire diameter. Further, in each cable joint there is a mechanical pressure transducer. When the pressure drops below the transducer's threshold level, contact "C" closes.

Now, let's assume that ℓ is the distance between two consecutive transducers, in miles, and r is the loop wire resistance in ohms per mile. When a fault condition exists the n^{th} device is activated and the corresponding contact closes, the formed loop represents a resistance $R = nr\ell$, which shunts one branch of a Wheatstone bridge. This lets us compute the approximate distance to the leakage. The use of three independent loops and three bridges increases the accuracy of the measurement.

HYBRID IC TRANSDUCERS IN THE CABLE

The system just described is relatively simple but suffers from a number of faults. First of all its accuracy leaves much to be desired. Then, the information received at the terminal indicates that the pressure of the n^{th} joint dropped below a fixed level, but doesn't provide an actual value. Further, a mechanical transducer's characteristics change with time (springs and membrane). And, last but not least, such a system is expensive.

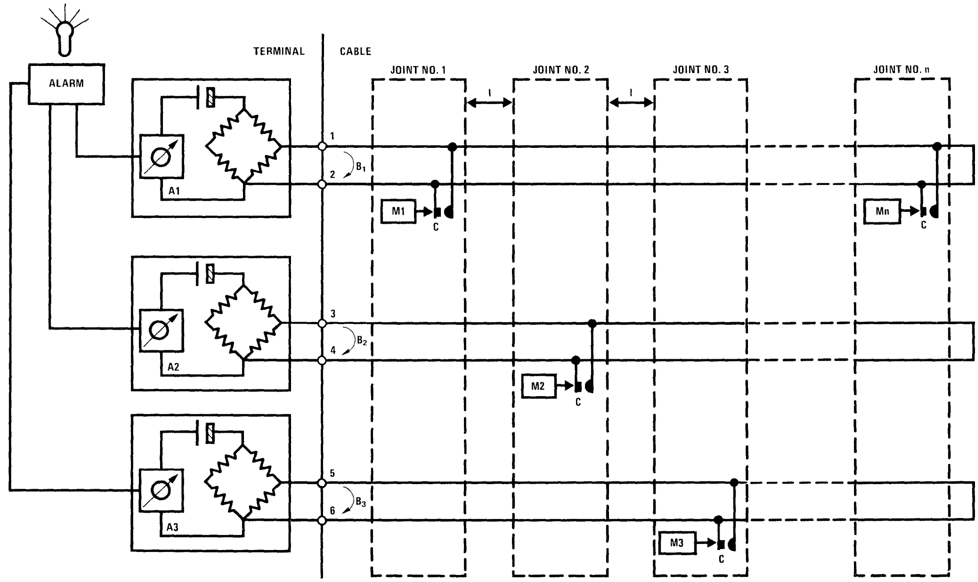


FIGURE 1. A Traditional Pressure Control System Using Mechanical Transducers

The use of IC pressure transducers improves system performance and saves money at the same time. Such a fully electronic cable control system is shown in *Figure 2.* The system comprises a main power supply; a digitally programmable generator capable of generating *n* different frequencies and having a digital display (FREQUENCY DISPLAY); a received-signal detector with display (PRESSURE DISPLAY) and alarm circuitry; and a number of transducers located at the joints.

HOW IT WORKS: THE CABLE

Referring to *Figure 3,* the main dc supply feeds the cable equipment through wires 1 and 2; the voltage at point Z is always at least 18V. (The resistance R1 compensates for the wire resistivity and is chosen separately for each joint.)

LM567 is a tone decoder capable of detecting its own characteristic frequency, which is different for each joint. When such a frequency is present at the input, the decoder output goes low and, translated in level, saturates Q1. Q1 then furnishes current to the local 15V power regulator, the pressure transducer (LX1703A)* and the voltage controlled oscillator (LM566).

The VCO input is so biased that for a nominal cable pressure (usually, 1.5 atm), the VCO output frequency is set around an arbitrarily-chosen value convenient to transmission efficiency. The linear voltage changes of the transducer's output (proportional to a measured pressure) cause linear frequency variations on the VCO output.

HOW IT WORKS: THE TERMINAL

A digitally-programmed generator cyclically transmits the interrogating frequencies f_1 to f_n. These frequencies correspond to the characteristic frequencies of the decoders on the line. The number of the interrogated device (1 to n) that corresponds to the number of the frequency being sent out is displayed on FREQUENCY DISPLAY. When the appropriate frequency is detected by one of the cable decoders, the corresponding VCO sends back fm-encoded pressure data. This data signal is counted (decoded), memorized and the received pressure value is displayed on the PRESSURE DISPLAY. A microprocessor provides a simple cost-effective method of managing the system. New data can be compared with previous data allowing for an "early-warning" detection system—a fault can be detected before any damage can occur.

During the whole interrogation cycle, only one transducer is energized at any given time. The supply current of an energized joint's circuitry is 35 mA (typ.), while the standby current of each non-interrogated joint is about 6 mA.

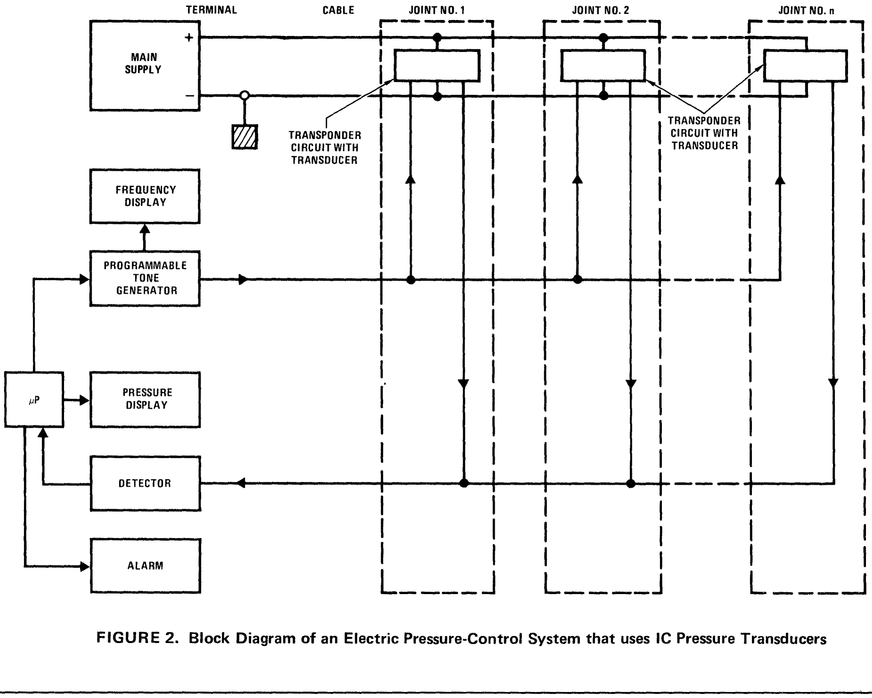


FIGURE 2. Block Diagram of an Electric Pressure-Control System that uses IC Pressure Transducers

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*LX1603A may also be used.

WHAT THE ELECTRONIC SYSTEM OFFERS

First of all, the expected, overall linearity of the electronic system is better than four percent.

Compared to a traditional mechanical system, the electronic system using IC pressure transducers offers: higher precision and an actual pressure value, which is necessary for pressure gradient evaluation along the cable to localize the leak; the possibility of a permanent pressure display via BCD outputs to a printer; and a cost savings, by decreasing the number of necessary wires (from six to four) through phantom feeding.

The principles of this system can be used, with some modifications, for remote pressure control in other applications such as liquid and gas flow, and, in the future, pressurized waveguides.

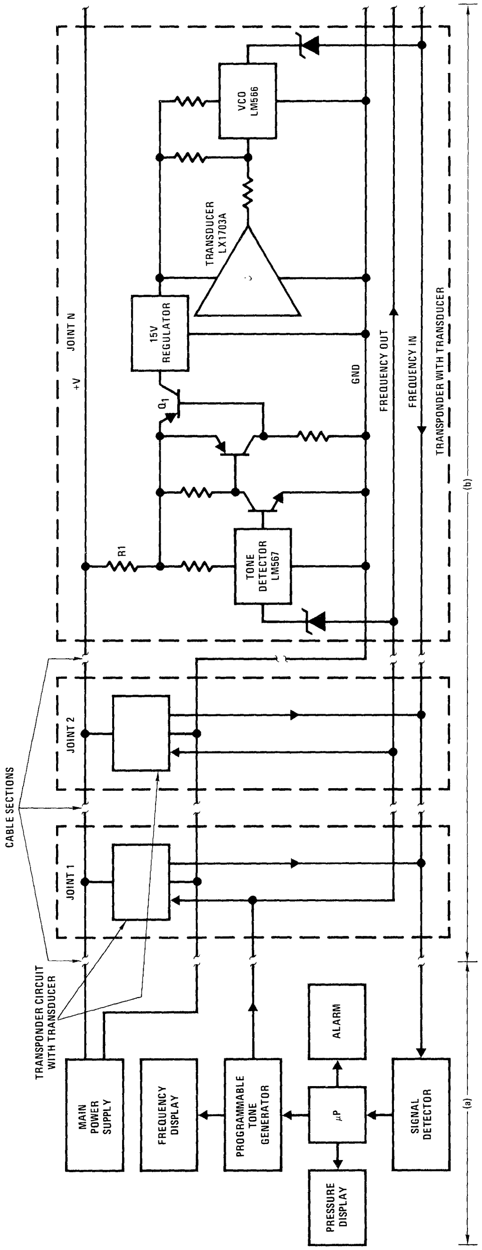


FIGURE 3. The Components of the Pressurized System

Flow Velocity Measurement—Example of Analog Shaping

The pressure developed by a flowing fluid is a direct function of the square of the flow velocity. Therefore, to use an LX series pressure transducer for the determination of a fluid's flow velocity it is necessary to extract the square root of the transducer's analog voltage output: $V_T = f(P_{IN})$; $P_{IN} = f(v^2)$; so, $(V_T)^{1/2} = f(v)$.

One way to accomplish square rooting is to make use of the logarithmic relationship that exists between the voltage drop across a diode junction and the current through it. We can use a diode's voltage/current relationship because, over a limited range of values, the ratio of the natural log of a number to its square root is approximately constant. Table I shows this relationship in terms of values of N that are numerically equal to the 2.5- to 12.5-V output voltage span of National's LX series of pressure transducers.

TABLE I

N	$N^{1/2}/\ln(N)$	1.37 X ln(N) (Const. Mult.)	% Deviation From True $N^{1/2}$
2.5	1.73	1.26	−20.6
3	1.58	1.51	−13.0
4	1.44	1.90	−5.00
5	1.39	2.20	−1.43
6	1.37	2.46	+0.24
7	1.36	2.67	+0.76
8	1.36	2.85	+0.71
9	1.37	3.01	+0.33
10	1.37	3.16	−0.22
11	1.38	3.29	−0.96
12	1.39	3.40	−1.73
12.5	1.40	3.46	−2.12

The implementation of the concept, however, is a bit more complex than simply forcing a current through a diode, measuring the junction voltage drop and scaling it in an amplifier. But an amplifier that works on that principle and does the job is shown in *Figure 1*; it uses a pair of matched, diode-connected transistors as the logarithmic elements. The transfer function of the circuit is complex, but the output voltage variation is of the form $V_{OUT} = A\ln(V_T/B)$, where A and B are constants.

Figure 2 shows the amplifier's performance in terms of the deviation of the output voltage (V_{OUT}) from a true square root of the input voltage ($V_T^{1/2}$). Varying the value of the resistor, R, shifts the curve along the percentage axis. This value may be set as required to suit any particular application.

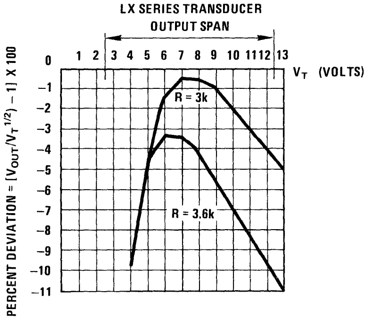


FIGURE 2. Square-Rooting Error Performance of the Amplifier

Better curve fitting can be achieved by using an LH0094 in place of the circuit of *Figure 1*.

Greater accuracy can be achieved using the dual slope integration technique described later in this section.

Still greater accuracy can be achieved using the flexural iris approach described in Section 6.

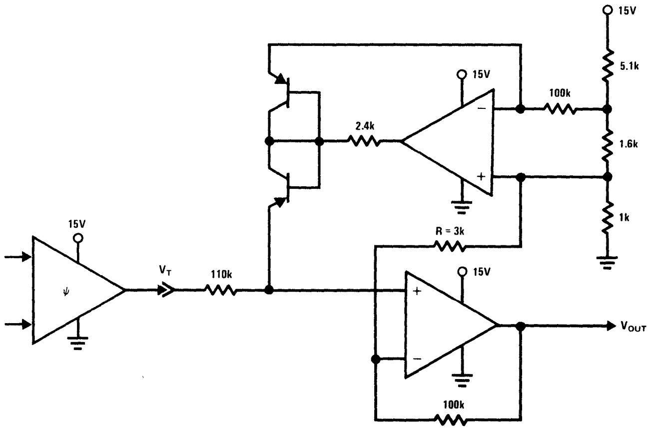


FIGURE 1. Square-Rooting Amplifier for Flow Velocity Measurements

Solid-State Altimeter for Transponder Applications— Example of Digital Conditioning

INTRODUCTION

An inexpensive, all solid state altimeter, which operates from −1000 feet to 50,000 feet is described. It is intended as an example of digital signal conditioning and not as a method for the manufacture of altimeters to meet FAA requirements.

BLOCK DIAGRAM

Figure 1 is the block diagram of a digital altimeter intended for use with altitude reporting transponders. The LX1702AN absolute pressure transducer is used to sense barometric pressure.

The integrator and comparator form the analog portion of a dual slope A to D converter. The 512 x 4 ROM is used to linearize altitude and pressure. The nine bit counter is part of the dual slope A to D and at the end of a conversion it contains the altitude value in the form of a binary number. Binary is used here to make the most efficient use of the ROM. The four bit scaling counter is used in conjunction with the ROM to linearize altitude and pressure.

The LED display logic presents the altitude reading in decimal form. It uses a three decade counter with a −1,000 foot preset that runs in parallel with the nine bit altitude counter. This is simpler than trying to do a binary to BCD conversion from the altitude counter. The altitude reporting code logic is similar to the LED logic in that it runs in parallel with the binary counter rather than doing a conversion from it.

PRESSURE TRANSDUCER

The most critical part of the altimeter is the transducer. The first question that comes up is how can we use a transducer whose specifications say its maximum error

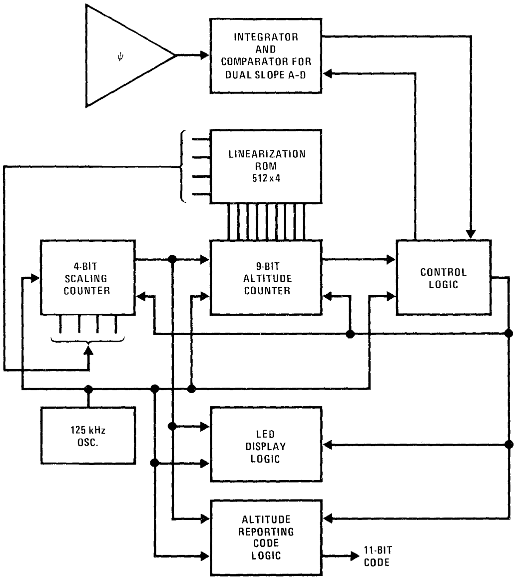


FIGURE 1. Block Diagram For Transponder Altimeter

can be as much as 2.5% of its span to do a job that calls for an accuracy of approximately 0.05% of span?

To answer that question we must examine a number of things. First the data sheet gives the specs that *all* devices will meet. If a system is designed around a 2.5% transducer, then no system calibration or transducer selection is necessary to ensure operation over temperature. All transducers would be interchangeable. However, if we are willing to trim each system to compensate for transducer variations, then the question becomes one of sensitivity, linearity and repeatability.

An individual transducer is easily sensitive enough since very minute pressure changes will cause corresponding changes in the output voltage. The linearity of an individual unit may not be perfect. However, we can compensate for transducer nonlinearities by the appropriate coding of the ROM that is being used to linearize pressure and altitude. It probably is not necessary to generate a special ROM for each transducer since many transducers exhibit very similar non-linearities. For this reason a few ROM patterns could probably compensate all transducers by simply matching a transducer with a certain class of non-linearity to its corresponding ROM.

So, we can summarize what we must do to be able to use the LX1702AN in an altimeter. First, we must be willing to trim each altimeter when we build it. And second, we must use auto-referencing if we are to approach accepted altimetric standards.

LINEARIZATION OF PRESSURE AND ALTITUDE

As you are probably aware, air pressure does not vary linearly with altitude. *Figure 2* is the curve of pressure versus altitude over our range of interest.

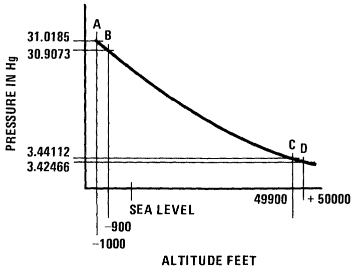


FIGURE 2. **Pressure vs Altitude**

There are a number of ways to linearize the curve using analog or digital techniques. For example, feeding a voltage proportional to pressure into a diode function generator would give us a voltage out that was proportional to altitude. We could digitize that voltage and we would have a digital value proportional to altitude.

Alternatively, we could digitize the pressure voltage directly and feed that value into a ROM. The ROM would simply do a code conversion, giving us an output in the appropriate code which represented the altitude corresponding to that pressure. This approach, though simple, requires a very large ROM. The number of bits in the ROM is given by the equation:

$$N = 2^M \times B$$

where M is number of output bits in the A to D converter, and B is the number of bits in the output code (in the case of the altitude reporting code, eleven). For this altimeter, an eleven bit A to D would be adequate; therefore, the ROM would have 2^{11} or 22,528 bits.

Another digital approach trades speed of conversion for ROM size. In this case the ROM stores only deltas, the incremental pressure differences between successive altitudes. The conversion is done sequentially using two counters. This technique is used in this altimeter and it will be fully described below. But before we do, let's discuss some general problems involved in linearizing curves using digital techniques. Some of the questions that come up are: How many bits should my A to D converter have? How big a ROM do I need?

The number of bits of the A to D is determined by two things. First, into how many increments do we want to divide our range of interest? In the case of the altimeter, we are interested in 510 increments of 100 feet each over the range of −1,000 feet to +50,000 feet of altitude.

Second, how drastic is the slope change? If the slope didn't change at all (if the curve were linear) a 9-bit A to D would be adequate for our job. The increasing slope with decreasing altitude forces the A to D to need more bits. The approximate number of bits required is given by:

$$A = RI/2$$

where R is the ratio of maximum slope to minimum slope, and I is the number of bits to encode the number of increments dividing our range of interest. This equation is valid for smooth or lumpy curves as long as the sign of the slope never changes. Also, this equation is valid regardless of which digital linearizing technique is used. Only the desired resolution and slope change determine the A to D requirements.

The simplest way to calculate the required resolution of the A to D is to first compute the incremental change, at the minimum slope, of the parameter we desire. Then divide the full range of the input parameter by this incremental change, to give us the number of increments the A to D must resolve.

For example, in the pressure versus altitude curve the maximum slope occurs at −1,000 feet and the minimum at +50,000 feet. Since we are interested in altitude increments of 100 feet, we would compute the incremental change in pressure between 50,000 feet and

49,900 feet. We would then divide this incremental pressure change into the pressure change over the full range of −1,000 to +50,000 feet. Using the numbers in Table I we have:

$$\text{Number of Increments} = \frac{P_{(-1,000)} - P_{(50,000)}}{P_{(49,900)} - P_{(50,000)}}$$

$$= \frac{31.0185 - 3.42466}{3.44112 - 3.42466}$$

$$= 1676.4180 \text{ increments}$$

Therefore, we would need at least an 11-bit analog to digital converter to resolve one part in 1676.

ALTITUDE (FEET)	EQUIVALENT PRESSURE (INCHES OF MERCURY)
-1,000	31.0185
-900	30.9073
0	29.9213
500	29.3846
1,000	28.8557
1,500	28.3345
2,000	27.8210
3,000	26.8167
4,000	25.8418
6,000	23.9782
8,000	22.2250
10,000	20.5770
12,000	19.0294
14,000	17.5774
16,000	16.2164
18,000	14.9421
20,000	13.7501
22,000	12.6363
25,000	11.1035
30,000	8.88544
35,000	7.04062
40,000	5.53802
45,000	4.35488
49,900	3.44112 (EST)
50,000	3.42466

TABLE I

The same factors affect ROM size. In the straight code conversion, the number of bits in the output code also affects ROM size. See the equation $N = 2^M \times B$ earlier in this section. In the case of the technique of storing only deltas, the ROM size is approximately determined by the equation:

$$N = R2^I$$

where N is the number of bits in the ROM, R is the *number of bits* needed to encode the ratio of max to min slope into binary, and I is the number of range bits as before. The organization of the ROM is 2^I locations by R bits wide.

Returning to the actual linearization technique used in the altimeter we can describe it simply by asking the following question: "If I have described a basic pressure increment and if I know that I am at a certain altitude of interest, how many basic pressure increments must pass before I know that I am at my next altitude of interest?"

In our altimeter, we use a dual slope A-D technique with a ROM to cause the conversion to be non-linear with pressure but linear with altitude. The R's and C's and the clock frequency are selected such that one clock period represents a pressure change equivalent to an altitude change of 100 feet at 50,000 feet.

Effectively, the converter starts at −1,000 feet and starts accumulating pressure increments until its accumualted pressure matches that of the pressure transducer. The total number of clock pulses to occur is equal to the number of pressure increments between −1,000 feet and the altitude being digitized. The ROM says, "if you are at −1,000 feet, accumulate six pressure increments before incrementing the altitude counter to −900 feet and so on."

This process continues with the ROM changing the number of pressure increments accumulated between successive altitudes. Ultimately the nine-bit binary counter has in it the binary representation of the altitude to the nearest 100 feet.

This technique is not restricted to use with a dual slope A-D, but can also be used if pressure information is already available in digital form. In that case the pressure information would be loaded into a down counter and counted down to zero, while the altitude counter and ROM count up from zero to the desired altitude value.

DUAL SLOPE ANALOG TO DIGITAL CONVERTER

In our altimeter we will have to take atmospheric pressure, which is analog information, and convert it to digital form for transmission to a ground station. We used a dual slope analog to digital conversion technique to do that job. We chose this technique because it is simple and cheap and we can tolerate the long conversion times typical of this approach.

