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PERFORMANCE PARAMETERS THAT CHARACTERIZE A DIFFERENTIAL-PRESSURE TRANSDUCER

by I. Warshawsky and C. C. Gettelman
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at
American Gas Association annual Transmission Conference
Cleveland, Ohio, May 27, 1968

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ABSTRACT

The parameters that characterize the performance of an industrial transducer are itemized, together with the method of their specification, and the order of magnitude of the limits of error, when applicable. Some techniques of reducing errors and increasing reliability, applicable to the design of the transducer or to its application, are suggested.

INTRODUCTION

The considerations that affect the specification of transducer performance can be illustrated by the specific example of a differential-pressure transducer for gas flow rate measurement. This type of transducer will be taken as the subject of this paper.

THE MEASUREMENT SYSTEM CONCEPT

The subject can be treated adequately only by considering the complete measuring system. A typical one is shown in Fig. 1. The elements of this system are

(1) The process itself (e.g., gas flow)

(2) The first transducer, flow rate to differential pressure (e.g., orifice or venturi)

(3) The second transducer, differential pressure to output (e.g., current)

(4) The installations of each of the transducers

(5) The power supply and the readout instrument for the second transducer

The system is intended to measure mass flow rate, but each of the above elements will contribute errors to this measurement. Some of the errors are systematic; they can be applied as corrections, if desired. They are summed algebraically. The rms value of all the random errors will constitute the irreducible uncertainty in mass flow rate. These random errors include the uncertainties in knowledge of the systematic corrections.

Although the inaccuracy of the measurement is definable in engineering units, a less readily measured but equally important parameter is reliability. Its cost in time and money must be balanced against or included with the cost of engineering accuracy. If "performance" is used to include both accuracy and reliability, the following brief list indicates examples of factors that affect performance and that originate in other system elements than the pressure transducer. Asterisked items also influence pressure-transducer selection.

The process

*1. Gas composition

*2. Gas pressure and temperature

*3. Fluctuations in flow rate and pressure

(Item 1 affects choice of diaphragm material and also molecular weight and supercompressibility in the flow rate equation; item 2 affects physical operating conditions and also density in the flow rate equation; item 3 affects linearity of averaging even if one is not interested in following the fluctuations.)

The first transducer installation

Its geometry - dimensions, edge sharpness for an orifice, surface roughness for a venturi

Its installation - concentricity, squareness of the orifice, or alignment of the venturi

The second transducer installation

*Its mounting

Installation strains

Vibration effects

*Its connection

Line slope for drainage of condensibles

Equalization of time lags in the two legs

The readout

For a chart-type recorder,

Accuracy of pen deflection (this is the accuracy generally quoted by the recorder manufacturer)

Chart stability (humidity produces length changes of 1/4 to 1/2 percent)

Registration of chart and pen over numerous chart changes

(Stability of the chart imposes a fundamental limitation on accuracy which generally is even more restrictive than chart readability. Nor does high readability imply high accuracy. If better accuracy is needed, a different form of readout becomes imperative.)

For a current or a voltage readout (e.g., digital ammeter or voltmeter plus printer),

Impedance loading effect

Gain accuracy

Gain and zero stability

THE DIFFERENTIAL-PRESSURE TRANSDUCER

NASA-Lewis Procurement Practice

The list of sources of error in a ΔP-transducer and in the other elements of the measurement system is so long that only careful control of each performance item can limit overall inaccuracy to less than 1 percent. NASA-Lewis procedure in transducer procurement illustrates how this control may be exercised.

1. Every relevant performance item is specified, by stating, for each item, the acceptable limit of error, and the exact test method that will be used for checking that item. Construction features that affect reliability are also specified in concrete terms of performance. No performance item is specified that cannot be checked.

2. The specification on each item is realistic. Generally, we make sure that the specification on any one item is met by at least two manufacturers with their standard advertised equipment. We try to specify performance, in the user's terms, rather than design, which is best left to the manufacturer.

3. For a transducer that will be used on several applications during its lifetime (as is generally the case), specifications are rigorous. The additional cost is negligible in comparison to the cost of a single lost test or lost datum caused by a defective transducer.

4. Once the specifications are written, award is made to the lowest bidder who meets all specifications.

5. Each transducer is inspected and tested for each performance item specified (except where there is strong statistical evidence that some test need be performed only on samples).

Parameters Characterizing ΔP-Transducer Performance

Some of these parameters may be separated into groups characterized by the nature of the equipment used to check performance. These groups are shown in Figs. 2-5. The entries in the right-hand column of these figures indicate the manner in which a limit of error may be specified. The actual numerical value that appears in the figure, although a realistic number, is not intended as a recommendation. The user's application will determine the proper value; this value will represent a balance between accuracy, availability (delivery time), cost, reliability, and convenience of use.

