OPTIMIZATION OF POTENTIOMETRIC TYPE PRESSURE TRANSDUCERS

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Abstract Potentiometric pressure transducer designs can be optimized to allow application of a given model or family to a very wide range of pressures with consistently low static error band. Analytical and imperical design relationships are developed and correlated to suggest specific otimization techniques.

Introduction Transducer design has developed over the years with as much art as science. It was shortly after World War II, or the beginning of the missile and telemetry age, that need arose for instrument transducers to supplant the more conventional direct visual gages. Various types of measurements such as pressure, motion, force, flow, and temperature required remote readouts for telemetry and control. Demand quickly developed for new families of instruments. Potentiometric, strain, and piezoelectric type transducer elements appeared early, followed by others such as capacitive, inductive, reluctive, photoresistive and piezoresistive.

Early transducer design concentrated on function and accuracy with little attention to environmental requirements. Most of the more recent types of transduction elements were developed in attempts to overcome the disadvantages of the earlier types. Concurrently, however, the early types have been consistently improved to meet the more stringent modern requirements.

This paper discusses the design philosophy, past and present, of one type of pressure transducer -- the potentiometric type. While it was one of the early types, the potentiometric type pressure transducer has undergone a series of improvements, and, as a result, it is still widely used in aerospace applications. Recent changes in accuracy specification and design philosophy appear to enhance the applicability of this type of transducer for many applications still to come in the future.

Past Design Philosophy Pressure measurement must be accurately accomplished over an extremely wide range of pressures, from vacuum to tens of thousands of pounds per square inch. It is axiomatic that no one particular sensor has been developed to cover the entire pressure spectrum with equal accuracy. Consequently, it has been customary to satisfy specific portions of the pressure range spectrum with various designs which are most applicable in particular range regions. In the extreme, each pressure range would require a new design in order to optimize performance. As a practical matter it has been desirable to provide basic design families of instruments which lend themselves to optimization at particular specific ranges by means of one or two easily changed variables.

As the aerospace industry developed, many transducer families were derived empirically to meet the various needs. Users found their shelves and systems filled with a bewildering variety of instruments to perform a seemingly similar function.

It is the intent of this paper to make certain observations which lead to optimization techniques. These techniques may be used to replace the multiplicity of empirical designs with a few basic designs theoretically selected for applicability over a wide range of pressures.

Change In Error Specification Initially, product designers concentrated on achieving a design which performed its function with a minimum of error. Due to the philosophy applied at that time, interest was directed to many individual performance parameters, and the individual error associated with each parameter. Such parameters as linearity, hysteresis, resolution, repeatability and friction were dealt with on an individual basis, in order to provide products which customers would buy because the errors (each in turn) were small or acceptable.

Several years ago, the concept of “Error Band” arose (1, 2). Use of this concept simplified the specification, testing for conformance, and application of transducers, but resulted in a relook at the design approaches being used. It was found that a basic design or product could now be looked upon as a family of instruments instead of a long list of instruments which differed in many ways as the many parameters seemed to indicate. It thus became possible to assign one accuracy number to each instrument range and, further, to plot these numbers vs. range. In effect, a family could be represented by one-line on one chart. Figure 1, Static Error Band (SEB) vs. Range for a high pressure transducer of potentiometric type employing a bourdon tube sensor, presents such a family. In essence, the SEB line is the error of performing the transducing function for all of the family, and includes the many errors of linearity, hysteresis, resolution, repeatability and friction without consideration as to how much each contributes to the total. While one family is presented, the relationship shown is typical or representative. It is of interest to note that the SEB increases at both extremities of the range applicability of the family.

Although the concept of Error Band gained wider usage, it was still frequently necessary to discuss the contribution of the individual errors with persons of “the old school”. From a design philosophy standpoint, this led to interest in defining the band makeup, even though it was irrelevant to the new type of error specification. As stated previously, these observations lead to optimization and ultimately to better designs.

Optimization Possibilities A general approach to optimization requires understanding and analysis of the basic components comprising the total error contribution.

Figure 2 presents a breakdown of Figure 1 into the individual errors which comprise Static Error Band (SEB). While Figure 2 has been plotted as a result of several years empirical data analysis and is admittedly approximate, it is the intention of this discussion to relate this empirical data to theoretical considerations and, thus, develop techniques of optimization.