Figure 3 shows the block diagram and basic timing of a dual slope A-D. Capacitor C1 is charged to some initial voltage V_{START} and I_{REF} is off. I_{IN}, which is variable and proportional to the voltage to be digitized, is allowed to charge C1 for time T1. T1 is constant. At the end of T1, I_{IN} is switched off and I_{REF} which is a constant, is switched on, discharging C1 back to V_{START} in time T2. T2 then, is proportional to the unknown input voltage. Times T1 and T2 are both measured by counting the oscillator and, therefore, at the end of T2, the counter contains a number proportional to the input voltage.

Figure 4 shows the actual circuitry employed in the altimeter to do the analog portion of the dual slope A-D.

V_{START} is set by R3 and R4. The setting is not critical as long as it is somewhere toward the lower end of the LM108 linear region. (An LM108 will not pull all the way down to the lower supply.)

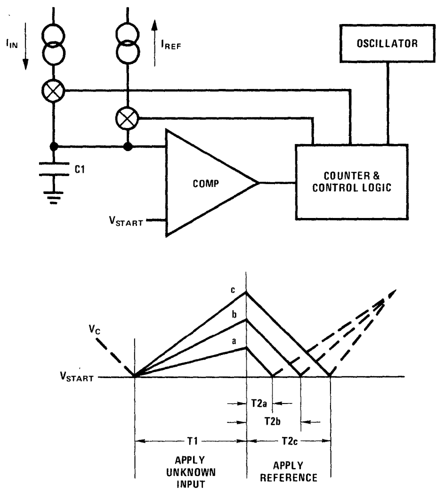


FIGURE 3. Dual Slope A-D

R2 is the zero adjust for the altimeter. R2 is adjusted until V_1 is equal to the transducer output voltage with an input pressure equal to −1,000 feet of altitude.

R1 is the full scale adjust. With R2 set, I_{IN} max is equal to V_1 minus the transducer output voltage at a pressure equivalent to 50,000 feet of altitude, divided by R1. I_{REF} is equal to 15V minus V_1 divided by some portion of R1.

When we apply full scale voltage, we are on curve C in *Figure 3.* In a typical A-D, times T1 and T2c would be equal for that condition. In our altimeter, however, T1 and T2 are not equal at 50,000 feet, or at any other altitude for that matter. To simplify some of the logic we chose T1 to be 2048 clock periods. T2 max becomes 1676 clock periods because of our linearization technique. Therefore, the ratio of I_{IN} max to I_{REF} is 1676 to 2048 with I_{REF} larger.

For others who will use this technique there is one thing that is not obvious from *Figures 3 and 4*. Many dual slope techniques use an initializing circuit of some sort to ensure that the capacitor starts from a known voltage each time.

If the capacitor were to accumulate some residual charge the final conversion would be incorrect. The critical time is at the end of T2 when the comparator is tripped. Unless I_{REF} is turned off immediately, it will continue to charge C1, applying an offset voltage that will affect the next conversion. If this happens with each conversion, succeeding conversions become more inaccurate.

The way around the problem is to be certain that I_{REF} is switched off and I_{IN} switched on at the next clock pulse after the comparator switches *(Figure 5).* This ensures that the residual voltage will always be one bit or less.

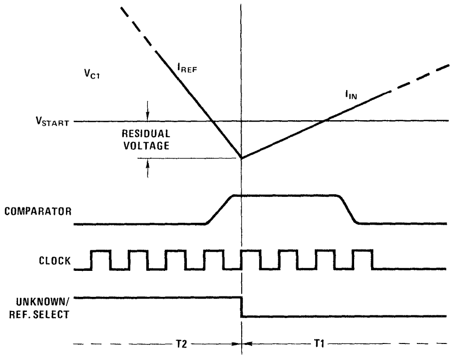
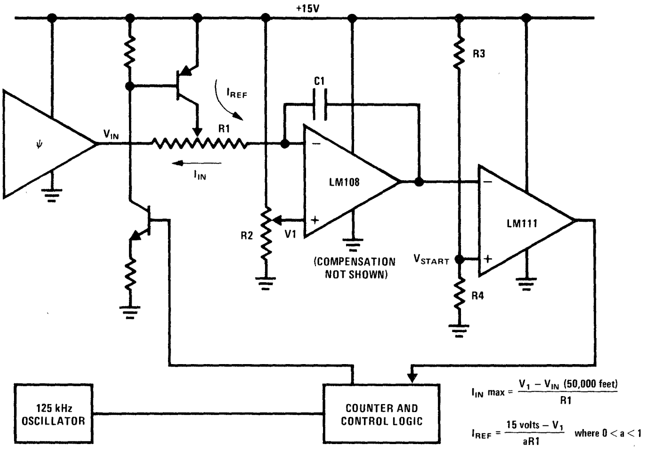


FIGURE 5

Even with the excellent function shaping afforded by dual slope integration and accuracy improvements resulting from use of the syringe—auto-referencing technique (see Section 7), it is doubtful that standard commercial grade pressure transducers can provide system accuracy and reliability required by FAA.

However, less stringent altimeter requirements for mountain climbers, drones, gliders, balloons, altitude rate indication and meteorological mensuration . . . are all good candidates for these techniques.



$$I_{IN}\ \max = \frac{V_1 - V_{IN}\ (50{,}000\ \text{feet})}{R1}$$

$$I_{REF} = \frac{15\ \text{volts} - V_1}{aR1} \quad \text{where } 0 < a < 1$$

FIGURE 4. Analog Circuitry For Dual Slope A-D

Section 9

Medical Applications (Non Life Support)

9

SUPER GNAT

When we said in the transducer accuracy section that we are working on the gnat's cardio-vascular system, we weren't joking. We have a very large gnat from Texas with many oil wells (which we monitor) and a heart condition complicated by money in the bank. But even though our IC pressure transducers are small enough to fold up in one of his fifty-dollar bills, we refuse to monitor his money because he would die if he lost a buck, then we would lose all our bucks and feel badly because he did and we did.

But we do monitor his blood pressure with a well-designed sphygmomanometer (even the gnat can't pronounce it) and his lung pressure (he also smokes cigars) with a pulmonometer, both of which use our model LX1701G IC pressure transducer. And because these instruments are conservatively designed, they are accurate and reliable, and our gnat lives on and on, even though some of his fifty-dollar bills have been transferred to a bank in Iran.

Pressure Transducers in Medical Applications

MEDICAL INSTRUMENT DESIGN

Because National's IC pressure transducers have high sensitivity, wide frequency response and easily improved accuracy by auto-referencing, they are ideal for a wide range of medical instruments. In designing such instruments, the most important thing to remember is that any medical system used for life support must be *fail-safe.* Since any component can fail, and IC pressure transducers are no exception, no pressure transducer or any other single component should be placed in a "life support" situation. For that reason, National does not recommend the use of its IC pressure transducers in any life support equipment wherein transducer failure could, in any way, endanger human life. Our policy:

NATIONAL SEMICONDUCTOR CORPORATION LIFE SUPPORT POLICY

National Semiconductor Corporation general policy does not recommend the use of its components of any type in "life support applications". National interprets "life support application" to mean a situation wherein failure or malfunction of the National component threatens life or makes injury probable.

We fully recognize that component application within a life support system is not necessarily a "life support application" of that component. In fact, many well designed life support systems have no single component in a "life support application".

When National is aware of the use of our commercial grade components within a life support system, we are required to determine whether or not our policy relative to component application is in jeopardy. In such cases we require a written statement, from an officer of the company bearing system responsibility, assuring that a malfunction of our component does not pose direct or indirect threat of injury or death.

MEDICAL APPLICATIONS

The following provides brief descriptions of some of the medical instruments for which IC pressure transducers are ideally suited. All use the model LX1701GN* gage device and, except for the audiometer, require auto-referencing to achieve the accuracy needed for most applications.

Sphygmomanometer: The apparatus used for years by physicians to wrap around a patient's arm and take his blood pressure can now be replaced by one using an IC pressure transducer with auto-reference and a suitable read-out device. The transducer version of the sphygmomanometer is more accurate, more versatile, faster, and so easy to use that the patient himself can do it. By monitoring the heart rate, the transducer instrument can detect the *true* low (diastolic) and *true* high (systolic) point and provide an accurate blood pressure history for the patient (see Section 12, Acoustics).

The block diagram in *Figure 1* shows the basic functions of the digital blood pressure measuring circuit in *Figure 2.* This circuit demonstrates a hardware approach to auto-referencing in a microprocessor controlled system. The microprocessor controls the sequencing of events; (1) the transducer is auto-referenced, (2) the cuff is inflated, (3) the systolic pressure is calculated, digitized and displayed, (4) the cuff is deflated, (5) the diastolic pressure is calculated, digitized and displayed.**An AC coupled low pass filter is also employed in this circuit to determine the heart rate.

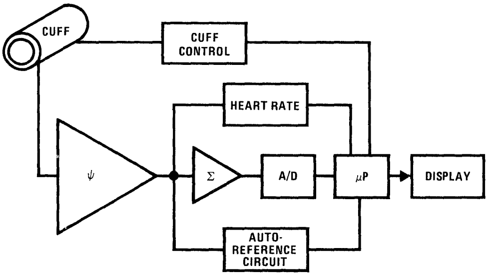


FIGURE 1. Block Diagram of a Digital Blood Pressure Measuring Circuit

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*LX1601G or LX1601GB may also be used

**In some applications, the "mean arterial pressure" (MAP) is used instead of the systolic and the diastolic pressure.

MAP ≃ 1/3 (systolic − diastolic) + diastolic

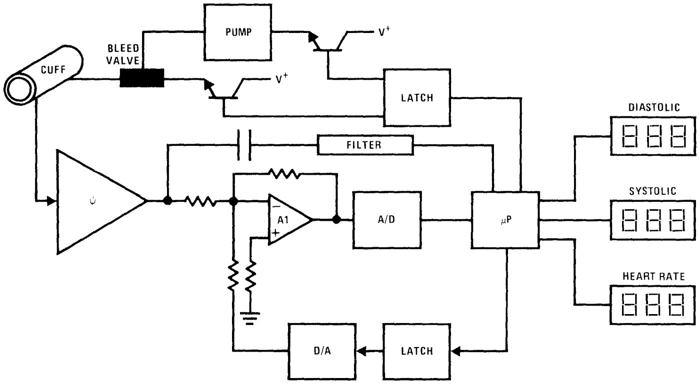

FIGURE 2. Digital Blood Pressure Measuring Circuit

In *Figure 2*, an LX1601G is used as the pressure transducer. The output voltage of this device is summed with the auto-reference correction voltage at amplifier A1. Two time periods exist for initiating the auto-reference correction sequence: one at power-up and the other during all times when not calculating the blood pressure. The latter period is preferred.

In this circuit, the microprocessor adjusts the output of the summing amplifier to be precisely 7.5V when the cuff is deflated. This is done by adding a positive or negative voltage from the digital-to-analog converter to the output of the transducer at A1. This corrects for the common-mode error terms of the transducer (i.e., TC offset, offset stability, offset calibration) as well as for changes in barometric pressure. The output of A1 goes to a successive-approximation type of analog-to-digital converter. The digital output is then stored by the microprocessor.

As the cuff pressure increases, the microprocessor continually updates this information as long as the AC component of the output is decreasing. The cuff pressure which corresponds to a minimum in AC component is then displayed. This is the systolic pressure. The cuff pressure is now gradually deflated and the same procedure is used to calculate the diastolic pressure. *Figure 3* shows a typical response curve for one cycle of this measurement.

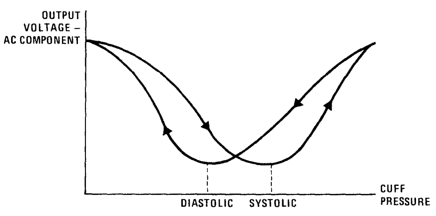

FIGURE 3. Arterial Pressure Response Curve

Tympanometer/Audiometer: The IC pressure transducer's high accuracy and excellent audio frequency response can be used to good advantage in instruments designed for measurements on the human ear. In the tympanometer, the transducer measures the compliance of the ear drum to detect hearing disability resulting from an overly stiff ear drum. The tympanometer is much faster than the audiometer but less comprehensive and hence is used primarily for screening. In the audiometer, the transducer serves to monitor the oscillator frequency and amplitude. Since a single IC pressure transducer can serve for both measurements, it makes good sense to combine these two instruments into one (see Section 12, Acoustics). Auto-reference the tympanometer only.

Tonometer: The discomfort caused by the hardness measurement traditionally used for detection of glaucoma can now be eliminated by a tonometer using an IC pressure transducer to measure intra-ocular pressure. The tonometer fills a sac placed against the eye with fluid until the pressure applied by the sac is equal to the pressure within the eye. The transducer simply measures the pressure within the sac, which begins to rise as the point of equality is reached. At that point the transducer turns off the pump and thus prevents pressure from being applied to the eye. Easy auto-referencing.

Pulmonometer: For detection of emphysema and other pulmonary diseases causing reduced compliance of the lungs, the IC pressure transducer can be used to either measure the volume of air that can be exhaled into an easy-to-inflate balloon or the pressure applied by exhaling into a small rigid chamber. The later method is practical for a pulmonometer design and can be readily implemented with an IC pressure transducer. A natural for auto-referencing.

THE BIRTH PROCESS

The IC pressure transducer turns out to be a most useful instrument for monitoring the birth process. Inserted into the birth canal, the transducer becomes a simple, direct, continuous and accurate monitoring device to be used in place of dilation measurements. As such, it is a great convenience to the hospital personnel, and does not present a patient sensitivity problem. If the transducer output data are entered into a patient monitoring system, or otherwise collected, one nurse at a central station can simultaneously monitor the birth progress of a number of women in labor.

Section 10

Accelerometers and Load Cells

10

RETURN OF RUBE GOLDBERG

Before leaving for paradise, Rube Goldberg created mechanisms so ingenious in balancing complex forces that some of our most brilliant mechanical technologists cried in envy. But now they're smiling because IC pressure transducers make it easy to build precision load cells, accelerometers and such by replacing those rachets, gears, pinions and balls, balance-beams and palls with a simple fluid cell that converts force to pressure on the transducer diaphragm. In fact, the very simplicity of the Force to Pressure Converter (FPC) was so inspiring that Rube Goldberg returned to give us spiritual assistance in conjuring up some of the application ideas described in this section.

Accelerometers, Load Cells and Displacement Meters

FORCE TO PRESSURE CONVERTER

The IC pressure transducer can be adapted to measure displacement, weight, acceleration or other force-related quantities simply by providing a means of coupling that converts the force to pressure. This "force to pressure converter" (FPC) is the principle element in such applications, but its configuration is generally different for each case. As shown in *Figure 1,* the FPC is a fluid cell coupled to the transducer with the fluid constrained by the walls of a rigid container and capable of being acted upon by the force. Implementation of the FPC can range from a simple fluid-filled transducer that measures the acceleration of the enclosed fluid (high g accelerometer) to a weight-driven piston with mechanical feedback (precision scale with zero displacement).

To see how the fluid-filled transducer responds to a force applied to the FPC, we can envision a gage transducer die submersed in an oil-filled container open at the top as shown in *Figure 2.* Since the atmospheric pressure P_{ATM} is balanced out by the gage input, the transducer measures only the pressure resulting from the weight of the oil due to one g acceleration of gravity*. At any depth h below the surface, the pressure P due to fluid weight is given by:

$$P = \overrightarrow{\rho g}h \qquad (1)$$

where ρ is the density of the oil. This formula shows that the pressure is directly proportional to the height of fluid above the pressure sensor (also known as "head" pressure), with zero pressure at the surface and maximum pressure at the bottom of the container. Since the fluid transmits pressure equally in all directions (Fluid Flow, Section 6), the sensor output signal is independent of die orientation within the fluid and hence proportional only to the weight of the fluid and the depth of the sensor.

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*The number of g's, ng, is a convenient acceleration unit where one g is the acceleration due to gravity acting on mass at the surface of the earth. The weight of the mass is given by W = mg.

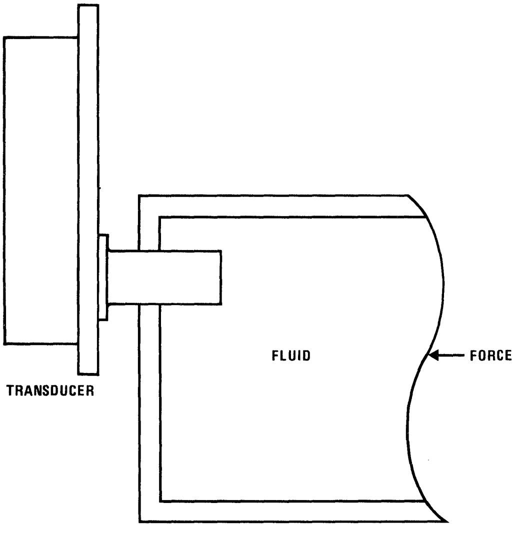

FIGURE 1. Basic Force-to-Pressure Converter

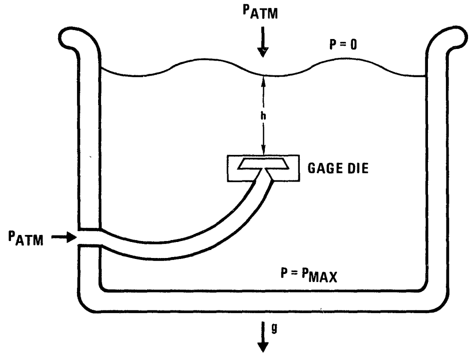

FIGURE 2. Gage Transducer Die Submersed in Oil

FLUID DISPLACEMENT METER

The FPC configuration described above provides a simple displacement meter which can be used directly to measure either the quantity of liquid in the container (with the sensor fixed) or the displacement of a shaft attached to the sensor (with the height of the fluid fixed). In a practical shaft-displacement meter, a flexible membrane could be added to seal the shaft-container interface as shown in *Figure 3.*

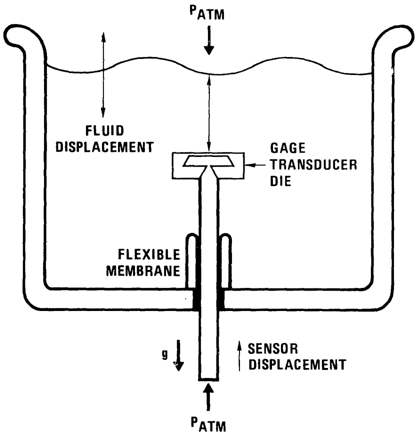

FIGURE 3. Simple Displacement Meter

BASIC ACCELEROMETER

The force-to-pressure converter can be adapted for use in an accelerometer by covering the container with a lid so that the fluid is fully enclosed in a rigid container. To evaluate the accelerometer response, we accelerate the whole container in some arbitrary direction as shown in *Figure 4*. By Newton's second law (F = ma), the pressure P_r applied to the transducer is the vector resultant of the dynamic acceleration and the static acceleration due to gravity.

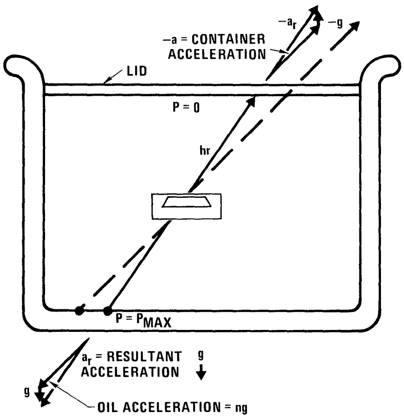

FIGURE 4. Basic Accelerometer

This is expressed by the formula:

$$P_r = \rho h_r (\overrightarrow{ng} + \vec{g}) \tag{2}$$

where h_r is measured from the sensor along the resultant fluid acceleration vector where it intersects the wall of the container, as shown in *Figure 4.* As a result, the response is zero at the wall-vector intersection point in the direction of container acceleration and maximum at the corresponding point on the opposite wall. The response profile is therefore proportional to the dimensions of the container as measured from the pressure sensor. Since the dynamic acceleration adds vectorially with the acceleration due to gravity, this accelerometer configuration is strictly linear only in the vertical direction. For large n, however, it is approximately linear in any direction and hence useful for high g acceleration measurements, as discussed in a later section.

SIMPLE LOAD CELL

Using essentially the same FPC principles described above, we can convert the pressure transducer into a load cell, a device for measuring weight. Comparing load cells with accelerometers, the main difference is that the accelerometer has a fixed mass M and a variable acceleration a, while the load cell uses fixed acceleration g (due to gravity) to measure a varying mass or weight. As shown in *Figure 5* a weightless, frictionless piston with area "A" square inches forms the weighing platform. Placing an object with mass M and weight W on the platform creates a pressure W/A pounds per square inch in the container. The sensor die translates this pressure into a voltage that is directly proportional to the weight W.

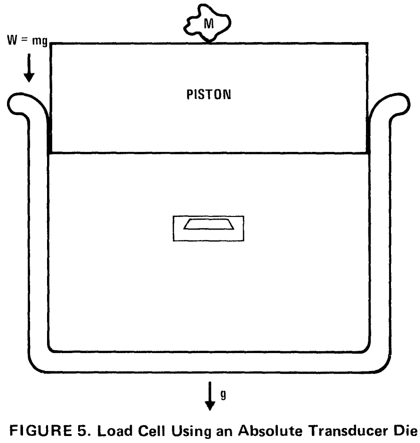

FIGURE 5. Load Cell Using an Absolute Transducer Die

REAL-WORLD ACCELEROMETER

With the FPC concept well in hand, we can now consider some real-world design problems associated with transforming an IC pressure transducer into an accelerometer. This requires us to consider whether only acceleration magnitude or full-directional sensitivity is required and the appropriateness of IC pressure transducers for the required operating conditions, acceleration magnitude range and dynamics.

Acceleration Dynamics: The variable used to describe the dynamics of acceleration is known as jerk . . . the time rate of change of acceleration. Dividing the world of acceleration into three categories (as shown in Table I) we have low jerk ranging from zero (as would be the case for the constant weight of an object on the surface of the earth) up to about a hundred Hz (as would be the case for phenomena with transients greater than a millisecond); medium jerk or acoustics ranging from a hundred Hz up to about 10,000 Hz (as would be the case for phenomena having transients greater than ten microseconds as well as the entire audible range); and finally high jerk or the world of ultrasonics and shock.

TABLE I. Pressure Transducer to Accelerometer Conversion Possibilities

Low Jerk (0 to 10^2 Hz)	Yes
Acoustic Jerk (10^2 to 10^4 Hz)	Maybe
Ultrasonic Jerk ($> 10^4$ Hz)	No

Acceleration Magnitude: Acceleration magnitudes are generally classified as *low, medium* and *high-g* ranges. The low-g range is from zero up to ten g, the medium from ten up to about a hundred g, and the high range from a hundred g on up.

The choice of when to use what physical mechanism to construct an accelerometer, and more specifically as in our case, when to transform and when not to transform a pressure transducer into an accelerometer, depends upon four areas of consideration. They are:

- The range with respect to g magnitude and jerk dynamics.
- The roll-off of a g sensitivity with frequency within the desired dynamic range.
- The unidirectionality and/or omnidirectionality* of sensitivity.
- The nominal specifications both of the operational and non-operational variety, particularly with respect to such standard environmental parasitics as temperature, position, etc.