I. Specifications based on tests that require an accurate standard

This group is listed in Fig. 2.

"Standard conditions," which must be defined in a procurement specification, may be a combination like the following:

(1) Ambient temperature (e.g., 75° F)

(2) Ambient pressure (e.g., 1 atm)

(3) $\Delta P = 0$ (both taps shortcircuited)

(4) Vertical attitude

(5) Line pressure (e.g., 1 atm absolute)

(6) Line voltage, if electrically operated (e.g., 117 V, 60 Hz)

(7) Supply pressure, if pneumatically operated (e.g., 20 psig)

The sensitivity change with temperature may be stated as a slope or as an absolute limit. In either method, there must be a statement of the temperature range over which the tolerance applies. Different slope limits may be specified for different temperature regimes.

The sensitivity change with time may be determined after the transducer has been under standard conditions for many days. However, a more meaningful test is one in which the transducer is cycled to full scale for several hundred cycles during the test period.

"Hysteresis" is the maximum difference, generally occurring at midscale, between output vs input calibrations taken with input steadily increasing and with input steadily decreasing (dashed curves). Hysteresis, as used here, is a catchall term that includes elastic defects, magnetic hysteresis, friction, backlash, and dead zone.

After several cycles through the hysteresis loop, a repeated unidirectional approach to some value of ΔP near full scale, starting from $\Delta P = 0$, will still not always produce the same reading. The maximum difference between output readings for, say, four repeated approaches, is termed the "repeatability."

The most probable calibration curve may be taken as the (solid) curve midway between the (dashed) ascending and descending calibrations. If a chord is drawn between the end points of this curve, the maximum difference between the ordinates of curve and chord may be termed the "nonlinearity." This definition is as good as any other, as long as instrument manufacturer and instrument user use the same definition. (There are at least six other definitions of nonlinearity, based on other methods of drawing the straight line.)

The designation "fs" may be considered as representing "full-scale ΔP range" or "full span of the output signal."

II. Specifications based on tests that require a stable differential pressure

A second group of tests (Fig. 3) requires that a differential pressure, near full-scale value, be held very constant for a few minutes, although it is not known accurately. The arrangement shown in Fig. 3 can accomplish this. A standard high-pressure gas cylinder, with the usual two-stage regulator, produces a pressure on the order of 25 psig. The gas then passes through a high-quality pressure regulator (e.g., a pilot-operated, null-balance type) and a needle valve. The fine regulator is adjusted to produce full-scale ΔP across the needle valve; the instrument under test is also connected across the valve. Such a system can maintain ΔP constant to better than 0.1 percent over a period of 10 minutes or more.

During this period, one can determine the effect of supply pressure changes (if the transducer is pneumatically operated) by turning a valve, or of line-voltage changes (if the transducer is electrically operated) by turning a variable autotransformer.

Similarly, the transducer may be tilted in four directions to determine acceleration effect. The 0.2 g range may be used for instruments that require operation in a vertical position. The 1 g range is a more sensitive test for more rugged, vibration-resistant instruments.

If there is doubt of the ability of the system illustrated in Fig. 3 to maintain constant ΔP while one of the above tests is being made, a second transducer may be kept connected across the needle valve at all times. This reference unit would be operated at standard conditions at all times. Its reading, if any drift in ΔP is indicated, may be used to correct the test-transducer indication.

III. Specifications based on tests that do not require precise equipment

A satisfactory estimate of instrument quality can often be made merely by observing transducer behavior at $\Delta P = 0$. Such tests require neither accurate nor stable standards.

Tests with shortcircuited input taps. - Tests that can be made with the transducer taps shortcircuited are listed in Fig. 4. The short-circuiting loop should be vented to the atmosphere through a capillary to prevent adverse effects of drafts and of ambient temperature changes.

The sensibility test merely checks the fineness with which the transducer zero can be adjusted.

Observing whether the output indication shifts when cover screws or the normal transducer-mounting bolts are tightened and loosened will check the adequacy of the transducer design in these respects.

The acceleration test listed in Fig. 4 is easier to perform than the one listed in Fig. 3 and often is sufficient. A transducer that is expected to operate under conditions of moderate vibration should be able to operate with ±1 g acceleration, in each of three orthogonal directions, with a zero shift of only a few percent of full span.