The prime components of Static Error Band, as presented, are Linearity, Resolution, Hysteresis and Friction. Other commonly referred to errors such as repeatability and uncertainty are excluded because they result from one or more of the prime components. As shown in Figure 2, Linearity Error and Resolution Error do not vary with range, while Friction and Hysteresis do. It will be of further interest from Figure 2 that the previous observation of Static Error Band increases at both range extremities is evident. This is a result of excessive Friction at the low end and excessive Hysteresis at the high end. Thus, a specific low range member of the family (A of Figure 2) has considerable Friction Error and negligible Hysteresis Error while a high range member of the family (B of Figure 2) has negligible Friction Error and considerable Hysteresis Error.

Without discussing the sources of Friction Error and Hysteresis Error, it can be observed that it would be of value to error reduction if an inverse relationship existed between these two types of errors. For instance, if it were possible to halve Friction Error of the low range unit at the expense of doubling Hysteresis Error, the sum of the two would be less than previously existed. Such a relationship allows optimization on the lower end and likewise on the high end of the family.

It is further observed from Region C of Figure 2 that when Friction Error is greater than Resolution, the Friction Error will hide the Resolution, and when Friction Error is less than Resolution it will be hidden by the Resolution. Thus, for a certain portion of the family, the low Friction characteristics do not contribute to error reduction. Such knowledge can be used to optimize Friction and Resolution.

The above two observations on optimization lead to a new design philosophy.

Present Design Philosophy It has become apparent that the old philosophy of minimizing individual errors is inadequate. While it is still necessary, it is not sufficient to do that alone. If interrelationships exist as observations indicate, then optimized designs can be produced. These optimized designs can only come about if a design philosophy is adopted which is consistent with all parameters.

Currently, a Design Philosophy is being applied to the potentiometric type pressure transducer which is consistent with the observations made and since established on a firm theoretical base. It is of significance that the philosophy results in greater applicability of any one design. Fewer design families are required. Let us now look at the Design Principles involved.

New Design Principles To apply the knowledge gained from the above observations, it is necessary to relate it to typical mechanisms. Figure 3 shows several types of sensor designs with potentiometric transduction elements.

Several features are common to all of the designs, and it is these which we will try to relate.

First, let us repeat one observation which is applicable to all of the designs shown. If we were to apply the old individual error reduction philosophy to any one of the designs shown, we would produce several families, each of which would have limited range applicability with error (SEB) increasing at either extremity of application.

Overall, there are three basic components to the designs shown. They are:

1. Pressure Sensor - Pressure to Force or Displacement
2. Mechanical Linkage - Displacement to Electrical
3. Electrical “pick-off” or Potentiometer

It is not the intention of this paper to discuss these items. If the reader is interested, he can refer to References #3 and #4. What is of interest is that the parameters of the three components are common to all of the designs shown in Figure 3, not to mention many other variations.

The parameters we are interested in are those related to errors of Hysteresis, Friction and Resolution. Let us look at parameters of Friction Error.

In general, percent error due to Friction is:
Equation 1:

$$\%E_f = \frac{f}{F} \times 100$$

where f = Force Restraining Motion
F = Total Full Scale Force Available

For a pressure transducer, potentiometric type, with both wiper friction and bearing friction:
Equation 2:

$$\%E_f = \frac{f_1 + f_2}{P\ Aeff} \times 100 = \frac{\mu_1 N_1 M_1 + \mu_1 N_2 M_2}{P\ Aeff} \times 100$$

Where:
E_f = Friction error
f_1 = Wiper friction force
f_2 = Bearing friction force
μ_1 = Coeff. of friction wiper to pot
N_1 = Contact force
M_1 = Multiplication of linkage
μ_2 = Coeff. of friction bearings
N_2 = Load on bearings
M_2 = Effective multiplication of brearing force at sensor
P = Full Scale Pressure (Range)
Aeff' = Effective Average Sensor Area

And for a pressure transducer, potentiometric type, with no friction other than the wiper:
Equation 3:

$$\%E_f = \frac{\mu NM}{P\ Aeff} \times 100$$

Let us now show that the above theoretical relationships of the variables involved correlate with the observations of Figure 2. Equation 3 says that friction error is inversely proportional to the,pressure range. Thus, to prevent excessive SEB at low ranges of a family, one or more of the other variables in the equation must be varied appropriately to prevent increase in error contribution by friction as range decreases. From Equation 3, there are four such variables. One (1) is a sensor parameter (Aeff), one (1) is a linkage parameter (M), and two (2) are potentiometric parameters (μ &N).

Since we are interested in optimization as well as error reduction, we must delay a closer look at these variables until we review Hysteresis error. The parameters of Hysteresis Error adequate for our purposes are essentially those associated with sensor stress.

