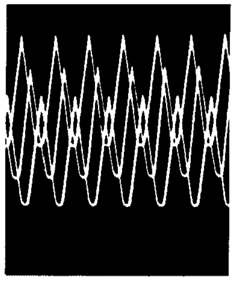
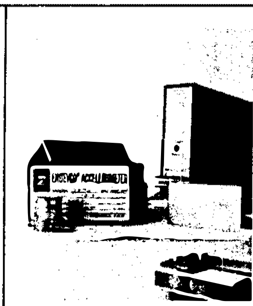
ENDEVCO
AN AMPHENOL COMPANY

Compendium on Endevco Diffused Piezoresistive Transducers

Technical Paper 268

ENDEVCO® TECH PAPER





TP268

COMPENDIUM

ON ENDEVCO

DIFFUSED PIEZORESISTIVE TRANSDUCERS

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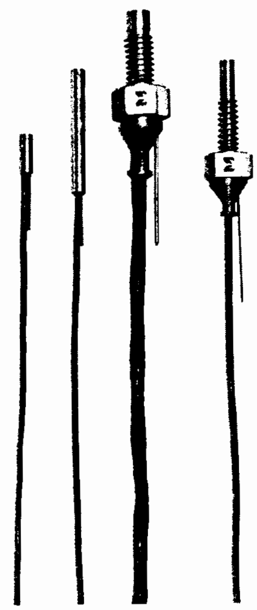
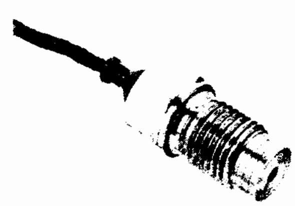


Four Examples of

Endevco's Miniature Pressure Transducers.



Endevco Model 8511 Miniature

High Pressure Transducer

1.0 INTRODUCTION

The ENDEVCO® Model 8500 Diffused Piezoresistive Pressure Transducers are a family of Pressure Transducers consistent with Endevco's tradition of producing high quality instruments. In addition to high quality and high performance, these transducers provide a high degree of miniaturization. One of the larger versions of the product family is cased in a 10-32 UNF threaded housing (5 mm diameter). The active area of the pressure sensing surface, which is made of silicon, is only 2 mm in diameter. Key to the performance and ruggedness is the unique* sensor design which incorporates a four-arm Wheatstone bridge diffused into the silicon chip. Instead of a simple flat diaphragm Endevco has developed a special shaped silicon chip which concentrates the stress at the location of the resistive elements. This results in a higher sensitivity for a given resonance frequency as well as a substantial increase in ruggedness. Included within the small cases of most models are bridge balancing and temperature compensating elements to optimize performance. This is accomplished through the use of hybrid circuit fabrication techniques.

Transducers with pressure ranges from 2 psi to 20 000 are currently available. Range is identified by a suffix to the model number for each product version. Nominal full scale output is specfied as 300 mV for 10 Vdc excitation. Resonance frequencies vary from 45 000 Hz for the 2 psi full scale to over 1 MHz for the 20 000 psi full scale transducer. Linearity of these transducers is not only very good to its nominal full scale, but well beyond. Burst pressure is specified to be more than 3 to 20 times full scale depending on the range. Complete product descriptions and specifications limits are shown on the Product Data Sheets.

The following sections of this compendium discuss some of the performance characteristics of these transducers. For additional background information on the design, the reader is referred to Endevco Technical Paper TP267.

2.0 DYNAMIC RANGE AND LINEARITY

The dynamic range of a piezoresistive pressure transducer is specified as the upper and lower limits of pressure over which the transducer is intended to measure. The sensitivity of a transducer should remain almost constant over this range.

* U.S. Patents 4,065,970 and 4,033,933

Although a piezoresistive transducer is theoretically linear down to zero pressure, a practical lower limit is imposed by its noise level. As for all electrical conductors, the thermal induced random motions of free electrons cause noise; this is usually called Johnson Noise. In addition, the current flow through the diffused gage elements causes some additional noise having the characterisitics of Schottky, or shot, noise. As a result, these diffused gage pressure transducers have a wideband noise characteristic of about 10-15 microvolts p-p, measured at 20° C. This corresponds to about .0001 psi (or 6 microbar) for a 2 psi full scale transducer. Because this noise level is very small, the lower limit of dynamic range is usually a function of the noise characteristics of the signal conditioning and power supply equipment used with the transducer.