LOW FREQUENCY RANGE

The low frequency range (0—10^2 Hz) includes mechanical vibrations associated with machinery, automobiles, trucks, missiles and aircraft. The IC pressure transducer is imminently qualified for this frequency range.

ACOUSTIC RANGE

In the acoustic range, at all g magnitudes, the desirability of transformed pressure transducers depends mainly on the desirability of range overlap. In the construction of standard microphones for audio pick-up a non-linearity in sensitivity allowing the microphone to range five orders of magnitude of sound energy is considered desirable. This would be indeed difficult to accommodate in the converted pressure transducer. Further, in audio work a sensitivity-frequency roll-off is desirable imitating that of the human ear. This too would be difficult to accommodate in a pressure transducer. However, the features of linear sensitivity with both frequency and magnitude make the converted pressure transducer ideal for the measurement and control of acoustic energy, where ordinary microphones perform poorly. In the useful frequency range, the transformed IC pressure transducers' natural frequency can be kept very high and the damping coefficient can be kept close to critical so as to minimize roll-off. The operational specifications of the resultant accelerometer can be made to approach very closely those of the LX series pressure transducers. Such characteristics are competitive with the very best of accelerometers.

ULTRASONIC RANGE

Not so in ultrasonics . . . for in the ultrasonic range the transformed pressure transducer is simply a bad choice. This is mainly due to the inability to achieve damping low enough to allow transient tracking. The mechanism in use, piezoresistance, is an absolute mechanism capable of sensing static or zero jerk phenomena . . . whereas the mechanisms more commonly used for high jerk phenomena are differential, having no static sensitivity, such as peizoelectricity or magnetostriction.

g-RANGE DESIGN

Now that we know when it is proper and when it is not proper to convert a pressure transducer to an accelerometer, based upon dynamic ranging, let us treat the three different accelerometer designs using the LX series transducers . . . one design for each of the magnitude ranges of g.

HIGH-g ACCELEROMETERS

The simplest is the high-g range. For this range, the fluid fill within the transducer has sufficient mass to give a reasonable pressure signal output according to equation 1 (since gravity is negligible). If the specific gravity of the oil is approximately 0.7, then its specific weight is: $\rho g = 0.7 \times 62.4\ \text{lbs/ft}^3 = 43.68\ \text{lbs/ft}^3 = 0.025\ \text{lbs/in}^3$. Equation 1 then becomes:

$$Pa = 0.025 \times h \times a \qquad (3)$$

Where the pressure Pa is given in pounds per square inch, "h" represents the length in inches of the rigidly-bounded fluid column in the direction of the acceleration, and "a" represents the magnitude of acceleration in the direction of interest expressed in g's.

Figure 6 shows the simplest possible high-g accelerometer configuration using an LX16XX or LX17XX package. Using typical dimensions of an LX16XX Series device in equation 3 (PX6 package outline) yields acceleration to pressure conversion in the Z direction of approximately 15 psi per thousand g; in the Y direction of approximately 3 psi per thousand g (simply because the Y dimension is approximately 0.2 times the Z direction); and in the long and short X directions of approximately 15 psi per thousand g and 3 psi per thousand g respectively. Values in all other directions can be calculated by determining the distance h from the sensor to the rigid boundary in the direction of acceleration.

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*Omnidirectionality, as opposed to multidirectionality, is defined as the ability to measure the magnitude but not the direction of acceleration. Since acceleration is a vector quantity, both magnitude and direction must be known for it to be completely defined. Multidirectional accelerometers can sense both magnitude and direction.

Transducers of the type shown in *Figure 6* are potentially useful in controlling the power delivery of rotating equipment in the hundreds RPM and up class. It should be pointed out that since the sensor is neither located in the center of a fluid sphere nor at the end of a long thin tube, the transformed pressure transducer is a poor choice if a very close approximation to either unidirectionality or onmidirectionality is required, as is the case in inertial guidance systems.

MEDIUM-g ACCELEROMETERS

This situation can be modified and the range of acceleration sensitivity extended to include the high tens of g's. By altering the column length dimensions or container dimensions of the fluid mass, as shown in *Figures 7* and *8*.

In *Figure 7* the fluid mass is only extended in the direction constituting a highly directional uniaxial Z access accelerometer. Note that as the fluid mass dimensions in the X and Y directions become small compared to that of the Z dimension the parasitic cross-axis sensitivity diminishes. In *Figure 8* the fluid mass is extended in all directions. Conceivably, if the X-directed fluid column length h_X were equal to the Y-directed fluid column length h_Y, which were equal to the Z-directed fluid column length h_Z (relative to the pressure sensing chip), the accelerometer of *Figure 8* would be omnidirectional in three dimensions.

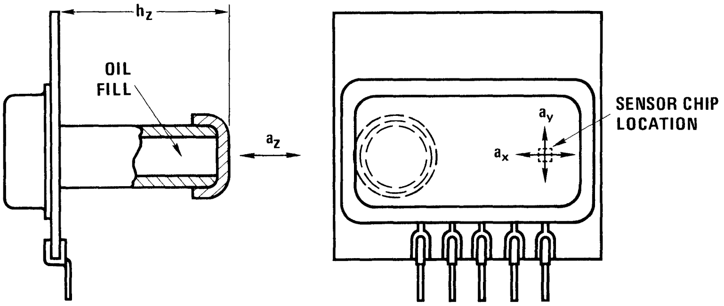


FIGURE 6. Simplest Very High-g Accelerometer

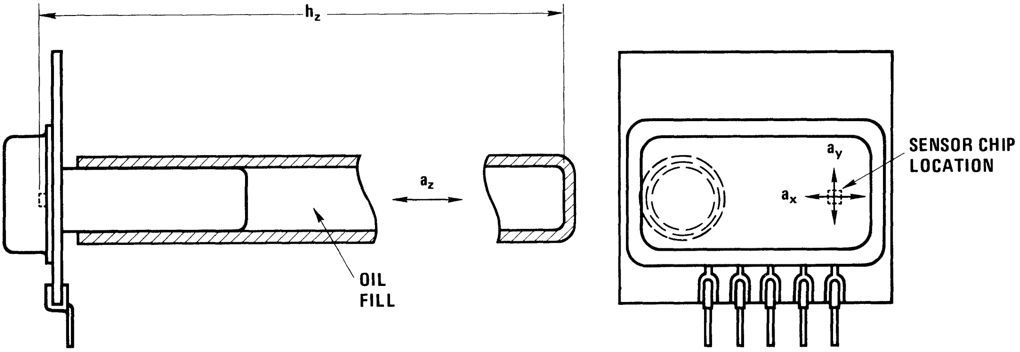


FIGURE 7. High-g Uniaxial Accelerometer

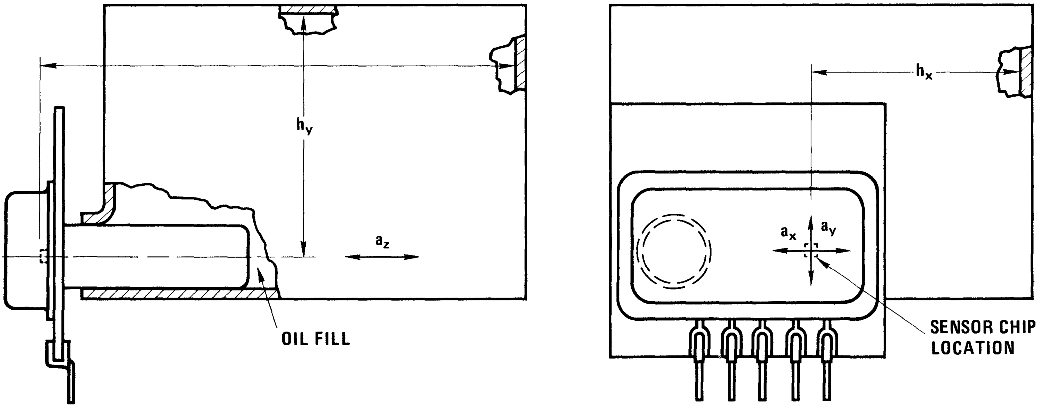


FIGURE 8. High-g Onmidirectional Accelerometer

Moving now to the medium g range of acceleration, the use of a fluid mass alone yields inadequate pressures. In this range, a solid mass can assist by pushing on the fluid medium in a directional fashion to yield adequate pressure conversion.

$$P_a = \left(\frac{W}{A} + 0.025\,h\right) a \qquad (4)$$

In equation 4, W/A represents the weight per unit area in pounds per square inch per g and is generally much larger than the second term. Although many mechanisms exist for directing force associated with an acceleration acting upon a mass in such a manner as to pressurize a fluid, the three most common and most readily available as standard plumbing parts are shown in *Figure 9. Figure 9a* shows a common piston cylinder arrangement wherein only Z oriented acceleration causes the piston to vary the pressure of the fluid column and the piston is the weight. *Figure 9b* shows a common bellows arrangement. The bellows is typically many times more compliant in the Z direction than it is in the Z plane . . . thus directing the attached weight along the Z axis. Along the same principle as the bellows, having an even greater compliance to stiffness ratio, is the rolling diaphragm approach shown in *Figure 9c*. Although *Figure 9* limits treatment to that of a uniaxial accelerometer the same principles can be extended to both omnidirectional and multidirectional accelerometers with greater complexity. Generally it is desired to keep the size of the solid weight to a minimum. For this reason tungsten alloys and even depleted uranium are often used for this purpose. However, more ordinary heavy metals usually suffice.

Plugging typical dimensions from *Figure 9* into equation 4 indicates that weights from a tenth of a pound to a pound acting on one square inch of area will typically yield ten psi for accelerations from one hundred g down to ten g.

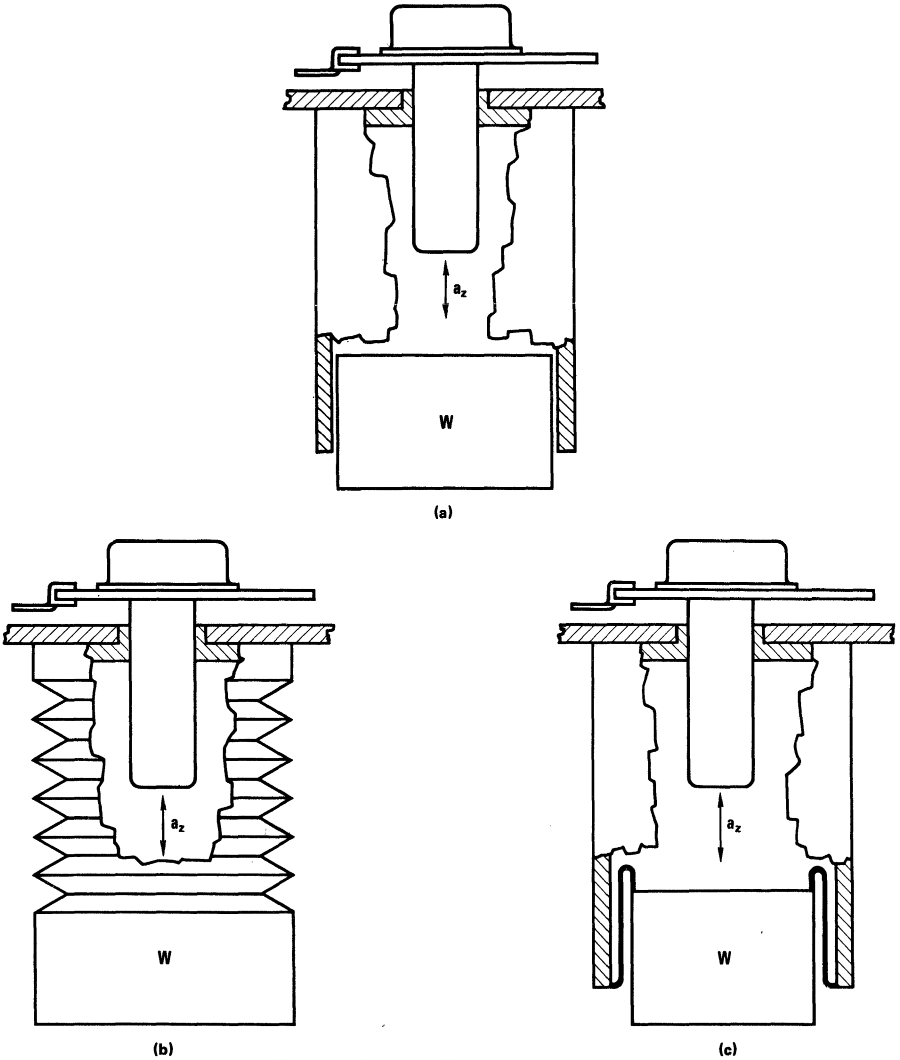


FIGURE 9. Medium-g Uniaxial Accelerometers

LOW-g ACCELEROMETERS

Finally, let us consider the lower acceleration ranges, below 10 g, wherein the use of techniques described in *Figure 9* and equation 4 would require either ridiculously small cross sectional areas in the fluid column or ridiculously large weights even for depleted uranium. Another way of stating the problem would be that acceleration levels less than 10 g, when applied to the structures of *Figure 9* would yield pressures too low to achieve acceptable accuracies. For these ranges it is desirable to produce a mechanical advantage in force before converting the force (caused by acceleration acting upon a mass) to a pressure. The mechanism most readily employed is a simple lever. *Figure 10* shows such a configuration.

Figure 10 clearly refers to a uniaxial accelerometer designed for Z axis oriented acceleration. Equation 5 expresses the conversion of acceleration to pressure in the same dimensions as those of equations 3 and 4.

$$P_a = \left(\frac{Y_1}{Y_2} \cdot \frac{W}{A_z} + 0.025\, h_z\right) a_z \qquad (5)$$

Y_1/Y_2 is the leverage ratio. One note of caution should be observed when uniaxial sensitivity to the Z oriented acceleration is desired to the exclusion of sensitivity in the X and Y axes: the initial hinge location and the stiffness of the lever should be such that the line between the weight center of mass and the hinge point remain in the Z plane.

If the weight center of mass and the hinge point were not in the Z plane, then the Y oriented acceleration would act on a Z oriented moment arm to form a parasitic output. More complicated variations of *Figure 10* can accommodate multidirectional and omnidirectional accelerometer needs as well.

Figure 11 shows the two rather simple, omnidirectional, low-g accelerometers. The structure of *Figure 11a* uses a bellows with laterally-constrained travel. Being fixed in place at its top but with its bottom free to move, the bellows can compress axially, even in a twisting, or skewed, mode. Thus, a movement of the pendulum mass, W, in any direction forces some compression of the bellows. The pivot point shifts, as required, to any location along the circumference of the bellows' bottom. The time rate of change of the transducer output voltage is a measure of the acceleration of the pendulum mass.

Figure 11b is a variation of this idea, which replaces the bellows with a rolling diaphragm and plate. The plate is free to move in the same manner as the bellows bottom of *Figure 11a*. The rolling-diaphragm-and-plate version is much less expensive to build than its bellows equivalent.

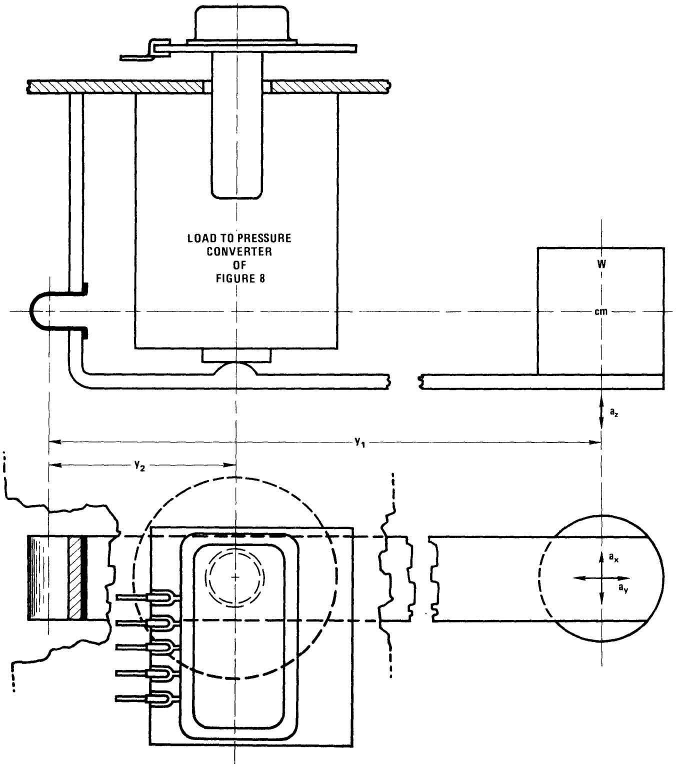
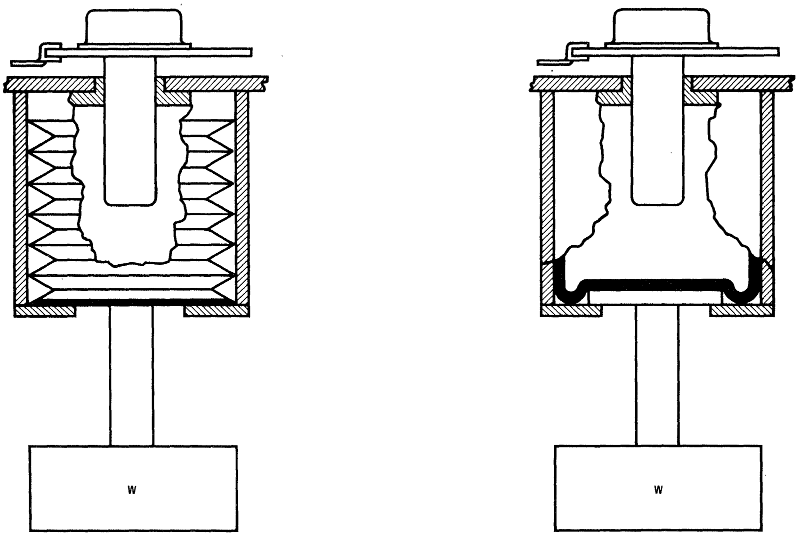


FIGURE 10. Low-g Uniaxial Accelerometer

Another variation on the theme, wherein an inner tube constrained in a block is substituted for the bellows (or rolling diaphragm), is shown in *Figure 12.* In this arrangement, varying the shape of the pivot and the moment arm determines which type of non-uniaxial accelerometer performance is achieved.

Accelerometers such as these are especially useful in automotive braking applications. (Vehicle braking falls into the less-than-one-g category of accelerometer usage.) With the addition of suitable electronics, even a simple device such as this is suitable for controlled-braking systems to prevent jackknifing. In towing situations, this type of accelerometer can sense the build-up of lateral oscillations in the towed vehicle, and electrically apply the trailer brakes sufficiently to dampen the sway. Note that automotive applications do not require dynamic and highly directional effects. Indeed, such effects are specifically not wanted. The converted pressure transducer may be, in fact, the only practical automotive accelerometer extant.



(a) (b)

FIGURE 11. Low-g Onmidirectional Accelerometers

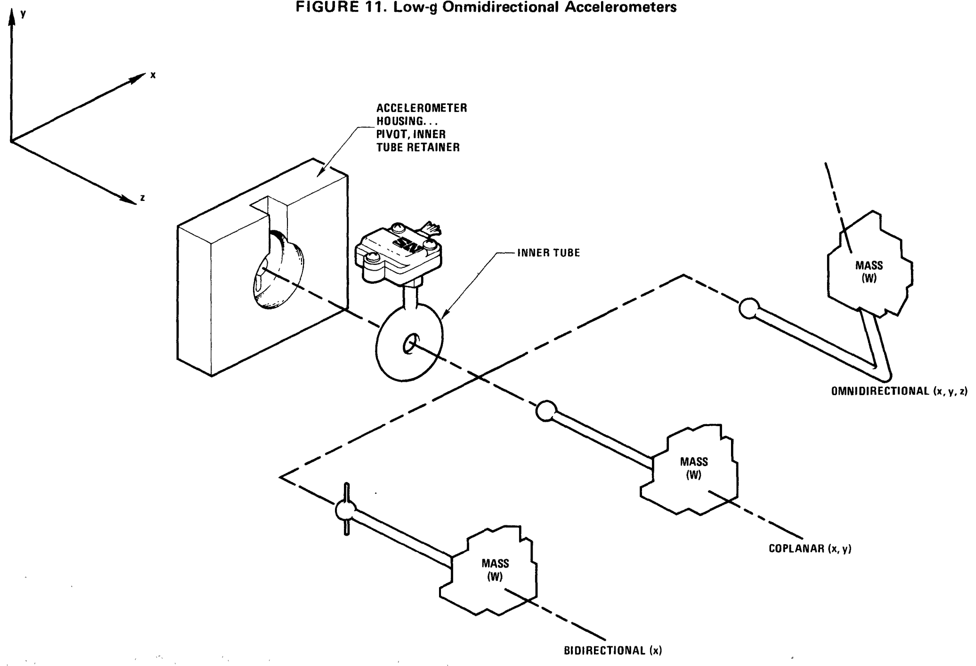


FIGURE 12. Non-Uniaxial Accelerometers

Other applications for these omnidirectional accelerometers include, for example, movement alarms (to warn of a shifting cargo), stabilization of floating platforms, and the cyberlight—a high-intensity brake light system that flashes at a rate determined by the rate of deceleration. The psychological reaction of the following driver is automatic: the higher the flash rate, the harder and faster is the following driver's application of his own brakes.

So we see that it is practical to convert pressure transducers to accelerometers using simple plumbing to cover ranges from fractional g on up to thousands of g as long as neither high directionality nor high frequency response is required.

REAL-WORLD LOAD CELLS

We can also apply most of accelerometer design principles directly to the problem of transforming a pressure transducer into a load cell. In order to convert a weight measurement to a pressure measurement, or construct a load to pressure converter, we must do the following:

1. Form a closed pressure sensing system.
2. Arrange to have the weight applied to a known area since the pressure will be defined as force per unit area (pounds per square inch).
3. Eliminate as much as possible the effects of friction which would show up as hysteresis loss.

In theory the size of the tank and the fluid are not important. In practice however, if the volume of the tank is too large or the fluid is too viscous or two compressible, the rise time, dynamic acceleration parasitic, or displacement of the system might be unacceptable even for a static scale.

It should be noted that a load cell, to be accurate, must be considered a static or near static accelerometer. As frequency increases, hysteresis due to friction and heat generated in the fluid of the system may make performance unacceptable. This, of course, is true of all load cells. In the particular case of a scale nearly all applications are static. The weighted accelerometer discussed previously *(Figure 9)* can be converted directly to a static weight measurement device; as shown in *Figure 13.*

Equivalent alternatives to the piston-cylinder approach of *Figure 13* are the rolling membrane and bellows approaches shown in *Figures 14a* and *14b* respectively. These same methods were used for the accelerometer and shown in *Figure 9a* and *9b*. All three approaches have in common high compliance in the direction of loading such that the load can be efficiently converted to pressure.