Equation 4:

$$\%E_h = f(S_s)$$

Where: E_h = Hysteresis Error
$f(S_s)$ = Function of sensor stress

For a pressure transducer, sensor stress is a function of range pressure, sensor size and deflection, as well as configuration:
Equation 5:

$$\%E_h = f(P, Aeff, d)$$

Where: d = sensor deflection for full range pressure
f ( ) = depends on configuration

And for a pressure transducer, potentiometric type, where sensor deflection (d) alone is not adequate and multiplication linkage is required to provide adequate motion along the potentiometer element:
Equation 6:

$$\%E_h = f(P, Aeff, D, M)$$

Where: D = Potentiometer wiper travel
M = Linkage multiplication

To establish the function f ( ), we must select a sensor configuration. Of the many types, such as sylphon, corrugated diaphragm, flat diaphragm and bourdon tube, let us select the flat diaphragm for simplicity:

From flat diaphragm theory (Ref. 5)
Equation 7:

$$\text{Sensor Stress}_{\text{max.}} = S_s \text{ max.} = K_1 \frac{P\,Aeff}{t^2}$$

Where: K = constant of proportionality
t = material thickness

Equation 8:

$$\text{Deflection}_{\text{max.}} = d \text{ max.} = \frac{D}{M} = K_2 \frac{P\,A_{eff}{}^2}{t^3}$$

Combining equations 7 and 8, eliminating t
Equation 9:

$$\text{Stress} = K_3 \frac{P^{1/3}}{A_{eff}{}^{1/3}\;M^{2/3}}$$

This is the form we are interested in relative to optimization of Hysteresis error with Friction Error.

Recalling Equation 3 for Friction Error and putting in general form similar to Equation 9, we can compare the two equations readily as shown below:

Equation 3:
$$\%E_f = K_4 \frac{M}{P\,A_{eff}}$$

Equation 9:
$$\%E_h = K_3 \frac{P^{1/3}}{A_{eff}^{1/3}\ M^{2/3}}$$

The inverse relationship of M to P in both equations and the inverse relationship of M to $M^{2/3}$ between equations satisfies the observation made about Figure 2.

While equations 7, 8 and 9 apply specifically to flat diaphragm sensors the general relationship applies to all sensors of Figure 3.

Optimization is possible between hysteresis and friction error by appropriate choice of multiplication ratio M. Applying this in transducer design achieves the objective of wider applicability for a given family, as shown in Figure 4.

In terms of transducer mechanism design, the solution is simply stated:

For members of a family with low pressure range input, it is best from an overall accuracy standpoint (SEB) to increase the sensor stress (S_s) and sensor deflection (d), reduce the linkage multiplication (M), and hold potentiometer wiper travel (D) minimum. For members of the same family with a high range input and the same wiper travel, it is best to reduce the sensor travel (d and S_s) and increase the linkage multiplication (M).

It thus becomes apparent that a given transducer design can be used with minimum error over a wide range of pressure by judicious selection of sensor material (thickness) and linkage multiplication ratio.

Further opportunity for optimization of potentiometric transducer Static Error Band is available by careful selection of the potentiometer and wiper. Because of the mutual masking effects of Friction Error and Resolution (as discussed in Section IV), low friction forces should be sought for low range transducers even at the expense of relatively poor resolution. For the higher pressure range transducers, however, high resolution potentiometers with their typically higher friction forces should be considered.

Utilization of the above principles in transducer designs at Bourns, Inc., has led to some rather significant departures from conventional design. Test results have borne out the theory that optimization can result in a family of transducers with very wide range capability and consistently low error band.

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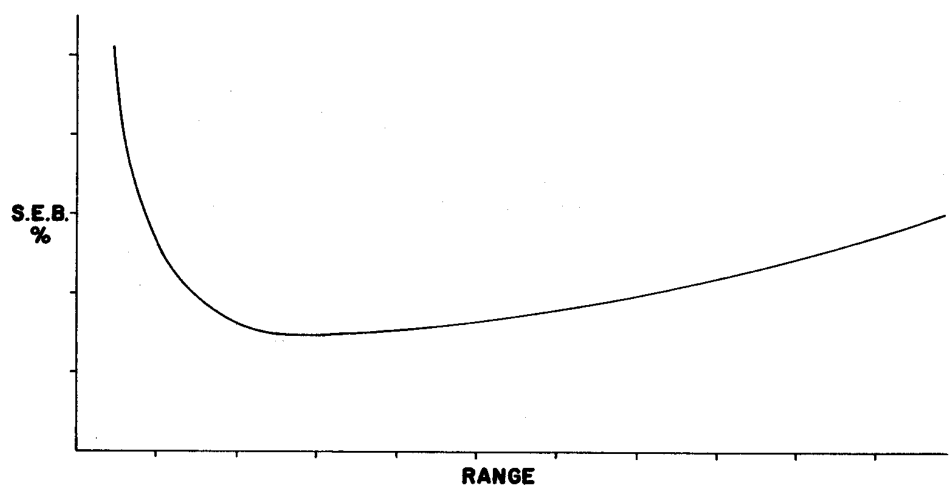