Remarks made earlier about the temperature effect on sensitivity apply also to the temperature effect on zero. Ordinarily, the latter effect is more severe. There is also a less-well-known effect which we have termed "thermal shift": if the transducer is brought back to room temperature after an excursion to the limit of the temperature range (say, -20° F), there may be a permanent shift in the zero indication. The phenomenon resembles hysteresis. (The "0.1% fs" which is added to the slope specification of "0.1% fs/°F" in Fig. 4 represents this thermal shift.) Because of this effect and the fact that we may want to specify a tighter tolerance on slope near room temperature than near the extremes of the temperature range, NASA-Lewis has found it desirable to state the temperature-effect tolerance in the form of a graph. The one shown in Fig. 4 illustrates the permissible thermal shift (finite vertical width even at room temperature), a tight slope tolerance between 20° and 120° F, and a looser slope tolerance from -20° to 20° F.

Since a shortcircuited transducer is ordinarily waterproof, a convenient way to perform the temperature test is to immerse the transducer in a bath of water at room temperature, a bath of water at, say, 120° F, and a dry ice-acetone mixture at, say, -20° F. The transducer may be wrapped in a plastic bag for greater convenience. Great care must be observed in assuring an isothermal condition of the transducer in each bath, since zero shifts during the transient interval are often much larger than the steady-state zero shift, yet may be irrelevant as far as the user is concerned because the transient situation may be unrealistic.

To determine the zero shift with line pressure applied equally to both sides of the transducer, an appropriate source of high pressure is applied to the capillary shown in Fig. 4; this high pressure needs to be monitored to only about 5% inaccuracy.

Tests with applied ΔP. - Some very important tests can be performed by applying a differential pressure that is known to only about 5 percent. These are shown in Fig. 5.

The overrange test is a nondestructive test in which increasingly larger overrange values of ΔP are applied until some nominal value of zero shift, say 1 to 4% fs, results.

The hysteresis-at-zero test generally produces numerical values twice as large as the hysteresis-at-midscale test described earlier, and is much easier to perform. The test is made by first applying a negative value of ΔP, on the order of full-scale range. The absolute magnitude of this differential pressure is then reduced smoothly until $\Delta P = 0$ is reached. The output is then read. The value of ΔP is then increased smoothly to near full scale, and then reduced smoothly to $\Delta P = 0$. The output is read again; the difference between the two output readings at $\Delta P = 0$ is the hysteresis.

The determination of zero drift is made by first holding ΔP at near to full scale for about 1/2 hour, then reducing it slowly so that $\Delta P = 0$ is reached in 10 to 30 seconds (an instantaneous drop must be avoided). The output is read and compared with a reading taken about 1/2 hour later. A continuous recording of the drift is often illuminating. Such drift is usually proportional to the initial pressure.

A related test is the shift in zero after the transducer has been cycled between zero and full-scale for several hundred cycles. Each complete cycle might have a period of 4 seconds, with care taken that pressure is applied and released slowly enough that there is no transient overshoot of the transducer mechanism. (This test should be one of the first tests performed on a transducer, because it may influence the subsequent behavior of the instrument.)

IV. Other characteristics that should be specified or known

There are a number of transducer characteristics that a user may not want to specify in terms of numerical tolerances, but which he may want to know in order to design or to understand the behavior of the complete measurement system.

A. Some electrical characteristics

Source impedance determines the loading effect of the readout instruments. More often than not, the user will match the readout instruments (including any controllers) to the transducer, rather than decide on the readout units in advance and then specify the transducer source impedance. A convenient, though not always attainable, practice is to have the effective source impedance less than 1/5000 of the parallel impedance of all readout units, if the transducer output is an emf, or to have the effective series source impedance greater than 5000 times the series impedance of all readout units if the transducer output is a current. A more favorable value of source impedance is generally achieved at the cost of greater power dissipation. "Transducer" here includes any amplifier at the transducer end.

An alternative to specifying source impedance, therefore, is to specify the effect of load impedance (for emf-type output) or the effect of line resistance (for current-type output).

If all output terminals are ungrounded (as they should be for emf-type instruments) a specification of insulation resistance to ground, when all power is removed and all terminals are shortcircuited together, is relevant. A resistance of 20 megohms at 50 V is a reasonable requirement.

A specification of common-mode hum rejection is a recognition of the practical reality that a 10-volt, 60-Hz difference may exist between two "grounded" points a few hundred feet apart. A rejection of at least 80 decibels to 60-Hz hum is a typical requirement.

B. Some pneumatic characteristics

These may influence the response to pressure and flow fluctuations. The user may want either to specify or to know the chamber volumes on each side of the transducer diaphragm, as well as the volume change when full-scale ΔP is applied.

The natural frequency and damping of the pneumatic system will depend on the installation; the user may therefore merely wish to know all relevant characteristics, rather than to specify them. Both frequency and damping of the pneumatic system are generally lower than the natural frequency and damping of the force-balance or deflection-measuring elements inside the transducer, and hence are more influential in system performance.