There are practical, readily available, pneumatic and hydraulic actuators of all three designs shown which could be converted to load cells by fitting them with pressure transducers. For more rugged and convenient installations, one of the LX17XXG Series transducers can be inserted anywhere into the bottom or sides of the fluid section. It will be found that because of the wall friction in actuators of this type it is desirable to minimize the piston travel and fill the system with oil. The rolling diaphragm type is a good low friction actuator; an example of the piston-cylinder type actuator is a hypodermic syringe. This is useful for measuring small weights if the cross sectional area of the plunger is small.

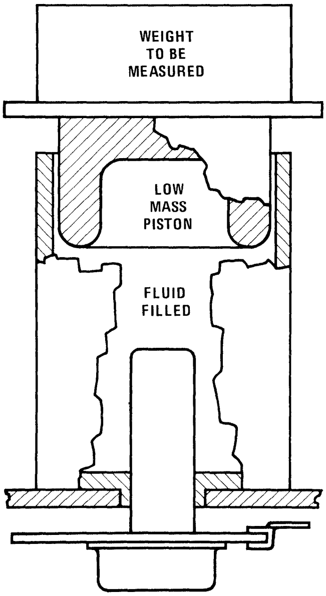


FIGURE 13. Scale Using Piston-Cylinder as Load to Pressure Converter and a Pressure Transducer

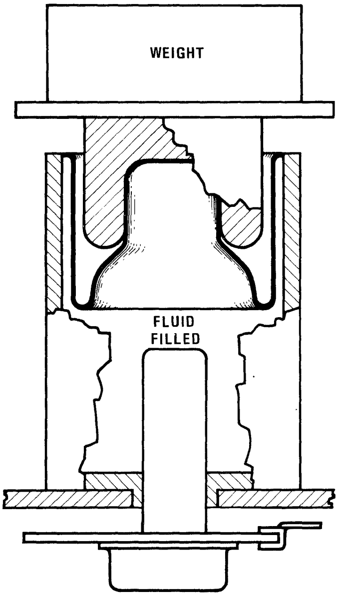


FIGURE 14a. Scale Using Rolling Membrane as Load to Pressure Converter and a Pressure Transducer

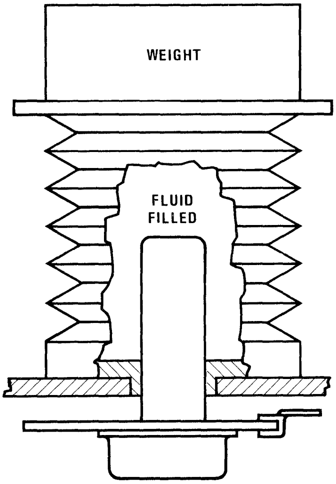


FIGURE 14b. Scale Using Bellows as Load to Pressure Converter and a Pressure Transducer

A novel system approximating the bellows approach employs a balloon constructed from a punching bag bladder, an inner tube, or a rubber ball, placed between solid platforms and connected to a pressure transducer. In practice you might couple three such balloons pneumatically to a common transducer so as to obtain a stable platform and good load averaging. In this case we have an area which will be somewhat dependent on the load so that the output of the transducer will not be linear with respect to the weight loaded into the platform. Also there will be some elastic support of the load by the rubber of the walls of the balloon.

Friction, however, will be reduced and an empirical calibration should give a reproducible reading.

One of the trouble areas to be aware of is the geometry of the set-up if your scale goes off vertical (i.e. if the piston carrying the weight or load is not vertically above the cylinder containing the fluid) then only the component of the weight acting along the direction of the cylinder will be measured as weight. The other component will add to the force acting on the side of the cylinder and thereby increase the frictional forces.

Since we are dependent in any scale on the acceleration due to gravity, any change in acceleration caused by vibrations or accelerations of the system can cause gross errors. In an accelerating system we must add the vertical vector of the acceleration to the acceleration due to gravity, a potentially serious parasitic.

$$W = m\,(\vec{g} + \vec{a}) \qquad (6)$$

This would be the case of a load cell in an elevator or a rotating device.

All traditional scales and balances use a series of levers to counter-balance the weight to be measured against either a spring or a smaller weight. In order to change the range of the pressure load cell, we can apply the same principle we used for low-g accelerometers, where a lever was employed to either increase the effect of the weight on our closed system or reduce it. Again, such an approach is particularly desirable where the load to be measured produces load cell areas that are inordinately large or small. *Figure 15* (same as *Figure 10*) shows the lever applied for a small weight that would otherwise require an area of the load to pressure converter that is too small to achieve reasonable pressure, without introducing significant errors from friction, effective area variations, etc.

The output of the scale shown in *Figure 15* may be adjusted by varying the leverage ratio.

$$P = \frac{Y_1}{Y_2} \cdot \frac{W}{A} \qquad (7)$$

Gage pressure transducers, rather than absolute pressure transducers (which would suffer output errors due to atmospheric pressure variation), in the LX17XXG Series are ideal devices for these weighing and load measurement applications. The high output level in a single-ended op amp configuration lends itself to many signal processing options. For example, output impedances are low enough to allow directly driving low cost current meters for inexpensive display. Stepping up in sophistication, the high signal level (10 V_{DC} span) permits driving a VCO for FM transmission or driving an A to D converter for computer interfacing. These features cover weighing applications ranging from bathroom scales to digital output produce scales. More general applications may be of interest where the force applied to the platform or piston is used to detect, monitor, or control some primary variable; examples include pushbuttons for manual control and thickness control in a hot rolled steel mill.

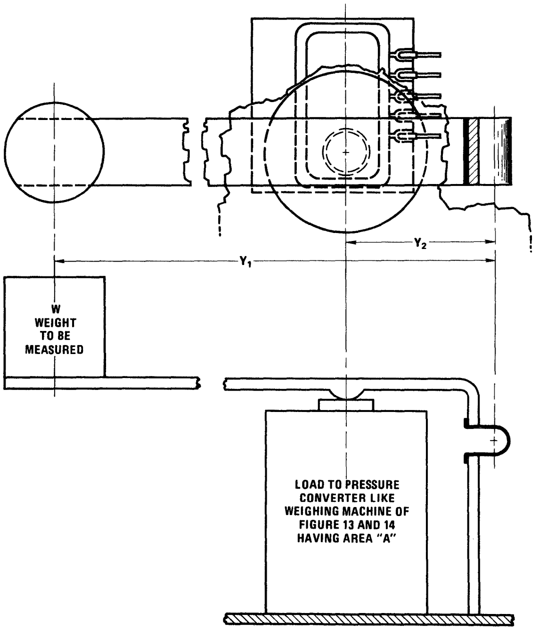


FIGURE 15. Scale Using Lever, Load to Pressure Converter and Pressure Transducer

Manual Control with Load Cells

The human body is a better force-making and force feedback mechanism than it is a positional feedback mechanism; it prefers to operate a stiff, rather than a compliant, mechanical device. This is particularly true for short time intervals. Over long intervals, the exertion needed to maintain a given force (a push or pull, say), and the sheer boredom of the act, result in body fatigue. Over long intervals, in other words, the situation reverses, and the body becomes a better positional feedback mechanism than a force-making machine.

Another phenomenon of the human body is that it is quite capable of splitting its operation between simultaneous force and displacement actions. It does this easily and instinctively, without prior training, and without interaction between the simultaneously-used modes. The phenomenon is most dramatic in the absence of visual feedback. Such feedback is a form of gain in our feedback loop—i.e., we tend strongly to believe what our eyes tell us.

Finally, in involuntary, sudden motions the body generates a lot of motion but not much force.

These principles are in daily use aboard modern, high performance aircraft. The F4, for example, may be flown"casually" with the control stick in a motional displacement mode. But at the push of a button—in, say, an alert situation—the aircraft is put into a tactical mode; stick operation is no longer displacement controlled, but is force actuated. The force-actuated stick permits the pilot finer performance of his aircraft than possible in the displacement mode. Furthermore, in the tactical (force actuated) mode, the aircraft is relatively insensitive to any involuntary motions of the pilot's body, because of the lack of force of such motions.

Traditional methods of force control use cantilevered beam mechanisms with sensors, strain meters and so forth, but a better way is the use of a pressure transducer with an activator suitable to the application. Good force controlled systems want a compliance about the same as that of the human body. The mechanism should be about as compliant as a body linkage, which in its normal mode is neither too stiff nor too soft, but which in its optimal control mode is quite stiff—ask any good golfer.

For manual force control, an air bellows fitted to a pressure transducer is hard to beat. The bellows becomes less compliant with increased displacement—its spring constant increases with loading—exactly as does the human mechanism. (For greater force levels, it is necessary to use hydraulic, rather than pneumatic, cells.)

In applications more down to earth than high performance aircraft, the use of stiff, manual force controls is already being considered for small or crowded laboratory instrument panels. Here, hard-to-operate, finger-pinching control knobs are being replaced by multi-push, fingertip operated push-buttons, for which the required force increases with each subsequent operation (*Figure 1*). A pressure transducer used as a load cell senses the force level, and the transducer's output voltage sets, through suitable control electronics, the desired circuit function. Some or all of the control electronics can be included within the transducer package because of the hybrid IC nature of the transducer's construction. A digital readout of the control setting augments the force feedback to the operator.

Force controlled push-buttons are the answer to the instrument designer's dream of being able to miniaturize control panels. Ultimately, all instrument controls will be based on this concept. Force controlled push-buttons will range from simple on/off switches to complex, sensitive controls for setting any function imaginable. Believe us: Our transducers have seen the future and it works.

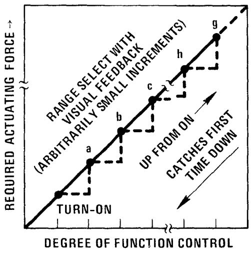
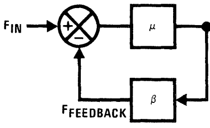


FIGURE 1. Concept of the Force Controlled Push-Button

The Undoing of Gears Scraping on Pinions, Ratchets Snapping on Palls, Balance-Beams Sliding on Balls, and the Like in the Construction of Precision Weight Scales

Before discussing the new idea for Precision scales, let's review the undoing of awkward mechanisms in the general, run-of-the-mill scale. The previous material of this section elegantly shows how easy it is to replace all those teetering, sliding, scraping, balancing, rolling, and snapping parts that come unsprung in your everyday scale with an extremely simple "force to pressure converter" (FPC) and one of National's snazzy pressure transducers. All that's needed between the force and the transducer is a fluid-filled pressure vessel with its boundary structure compliant in one direction, that of the force, and stiff in all other directions. A bellows or a bellofram or a piston-cylinder is ideally suited for the FPC, but then there's the matter of range and accuracy. Whereas a pressure transducer of moderate price can be expected to have a best total error band of two to three percent of the measurement range, only a bathroom scale is of like tolerance. While it is true that some of the error parameters of the pressure transducers do not apply to the scale applications, in terms of directly applicable error, the moderately priced pressure transducers could make one to two percent of range scales using the aforementioned auto-referencing techniques (Section 7). This is fine for many industrial applications. But, the precision scales need a quarter percent of range accuracy or better. Lest you should think that precision scales live only in laboratories, be aware that the scales used in supermarkets, drugstores, and the post office qualify as precision scales. These precision scales live in an environment that is far from the laboratory, even if less harsh than that of some industry. The new idea is merely a slick variation of the apparatus of the FPC that creates a feedback "Force Rebalance System", (FRS) rather than the open loop FPC system previously demonstrated.

Having reviewed the simplification of scales in general, before describing the nitty-gritty details of the new idea, let's review the advantages and cautions of the FRS. In such a system, the major input phenomenon (in our case, force or weight) is bucked-out or opposed by a feedback phenomenon (also a force) such that the net difference between the input and feedback forces always approaches zero. When the net difference or error signal is zero, the phenomenon causing the feedback force (in our case, the current to the pump controlled by the output of a pressure transducer) is proportional to the input force. The classic concept is shown in *Figure 1.*



$$\text{System Gain} \equiv G = \left(\frac{\mu}{1+\mu\beta}\right)$$

FIGURE 1

In FRS, the product of the open loop and feedback gains ($\mu\beta$) is much greater than one (1). Therefore, the system gain (G) approaches the inverse feedback gain ($1/\beta$). Applying this concept to a FRS scale, two important new elements are needed that were not discussed previously . . . namely the pump and the microprocessor. *Figure 2* shows how these elements fit into the classic system.

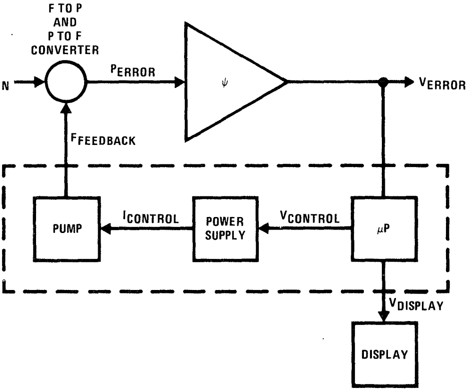


FIGURE 2

The job of the microprocessor is to deliver a control signal that causes the error signal to approach zero . . . which, of course, is the control signal that causes the pump to buck-out the input force. The microprocessor also correlates the control signal value to input force value to run a display. The pump is worthy of separate discussion . . . for it is the "punchline" of this treatise. It can be seen intuitively or by working with the gain equation, that the forward loop element (the pressure transducer) determines the accuracy of the system, and the feedback elements (the pump and microprocessor) determine the range of the system if some common sense design rules are obeyed. For example, if you're careful to make the pump fast acting compared to the FPC, then the pressure transducer can stay within a very small fraction of the input range under all conditions. This is, of course, the whole idea since the inaccuracy of the display (in the absence of control signal error) is the transducer inaccuracy multiplied by the ratio of error range (P_{ERROR}) to input range ($P_{FEEDBACK}$). The object is to get that ratio to be as small as possible without requiring an impossible over-pressure survival capability of the transducer. One obvious precaution is to provide a mechanical stop such that when all power is off, and some unsympathetic soul insists on dropping weight on the scale, the transducer won't feel the total pressure that would result from a zero feedback signal.

Now let's consider the pump. First, the common uninspired way . . . a piston cylinder actuated by a solenoid. *Figure 3* shows this approach.

But, a piston sliding in a cylinder in terms of cost and performance is close relative of springs, levers and gears. Let's get inspired and kill those moving parts. Consider a tube made of electrically nonconducting and magnetically nonferromagnetic material. Fill it with a conductive liquid like mercury or dirty water. Place electrodes and a permanent magnet in such a manner as to form a one-turn motor/pump. *Figure 4* shows the scheme.

The only things moving besides electrons, are molecules of liquid . . . and not very fast and far at that.

A look at the entire FRS with no moving parts shows that the system is a good deal simpler than its explanation . . . and more important, simpler than presently available precision scales. *Figure 5* is a schematic of the fluid/electronic FRS precision scale. With a little imaginative development, it should be feasible to achieve an FRS scale that weighs hippopotami with the same absolute accuracy as an open loop scale weighing pussycats, or Raquel Welch as lambchop, and a glass of beer as a postcard.

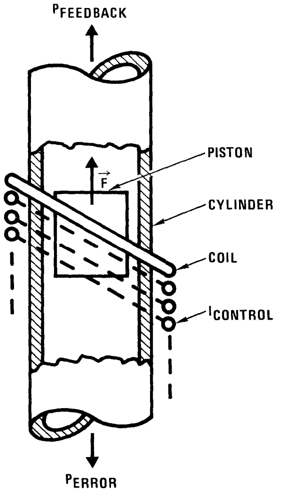


FIGURE 3

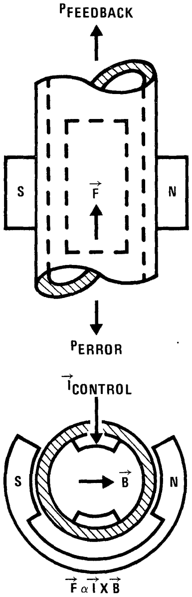


FIGURE 4

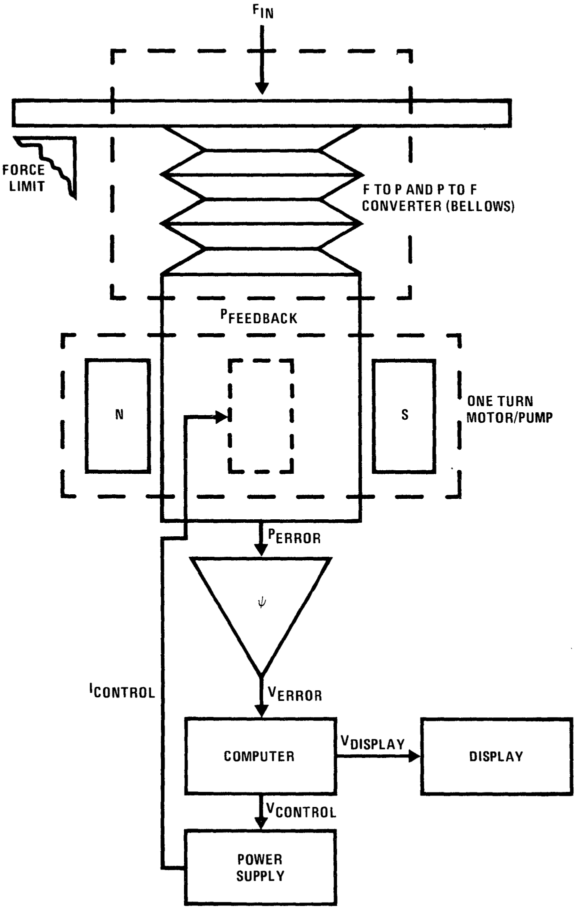


FIGURE 5

Section 11

11

Switch Control

THE ABOMINABLE SNOWPERSON

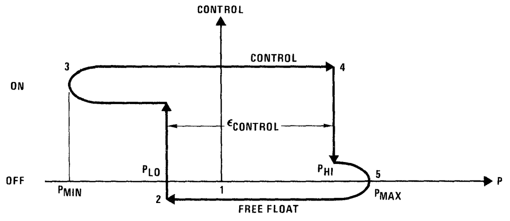
When it gets so cold in your office that you have to hire an abominable snowperson to do your typing, chances are that your air conditioning system has a limit switch wandering somewhere between the basement compressor and the rooftop heat exchanger. We don't say that National's pressure transducers *never* fail, but they do outlast mechanical types by a wide margin. They also have higher accuracy, near-perfect linearity and high output signals that are perfect for the tight control loops used in modern comfort control systems. So bring back that lovely lady by giving her an IC pressure transducer and let the wandering limit switch wander off along with the abominable snowperson. If the IC pressure transducer doesn't quite do it, try a little auto-referencing. It always works.

Switch Control

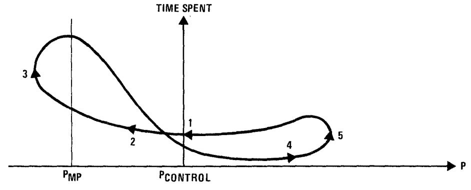
SINGLE-SWITCH CONTROL

Most control systems using pressure transducers employ a single control element, such as a valve or pump, that is either ON or OFF. Examples include the pressure in a boiler, liquid level in a container, and air flow in environmental control systems. In these single-switch systems, the control cycle can be represented as shown in *Figure 1a.* Beginning with the switch OFF and the pressure at $P_{CONTROL}$ (Point 1), the pressure decreases until the control element is activated at P_{LO} (Point 2). The momentum of the system carries the pressure to P_{MIN} (Point 3) where the control element finally succeeds in turning the system around. The control element drives the pressure to P_{HI} (Point 4) which turns off the control element, and the momentum imparted to the system carries it to P_{MAX} (Point 5), after which the system is free floating until it reaches P_{LOW} again.

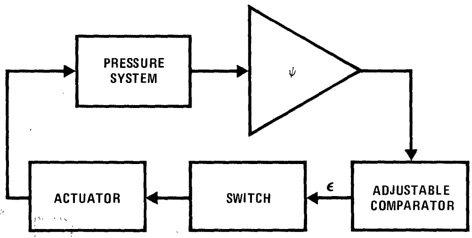
Because of the momentum of the system and the generally different forcing functions acting in the ON and OFF states, the rate of pressure change varies throughout the control cycle. The inverse of this rate can tell us the time spent or the probability of finding the system in any pressure interval within the control range. This is shown in *Figure 1b* for a weak control element, (system momentum large compared to effect of control element, i.e., small fan in large, long room). In this situation, the most probable pressure, P_{MP}, is offset from the average pressure, $P_{CONTROL}$. Although this effect is of little consequence in many applications, it is important in comfort control since the system seems to "always" be below its proper setting.



a. Control Cycle



b. Time-Spent



c. Block Diagram

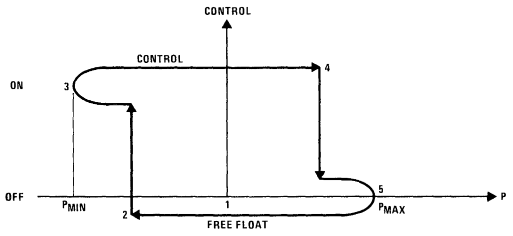
FIGURE 1. Single-Switch System, Weak Control

If the control element is made stronger or the system weakened (bigger fan in smaller room), as shown in *Figure 2*, another peak in pressure probability, $P_{MP\ HI}$, develops at the high pressure end. When the control element force is twice that of the system the pressure change rate is the same for the ON and OFF states, and the time-spent plot is symmetrical about $P_{CONTROL}$. The system then spends much of its time near P_{HI} and P_{LO}, thus seeming to "always" be too high or too low and "never" at $P_{CONTROL}$. If the uncontrolled system rate is further reduced (or the control element strengthened), the result is a cycle that is skewed to the high pressure side, a mirror image of the case shown in *Figure 1.*

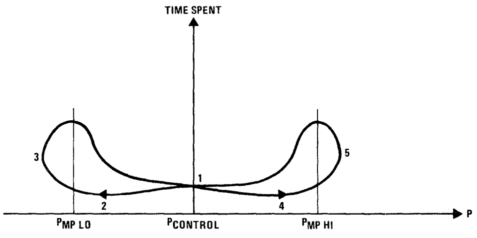
DUAL-SWITCH CONTROL—SINGLE-SIDED

To compensate overshoot in a single-sided system, a second switch can be added to activate another control element acting in the same direction (opposing system momentum). This element could be a valve, pump, alarm or another fan in the aforementioned large room. An example is shown in *Figure 3.*

Once again at $P_{CONTROL}$ (Point 1), the system pressure is decreasing and all control elements are OFF. At Point 2, the first control element turns ON, (i.e., first fan), slowing the rate of pressure decrease. At Point 3, the second control element turns ON (i.e., second fan), further slowing pressure decrease and reducing system overshoot such that Point 4 represents minimum system pressure. With control elements 1 and 2 activated, the system pressure increases quickly to Point 5, where one control element is shut down. At Point 6, the second control element is turned OFF, allowing return to Point 1.