FIGURE 1 - Static Error Band vs. Range

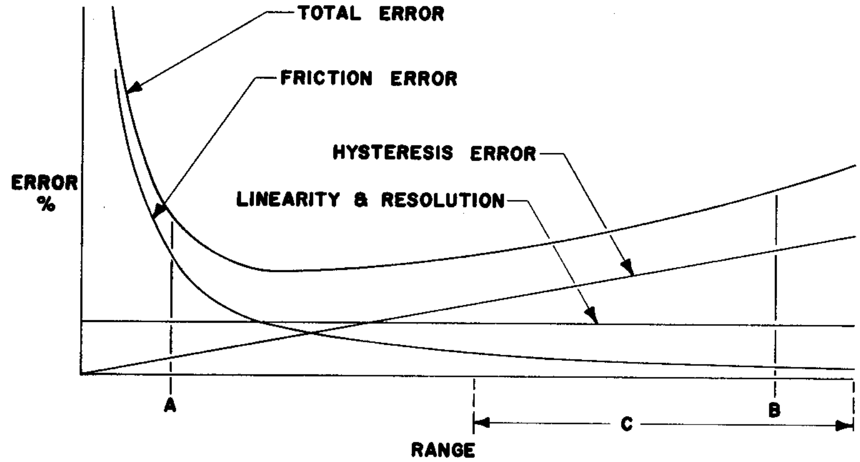

FIGURE 2 - Error Band Composition

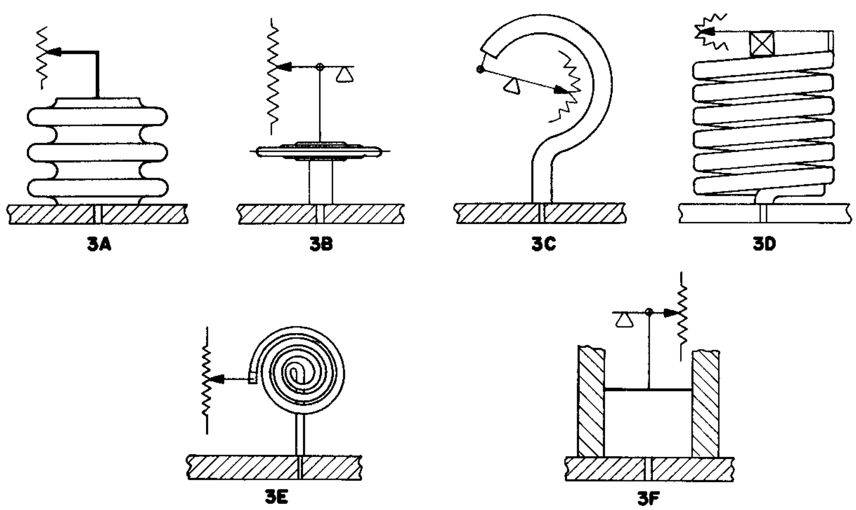

FIGURE 3 - Pressure Transducer Designs Potentiometric Type

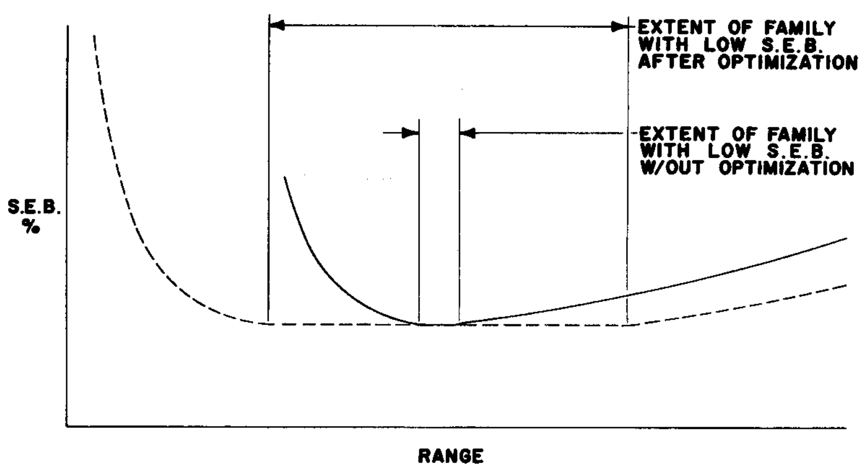

FIGURE 4 - Optimization of Transducer Family