C. Some mechanical characteristics

The natural frequency and damping of the internal elements just mentioned will influence the response to case vibration. It is important that damping exist and therefore it should be specified. It should not be less than one-half of critical. It is desirable to know the resonant frequency, if the mechanism is underdamped, or the time constant, if the mechanism is considerably overdamped, although it is rarely necessary to specify these.

The user may want to standardize on the pressure connections. NASA-Lewis prefers the 37°-flare type (with idler ferrule), with soft-copper conical gasket, because

(1) Connections may be made and broken repeatedly without loss of reliability (a new copper gasket is used each time).

(2) No compound, tape, or other packing is required, that may enter the transducer chamber.

Although only moderate torque is required when the copper gasket is used, a specification of a tightening torque and the use of a torque wrench further increase reliability.

Vent or bleed connections, or both, may be required if the user expects to flush the transducer chambers.

Filters at the pressure ports are desirable if the process gas may contain dust. Sintered stainless steel filters may be used. The pneumatic lag they introduce will be proportional to their C_V and to chamber volume, if chamber volume change is negligible. A 10-micron, 1/4-inch-tube-fitting filter with a C_V of 0.2 gpm of H_2O at 1 psi would produce time constants on the order of 3 and 50 milliseconds if the chamber volumes are 2 and 30 cubic inches, respectively. The respective corner frequencies would be 50 and 3 Hz.

D. Some other characteristics

Some other specifications, that require no commentary, are range, sensitivity (transduction factor), ambient temperature range, maximum line pressure, supply pressure or line voltage and frequency, degrees of weather protection and explosion protection, and mounting provisions.

V. Testing sequence

Among the many tests that have been itemized, there are a few, such as those involving cycling or overpressure, whose consequences may be to alter some other performance items, such as drift or hysteresis. In preparing specifications, it is therefore important that the sequence in which the pertinent tests will be performed shall also be specified, in order that there be no misunderstanding between buyer and seller.

METHODS OF REDUCING ERRORS

Several methods of improving transducer performance are available to the instrument designer and to the instrument user. The user may also be interested in the designer's tools, because such deeper understanding may facilitate intercommunication and the preparation of realistic specifications that allow for trade-offs between accuracy and cost.

Elastic Errors and Friction

Deflection-type instruments rely wholly on the springs that are used to measure the pressure-developed forces. Force-balance instruments may have only about 1/100 of this dependence on springs, but the dependence still exists because the feedback is less than 100%, so that there is still some spring deflection. Spring quality therefore remains important.

From the standpoint of hysteresis and drift, properly tempered tool steel, music wire, and spring steel are superior to most other materials. However, because they are not resistant to corrosion, their use may have to be confined to that portion of the transducer that is not in contact with the process fluid. The temperature coefficient of Young's modulus (about -2% for 100^{o} F for these steels) may be reduced if nickel alloys like NiSpan C, Elgiloy, Dynavar, or Iso-elastic are used. The hysteresis and drift of beryllium copper, phosphor bronze, and cold-worked 300-series stainless steel may be reduced to small values only by careful stress-equalizing heat treatments that follow the conventional processing. (Even tool steel will benefit from a second tempering treatment.)

Elastic errors are further reduced if operating stresses are lowered and care is taken not to exceed the elastic limit on maximum overload, by careful design and provision of stops.

Cycling of the transducer mechanism through several hundred cycles, as discussed earlier in connection with zero drift (Fig. 5), may also improve calibration stability.

Friction at bearings, pivots, and knife edges may be eliminated by replacing these components with flexure plates, straight or crossed (Fig. 6), but then these add to the spring forces and must be treated with the same considerations as other springs.

All important spring elements must be mounted so that stress concentrations are avoided. The flexing portion must be expanded to one of larger cross section, <u>via</u> a generous fillet, before the spring is clamped. The expansion may be in increased thickness, as shown on the right-hand sketch of Fig. 6, or in increased width, as shown in the center sketch. The latter shape would apply to a sheet-metal flexure. Soldered or welded joints may not appear where good spring properties are required, because such joints show high "elastic friction."

Calibration Stability

Reliability of operation and stability of calibration are generally increased considerably if the transducer case can be sealed so that it need never be opened in the field. In transducers with electrical output, external electrical adjustment of span and zero can be provided. Thereby, mechanical adjustment of zero and span can be dispensed with, and the use of a fixed mechanical magnification further simplifies the construction. Possible benefits of this approach are a reduction of friction or elastic errors, and better compensation for temperature and for line pressure. A clean, sealed, bearingless instrument of this type might work indefinitely, except for catastrophic failures.