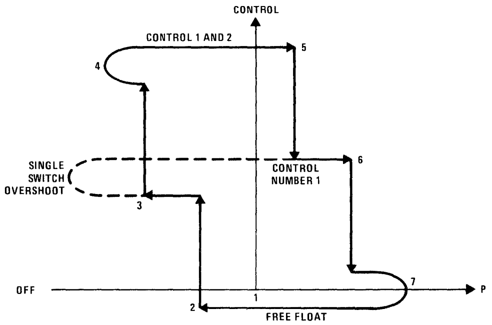


a. Control Cycle

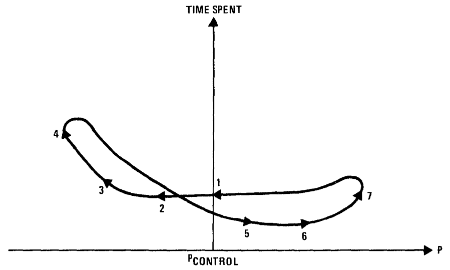


b. Time-Spent

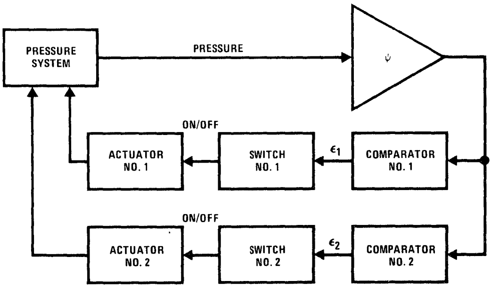
FIGURE 2. Symmetric Control Function



a. Control Cycle



b. Time-Spent



c. Block Diagram

FIGURE 3. Dual-Switch Control—Single-Sided

SINGLE-SWITCH CONTROL—DUAL-SIDED

In single-sided control, the system needs a tendency to move in one direction without controlling influence. In dual-sided control, the control elements drive the system in both directions. That is, if one control element increases pressure, the other must decrease pressure. This would equate to opening (ON) and closing (OFF) a door at end of our large, long room while turning the fan at the other end OFF and ON. This approach is shown in *Figures 4, 5 and 6*.

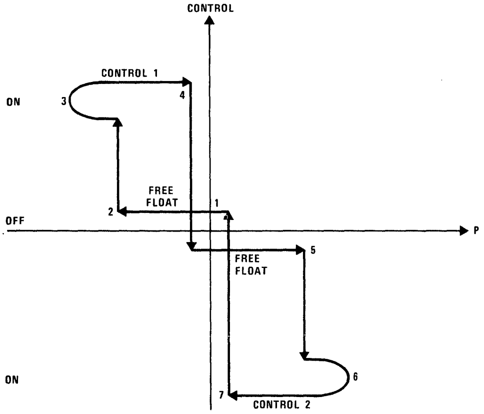
Figure 4 shows a properly designed control for a system with little undriven tendency to move. The control elements have roughly equal effect in driving the system. The system is free floating at $P_{CONTROL}$ and spends much of its time there ($P_{CONTROL} \approx P_{MP}$). Points 1 through 4 of *Figure 4a* operate exactly as discussed for *Figure 1a*. The system then free floats to Point 5. The identical process now occurs for the control element that decreases pressure.

If the control elements are too strong for the system momentum, and wide pressure limits are desired (perhaps to provide low switching rate), an "undercontrolled" system may result. In this situation *(Figure 5)*, too much time is spent in free float. The system seems to "hunt" for $P_{CONTROL}$.

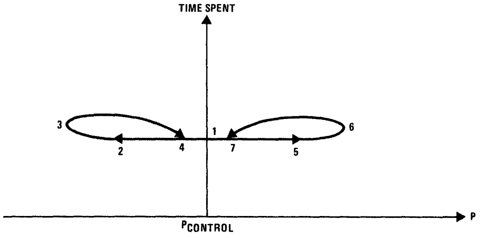
If the control elements are weak relative to system momentum, and narrow pressure limits are required, an "overcontrolled" system may result. In this situation *(Figure 6)*, too little time is spent in free float. More important, minimum time is spent at $P_{CONTROL}$ because the system is driven through $P_{CONTROL}$ from both directions. The system seems most stable at its pressure limits.

MULTIPLE-SWITCH CONTROL

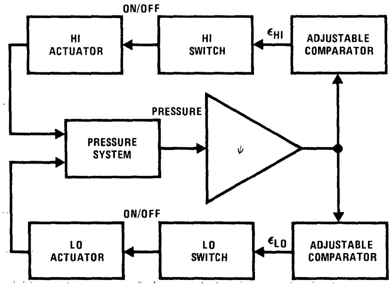
As with the single-switch controller, an additional switch can be added on each side of the dual-sided controller to achieve tighter tolerances around $P_{CONTROL}$. The control properties of each loop would then be equivalent to the single-sided dual-switch loop shown in *Figure 3*. Of course, further improvement can be obtained by adding still more switch loops until a "continuous" control function is approached. This is indeed the trend is modern large comfort control systems (see Section 7).



a. Control Cycle

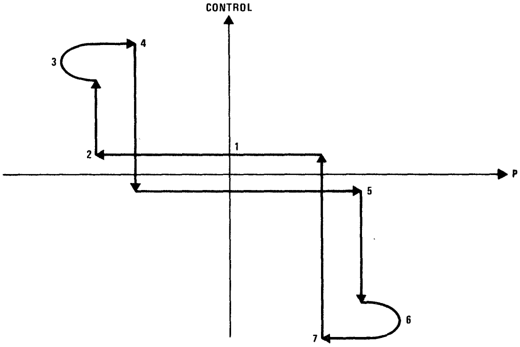


b. Time-Spent

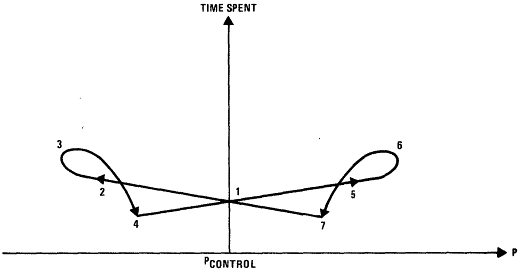


c. Block Diagram

FIGURE 4. Dual Control System, Properly Designed

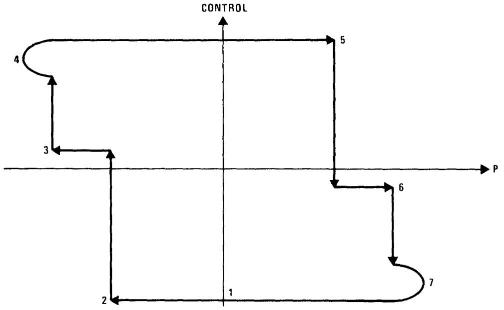


a. Control Cycle

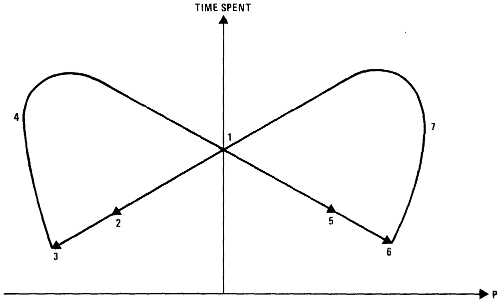


b. Time-Spent

FIGURE 5. Undercontrol



a. Control Cycle



b. Time-Spent

FIGURE 6. Overcontrol

SWITCHING ACCURACY AND AUTO-REFERENCING

In the previous discussion, the pressure switch was assumed to be error free, but in practice there will be some error in the switching points P_{LO} and P_{HI}, resulting from errors in the pressure transducer. The primary effect of these errors, as shown in *Figure 7,* is to extend the possible pressure excursion, P_{MIN} to P_{MAX}, by the total error, $P_{ERROR\ HI} + P_{ERROR\ LO}$. Although the errors in IC pressure transducers are normally small as compared with the required $\epsilon_{CONTROL}$ in a single-switch system, the use of a single transducer for multiple-switch control may result in errors that are a significant part of the control range. In such cases, auto-referencing can be used to improve its accuracy (Section 3, Accuracy; Section 7, Auto-Referencing), as illustrated by the system shown in *Figure 8*. In this system, $P_{CONTROL}$ is set by a pressure line to the differential pressure transducer. This places the output of the transducer at V_{REF} when the system is at $P_{CONTROL\ DES}$ which allows simple auto-referencing by momentarily connecting $P_{CONTROL}$ to the pressure system with a valve. It also simplifies detection of the switch pressures, P_{HI} and P_{LO}, and minimizes the errors, $P_{ERROR\ HI}$ and $P_{ERROR\ LO}$. For control systems where the accuracy of the transducer is adequate, such as in many single-switch controllers, the auto-reference circuit and valve will not be required.

Most commonly, the system pressure limits (ϵ_{SYSTEM}), overshoot ($\epsilon_{OVERSHOOT}$) and pressure to be controlled ($P_{CONTROL\ DES}$) are known. The designer need choose values for each switch circuit ($P_{HI\ DES}$, $P_{LO\ DES}$ and $\epsilon_{CONTROL\ DES}$) consistent with the errors contributed by the pressure transducer (P_{ERROR}).

Inspection of *Figure 7* yields the following relationships:

$$P_{LO\ DES} = P_{CONTROL\ DES} - 1/2\,\epsilon_{SYSTEM} + \epsilon_{OVERSHOOT\ LO} + P_{ERROR\ LO}$$

$$P_{HI\ DES} = P_{CONTROL\ DES} + 1/2\,\epsilon_{SYSTEM} - \epsilon_{OVERSHOOT\ HI} - P_{ERROR\ HI}$$

For symmetric systems, the relationships reduce to:

$$P_{LO\ DES} = P_{CONTROL\ DES} - 1/2\,\epsilon_{CONTROL} + P_{ERROR\ LO}$$

$$P_{HI\ DES} = P_{CONTROL\ DES} + 1/2\,\epsilon_{CONTROL} - P_{ERROR\ HI}$$

The transducer errors expand to:

$$P_{ERROR\ LO} = P_{ERROR\ COMMON\text{-}MODE}\,(P_{REF}) + P_{ERROR\ NORMAL\ MODE}\,(P_{REF} - P_{LO})$$

$$P_{ERROR\ HI} = P_{ERROR\ COMMON\text{-}MODE}\,(P_{REF}) + P_{ERROR\ NORMAL\ MODE}\,(P_{HI} - P_{REF})$$

For $P_{REF} = P_{CONTROL\ DES}$:

$$P_{ERROR\ LO} = P_{ERROR\ HI} = P_{ERROR\ COMMON\text{-}MODE}\,(P_{CONTROL\ DES}) + P_{ERROR\ NORMAL\ MODE}\,(\epsilon_{CONTROL\ DES})$$

Section 3, Accuracy and Specifications, gives specific examples of how to calculate P_{ERROR} with and without auto-referencing.

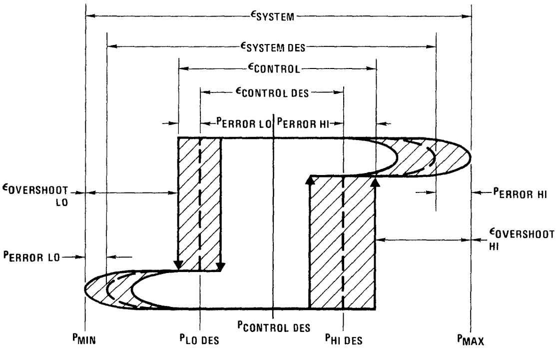


FIGURE 7. Switching Errors in Single-Switch Control Cycle

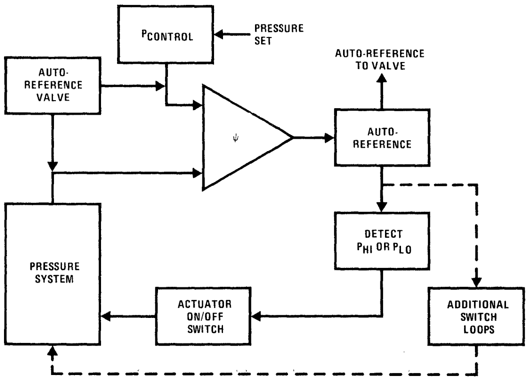


FIGURE 8. Pressure-Controlled Single-Switch Control Element With a Differential Pressure Transducer

Section 12
Acoustic Applications

12

THE PIG WHO SQUEALED DIXIE

There was a time when pigs only squealed in the barnyard, but ever since the microphone was invented, every "mike" has included a pig that squeals the fifth harmonic of the first note of *Dixie* when prodded by a feedback transient. Although some long-time microphonists have evolved a curious notch filter in their ears that attenuates the pig's rendition of *Dixie,* most are anxious to trade in their performing pig for an IC pressure transducer microphone with zero harmonic feedback.

Of course, we're all for it here at National because we have sensitive ears, and we're also aware that our IC pressure transducers have many other good sound pickup qualities, such as wide frequency response, high sensitivity, built-in amplification, and another pig-squelching property, DC level control. So when we say that our IC pressure transducers make good microphones, you know we're not just squealing *Dixie,* and neither will the microphone.

Acoustic Applications of Pressure Transducers

The IC pressure transducer can be used as an acoustic sensor in microphones, hydrophones, sound level meters, musical instrument pickups, audiometers (Section 9, Medical) and other sound detection applications. The IC transducer has a wide frequency response (from DC to 50 kHz) and a built-in operational amplifier that provides a high level signal output for audio range (DC to 30 kHz) pressure variations. Because the transducer diaphragm's natural frequency is outside the audio range (~50 kHz), it doesn't generate audio-range harmonics from input sound waves. This totally eliminates tricky microphone squealing even in heavy feedback siutations. The IC pressure transducer's high accuracy, which can be further improved by auto-referencing (Section 6, Auto-Referencing), qualifies it for use in precision audio instruments.

ACOUSTIC INTERFACING

With the pressure port tube in place, the IC transducer has a directional acoustic pickup pattern that can be broadened by reducing the length of the tube. If the tube is removed, the pickup pattern is similar to a high quality cardioid microphone. The transducer can be used as is for musical instrument pickups *(Figure 1)* or for close-up directional microphones, but may require tube modification for other types of microphones.

> **Important:** The port must be protected by an acoustically compliant material to prevent breath moisture from reaching the transducer circuit in any microphone, wind instrument, or other application where someone could blow into the port (Section 5, Installation).

For stand-off microphones, additional gain can be obtained by use of reflective sound collectors. Use a paraboloid reflector for directional pickup, as shown in *Figure 2,* or a hyperboloid for wide angle pickup, as shown in *Figure 3.* In either case, the pressure port should be shortened to accept the wide angles within the acoustic optical system.

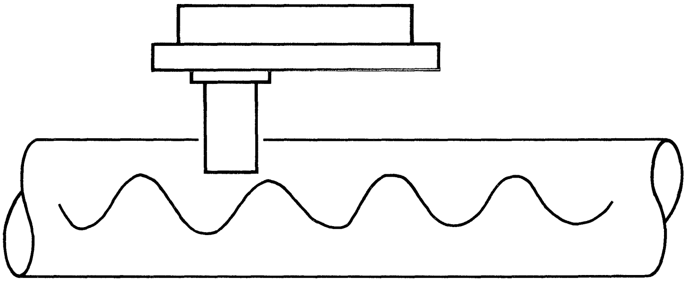


FIGURE 1. Instrument Sound Pickup

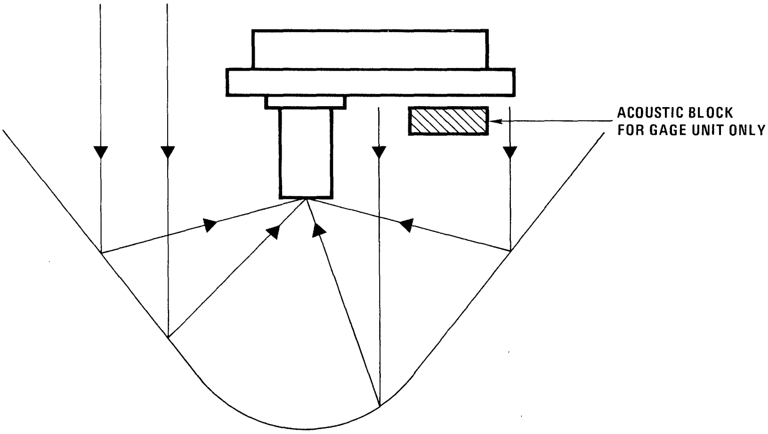


FIGURE 2. Directional Paraboloid "Mike"

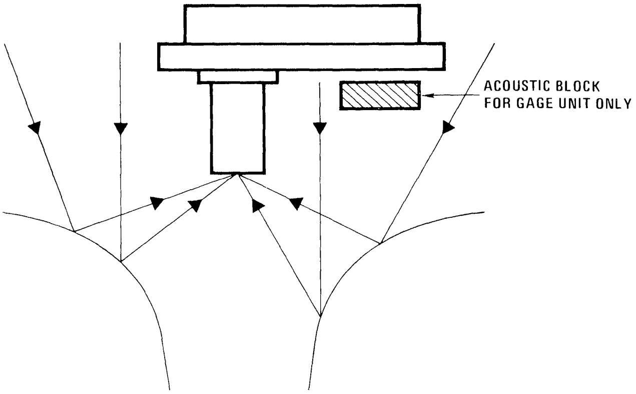


FIGURE 3. Wide Angle Hyperboloid "Mike"

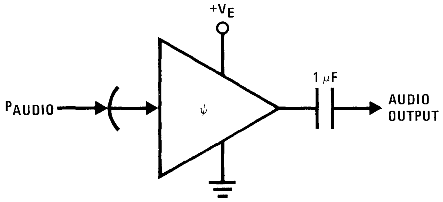


FIGURE 4. Transducer as a Solid-State Microphone

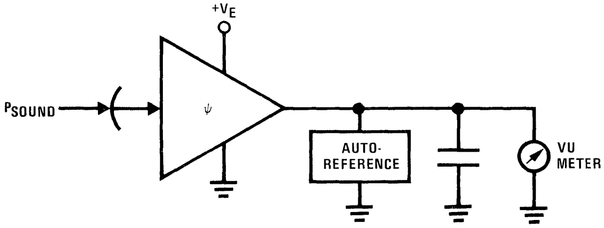


FIGURE 5. Transducer as a Sound Pressure Level Meter

ACOUSTIC TRANSDUCER SELECTION

For acoustic measurements, the most sensitive gage pressure transducer is normally selected. The sound pressure waves are usually small, requiring high sensitivity, and the gage inlet balances out atmospheric pressure. Since sound pressure waves go both positive and negative around the mean atmospheric pressure, the ±5 psig range of the LX1701G is ideal for the following applications. The LX1701A can also be used since its response is centered at 15 psi (atmospheric pressure), and it has the advantage of not requiring an acoustic block for the gage inlet.

Audio Pickups: For microphones and other audio pickups, the transducer only requires excitation voltage V_E and a 1 µF series capacitor to function effectively as a sound sensor *(Figure 4).* The sound can be coupled in by any appropriate means as discussed above and by following the general principles used for all acoustic pickups.

Sound Pressure Level Meter: Conventional sound pressure level (SPL) meters normally use a microphone pickup. The resulting signal is amplified, rectified and used to drive a meter readout. Since the IC transducer's signal is already amplified, it eliminates much of the SPL meter circuitry *(Figure 5).* But to be accurate, the SPL meter must be precisely coupled with the sound pressure level input, which should be discussed with National's pressure transducer applications engineers. If an accuracy better than 3% of amplitude is required, either restricted temperature range or normal mode auto-referencing should be used (Section 3, Accuracy and Section 7, Auto-Referencing).

Hydraphones: In underwater sound pickup applications, an absolute pressure transducer is used. As discussed in the Installation section, a very simple hermetic enclosure can be used to protect the transducer. Here again the model LX1601A transducer can be used, as shown in *Figure 6.*

Audiometer/Tympanometer: The audiometer/tympanometer (Section 9, Medical) combines the capabilities of the IC pressure transducer for precise sensing of both audio pressure variations and static pressure. As shown in *Figure 7,* this instrument uses an audio generator to test the response of the human ear. The audiometer funtion relies on patient response and hence is only required to measure the AC amplitude (and frequency, if desired) of the audio signal entering the ear via the ear plug. The tympanometer measures the compliance of the ear drum without patient cooperation by comparing AC amplitude with DC level shift resulting from back pressure between the ear plug and the ear drum. Both normal mode and common-mode auto-referencing can be used to increase measurement accuracy.

Sphygmomanometer: Like the audiometer/tympanometer, this instrument makes use of both AC and DC pressure detection level measurements. It measures the absolute blood pressure levels for the systolic and diastolic points while monitoring the phase of the heartbeat cycle for more accurate location of the "true" systolic point, the point where the apparent heartbeat at the point of measurement undergoes a change in phase.

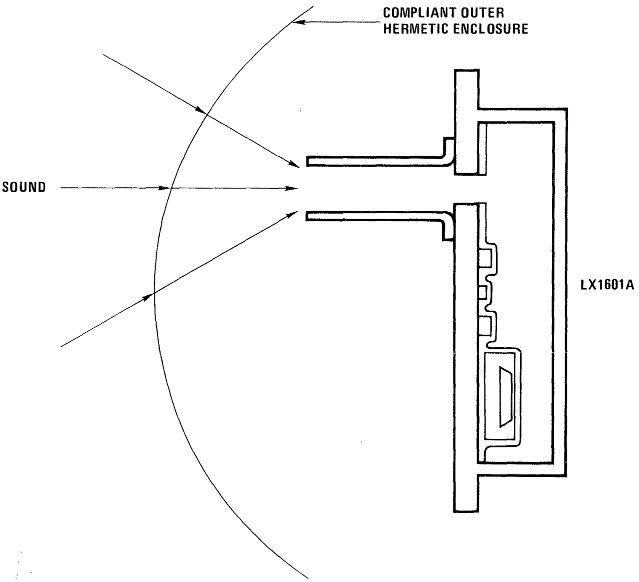


FIGURE 6. Conceptual Diagram of Transducer Hydraphone

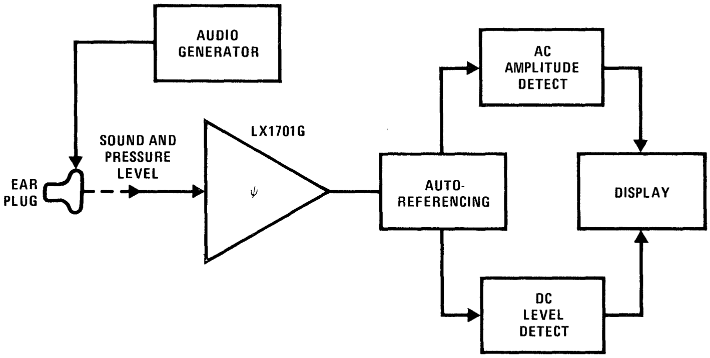


FIGURE 7. Audiometer/Tympanometer

FROM FAT TO CRISP AS EASILY AS BURNING BACON

It seems that professional musicians—horn players, in particular—have a problem. On stage and in the recording studio, they are forced to "play to the mike". These pros are not free to spin, dip, swoop and otherwise trip through all sorts of Body English as they feel the urge, for fear that the sound system will lose the full quality of the instrument's tone. And so the dream of this group is to have an omnidirectional sound system capable of detecting the most subtle nuances of their particular sound, regardless of how many dimensions of freedom the musician feels he must move through.

