AN935

Compensating for Nonlinearity in the MPX10 Series Pressure Transducer

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INTRODUCTION

This application note describes a technique to improve the linearity of Motorola's MPX10 series (i.e., MPX10, MPX11, and MPX12 pressure sensors) pressure transducers when they are interfaced to a microprocessor system. The linearization technique allows the user to obtain both high sensitivity and good linearity in a cost effective system.

The MPX10, MPX11 and MPX12 pressure transducers are semiconductor devices which give an electrical output signal proportional to the applied pressure over the pressure range of 0–10 kPa (0–75 mm Hg). These devices use a unique transverse voltage–diffused silicon strain–gauge which is sensitive to stress produced by pressure applied to a thin silicon diaphragm.

One of the primary considerations when using a pressure transducer is the linearity of the transfer function, since this parameter has a direct effect on the total accuracy of the system, and compensating for nonlinearities with peripheral circuits is extremely complicated and expensive. The purpose of this document is to outline the causes of nonlinearity, the trade–offs that can be made for increased system accuracy, and a relatively simple technique that can be utilized to maintain system performance, as well as system accuracy.

ORIGINS OF NONLINEARITY

Nonlinearity in semiconductor strain–gauges is a topic that has been the target of many experiments and much discussion. Parameters such as resistor size and orientation, surface impurity levels, oxide passivation thickness and growth temperatures, diaphragm size and thickness are all contributors to nonlinear behavior in silicon pressure transducers. The Motorola X–ducer was designed to minimize these effects. This goal was certainly accomplished in the MPX50, MPX100 and MPX200 series which have a maximum nonlinearity of 0.1% FS. However, to obtain the higher sensitivity of the MPX10 series, a maximum nonlinearity of ±1% FS has to be allowed. The primary cause of the additional nonlinearity in the MPX10 series is due to the stress induced in the diaphragm by applied pressure being no longer linear.

One of the basic assumptions in using semiconductor strain–gauges as pressure sensors is that the deflection of the diaphragm when pressure is applied is small compared to the thickness of the diaphragm. With devices that are very sensitive in the low pressure ranges, this assumption is no longer valid. The deflection of the diaphragm is a considerable percentage of the diaphragm thickness, especially in devices with higher sensitivities (thinner diaphragms). The resulting stresses do not vary linearly with applied pressure. This behavior can be reduced somewhat by increasing the area of the diaphragm and consequently thickening the diaphragm. Due to the constraint, the device is required to have high sensitivity over a fairly small pressure range, and the nonlinearity cannot be eliminated. Much care was given in the design of the MPX10 series to minimize the nonlinear behavior. However, for systems which require greater accuracy, external techniques must be used to account for this behavior.

PERFORMANCE OF AN MPX DEVICE

The output versus pressure of a typical MPX12 along with an end–point straight line is shown in Figure 1. All nonlinearity errors are referenced to the end–point straight line (see data sheet). Notice there is an appreciable deviation from the end–point straight line at midscale pressure. This shape of curve is consistent with MPX10 and MPX11, as well as MPX12 devices, with the differences between the parts being the magnitude of the deviation from the end–point line. The major tradeoff that can be made in the total device performance is sensitivity versus linearity.

Figure 2 shows the relationship between full scale span and nonlinearity error for the MPX10 series of devices. The data shows the primary contribution to nonlinearity is nonproportional stress with pressure, while assembly and packaging stress (scatter of the data about the line) is fairly small and well controlled. It can be seen that relatively good accuracies (<0.5% FS) can be achieved at the expense of reduced sensitivity, and for high sensitivity the nonlinearity errors increase rapidly. The data shown in Figure 2 was taken at room temperature with a constant voltage excitation of 3.0 volts.