Temperature Effects

Systematic shifts in zero and sensitivity, that vary linearly with temperature, may be compensated by bimetallic elements in the transducer lever system (Fig. 7). In transducers with electrical output, alternative electrical compensation can be provided with a copper-wire resistor or a thermistor in an appropriate network. The most difficult problem associated with either the mechanical or the electrical compensation is to place the temperature-sensitive element at the place where the temperature effect occurs. This latter place is not always known, or discrete; consequently, severe transient effects may take place while temperature is changing.

If such transient effects exist, and are serious, the expedient available to the designer is to provide thermostatic control of the entire transducer, or, preferably, to design the transducer so that temperature effects on critical mechanical or electrical components will be localized in one or two thermally-isolated modules that can be individually thermostated with greater ease. The expedient available to the user is to provide a secondary enclosure for the transducer, thermally isolated from the transducer, that will prevent rapid transmission of external temperature changes to the transducer, and will produce an integrating action that will help the transducer remain isothermal.

Vibration Effects

Inside the transducer case, effects of linear vibration may be compensated by counterbalancing all pivoted elements in two orthogonal directions (Fig. 7). In an instrument with several pivoted elements, such an approach may be awkward. A more elegant approach available to the designer is first to determine the overall acceleration effect on the instrument, in two orthogonal directions, and then to add one or two appropriately-placed weights that will exert equal and opposite effects.

Generally, neither of the above approaches will be completely effective if the magnification ratio is mechanically variable.

It is essential that the mechanical mechanism be critically damped (within a factor of 2). If sources of friction have been eliminated by use of flexure-plate pivots, a high-quality instrument will have very little natural damping. Under such circumstances, no amount of electrical damping of the output will keep a mechanically-undamped mechanism from tearing itself to pieces at resonance. Mechanical damping must be provided.

The user's means for counteracting effects of vibration are to mount the transducer on commercially-available vibration isolators that use rubber-in-shear or equivalent means for damping, and to use comparatively-flexible pressure and electrical connections that cannot effectively transmit vibration.

Effects of Mounting Strains

Zero shifts have been reported on transducers when cover screws or the main mounting bolts were tightened. Fig. 8 is intended to illustrate some design principles that would prevent such effects. Fig. 8 is not intended to represent an actual transducer design.

For convenience, a symmetrical two-diaphragm design has been assumed. The volume between the diaphragms is sealed by a small diaphragm that also acts as a pivot for the main lever arm. This volume is filled with a liquid and is so shaped that overpressure protection is achieved when either diaphragm deflects against its stop. The main lever transmits diaphragm force and deflection to the force-balance unit. The latter may consist of a magnifying lever, a null-position detector, and an electromotor that exerts the necessary counterforce. The two diaphragms are on a massive block; a boss at the top of the block carries the small, isolating pivot diaphragm. The force-balance unit is assembled on a single, rigid plate which is supported entirely by the boss.

At the opposite end of the block holding the diaphragms is a projecting pad by which the entire transducer is supported. Thus, the strains on this pad cannot be communicated to the boss which holds the force-balance unit and the main-lever pivot diaphragm.

The cover is screwed to a separate plate which is attached to the main block by three or four screws on an O-ring seal. This separate plate is not in contact with the boss that supports the force-balance unit. The electrical conduit is also carried by this separate plate. Thus, forces exerted on or by the cover are not transmitted to the force-balance unit.

If there is any concern that strains exerted in the act of making the pressure connection may affect the clamping of the diaphragms, then the construction shown on the left side of the figure may be used. Here, a gooseneck connection leads to a bulkhead fitting that is supported on a separate plate attached either to a separate pad on the bottom of the main block or to the pad used as the principal support.

There are some additional minor design points illustrated in Fig. 8. They are not related to the problem of strain-free support.

1. Illustrating the principle that the inside of the transducer must always be kept clean, a cap is shown, to be kept on the pressure tap when

the latter is not attached to the process line. The cap is chained to prevent its loss, and it is screwed on to a dummy boss so that it will remain clean while the transducer is connected to the process line.

2. If the boss carrying the force-balance unit were attached to its supporting block through a hermetically-joined ceramic disc, the force-balance unit would constitute a thermally-isolated module that perhaps could be separately thermostated, as suggested in the discussion of temperature effects.

Effects of Flow or Pressure Pulsations

If the transducer output is fluctuating, its average value may be obtained by linear damping that produces linear integration. For an electrical output, this may be accomplished by an R-C circuit; for a pneumatic output, by a surge chamber and capillary.

However, the output does not represent the input ΔP at the process pipe unless pressure is transmitted with equal lag to both diaphragms. Such equality can be achieved if both transducer-chamber volumes are equal, both tubing connections to the process pipe were cut from the same piece of tubing and are of equal length, and the internal geometries of both pressure taps on the orifice or venturi are identical.