And of this group, woodwind players have yet another, secret dream. Since there have been pros around to hear it, woodwind players have greened with envy at the quality of a brass' attack. ("Attack" is a musical term descriptive of a tone's risetime.) A saxophone player simply tingles all over at the mere thought of having his instrument come on like a trumpet, for example.

To solve this heretofore insoluble problem for mankind in general—and for professional musicians in particular—National Semiconductor unleashed the full genius of its transducer applications engineers, who attacked the attack problem (with gusto) and promptly solved it. We modestly present the basic concepts here.

In brass instruments, the musician's mouth and throat are part of the instrument's air column. As such, the input air pressure is an important determinant of pitch, volume and the tonal quality of the sound. But in woodwinds, the musician's mouth and throat are not part of the air column; they are part of the reed. And as such, the input air pressure is associated with pitch only, and not, basically, with the final quality of the sound. Thus the need of woodwind players for an external method to manipulate the tonal quality of their instruments.

Figure 8 shows a fundamental, sound system for woodwind instruments—the musician's concept of the perfect microphone. It consists of an IC pressure transducer coupled tightly to the instrument's mouthpiece, serving both as a microphone and as a sound pressure meter.

If the AC signal is modulated by the DC signal, the output of the sound system is quite similar to that of an instrument with square-law attack. The woodwind has now already acquired the attack quality of a brass; it's still up to the musician as to how the attack is to be used.

The system using microprocessor-controlled modulation gives an instrument of selectable bell size, a tonal quality that varies from "fat" (full and rich) to "crisp" (sharp and clear-edged), and something that no echo chamber could ever achieve—selectable delay.

A clarinet, for example, can be given the attack of a trombone with the bell of a sousaphone, and yet retain the clarinet's characteristic playing facility. In short, we have brought the woodwinds out of their Dark Ages.

(P.S. to brass players: don't let the woodwind players know, but if you guys decide to try this system on your instruments . . . all we can say is that the results would be complex, difficult to guess at, but good!)

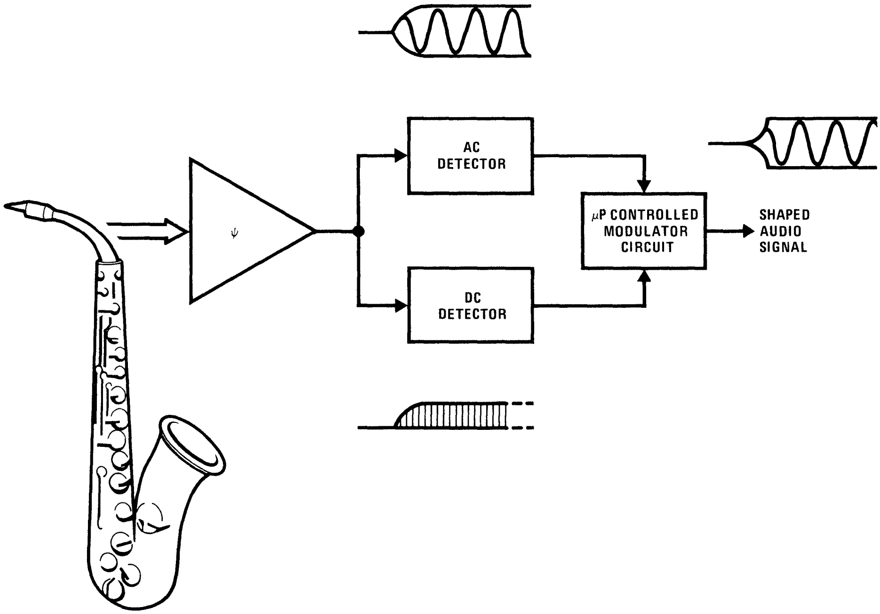


FIGURE 8. The Woodwind Player's Dream

Section 13

Temperature Measurement

13

SQUARE PIG IN A ROUND OVEN

Most people wouldn't think a square ham would even venture near, much less fit in, a round oven. But unlike a peg, a pig is compliantly versatile and, like an IC pressure transducer, can be made to fit almost any place with a simple interface and a suitable reward. To fit a pressure transducer into an oven, convert it to a *hot bulb thermometer* by attaching a long thin tube and a bulb full of gas. When the bulb heats up the gas pressure goes up by Charles' Law, and the reward is a high level output signal that is linear with temperature and accurate for engines, furnaces and ovens. To get the ham into the oven give him an apple and use a large shoe horn. If that doesn't work try auto-referencing. It always works.

Thermometers Using Pressure Transducers

Constant-volume gas, or "hot bulb," thermometry is an interesting application area for the LX16XXA pressure transducer. Such thermometers are based on Charles' Law, which states that, for a gas at a constant volume, pressure is proportional to absolute temperature: $p_1/p_2 = T_1/T_2$, $V = \text{constant}$. For a constant-volume system, as the gas in a bulb heats up its pressure increases, and vice versa. The pressure increase or decrease, when compared to a reference pressure and temperature, indicates the new temperature of the gas in the bulb.

A hot bulb thermometer is a viable alternative to a conventional electronic thermometer, particularly at temperatures above about 200°C. At this temperature most junction techniques are already going awry; junctions and ohmic contacts become untrustworthy, and Seebeck effects begin to appear.

While thermocouples do operate at the elevated temperatures, their worth is in the reproducibility of their results, not in the accuracy of those results.

Furthermore, in a high radiant heat flux environment, electronic thermometry invariably compromises the required shielding. And it turns out that such thermometers really measure only the shield temperature.

The hot bulb thermometer is a two-step transduction process—temperature to pressure, pressure to voltage—for temperature measurement, which does not suffer from any of the problems just mentioned. The transducer electronics are removed from the high-temperature environment; junction, ohmic and Seebeck effects cannot appear, nor can any other temperature effects deleterious to operation. And shielding is not compromised in hot bulb thermometry, since the pressure vessel itself (the bulb) is intimately involved in the measurement. That is, the nature of the bulb's wall in fact determines the nature of the measurement. The following examples briefly demonstrate this fact.

[In the following examples it is assumed that the bulb contains a fluid of known properties, that the entire system is of a fixed volume determined essentially by the volume of the bulb itself, and is rigid between the bulb and the transducer (i.e., the transducer is the most compliant part of the system].

For a first example consider the bulb to have a black, absorbing outer surface and a bright, reflective inner surface. Such a bulb retains any UV energy within it and absorbs all IR energy external to it. In short, it collects all thermal information surrounding it, through radiative and conductive effects, and becomes a total heat transducer.

Now reverse the conditions: make the bulb's outer surface reflective, and its inner surface absorptive. Here, thermal radiation from within the bulb is trapped inside, and all thermal energy that enters the bulb from the surrounding fluid (here, via conduction) is similarly caught. The fluid within the bulb reaches thermal equilibrium with the fluid surrounding the bulb, and the bulb acts as a perfect thermometer. Such a device is useful in cooking ovens, where it closely simulates what is happening inside a shiny, stainless steel or aluminum cooking vessel lined with the new, black Teflon®.

A third example assumes the bulb to be totally transparent in both directions, which is very difficult at elevated temperatures because of the heat energy's spectrum width. But quartz and pyrex® do approach the required transparency. Here, if the properties of the inner and outer fluids are similar, the system becomes a total enthalpy sensor. In an internal combustion engine, for example, such a sensor (using air inside the bulb) when positioned in the path of the flame front will measure the efficiency of the burn. These data may then be compared to the maximum (stoichiometric) burn efficiency for thermodynamic engine analysis.

Yet another example of hot bulb thermometry uses a bulb of the same, or similar, material as the object to be measured (the process material). Ideally, the bulb should be of the same geometry as the object, and its inner fluid should be of low heat capacity—air works well. This structure results in a process (reference) thermometer.

Finally, consider the example of a differential thermometer, which uses two bulbs. The simplest case uses one bulb similar to our first example (black outside, reflective inside) and another similar to our second example (black inside, reflective outside). The bulbs should be very small (ideally, infinitesimally small and tending to occupy the same point simultaneously).

Subtracting the thermal information of one bulb from that of the other, by means of a differential pressure transducer, yields information on radiant heat energy only; the device acts as a perfect radiometer. This idea can be expanded. For example, a differential hot bulb thermometer comprised of a bulb similar to our third example (transparent) and one similar to our fourth example (bulb material same as object material), and operating with the same inner and outer fluids, eliminates the effects of the fluid.

Figure 1 shows a hot bulb thermometer. The gas volume contained within the tubing between the bulb and the transducer must be small compared to the volume of the gas within the bulb.

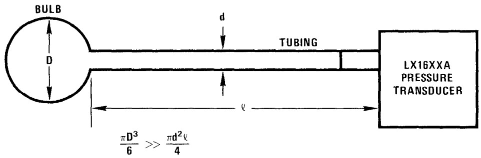


FIGURE 1. Hot-Bulb Thermometer

As an example, suppose that we wish to measure the temperature of a semiconductor diffusion furnace, which is, say, 1200°C nominally. The system's reference temperature and pressure will be 20°C (293°K) and 14.697 psia, respectively. Charles' Law tells us that the transducer will read 73.89 psia when the gas in the bulb is at 1200°C. (This also tells us that we must use an LX1620A, which has a 0—100 psia range.)

But what is the resolution of this thermometer system? Suppose that the furnace temperature increases to 1500°C. The LX1620A now sees a pressure of 88.93 psia. For a temperature change of 300°C, the pressure has increased 15.04 psi. Thus, the slope—or resolution—of our hot bulb thermometer is 50.1 mpsi/°C.

Is such a thermometer resolution practical? Can it be used? The answer is a definite yes, because of the use of the temperature-compensated pressure transducer. The LX1620A swings 10V for a 0—100 psia change. Thus, the transducer's resolution is 100 mV/psi. Multiplying the transducer's resolution (mV/psi) by the slope of the hot bulb thermometer (psi/°C) yields a system transfer ratio of 5.01 mV/°C. Such a ratio is usable because the transducer has a temperature coefficient of only ±2.16 mV/°C.

Further, the long term (hours) thermal stability of the transducer is ±0.4% of span, or ±40 mV. This thermal drift voltage corresponds to an error of ±40/5.01 = ±7.98 which is only ±0.67% of 1200°C.

Are the required dimensions of the bulb and tubing practical? Again, the answer is yes. For a diffusion furnance, such a thermometer might consist of, say, 1.25 feet (for a two-foot diameter furnace) of 10-mil ID steel tubing between the transducer and the bulb. The tubing volume is 1.18×10^{-3} in.^{3}. For the bulb volume to be 0.118 in.^{3} (a hundred times larger than the tubing volume) the bulb diameter must be 0.61 inches—entirely practical. Furthermore, a number of such thermometers, distributed through the furnace, would easily give an accurate and continuous temperature profile.

Section 14

Automotive Applications

THE MULTI-FACETED WACKY-TOO FROM KALAMAZOO

Although Kalamazoo is normally aloof from automotive engineering, the people there are rightly proud of their heritage of inspiration to poets and designers of world-saving inventions, the latest being the multi-faceted wacky-too. This amazing device has thirteen right-angle facets with plug-in pressure transducers multiplexed by a high speed cam to monitor virtually every automotive parameter from manifold pressure to tire-pavement friction. Upon special request by its inventor, Kalamazooan, Otto Motiff, National transducer engineers tested the wacky-too, but unfortunately it had one too many facets and wouldn't fit in the carburetor. So we decided to keep the Automotive Applications section in this edition, since the field is still wide open.

Automotive Applications

Probably the most dramatic field of applications for pressure transducers today—and the first high-volume field—is automobile electronics. It's also the farthest developed. ICs have hit the auto industry with the full force of an idea whose time has come. Air pollution provided an immediate entree, but other factors would have brought ICs to Detroit by 1975 anyway—factors such as wiring costs and callbacks, safety, maintenance and new accessories. Smog simply opened the door early, and provided the means for rapidly amortizing technical innovations that will ultimately lead to economies and new, saleable features for the auto makers.

Auto makers break down electronics into three (non-entertainment) areas; engine control; safety; and maintenance. This is actually an artificial division. For example, the half-dozen parameters needed to control the engine are the same as those needed for engine diagnostics and maintenance. The Bosch system already uses them for that purpose in the Volkswagen; all it takes is a connector for the engine analyzer. (The U.S. military, in fact, has such a system for rapid repair of field vehicles.) Similarly, certain engine control electronics could perform safety functions. (Our IC pressure transducers, for example, could include—at almost no extra cost—accelerometers for crash protection.)

Now, it's pretty certain that smog specs can't be met with existing smog control methods. It is feasible to collect emissions and dump them back into the engine to oxidize the CO to CO_2 and the hydrocarbons to H_2O and CO_2. But this scheme works well only to a point. Besides, the required long burning-times and high temperatures produce objectionable oxides of nitrogen. Thus what's good for hydrocarbon control is bad for nitrogenous oxide control. If the two goals are to be balanced—somewhere in the equation the engine has to deliver reasonable power—tight control of combustion conditions (fuel/air ratios, ignition and fuel-supply timing, and so on) must enter the picture.

Operating the engine at its optimum has always been a concern. There have been many attempts to generate analytical models of the engine and to embed a model of the engine's needs, over its operating range, within the carburetion and ignition systems. Analytically, the engine has proved too complex for such mathematic description (although Ford, for one, has such a model under development). Practically, the result has been a proliferation of increasingly complicated intake and ignition systems. Today's carbs have taken on the proportions—and the adjustment and reliability problems as well—of self-grown fluidic computers.

The chief problem areas are the degradations in the manifolding carburetion and ignition adjustment. Many typical manifolds have optimum carb adjustments that leave one cylinder starved for fuel, while another runs over-rich and exhausts smog components. In general, fuel separation and delays in the manifold account for combustion errors that are 25% off optimum. At their best adjustment, the best carbs introduce another off-optimum condition of 3%-5%, and ignition systems still another 5%.

A popular approach to this problem in performance cars is the use of multiple carbs with a minimum of manifolding. The Porsche 911, for example, has six, separate Weber carburetors. The trouble there, as Detroit sees it, is that carbs are costly—about $20 each, to the auto maker—and still contribute errors. Detroit, therefore, will go to fuel injection, using relatively inexpensive manifold-type injection systems. Injecting into a very simple manifold introduces a minimum of error, and protects critical components from the very severe cylinder environment.

In Europe, manifold-type injection systems have been successfully applied to Citroen, Mercedes, VW and Volvo, among others, with Bosch dominating the field. In the U.S.A., Bendix-Bosch elaborations are the leading contenders, with IC control of the electro-mechanical injectors. And such systems represent a major advance over the ten-year-old, discrete-component Bosch design. The economics of discrete components restrict the processing available for the half-dozen input conditions. Since the optimum tailoring of the fuel/air supply is a complex nonlinear operation, these early electronic fuel injection (EFI) systems entail compromises unacceptable by current smog standards.

All new EFIs (*Figure 1*) will use ICs to combine a number of quantities: manifold absolute pressure (MAP); cylinder head temperature; throttle position; crankshaft position; intake air temperature; battery voltage; and possibly data from an exhaust gas analyzer. Pressures must be measured with great accuracy over the 1-15 psi range, while the underhood environment ranges in temperature from −40°C to about +90°C. In addition, current surges from starters, alternators, ignition wiring and so forth all generate noise; it's a heavy EMI environment, and early signal amplification is necessary. National's LX1700 series pressure transducers—highly accurate and temperature stable—meet the challenge of such an environment.

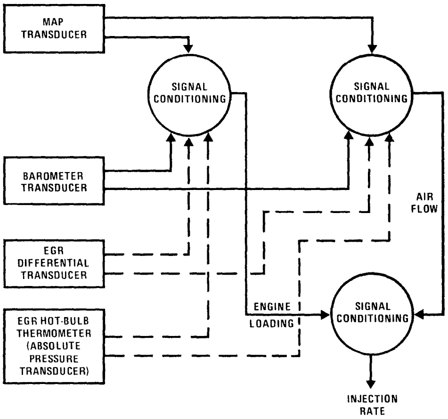


FIGURE 1. Fuel Metering Module

Yes, IC transducers do meet the challenge. Such devices feature very low cost in high volume, unit-to-unit interchangeability, long cycle-life and absolute life, internal supply-voltage regulation and circuit protection, compatibility with other ICs in the EFI system's analog/digital processor and so on.

Other types of transducers—including those in the present Bosch and Mitsubishi EFI systems—use linear variable differential transformers (LVDTs) as pickoff elements; pressure diaphragms drive the transformer cores. This requires generating ac for the transformer primaries, then demodulating the ac output. Such systems present a difficult economic problem in a world of five-dollar transducers and one-percent accuracies, because the LVDT signal levels are very much lower in the outputs than in the inputs. The difference in signal levels makes isolation a major consideration, and necessitates either expensive chip processing or a separate chip for input generator and output demodulator. And these costs must be charged to the ac transduction device. Either way, when accuracy is required, such techniques add cost to the package price. Further, LVDT-type transducers show a performance degradation in the presence of vibration. The cost of satisfactorily shock mounting such transducers far exceeds the cost of the transducer itself. (The same is almost as true of potentiometer-type transducers.)

In comparison, the simplicity of a variable resistance element makes the piezoresistive IC transducer an attractive choice. Adding to our transducer's usefulness is yet another of its features—temperature sensing. With it, you can make simultaneous pressure and temperature measurements. As an example of its use, EFI injectors require intake air temperature as an essential input for their underhood computer. There are, in fact, a tremendous number of uses for IC transducers in automotive applications: *Figure 2* shows some of them.

THE PILGRIM'S PROCESS: SIMPLE TO SOPHISTICATED

Telemetered pressures and IC pressure transducers mix very nicely and lend themselves to some rather unexpected applications. We'll begin with an example of a tire-pressure warning system.

The basic measurement of tire pressure is not difficult; getting that information to the dashboard is difficult, however, because of the motion of the wheel relative to the car's body. As an example of one solution to the problem, consider the Gauer AG (Zurich) telemetered pressure system. The Gauer system attaches a pressure sensor to the tire valve stem. The sensor contains a battery and a radio transmitter. Reduced tire pressure actuates the transmitter. A small antenna adjacent to the wheel picks up the low pressure warning signal, which is processed by a central receiver. The receiver output triggers audible and visual signals to alert the driver, and the faulty tire is indicated by the dashboard display.

For today's purposes, such a fixed-switch system is adequate because of the limited tire pressure range that must be dealt with. However, future tire developments will require upper- and lower-limit pressure alarms (as do radial tires now, actually), and over a great range of pressures. Economics and system operation will thus require a variable switch usable over a wide range of pressures, and with upper- and lower-limit set-points, exactly as already available in our IC transducers. And by the way, the thermodynamics of a tire are closer to those of a pressure vessel than to those of a balloon. This means that overpressure can be indicative of a hot tire, in the fashion of a hot bulb thermometer.

Now consider what else you can do with that tire pressure transducer, since you have it available. How much work can it do for you? Well, going back to the basic concept of a transduction system, you can use the tire as an input modifier that converts load to pressure. And the entire transducer may be considered the system's sensor. You now have a system to measure vehicle load. You can, in fact, use such a system as the basis of an overload and ignition interlock scheme to prevent operation of overloaded vehicles. Further, if you can do that—and you can—extend the concept to a load leveling system with ignition interlock. (A simultaneous measurement of temperature and pressure with the same transducer gives you a reference density. This lets you separate the pressure change due to tire temperature change from the pressure change due to vehicle loading.)

But you don't have to stop there. Suppose now that you mount another (telemetering) pressure transducer to the wheel. Consider also that this transducer is radially oriented, and its pressure inlet tube is sealed and liquid filled. A pressure transducer mounted and operated in such a way becomes a centripetal accelerometer. And centripetal acceleration is a function of wheel speed, which, aside from its use in electronic speedometry, is a critical parameter necessary to the implementation of anti-skid and adaptive braking systems. And all of this came from a simple, wheel-mounted measurement of tire pressure.

Fuel Monitoring

Fuel monitoring, by means of an electronic fuel flow signal, is also possible, and we can generate such a signal accurately and inexpensively. (See *Figure 3.*) A vehicle's fuel pump, to a first-order approximation, is a constant-pressure source. Place a venturi or flow nozzle in the fuel line between the fuel pump and the carburetor, and use a differential pressure transducer to measure the pressure difference between the pump and the narrowest point of the nozzle. The differential pressure is a function of the fuel flow rate. The electronic speedometer signal, mentioned earlier, divided by the (conditioned) fuel flow signal gives a fuel consumption figure (miles per gallon).

Signal conditioning and the division process are best carried out in the digital domain. Such circuitry readily interfaces with a central processing unit (CPU), and the CPU, in turn, interfaces with control and/or display functions. For example, besides displaying miles-per-gallon, the CPU can also compute, for display purposes, miles-to-go. This signal derives from miles-per-gallon and fuel-level signals.

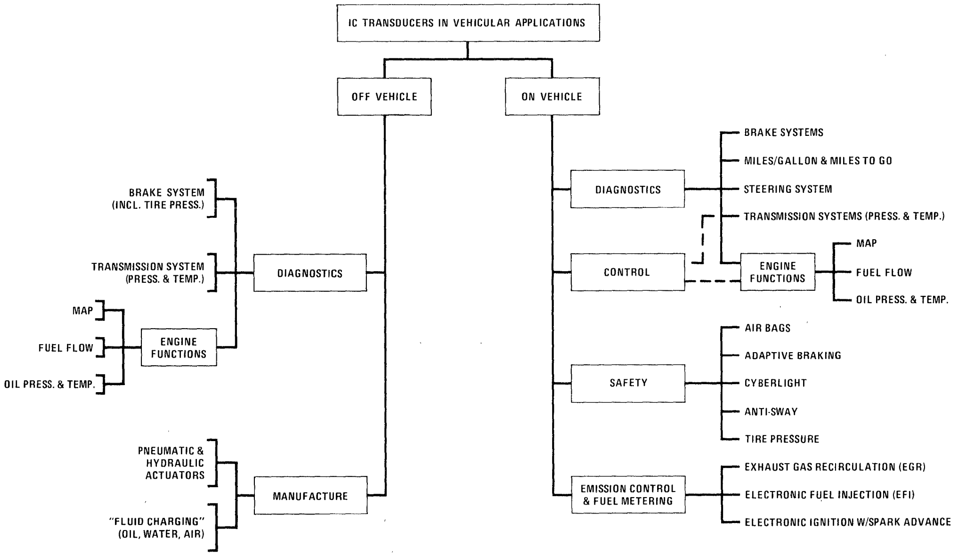
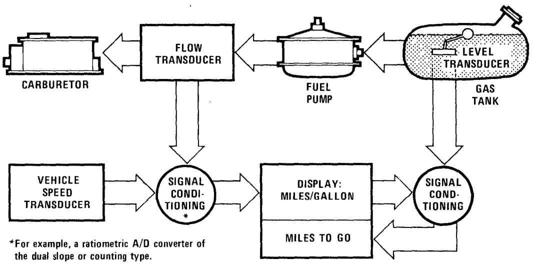


FIGURE 2. Uses of Hybrid IC Transducers in Vehicular Applications



*For example, a ratiometric A/D converter of the dual slope or counting type.