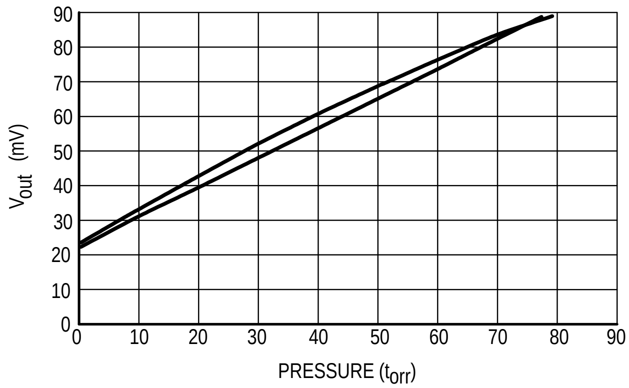

Figure 1. MPX12 Linearity Analysis Raw Data

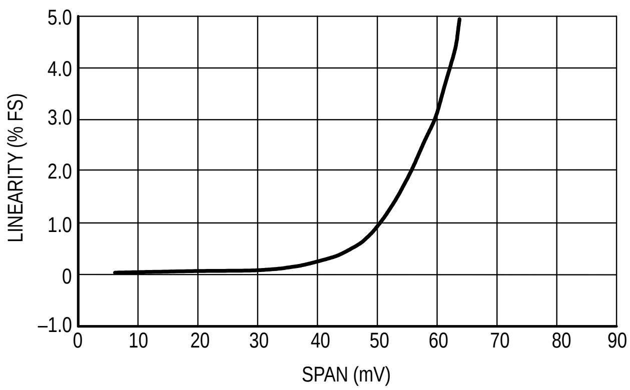

Figure 2. MPX10 Series Span versus Linearity

COMPENSATION FOR NONLINEARITY

The nonlinearity error shown in Figure 1 arises from the assumption that the output voltage changes with respect to pressure in the following manner:

$$V_{out} = V_{off} + sens*P \quad [1]$$

where V_{off} = output voltage at zero pressure differential
sens = sensitivity of the device
P = applied pressure

It is obvious that the true output does not follow this simple straight line equation. Therefore, if an expression could be determined with additional higher order terms that more closely described the output behavior, increased accuracies would be possible. The output expression would then become

$$V_{out} = V_{off} + (B_0 + B_1{*}P + B_2{*}P^2 + B_3{*}P^3 + \ldots) \quad [2]$$

where B_0, B_1, B_2, B_3, etc. are sensitivity coefficients. In order to determine the sensitivity coefficients given in equation [2] for the MPX10 series of pressure transducers, a polynomial regression analysis was performed on data taken from 139 devices with full scale spans ranging from 30 to 730 mV. It was found that second order terms are sufficient to give excellent agreement with experimental data. The calculated regression coefficients were typically 0.999999+ with the worst case being 0.99999. However, these sensitivity coefficients demonstrated a strong correlation with the full scale span of the device for which they were calculated. The correlation of B_0, B_1, and B_2 with full scale span is shown in Figures 3 through 5.

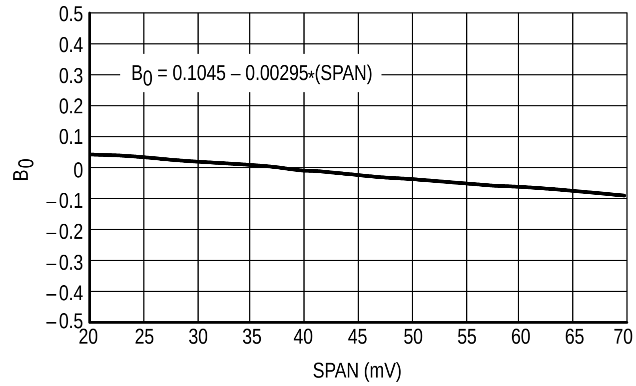

Figure 3. MPX10 Linearity Analysis — Correlation of B_0 $V_{out} = B_0 + B_1 (P) + B_2 (P)^2$

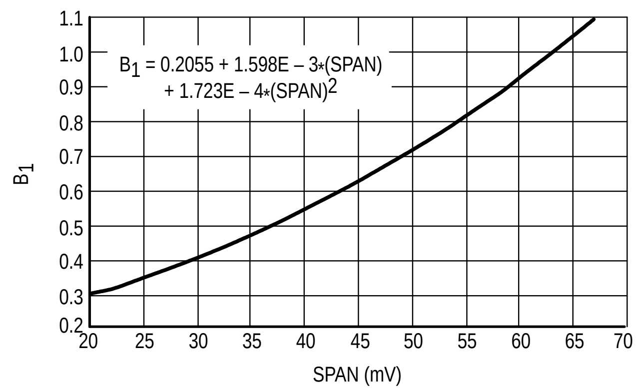

Figure 4. MPX10 Linearity Analysis — Correlation of B_1 $V_{out} = B_0 + B_1 (P) + B_2 (P)^2$

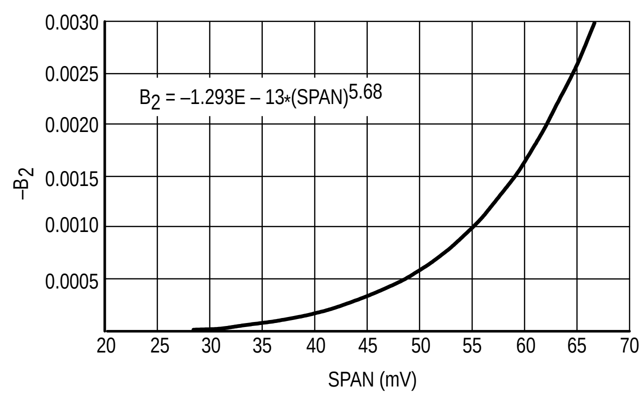

Figure 5. MPX10 Linearity Analysis — Correlation of B_2 $V_{out} = B_0 + B_1 (P) + B_2 (P)^2$