If all of these equalities are not realized, it may be necessary to adjust for equal lag. The arrangement shown in Fig. 9 may be used. A manifold carries two pipe fittings having the same internal geometry as those to be used on the process pipe. The connecting tubing is the same as will be used in the final installation. The manifold is symmetrical with respect to the pipe fittings and is connected at its midpoint to an upstream needle valve and a source of air pressure, and also to a downstream toggle valve.

With toggle valve closed, manifold pressure is raised to some value to be determined by trial; a convenient initial trial value is a pressure numerically equal to the ΔP range of the transducer. The upstream valve is then closed, and then the toggle valve is opened abruptly. If lags are not equal, there will be a momentary deflection of the output, as shown in Fig. 9. Additional external volume, or an additional length of connecting tubing, must be added to the side with the shorter lag, until the resultant pulse amplitude is acceptably small. (Orifices are undesirable because they provide nonlinear damping.) A maximum pulse amplitude which is 10 percent of the initial pressure in the manifold represents a 24% mismatch of time constants; this inequality is often acceptable.

When the flow rate is fluctuating, the square-root law followed by the orifice or venturi causes nonlinear averaging, so that the average flow rate indicated by a perfect transducer is still higher than the true average. The effect is not very large. If the flow rate fluctuates sinusoidally with an amplitude that is a fraction b of the average flow rate, the indicated average flow rate is higher than the true average flow rate by the fraction $b^2/4$.

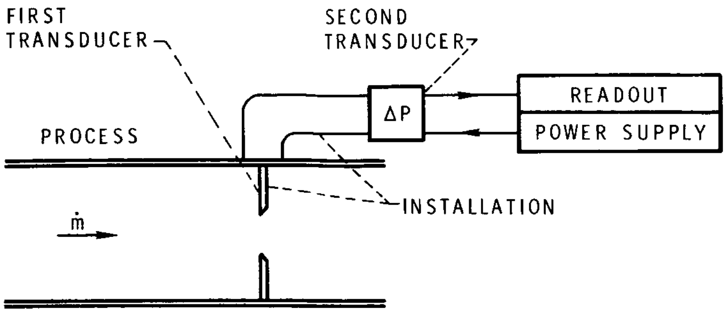
CONCLUDING REMARKS

The performance specifications, design techniques, and application techniques that have been presented may provide a convenient check list for a measurement-system design. The list presented is not a complete one; perusal of instrument-manufacturer's literature may suggest additional items. Furthermore, some items have been excluded deliberately because rather elaborate equipment would be required to check them. In any event, the user must determine, for his own particular application, what specifications should apply, what numerical tolerances should be specified, and what application techniques are necessary. In this determination, there must be full appreciation of the large number of sources of error that exist not only in the transducer but also in the other elements of the measuring system, and of how these errors combine.

It should be recognized also that, although limits of error are stated in a specification as a matter of convenience, the probable error for each item, and the probable error of the rms summation, are only about one-half of the respective limit of error.

E-4491

MASS FLOW RATE MEASURING SYSTEM



$$\dot{m}_{TRUE} = \dot{m}_{IND.} + \sum(\delta\dot{m})_{SYSTEMATIC} \pm \sqrt{\sum(\delta\dot{m})^2_{RANDOM}}$$

CS-46742

Fig. 1

DIFFERENTIAL–PRESSURE TRANSDUCER CHARACTERISTICS

I. TESTS THAT REQUIRE AN ACCURATE STANDARD

SENSITIVITY ACCURACY AT STANDARD CONDITIONS	0.2%
SENSITIVITY CHANGE WITH TEMPERATURE	[0.01%/°F OR ±2% ; $-20^\circ \le T \le 120^\circ$ F]
SENSITIVITY CHANGE WITH TIME	0.2% IN 1 WEEK
HYSTERESIS AT MIDSCALE	0.1% fs
REPEATABILITY UPON UNIDIRECTIONAL APPROACH	0.1% fs
NONLINEARITY	0.2% fs

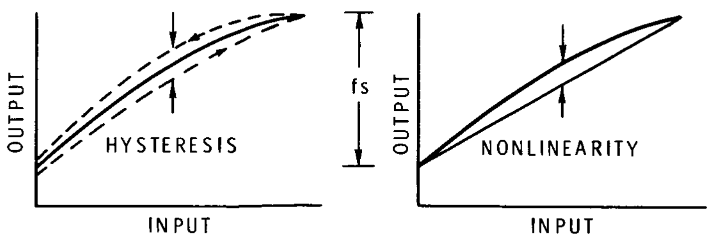


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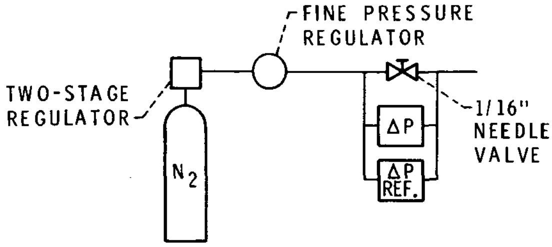
Fig. 2

ΔP–TRANSDUCER CHARACTERISTICS (CONT'D.)