FIGURE 3. Electronic Miles-per-Gallon and Miles-to-Go Measurement and Indication System

Fuel Metering and Ignition Management

It is also possible to compute the cyclic power demands of the engine for fuel metering and ignition management purposes. To compute the engine's cyclic power demands, we must generate and combine a complex array of signals (*Figure 4*): crankshaft speed and position, for the determination of engine speed and cylinder position; and intake MAP, ambient absolute pressure (barometer) and air temperature to synthesize engine loading (torque).

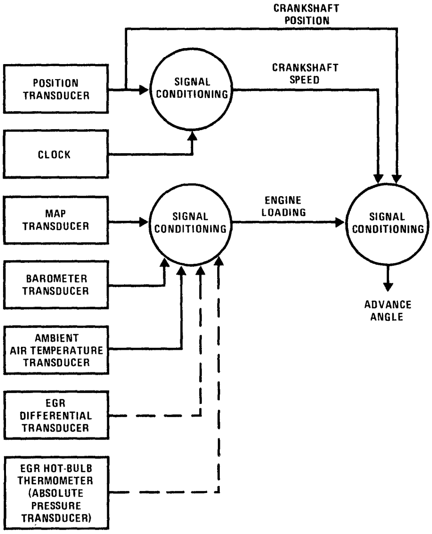


FIGURE 4. Ignition Timing Module

There is some disagreement among engine experts as to the use of absolute pressure *vis-a-vis* gage pressure in model computations for EFI, exhaust gas recirculation (EGR), spark advance and so forth. Some feel that density, as approximated by the ratio of absolute pressure to temperature, is a more useful variable.

In even the most complex model, however, you can use an LX17XX hybrid IC pressure transducer, in which, say, two ceramic substrates are interconnected prior to a *single* active trim. (We're referring to a single package, which holds two transducers and is subject to one active trim as a single device.) In double transducers such as this, you can scale the difference between the MAP and barometer signals to be anything between absolute and gage, as required by your model.

For accurate temperature signals in a format easily combined with the pressure signals, you can implement the hot bulb thermometer principle with a pressure transducer. This is particularly applicable to exhaust gas temperature measurement. The pressure and temperature sensors can be part of a single-package, active trimmed, multi-hybrid circuit that is accurate, temperature-stable, and economical to procure.

Line Pressures

Line pressures are useful for off-vehicle and onboard diagnostics. For example, brake-line pressure maxima and minima, as well as the whole profile of brake pedal loading and displacement, are important diagnostic parameters. A pressure transducer at the master cylinder, monitoring such values, can read out externally or on an internal diagnostic panel. The output of this transducer also can be used to operate the electric brake of a trailer or other towed vehicle.

An engine oil pressure and temperature monitoring transducer can produce both external and internal displays. You can set limits on the pressure and temperature values for automatic display on the trouble panel.

Similarly, transmission oil pressure and temperature transducers can monitor values for external and internal display. Just as in the case of exhaust manifold gas temperature measurement, the hot bulb thermometer approach may also be applicable here because of the high temperatures involved. Again, you can set limit switches for trouble panel display.

Once again, we can carry forward the story in a predictory fashion. If transducer cost is compatible with onboard installation, and if transducer accuracy and reliability are suitable, then you can attempt control functions as well as diagnostics. The goal of vehicle control improvement is, in fact, the very justification of onboard diagnostics. Thus, monitoring the transmission's torque converter pressure, and being armed with other signals related to vehicle speed, engine speed and so on, you can create a properly combined function signal. Such a signal is usable to alter transmission valving, which in turn accomplishes power conversion. A fluidic/electronic transmission now becomes a reasonable goal.

In concluding, we note that we have touched on only some of the vehicular applications areas for IC pressure transducers. Among other onboard applications we may list, in the safety area, air bags, anti-sway and cyberlight systems. In onboard diagnostic systems, IC pressure transducers will find use in power steering applications. Off-vehicle applications not discussed include, for example, transducers in pneumatic/hydraulic actuators for vehicle manufacture, and in "fluid charging" systems for air, oil and water vessels of any type. In brief, like the IC, the IC pressure transducer's time has come.

Section 15

Quick Selection and Ordering Guide

15

THE CHALLENGE OF CHOICE

Selecting the right pressure transducer for the right job is a challenging task, even for National's hybrid IC pressure transducers. This quick selection and ordering guide provides a strategic picture of National's pressure transducer product line, but before making a final choice, chances are you'll want to refer to other sections, such as *Accuracy & Specifications, Product Descriptions, Configurations, Packaging & Environment* and the numerous application sections. If you have but our transducers still don't seem to fit, contact one of our representatives. They like a challenge, too.

Quick Selection and Ordering Guide

TRANSDUCER ORDERING INFORMATION

LX1 7 03 A FN

STANDARD OPTIONS

B — Backward Gage Version (PX6B, PX7B)
D — High Common-Mode Differential Version (PX7DD)
F — Fluid-Filled Version (PX6F or PX4F)
N — Nylon Package (PX7N)
S — Stainless Steel Package (PX4S)
DF — Combine "D" and "F" Options (PX7DDF)
FN — Combine "F" and "N" Options (PX7FN)
FS — Combine "F" and "S" Options (PX4FS)

PRESSURE TYPE

A — Absolute
D — Differential
G — Gage

PRESSURE RANGE (See Selection Guide)

PACKAGE TYPE

4 — Rugged Cylindrical Plumbed Fitting (PX4 Series)
6 — Hybrid IC for PCB Mounting (PX6 Series)
7 — Rugged Zinc or Nylon Housing with Optional Plumbing (PX7 Series)

DEVICE TYPE

LX1 — Linear Transducer, Pressure

TRANSDUCER SELECTION GUIDE

MAXIMUM RATINGS

Excitation Voltage	30V
Output Current	
Source	20 mA
Sink	10 mA
Transducer Bias Current	20 mA
Operating Temperature Range	0°C to +85°C
Storage Temperature Range	−40°C to +105°C
Lead Soldering Temperature (10 seconds)	260°C

TYPICAL CHARACTERISTICS

Output Voltage Sensitivity to Excitation Voltage	0.5%
Output Impedance	$<50\Omega$
Electrical Noise Equivalent ($0 \leq f \leq 1$ kHz)	0.04% Span
Natural Frequency of Sensor Diaphragm	> 50 kHz
Transducer Bias Current	
LX14XXA	7–10 mA
LX16XXA, D, G	11–15 mA

TRANSDUCER SELECTION GUIDE (Continued)

DEVICE TYPE	OPERATING PRESSURE RANGE	MAXIMUM OVER PRESSURE	GUARANTEED SPECIFICATIONS							
			REFERENCE TEMPERATURE = 25°C V_E = 15 V_{DC}				OPERATING TEMPERATURE RANGE = 0°C to 85°C REFERENCE PRESSURE = 0 psi†			
			OFFSET CHARACTERISTICS				SPAN CHARACTERISTICS			
			OFFSET CALIBRATION V	TEMP. COEFFICIENT ±psi/°C	REPEATABILITY ±psi	STABILITY ±psi	SENSITIVITY CALIBRATION mV/psi	TEMP. COEFFICIENT ±psi/°C	LINEARITY HYSTERESIS REPEATABILITY ±psi	STABILITY ±psi
ABSOLUTE PRESSURE DEVICES										
LX1601A(F), LX1701A(F)(N)	10 to 20 psia	40 pisa	2.5 ±0.5†	0.0054	0.05	0.3	1,000 ±20	0.0054	0.05	0.05
LX1602A(F), LX1702A(F)(N)	0 to 15 psia	40 psia	2.5 ±0.3	0.0072	0.06	0.3	670 ±13	0.0072	0.07	0.06
LX1603A(F), LX1703A(F)(N)	0 to 30 psia	60 psia	2.5 ±0.25	0.009	0.1	0.3	333 ±6	0.009	0.16	0.10
LX1610A(F), LX1710A(F)(N)	0 to 60 psia	100 psia	2.5 ±0.25	0.018	0.2	0.6	167 ±3.3	0.018	0.36	0.24
LX1420A(F)(S)	0 to 100 psia	150 psia	2.5 ±0.25	0.030	0.4	1.0	100 ±2	0.03	0.60	0.40
LX1620A(F), LX1720A(F)(N)	0 to 100 psia	150 psia	2.5 ±0.2	0.0216	0.4	1.0	100 ±2	0.0216	0.60	0.40
LX1430A(F)(S)	0 to 300 psia	450 psia	2.5 ±0.25	0.090	1.0	2.0	33.3 ±0.67	0.09	2.0	1.0
LX1730A(F)(N)	0 to 300 psia	450 psia	2.5 ±0.2	0.063	1.0	2.0	33.3 ±0.67	0.063	2.0	1.0
LX1440A(F)(S)	0 to 1000 psia	1500 psia	2.5 ±0.25	0.3	3.5	7.0	10 ±0.2	0.3	6.0	3.0
LX1450A(F)(S)	0 to 2000 psia	3000 psia	2.5 ±0.25	0.6	7.0	14	5 ±0.1	0.6	20.0	7.0
LX1460A(F)(S)	0 to 3000 psia	4500 psia	2.5 ±0.25	0.9	10.0	20.0	3.33 ±0.067	0.9	30.0	10.0
LX1470A(F)(S)	0 to 5000 psia	5000 psia	2.5 ±0.25	1.5	17.0	35.0	2 ±0.04	1.5	75.0	17.0
GAGE PRESSURE DEVICES										
LX1601G(B),LX1701G(B)(N)*	−5 to +5 psig	40 psig	7.5 ±0.5	0.0054	0.05	0.3	1,000 ±20	0.0054	0.05	0.05
LX1611G(B),LX1711G(B)(N)*	−5 to +5 psig	100 psig	7.5 ±0.5	0.0054	0.05	0.3	1,000 ±20	0.0054	0.05	0.05
LX1602G(B),LX1702G(B)(N)*	0 to 15 psig	40 psig	2.5 ±0.3	0.0072	0.06	0.3	670 ±13	0.0072	0.07	0.06
LX1603G(B),LX1703G(B)(N)*	0 to 30 psig	60 psig	2.5 ±0.25	0.009	0.1	0.3	333 ±6	0.009	0.16	0.10
LX1604G(B),LX1704G(B)(N)*	−15 to +15 psig	40 psig	7.5 ±0.25	0.009	0.1	0.3	333 ±6	0.009	0.16	0.10
LX1610G(B),LX1710G(B)(N)*	0 to 60 psig	100 psig	2.5 ±0.25	0.018	0.2	0.6	167 ±3.3	0.018	0.36	0.24
LX1620G(B),LX1720G(B)(N)*	0 to 100 psig	150 psig	2.5 ±0.2	0.0216	0.4	1.0	100 ±2	0.0216	0.60	0.40
LX1730G(B)(N)*	0 to 300 psig	450 psig	2.5 ±0.2	0.063	1.0	2.0	33.3 ±0.67	0.063	2.0	1.0
DIFFERENTIAL PRESSURE DEVICES										
LX1601D(F), LX1701DD(F)	−5 to +5 psid	40 psid	7.5 ±0.5	0.0054	0.05	0.3	1,000 ±20	0.0054	0.05	0.05
LX1611D(F), LX1711DD(F)	−5 to +5 psid	100 psid	7.5 ±0.5	0.0054	0.05	0.3	1,000 ±20	0.0054	0.05	0.05
LX1602D(F), LX1702DD(F)	0 to 15 psid	40 psid	2.5 ±0.35	0.0072	0.06	0.3	670 ±13	0.0072	0.07	0.06
LX1603D(F), LX1703DD(F)	0 to 30 psid	60 psid	2.5 ±0.3	0.009	0.1	0.3	333 ±6	0.009	0.16	0.10
LX1604D(F), LX1704DD(F)	−15 to +15 psid	40 psid	7.5 ±0.3	0.009	0.1	0.3	333 ±6	0.009	0.16	0.10
LX1610D(F), LX1710DD(F)	0 to 60 psid	100 psid	2.5 ±0.25	0.018	0.2	0.6	167 ±3.3	0.018	0.36	0.24
LX1620D(F), LX1720DD(F)	0 to 100 psid	150 psid	2.5 ±0.2	0.0216	0.4	1.0	100 ±2	0.0216	0.60	0.40
LX1730DD(F)	0 to 300 psid	450 psid	2.5 ±0.2	0.063	1.0	2.0	33.3 ±0.67	0.063	2.0	1.0

†Reference pressure for LX1601A and LX1701A is 10 psia.

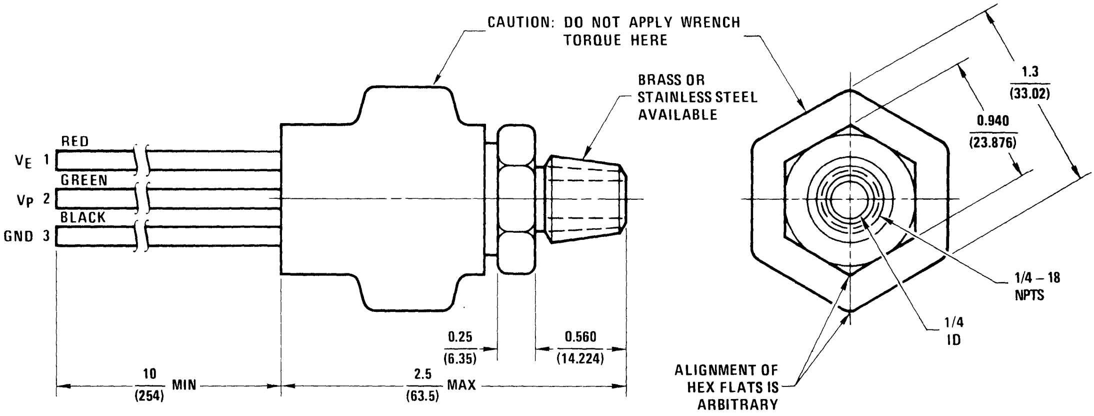
*Available as LX17XXGB or LX17XXGN

PRESSURE TRANSDUCER FEATURE CHART

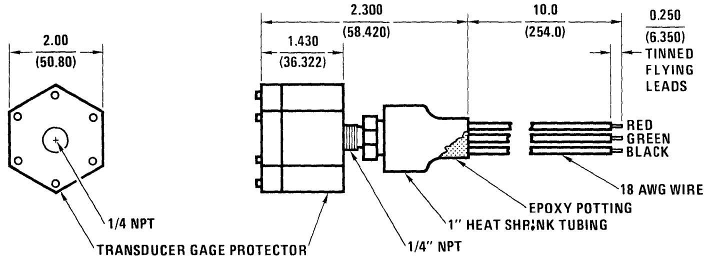
Feature Product	Brass Housing	Stainless Steel Housing	Ceramic Package	Nylon Housing	Zinc Housing	High Common-Mode Differential Housing	Fluid-Filled Isolator	Backward Gage Isolator
LX14XX Absolute	LX14XXA	LX14XXAS					LX14XXAF LX14XXAFS	
LX16XX Absolute			LX16XXA				LX16XXAF	
LX16XX Gage			LX16XXG					LX16XXGB
LX16XX Differential			LX16XXD				LX16XXDF	
LX17XX Absolute				LX17XXAN	LX17XXA		LX17XXAF LX17XXAFN	
LX17XX Gage				LX17XXGN	LX17XXG			LX17XXGB (Zinc)
LX17XX Differential						LX17XXDD (Brass)	LX17XXDDF	

Package Key

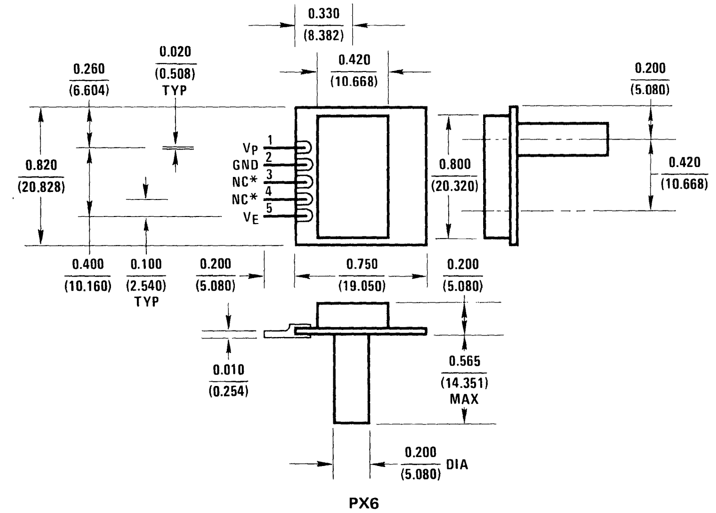
TYPE	PACKAGE
LX14XXA(S)	PX4(S)
LX14XXAF(S)	PX4F(S)
LX16XXA	PX6
LX16XXG	PX6
LX16XXGB	PX6B
LX16XXD(F)	PX6D(F)
LX17XXA(F)(N)	PX7(F)(N)
LX17XXG(N)	PX7(N)
LX17XXGB	PX7B
LX17XXDD(F)	PX7DD(F)



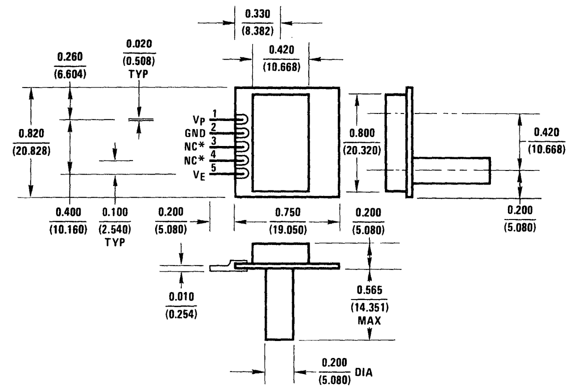
PX4(S)
1/4" NPT Pressure Transducer Package
Wt: 100 G



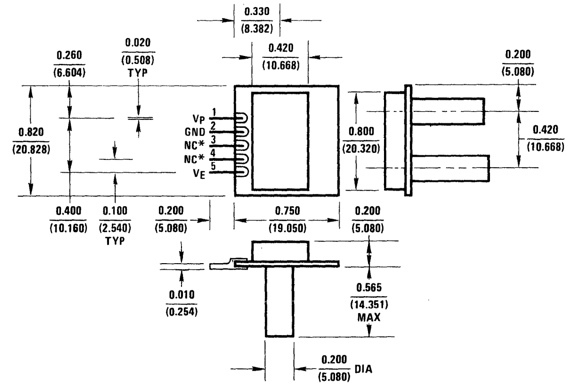
PX4F(S)
1/4" NPT Pressure Transducer Package, Fluid Filled
Wt: 700 G



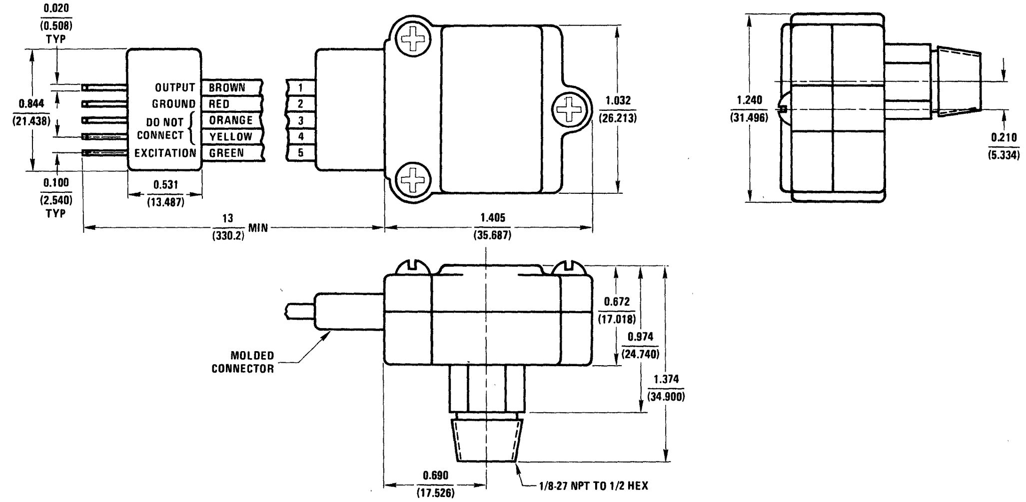
PX6
0.2" Port, Hybrid Pressure Transducer Package
Wt: 5 G



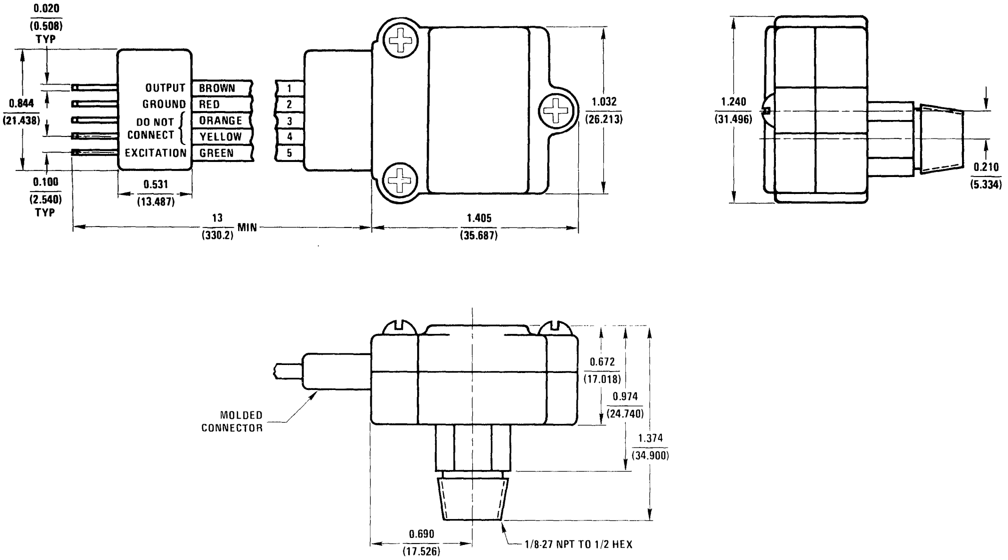
PX6B
0.2" Port, Hybrid Pressure Transducer Package
Wt: 5 G