In order to simplify the determination of these coefficients for the user, further regression analysis was performed so that expressions could be given for each coefficient as a function of full scale span. This would then allow the user to do a single pressure measurement, a series of calculations, and analytically arrive at the equation of the line that describes the output behavior of the transducer. Nonlinearity errors were then calculated by comparing experimental data with the values calculated using equation [2] and the sensitivity coefficients given by the regression analysis. The resulting errors are shown in Figures 6 through 9 at various pressure points. While using this technique has been successful in reducing the errors due to nonlinearity, the considerable spread and large number of devices that showed errors >1% indicate this technique was not as successful as desired.

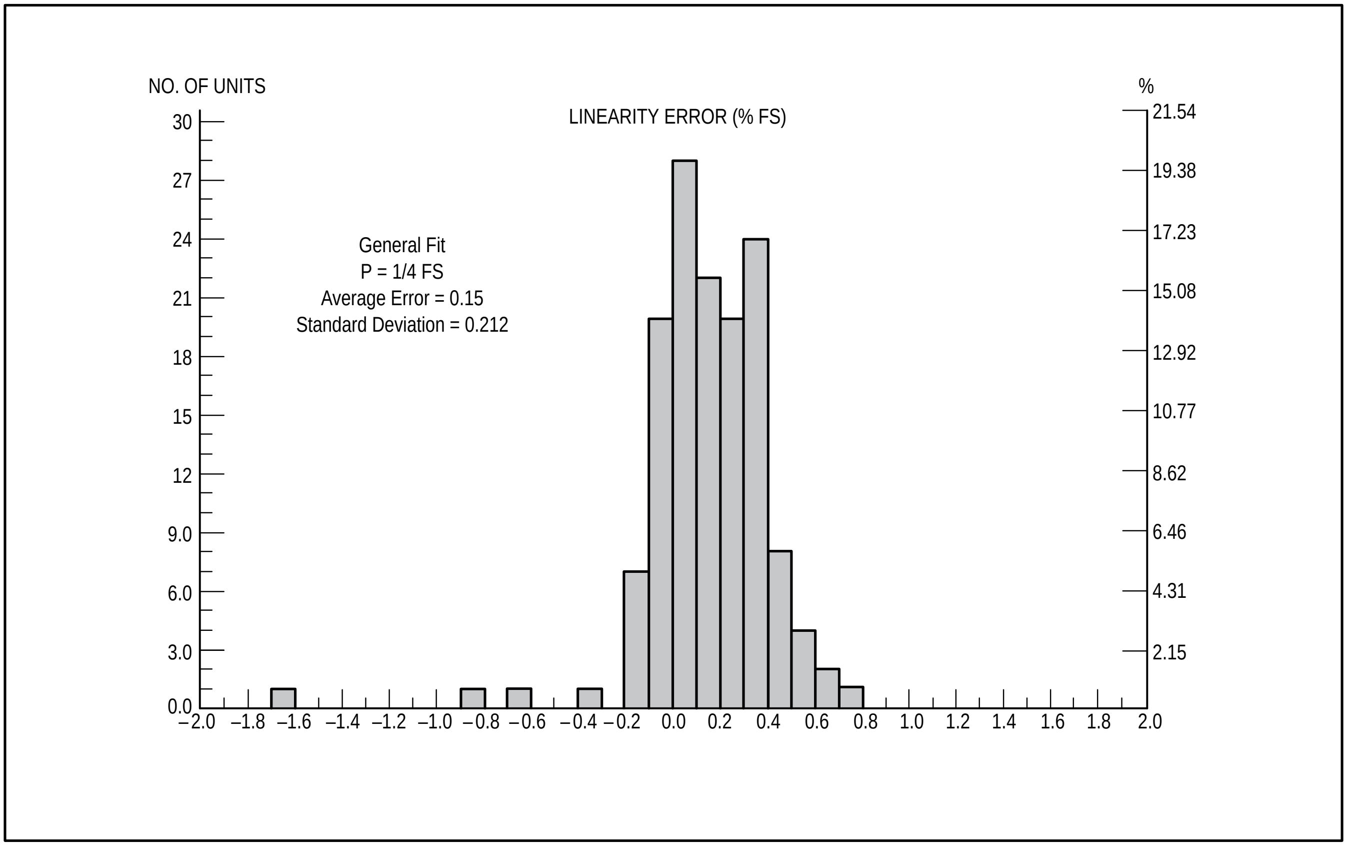

Figure 6. Linearity Error of General Fit Equation at 1/4 FS

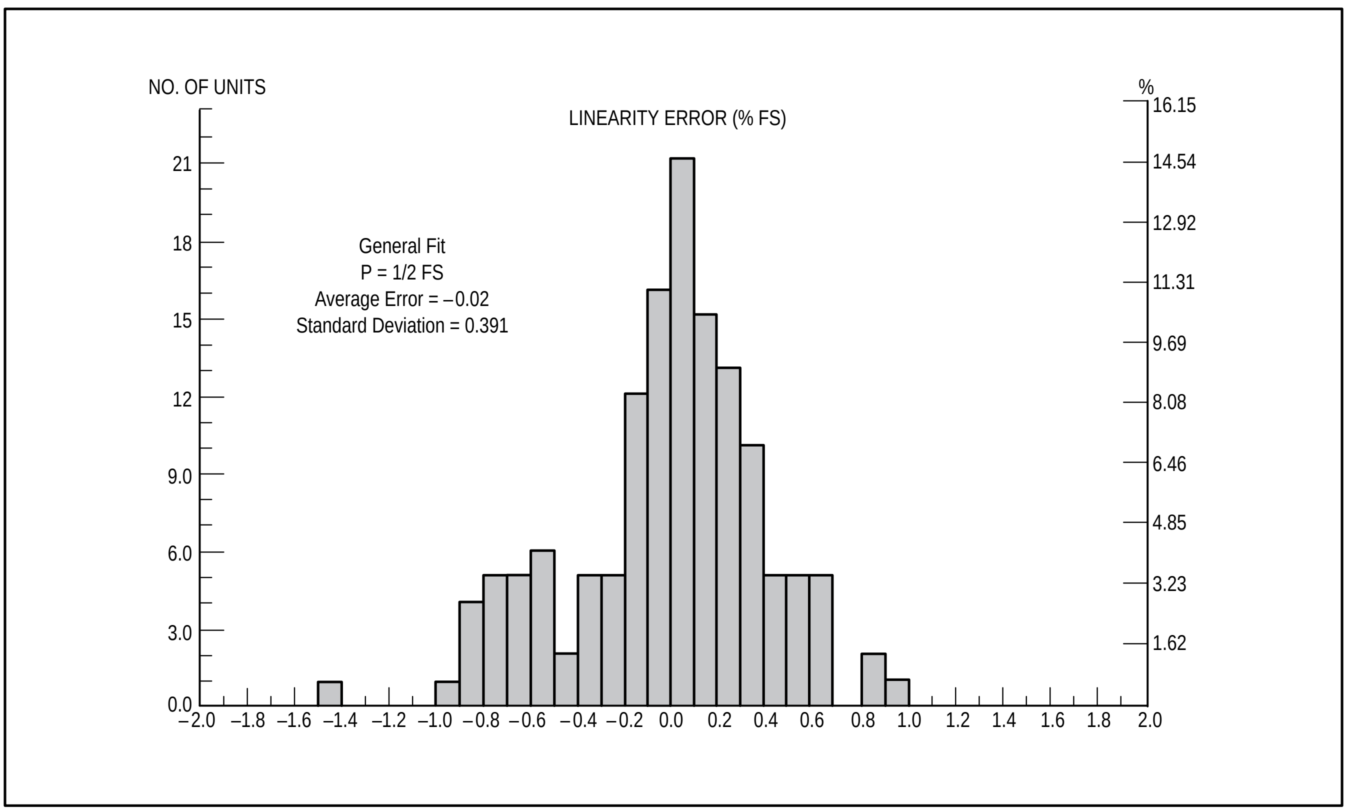

Figure 7. Linearity Error of General Fit Equation at 1/2 FS

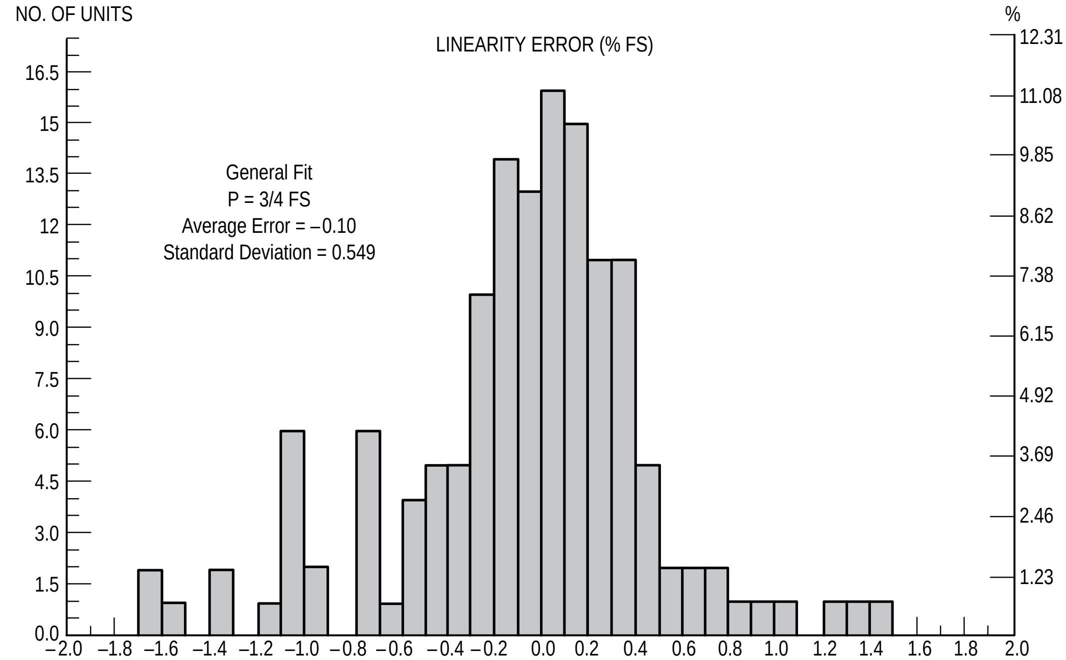

Figure 8. Linearity Error of General Fit Equation at 3/4 FS

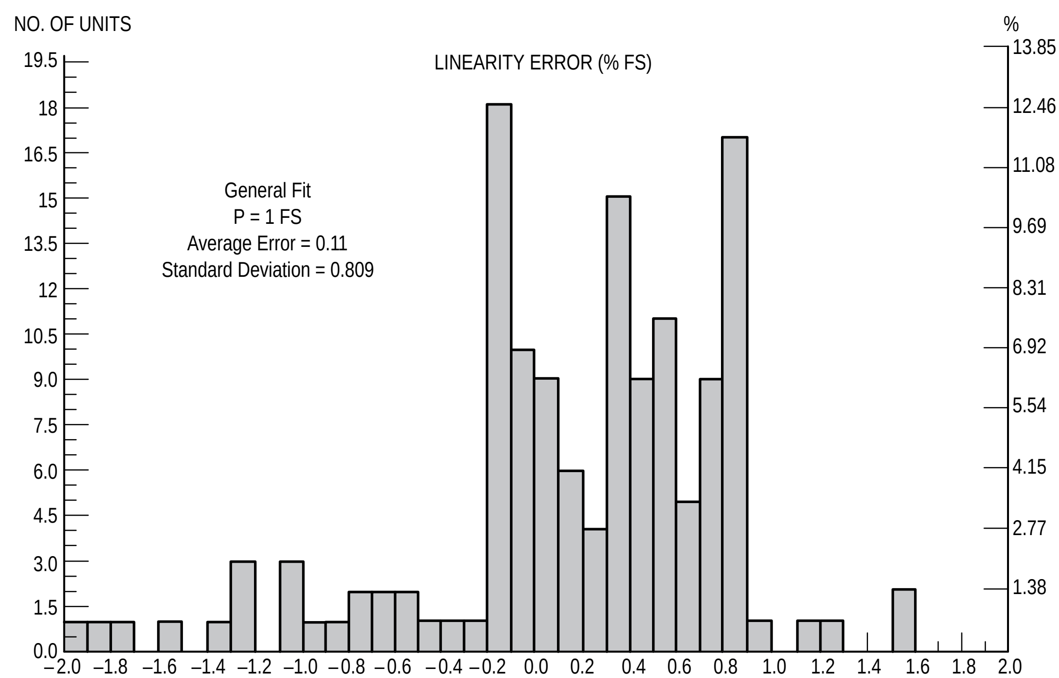

Figure 9. Linearity Error of General Fit Equation at FS

A second technique that still uses a single pressure measurement as the input was investigated. In this method, the sensitivity coefficients are calculated using a piece–wise linearization technique where the total span variation is divided into four windows of 10 mV (i.e., 30–39.99, 40–49.99, etc.) and coefficients calculated for each window. The errors that arise out of using this method are shown in Figures 10 through 13. This method results in a large majority of the devices having errors <0.5%, while only one of the devices was >1%. The sensitivity coefficients that are substituted into equation [2] for the different techniques are given in Table 1. It is important to note that for either technique the only measurement that is required by the user in order to clearly determine the sensitivity coefficients is the determination of the full scale span of the particular pressure transducer.