II. TESTS THAT REQUIRE A STABLE (BUT NOT ACCURATE) DIFFERENTIAL PRESSURE. (ALL MEASUREMENTS MADE AT NEAR-FULL-SCALE OUTPUT)

EFFECT	TYPICAL REQUIREMENT
SUPPLY PRESSURE	1/2% fs FOR ±10%
LINE VOLTAGE	0.1% fs FOR ±10%
ACCELERATION	[0.2% fs FOR ±0.2 g 1% fs FOR ±1 g]



A METHOD OF OBTAINING STABLE PRESSURE

CS-46732

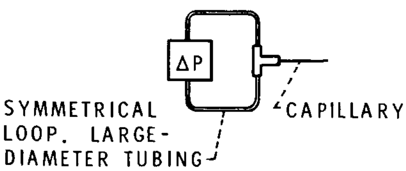
Fig. 3

ΔP–TRANSDUCER CHARACTERISTICS (CONT'D.)

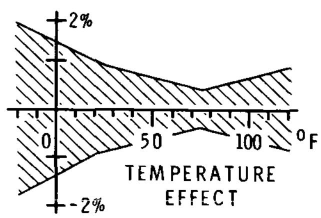
III. TESTS THAT DO NOT REQUIRE PRECISION EQUIPMENT

A. TESTS WITH INPUT TAPS SHORT-CIRCUITED

ZERO ADJUSTMENT SENSIBILITY	0.1% fs
ZERO SHIFT WITH MOUNTING STRAIN	[0.1% fs LOOSE → TIGHT]
ZERO SHIFT WITH ACCELERATION	[0.2% fs/0.2 g (4 DIRECTIONS) 1% fs/g (6 DIRECTIONS)]
ZERO SHIFT WITH TEMPERATURE	[(0.01% fs/°F +0.1% fs) OR ±2% fs, $-20 \leq T \leq 120^{\circ}$ F <u>OR</u> GRAPH]
ZERO SHIFT WITH LINE PRESSURE	1% fs/1000 PSI



LINE-PRESSURE EFFECT



TEMPERATURE EFFECT

CS-46744

Fig. 4

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ΔP–TRANSDUCER CHARACTERISTICS (CONT'D.)

III. TESTS THAT DO NOT REQUIRE PRECISION EQUIPMENT (CONT'D.)

B. TESTS WITH APPLIED ΔP

ZERO SHIFT WITH OVERRANGE	1% fs/1000 PSID
HYSTERESIS AT ZERO	0.1% fs
ZERO DRIFT AFTER fs LOAD	0.2% fs IN 1/2 HR
ZERO SHIFT AFTER CYCLING	0.2% fs AFTER 500 CYCLES

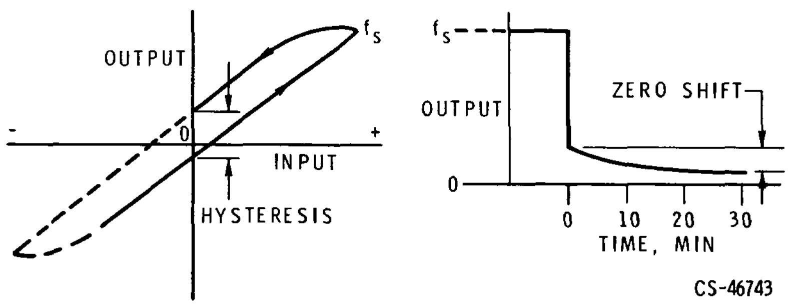

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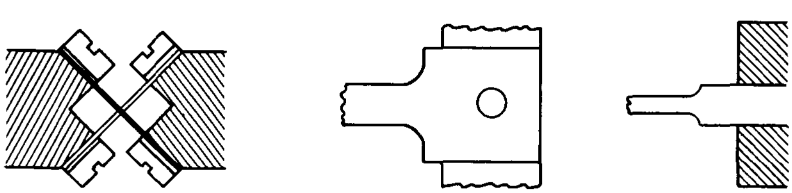
Fig. 5