The maximum limits of range are established as a fraction of the maximum pressure level that the unit will withstand without damage. In many transducers, as the pressure is increased, and as it approaches the ultimate failure point, or burst pressure, the transducer becomes highly nonlinear. This is due to the nonelastic characteristics of ductile metals and even very good metallic spring materials. Single crystal silicon is a very good spring material, having essentially no plastic zone to its stress-strain curve and very low hysteresis. Because the input pressure to these transducers is supported only by the silicon element, these transducers do not become highly nonlinear before burst is reached. It is usually difficult to measure more than a 5% zero shift level before burst. The task, therefore, becomes one of simply establishing an adequate safety margin below the probable burst level. Although each transducer is identified with a particular full scale range, there is no absolute end to the scale (with the exception of burst). One may elect to use a transducer at some pressure above full scale, or well below full scale, depending on the requirements of the application. Each transducer is tested prior to shipment to a maximum limit for combined linearity and hysteresis to the "defined" full scale level, and for stability to a specified overrange level, typically 3 times full scale. Based on design and sample testing, the linearity characteristics at pressures other than full scale are understood. A complete discussion of the theoretical considerations and nominal characteristics for linearity are included in TP267.

The general linearity characteristics of these diffused transducers might best be explained by referring to Figures 1-a and 1-b which show the general shape of the input to output curve and the degree of nonlinearity for increasing input for up to three times full scale. In addition, for applications requiring better linearity one can use a transducer to some value below the rated full scale. For example, the calibration of the same transducer used for the data of Figure 1-b provided a sensitivity change from 2 psi to 3 psi of less than 0.1%. Experience shows that the linearity for ranges greater than 5 psi is usually about twice as good as that for the 5 psi range, and the non-linearity of the 2 psi full scale transducer is almost twice as much as that for the 5 psi full scale range.

The linearity shown by Figure 1-b and which is shown on the specifications for the transducers is the "independent linearity." This is defined as the maximum difference between the calibration point and the most favorable straight line drawn through the points for either increasing or decreasing measurand, zero to + or - full scale. Numerically, this is usually about one-half the value when using an end-point, or terminal based, linearity definition.

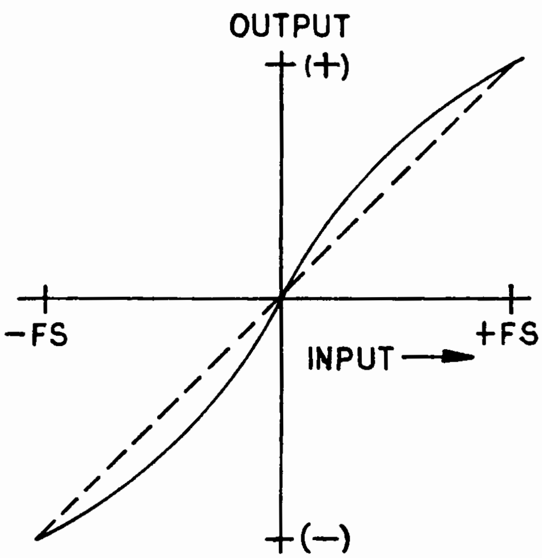


Figure 1-a. Typical input to output curve shape

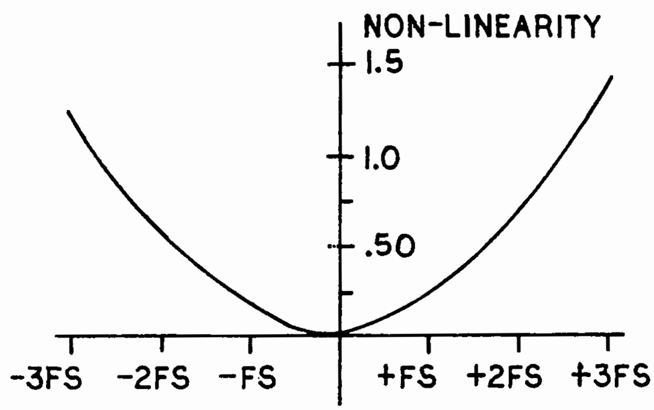


Figure 1-b. Typical independent linearity of 8510-5 for up to three times full scale input

Because of the excellent elastic characteristics of silicon, the hysteresis of these gages is usually quite small, most of the time under 0.1% of full scale, and quite often even .03%. As such, the specifications have simply been stated by indicating typical values for linearity and hysteresis, and then indicating a maximum limit for the two combined. For applications requiring improved values or characteristics over particular pressures, special selections and tests can easily be made.