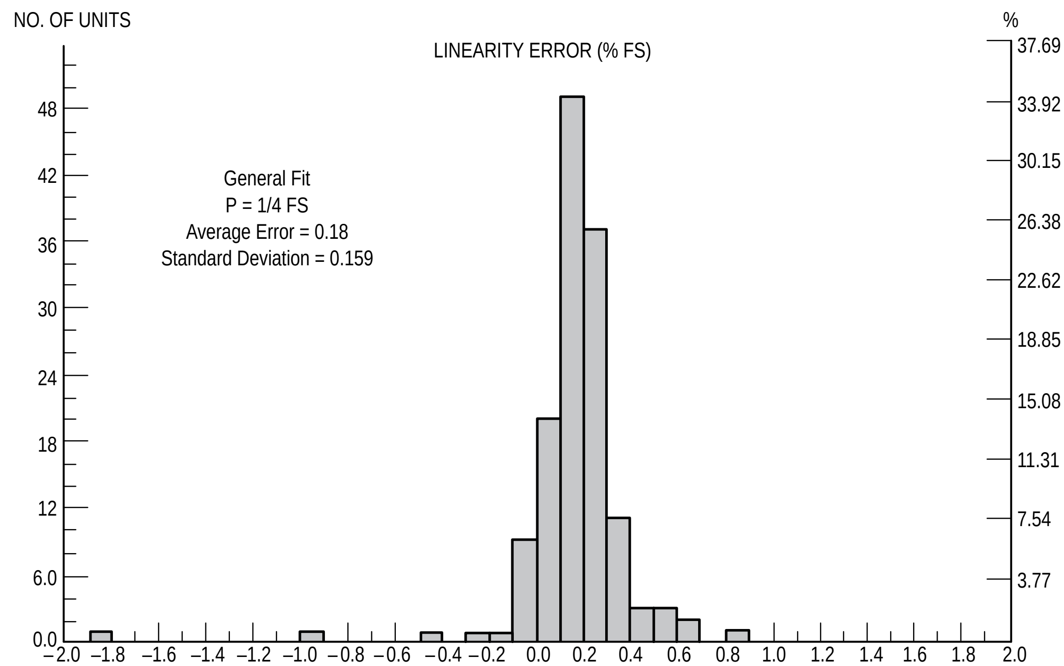

Figure 10. Linearity Error of Piece–Wise Linear Fit at 1/4 FS

Table 1. Comparison of Linearization Methods

SPAN WINDOW	B_0	B_1	B_2
	GENERAL FIT		
	0.1045 + 2.95E – 3X	0.2055 + 1.598E – 3X + 1.723E – 4X^2	1.293E – 13X$^{5.681}$
	PIECE–WISE LINEAR FIT		
30–39.99	0.08209 – 2.246E – 3X	0.02433 = 1.430E – 2X	–1.961E – 4 + 8.816E – 6X
40–49.99	0.1803 – 4.67E – 3X	–0.119 + 1.655E – 2X	–1.572E – 3 + 4.247E – 5X
50–59.99	0.1055 – 3.051E – 3X	–0.355 + 2.126E – 2X	–5.0813 – 3 + 1.116E – 4X
60–69.99	–0.288 + 3.473E – 3X	–0.361 + 2.145E – 2X	–5.928E – 3 + 1.259E – 4X