SOME METHODS OF REDUCING ERRORS

TO REDUCE ELASTIC ERRORS AND FRICTION:
- USE HIGH-QUALITY SPRING MATERIALS
- USE LOW WORKING STRESSES
- USE FLEXURE-PLATE PIVOTS
- AVOID STRESS CONCENTRATIONS
- AVOID CRITICAL SOLDERED OR WELDED JOINTS
- AVOID EXCEEDING ELASTIC LIMIT ON OVERLOAD

TO IMPROVE CALIBRATION STABILITY:
- USE FIXED MECHANICAL MAGNIFICATION
- USE SEALED CASE
- PROVIDE EXTERNAL ELECTRICAL ADJUSTMENT OF ZERO AND SPAN



FLEXURE-PLATE PIVOT

STRESS-CONCENTRATION RELIEF

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Fig. 6

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TO REDUCE TEMPERATURE EFFECTS, USE
- BIMETALLIC ELEMENTS FOR ZERO AND SPAN
- ELECTRICAL COMPENSATION
- SECONDARY ENCLOSURE TO REDUCE GRADIENTS
- THERMOSTATIC CONTROL OF CRITICAL MODULES

TO REDUCE VIBRATION EFFECTS
- INTERNALLY
  - COUNTERBALANCED LEVERS
  - CRITICAL DAMPING
- EXTERNALLY
  - RUBBER-IN-SHEAR VIBRATION ISOLATORS
  - FLEXIBLE PRESSURE AND ELECTRICAL CONNECTIONS

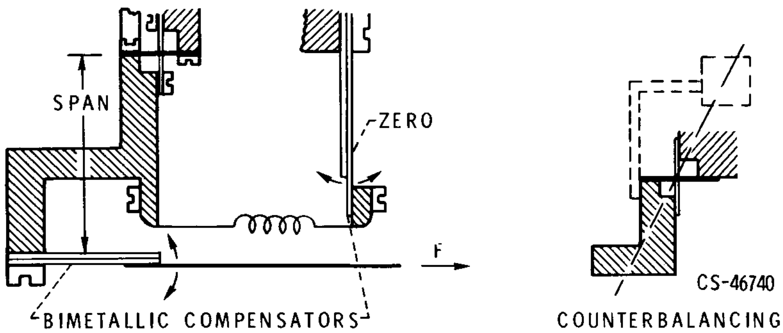

Fig. 7

STRAIN - FREE MOUNTINGS

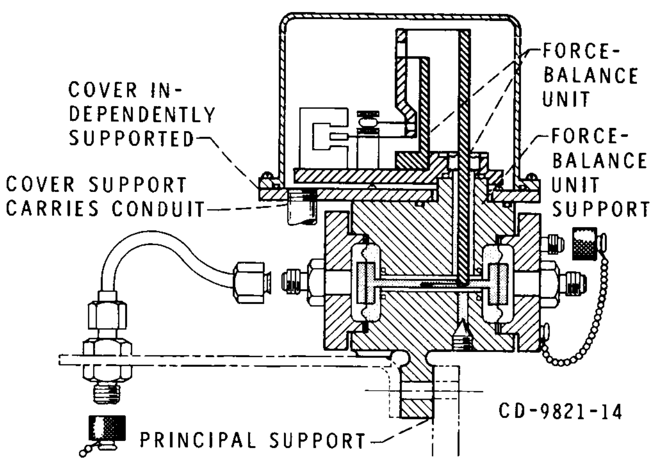

Fig. 8

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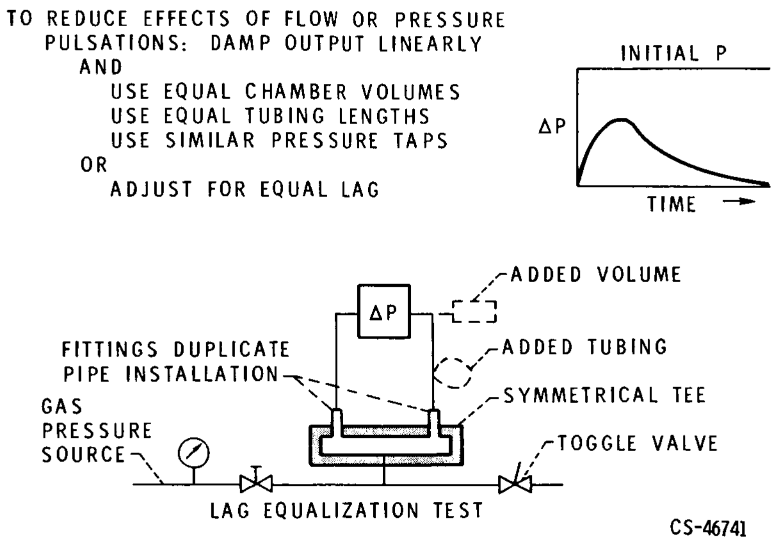

Fig. 9

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