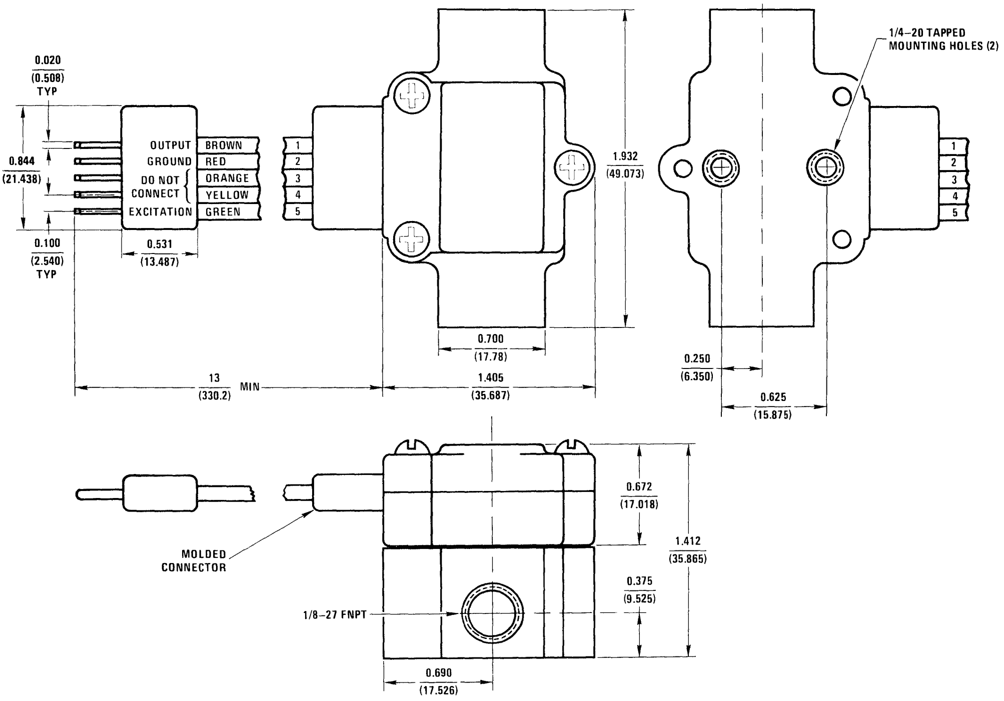
PX6D
0.2" Port, Hybrid Pressure Transducer Package
Wt: 5 G



PX7
1/8" NPT Zinc Cast Pressure Transducer Package
Wt: 100 G (Zinc), 50 G (Nylon – With Identical Mechanical Performance)



PX7B
1/8" NPT Zinc Cast Pressure Transducer Package
Wt: 100 G (Zinc)



PX7DD
1/4" NPT Brass Pressure Transducer Package
Wt: 270 G

Section 16

16

Definition of Terms

Definition of Terms

GENERAL TRANSDUCER TERMS

Absolute Pressure
Absolute Pressure Transducer
Differential Pressure
Differential Pressure Transducer
Gage Pressure
Gage Pressure Transducer
Barometric Pressure Transducer
Altimetric Pressure Transducer
Vacuum
Vacuum Range
Vacuum Transducer

TRANSDUCER PARAMETERS

Range
Span
Sensitivity
Reference Temperature
Reference Pressure
Offset Voltage
Over Pressure—Maximum
Common-Mode Pressure—Maximum
Seal Pressure
Burst Pressure

GENERAL ERROR TERMS

Best Straight Line (BSL)
BSL with Forced Reference
Error Band
Temperature Coefficient (TC)
Repeatability
Stability
Interchangeability
Normal Mode Error
Common-Mode Error
Auto-Referencing

OFFSET ERROR TERMS (COMMON-MODE)

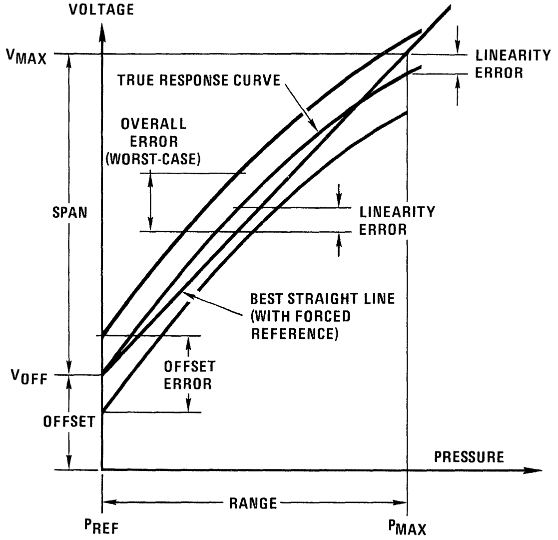
Offset Error
Offset Calibration
Offset Temperature Coefficient
Offset Repeatability
Offset Stability

SPAN ERROR TERMS (NORMAL MODE)

Span Error
Sensitivity Calibration
Span Temperature Coefficient
Linearity
Hysteresis
Span Repeatability
Span Stability

OVERALL ACCURACY

Overall Accuracy—Calibrated
Overall Accuracy—Interchangeable
Most Probable Error
Worst-Case Error



GENERAL TRANSDUCER TERMS

Absolute Pressure: Pressure measured relative to a perfect vacuum. Usually expressed in pounds per square inch absolute (psia).

Absolute Pressure Transducer: A device containing a vacuum reference such that it measures absolute pressure either of the local ambient or of a pressure source piped to its input.

Differential Pressure: The pressure difference measured between 2 pressure sources. Usually expressed in pounds per square inch differential (psid). When one source is a perfect vacuum, the pressure difference is called *absolute pressure*. When one source is the local ambient, the pressure difference is called *gage pressure.*

Differential Pressure Transducer: A device that measures the differential pressure between 2 pressure sources piped to its inputs.

Gage Pressure: Differential pressure between the local ambient and another pressure source.

Gage Pressure Transducer: A differential pressure transducer with the local ambient as one source and the pressure piped to its input as the other source.

Barometric Pressure Transducer: An absolute pressure transducer measuring the local ambient pressure.

Altimetric Pressure Transducer: A barometric pressure transducer used to determine altitude from the pressure-altitude profile.

Vacuum: A perfect vacuum is the absence of gaseous fluid.

Vacuum Range: The range of absolute pressures between a perfect vacuum (0 psia) and one standard atmosphere (14.697 psia).

Vacuum Transducer: A transducer scaled for pressure measurement in the vacuum range. This is usually an absolute transducer but sometimes a gage transducer.

TRANSDUCER PARAMETERS

Range: The specified endpoint pressures of the transducer operating pressure range usually expressed in psia, psid or psig (e.g., 10 to 20 psia).

Span: The arithmetic difference in transducer output signal measured at the specified minimum and maximum operating pressures. Span is usually expressed in volts (V).

Sensitivity: The ratio of output signal voltage change to the corresponding input pressure change. Sensitivity is determined by computing the ratio of span to the specified input pressure range (slope of the *best straight line with forced reference*). It is usually expressed in volts per psi (V/psi).

Reference Temperature: The temperature used as reference in measuring transducer errors is 25°C for National transducers.

Reference Pressure: The pressure used as a reference in measuring transducer errors. Reference pressure is usually the lowest operating pressure. This is 0 psi for most transducers in National's line. However, it is the mid-point pressure for some gage and differential transducers.

Offset Voltage: The transducer output signal obtained when the reference pressure is applied, usually expressed in volts (V).

Over-Pressure—Maximum: The maximum *normal mode* (measured) pressure that can be applied without changing the transducer's performance or accuracy beyond the specified limits. This would be applied to either port of a differential transducer. This is also called proof pressure.

Common-Mode Pressure—Maximum. The maximum pressure that can be applied to both ports of a differential transducer without changing its performance or accuracy beyond the specified limits.

Seal Pressure: The maximum pressure that can be safely applied to a gage or differential transducer and still ensure no leakage of the pressurized fluid to the surroundings.

Burst Pressure: The maximum pressure that can safely be applied to an absolute transducer and still ensure no leakage of the pressurized fluid to the surroundings.

GENERAL ERROR TERMS

Best Straight Line (BSL): The best straight line chosen such that the true transducer response curve contains 3 points of equal maximum deviation.

BSL With Forced Reference: The best straight line chosen to intersect the true response curve at *reference pressure* and such that the true response curve contains 2 points with equal maximum deviation. The slope of the line is the *sensitivity* of the transducer. The voltage deviation of the 2 points, when divided by the *sensitivity*, is the *linearity error band,* expressed in psi.

Error Band: The deviation of transducer response from its *BSL with forced reference*, defined by lines on either side of its BSL and including the maximum deviation measured for a given *normal mode* or *common-mode* error.

Temperature Coefficient (TC): The *error band* resulting from maximum deviation of a transducer output parameter (such as *offset* or *span*) as temperature is varied from 25°C to any other temperature within the specified range. It is usually measured in V/°C and divided by *sensitivity* to express the magnitude of the *error band* in psi/°C.

Repeatability: The *error band* expressing the ability of the transducer to reproduce an output signal parameter (such as offset or span), at specified pressures and temperature, after exposure to any other pressure and temperature within the specified range. It is usually measured in volts and divided by *sensitivity* to obtain the magnitude of the *error band*, expressed in psi.

Stability: The *error band* expressing the ability of a transducer to maintain the value of an output parameter (such as offset or span) with constant temperature and pressure inputs. The maximum deviation is usually measured in volts and divided by *sensitivity* to obtain the magnitude of the *error band,* expressed in psi.

Interchangeability: The *error band* defined by the maximum signal deviation obtained when a transducer is replaced by any other transducer of the same type with equivalent pressure inputs and temperature ranges. It is usually expressed in psi.

Normal Mode Error: An error that is a function of (and usually assumed to be proportional to) the major input variable (input pressure). For National transducers all *span errors* are normal mode errors.

Common-Mode Error: An error that is independent of the major input variable (input pressure). For National transducers, all *offset errors* are common-mode errors.

Auto-Referencing: A technique for eliminating errors by sampling one or more reference pressures, then correcting the output signal function.

OFFSET ERROR TERMS (COMMON-MODE)

Offset Error: The *common-mode error band* defined by the maximum deviation of *offset voltage* from its specified value. It may include calibration, temperature coefficient, repeatability and stability errors.

Offset Calibration: The *error band* defined by the maximum error in calibrating the *offset voltage.*

Offset Temperature Coefficient: The *error band* defined by the maximum deviation in *offset voltage* as the temperature is varied from 25°C to any other temperature within the specified range. The deviation is measured in volts, divided by the temperature excursion then divided by *sensitivity* to express the magnitude of the *error band* in psi/°C.

Offset Repeatability: The *error band* expressing the ability of the transducer to reproduce the *offset voltage,* measured at 25°C, after exposure to any other temperature and pressure within the specified range. The deviation is measured in volts then divided by *sensitivity* to obtain the magnitude of the *error band* in psi.

Offset Stability: The *error band* expressing the ability of the transducer to maintain the offset voltage with constant pressure and temperature.

SPAN ERROR TERMS (NORMAL MODE)

Span Error: The *normal mode error band* defined by the maximum deviation of *span* from its specified value. It may include sensitivity calibration, temperature, coefficient, linearity, hysteresis, repeatability and stability deviations.

Sensitivity Calibration: The *error band* defined by the maximum error in calibrating *sensitivity.*

Span Temperature Coefficient: The error band defined by the maximum deviation of the *span* as the temperature is varied from 25°C to any other temperature within the specified range. It is obtained by measuring output voltage change as pressure is varied from *reference* to maximum, dividing by the temperature excursion then by sensitivity to express the magnitude of the *error band* in psi.

Linearity: The *error band* defined by the maximum deviation of the true output curve from the *BSL with forced reference.* It is measured in volts and divided by *sensitivity* to obtain the magnitude of the *error band,* expressed in psi.

Hysteresis: The *error band* defined by the maximum deviation in output signal obtained when a specific pressure point is approached first with increasing pressure, then with decreasing pressure or vice versa.

Span Repeatability: The *error band* expressing the ability of a transducer to reproduce its *span,* measured at 25°C, after exposure to any other pressure and temperature within the specified range. The maximum deviation of *span* voltage is measured for a given number of pressure and temperature excursions, then divided by *sensitivity* to express the *error band* in psi.

Span Stability: The *error band* expressing the ability of the transducer to maintain the *span* voltage with pressure varied from minimum to maximum and temperature held constant. The maximum measured deviation in *span* voltage is divided by *sensitivity* to express the *error band* in psi.

OVERALL ACCURACY

Overall Accuracy—Calibrated: The combined *error band* relative to the *BSL with forced reference* unique to one specific transducer. It excludes offset and sensitivity calibration errors. It includes all other offset and span errors: temperature coefficient, repeatability, stability, linearity and hysteresis.

Overall Accuracy—Interchangeable: The combined *error band* relative to an ideal transducer response characteristic. It excludes stability errors because stability error is already included in specified calibration error. It includes all other offset and span errors: calibration, temperature coefficient, repeatability, linearity and hysteresis.

Most Probable Error: The *error band* obtained by computing the square root of the sum of the squares of all applicable errors specified for the transducer.

Worst-Case Error: The *error band* obtained by simple addition of all applicable errors specified for the transducer.

Section 17

Conversion Constants

Conversion Constants—Voltage to Pressure Sensitivity

All standard LX series devices have an output voltage that is linear with the pressure input and spans 10V. Thus, the sensitivity, or slope, of a transducer may be determined by dividing the 10 V span by the pressure range of the particular device. An LX1602A, 0-15 psia device, for example, has a sensitivity of 10/15 = 0.667 V/psi = 667 mV/psi. Conversion to other pressure units follows immediately from this figure via a table of pressure unit conversion constants. Table I lists such sensitivities in terms of a number of commonly used pressures.

Similar tables may be prepared for other LX transducers merely by multiplying the LX1602's sensitivity factors by the ratio of the LX1602's pressure range to that of the transducer in question.

Clearly, the high absolute pressure sensitivity of the LX1601A and LX1602A make them well suited to barometric and altimetric measurements, respectively, (see Section 8). The altimetric sensitivity of the LX1602A is shown in Table II.

In the lower pressure ranges (subatmospheric to about 20 atmospheres), it is very important for the user to distinguish between an application requiring a gage pressure transducer and one requiring an absolute pressure transducer. This is because altimetric pressure variation can represent a very large error in a gage pressure application mistakenly served by an absolute pressure transducer. In fact, in the lowest pressure ranges (subatmospheric to about 4 atmospheres), even the daily barometric pressure variations at fixed altitude can represent significant error. Although auto-referencing (see Section 7) can reduce the penalty for such a mistake, it's important to use gage pressure transducers when absolute pressure sensitivity is undesirable.

In the higher pressure ranges (above 20 atmospheres), the distinction between gage pressure and absolute pressure becomes less important. In gage pressure applications, altitude error is small and barometric error is negligible when compared with (for example) a 1000 psi range. At 1000 psi and up, National doesn't offer a gage pressure transducer, since absolute pressure transducers serve the range well. The altimetric sensitivity of the LX1440A is shown in Table II.

TABLE I

LX1602A	
UNITS	**SENSITIVITY**
psi	667 mV/psi
in. Hg	327 mV/in. Hg
in. H_2O	24.1 mV/in. H_2O
mm Hg	12.9 mV/mm Hg
ft. H_2O	289 mV/ft. H_2O
mm H_2O	948 μV/mm H_2O
cm Hg	129 mV/cm Hg
cm H_2O	9.48 mV/cm H_2O

For example: LX1601 constants = LX1602 constants x1.5 (15/10); LX1603, x 0.5; and so on.

TABLE II

ALTITUDE (k FT)	psia	LX1602A SENSITIVITY (mV/k FT)	LX1602A TYPICAL OUTPUT V_P (V)	LX1440A SENSITIVITY (mV/k FT)	LX1440A TYPICAL OUTPUT V_P (V)
−1	15.236	364.1	12.657	5.46	2.652
0	14.697	354.1	12.298	5.31	2.647
1/2	14.434	348.9	12.123	5.23	2.644
1	14.174	343.8	11.949	5.16	2.642
1 1/2	13.912	338.8	11.775	5.08	2.639
2	13.666	333.8	11.611	5.01	2.637
3	13.172	324.0	11.281	4.86	2.632
4	12.693	314.6	10.962	4.72	2.627
6	11.778	296.1	16.352	4.44	2.618
8	10.917	278.4	9.778	4.18	2.609
10	10.107	261.6	9.238	3.92	2.601
12	9.347	245.6	8.731	3.68	2.594
14	8.634	230.3	8.256	3.45	2.586
16	7.966	215.7	7.811	3.24	2.580
18	7.340	201.9	7.393	3.03	2.573
20	6.754	188.8	7.003	2.83	2.568
22	6.207	173.3	6.638	2.60	2.562
25	5.454	159.3	6.136	2.39	2.555
30	4.365	133.0	5.410	2.00	2.544
35	3.458	109.6	4.805	1.64	2.535
40	2.720	87.9	4.313	1.32	2.527
45	2.139	69.2	3.926	1.04	2.521
50	1.682	53.9	3.621	0.81	2.517

PRESSURE UNIT CONVERSION FACTORS

	lb./in.^{2*}	oz./in.^{2}	lb./ft.^{2}	ton/in.^{2}	ton/ft.^{2}	in. $H^{2}O$	ft. H_2O	in. Hg.	A_n	dyne/cm.^{2**}	g/cm.^{2}	kg./cm.^{2}	cm. H_2O	m. H_2O	mm. Hg.***	μ Hg.
ENGLISH																
1 Pound/sq. in.* =	1.0000	16.000	144.00	5.0000 x10^{-4}	7.2000 x10^{-2}	27.680	2.3067	2.0360	6.8045 x10^{-2}	68947.	70.306	7.0306 x10^{-2}	70.308	0.7031	51.715	51715.
1 Ounce/sq. in. =	0.0625	1.0000	9.0000	3.1250 x10^{-5}	4.5000 x10^{-3}	1.7300	0.1442	0.1272	4.2528 x10^{-3}	4309.2	4.3941	4.3941 x10^{-3}	4.3942	4.3942 x10^{-2}	3.2322	3232.2
1 Pound/sq. ft. =	6.9445 x10^{-3}	0.11111	1.0000	3.4723 x10^{-6}	5.0000 x10^{-3}	0.19223	1.6019 x10^{-2}	1.4139 x10^{-2}	4.7254 x10^{-4}	478.80	0.4882	4.8824 x10^{-4}	0.4882	4.8825 x10^{-3}	0.3591	359.13
1 Ton/sq. in. =	2000.0	32000.	2.8800 x10^{5}	1.000	144.00	55361.	4613.4	4072.0	136.09	1.3789 x10^{8}	1.4061 x10^{5}	140.61	1.4062 x10^{5}	1406.2	1.0343 x10^{5}	1.0343 x10^{8}
1 Ton/sq. ft. =	13.889	222.22	2000.0	6.9445 x10^{-3}	1.0000	384.45	32.038	28.278	0.9451	9.5760 x10^{5}	976.48	0.9765	976.51	9.7651	718.26	7.1826 x10^{5}
1 Inch water 39° F. =	3.6127 x10^{-2}	0.5780	5.2022	1.8063 x10^{-5}	2.6011 x10^{-3}	1.0000	8.3333 x10^{-2}	7.3554 x10^{-2}	2.4582 x10^{-3}	2490.8	2.5399	2.5399 x10^{-3}	2.5400	2.5400 x10^{-2}	1.8683	1868.3
1 Foot water 39° F. =	0.43352	6.9363	62.427	2.1676 x10^{-4}	3.1213 x10^{-2}	12.000	1.0000	0.8826	2.9499 x10^{-2}	29890.	30.479	3.0479 x10^{-2}	30.480	0.3048	22.419	22419.
1 In mercury 32° F. =	0.49116	7.8586	70.727	2.4558 x10^{-4}	3.5363 x10^{-2}	13.596	1.1330	1.0000	3.3421 x10^{-2}	33864.	34.532	3.4532 x10^{-2}	34.532	0.3453	25.400	25400.
INT'L																
1 Normal Atm'ere =	14.696	235.14	2116.2	7.3480 x10^{-3}	1.0581	406.79	33.900	29.921	1.0000	1.0132 x10^{6}	1033.2	1.0332	1033.3	10.333	760.00	7.6000 x10^{5}
1 Dyne/sq. cm.** 1 Microbar =	1.4504 x10^{-5}	2.3206 x10^{-4}	2.0886 x10^{-3}	7.2519 x10^{-9}	1.0443 x10^{-6}	4.0147 x10^{-4}	3.3456 x10^{-5}	2.9530 x10^{-5}	9.8692 x10^{-7}	1.0000	1.0197 x10^{-3}	1.0197 x10^{-6}	1.0197 x10^{-3}	1.0197 x10^{-5}	7.5006 x10^{-4}	0.7501
METRIC																
1 Gram/sq. cm. =	1.4224 x10^{-2}	0.2276	2.0482	7.1117 x10^{-6}	1.0241 x10^{-3}	0.3937	3.2809 x10^{-2}	2.8959 x10^{-2}	9.6784 x10^{-4}	980.66	1.0000	0.0010	1.00003	1.00003 x10^{-2}	0.7356	735.56
1 Kilogram/sq. cm. =	14.224	227.58	2048.2	7.1117 x10^{-3}	1.0241	393.71	32.809	28.959	0.9678	9.8060 x10^{5}	1000.0	1.0000	1000.03	10.0003	735.56	7.3556 x10^{5}
1 Cm. water at 4°C. =	1.4223 x10^{-2}	0.2276	2.0481	7.1115 x10^{-6}	1.0240 x10^{-3}	0.3937	3.2808 x10^{-2}	2.8958 x10^{-2}	9.6781 x10^{-4}	980.64	0.99997	9.9997 x10^{-4}	1.0000	0.0100	0.7355	735.54
1 Meter water 4°C. =	1.4223	22.757	204.81	7.1116 x10^{-4}	0.1024	39.370	3.2808	2.8958	9.6781 x10^{-2}	98064.	99.997	9.9997 x10^{-2}	100.00	1.0000	73.554	73554.
1 Mm. Hg. at 0°C.*** =	1.9337 x10^{-2}	0.3094	2.7845	9.6684 x10^{-6}	1.3922 x10^{-3}	0.53525	4.4605 x10^{-2}	3.9370 x10^{-2}	1.3158 x10^{-3}	1333.2	1.3595	1.3595 x10^{-3}	1.3595	1.3595 x10^{-2}	1.0000	1000.0
1 Micron Hg. 0°C. =	1.9337 x10^{-5}	3.0939 x10^{-4}	2.7845 x10^{-3}	9.6684 x10^{-9}	1.3922 x10^{-6}	5.3525 x10^{-4}	4.4605 x10^{-5}	3.9370 x10^{-5}	1.3158 x10^{-6}	1.3332	1.3595 x10^{-3}	1.3595 x10^{-6}	1.3595 x10^{-3}	1.3595 x10^{-5}	0.0010	1.0000

*1 lb./in.^{2} = 1 psi

**1 dyne/cm.^{2} = 1 microbar = 10^{-4}K Pa = 0.1 Pa (Pascal)

***1 mm. Hg. = 1 torr

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