X = Full Scale Span

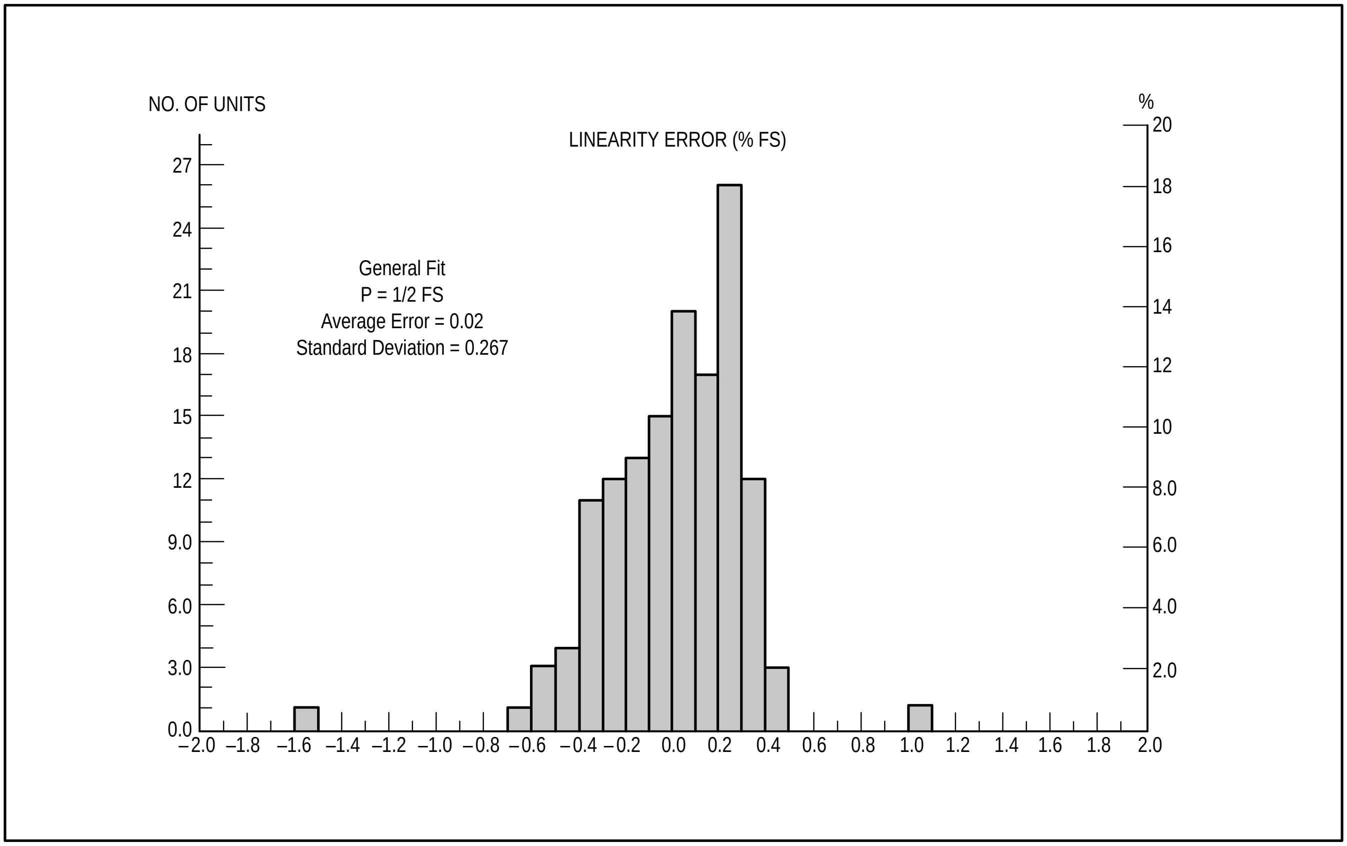

Figure 11. Linearity Error of Piece–Wise Linear Fit at 1/2 FS

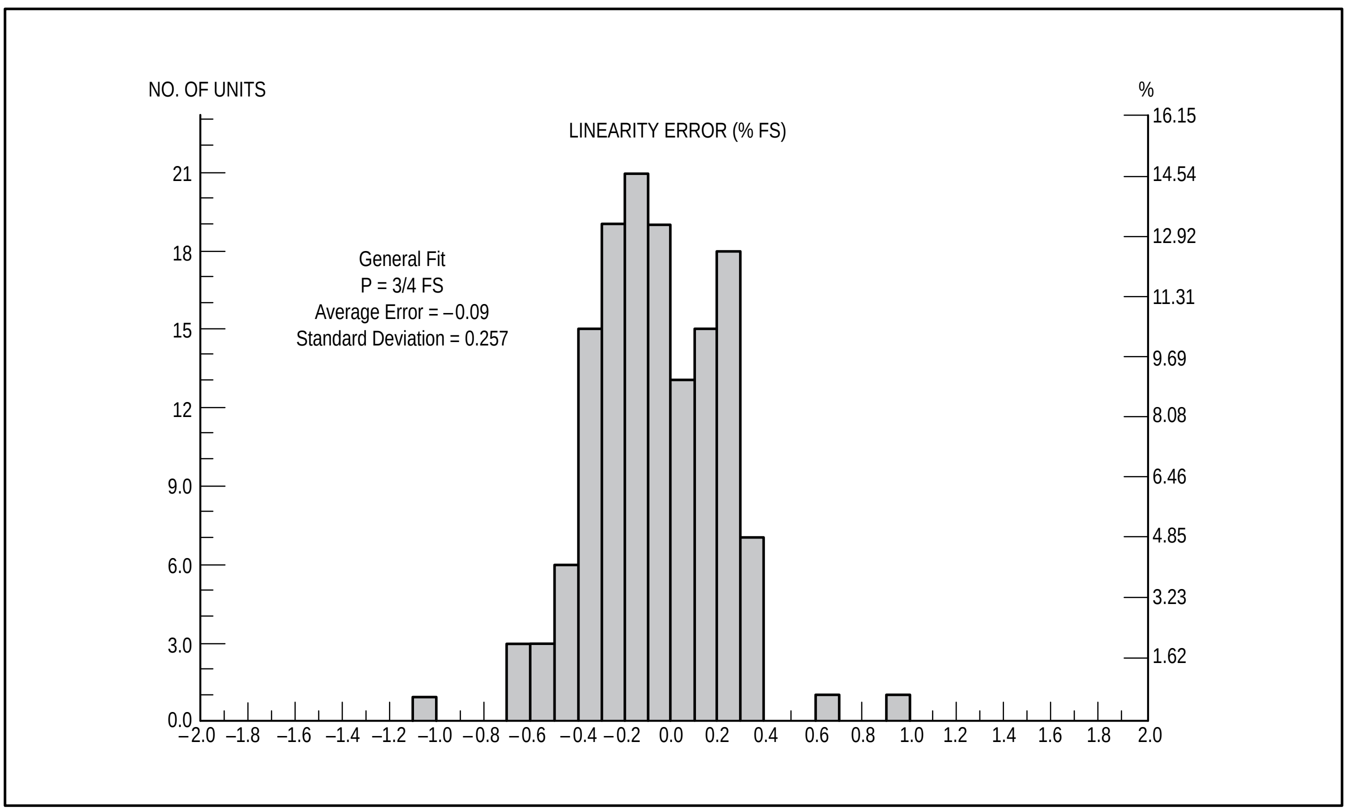

Figure 12. Linearity Error of Piece–Wise Linear Fit at 3/4 PS

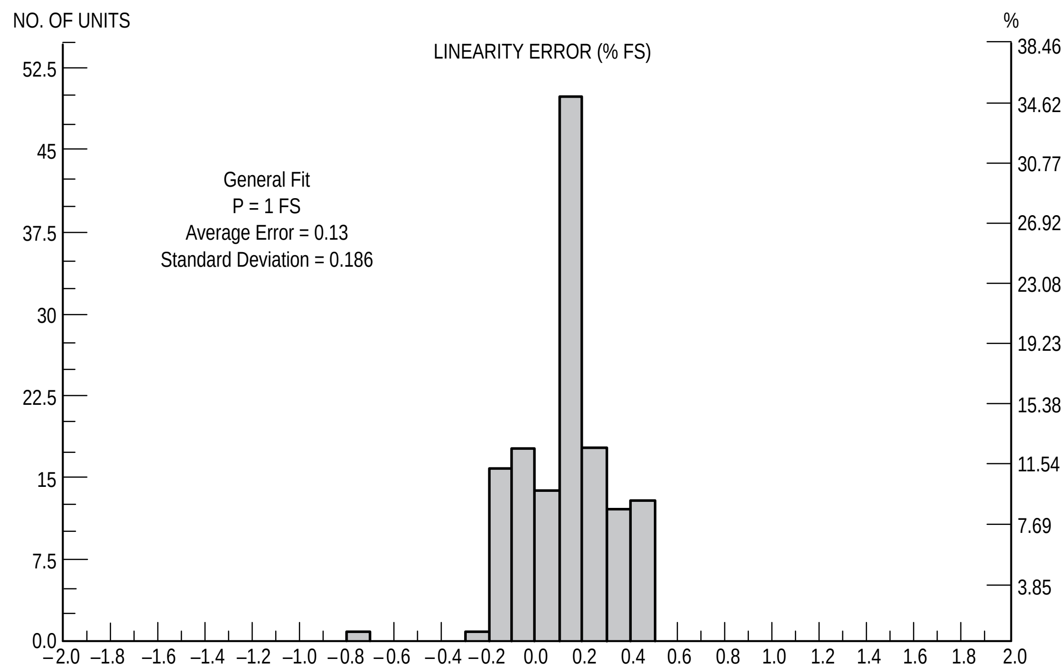

Figure 13. Linearity Error of Piece–Wise Linear Fit at FS

Once the sensitivity coefficients have been determined, a system can then be built that provides an accurate output function with pressure. The system shown in Figure 14 consists of a pressure transducer, a temperature compensation and amplification stage, an A/D converter, a microprocessor, and a display. The display block can be replaced with a control function if required. Further details on the temperature compensation and amplification block may be obtained by consulting Application Note AN840. The A/D converter simply transforms the voltage signal to an input signal for the microprocessor, in which resides the look–up table of the transfer function generated from the previously determined sensitivity coefficients. The microprocessor can then drive a display or control circuit using standard techniques.

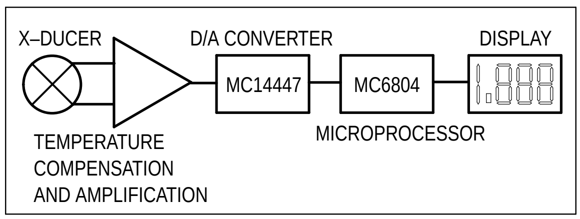

Figure 14. Linearization System Block Diagram

SUMMARY

While at first glance this technique appears to be fairly complicated, it can be a very cost effective method of building a high–accuracy, high–sensitivity pressure–monitoring system for low–pressure ranges.

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