Pressure input equipment used at Endevco for testing the amplitude characterisitcs are listed below with an abbreviated statement of accuracy.

20 inches water	Meriam Manometer	±.005% F.S.
100 psi	Manfield & Green Air Dead Weight	±.025% Reading
1 000 psi	Ruska Quartz Gage	±0.015% F.S
10 000 psi	Mansfield & Green Oil Dead Weight	±0.1% Reading
25 000 psi	Heise Dial Gage	±0.1% F.S.
60 000 psi	Heise Dial Gage	±0.1% F.S.

3.0 FREQUENCY RESPONSE CHARACTERISTICS

These diffused piezoresistive pressure transducers are capable of response from steady state to frequencies into the ultrasonic range, and of response to fast rise time transient inputs. The sensing chip is mounted at the front of the transducer making it equivalent to a flush mounted diaphragm for most applications. The protective screen over the sensing surface has been designed to not degrade performance of the gauge; however, for some applications one may wish to remove it. These applications usually involve high speed fluid flow, high frequency response, and a need to not disturb the surface of the body in the flow. Some special transducers have also been produced with silicon rubber added to the front to smooth out the surface.

Three different types of tests have been conducted at Endevco to characterize the dynamic response. These are (1) free field microphone calibration in air, (2) sinusoidal comparison in oil, and (3) response to step input from a shock tube. Each of these is discussed on the next page.

Calibrations of a 2 psi full scale 8510-2 have been made in a free field by comparison to a Western Electric condenser microphone. This was done in an anechoic chamber using normal incident plane progressive sound waves at a sound pressure level of about 120 dB (re 0002 N/m^2) Backbround residual electronic noise was approximately 103 dB SPL. Results correspond well to theory for a transducer of this size and resonance frequency. Refer to Figure 2 for results. Note that the vent tube was plugged to keep pressure from entering the case; cut off frequency of the vent was about 300 Hz.

Comparison pressure calibrations are performed dynamically with a sinusoidal pressure generator. This device incorporates a compression spring, piston and seismic mass assembly, hydraulic oil-filled chamber, and mounting cavities for the reference standard and test transducers. Sinusoidal vibratory motion applied to the generator housing imparts sinusoidal pressure to oil which is exposed simultaneously to the sensing surfaces of both transducers providing a direct comparison calibration capability. A digital readout technique, with ±0.2% resolution uncertainty, identical to that used for accelerometer sine comparison calibrations, is used for equalization of test and standard outputs at discrete test frequencies. The operating range of the generator is 10 Hz to 2 000 Hz, and 300 psi peak magnitude sine pressure can be developed. Figure 3 shows a design illustration of the generator.

An Endevco Model 8510-500 piezoresistive pressure transducer selected for a linearity characteristic of less than 0.1% FSO (predicated on a dead weight tester static calibration) is utilized as the standard. For verification, a piezoelectric pressure transducer was also statically calibrated with the same dead weight tester over an identical 0-500 psi operating range. A long time constant following electronics accommodated the static sensitivity determination. Subsequent comparison calibrations utilizing the piezoresistive and piezoelectric transducers with the Sinusoidal Pressure Generator yielded dynamic sensitivity values for the PE test transducer within ±1% of its static calibration.

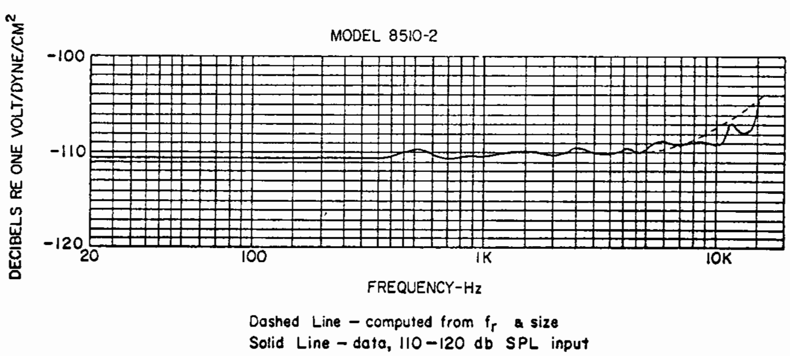


Figure 2. Acoustic Calibration. Free field perpendicular incidence.

In addition to testing new designs, this equipment has been used to compare sensitivities from low frequency dynamic inputs to steady state inputs. The reason for doing this is that resistive elements within a transducer which has internal heating will stabilize at a different temperature for static and alternating input. Test results for the 8510 comparing steady state and sinusoidal calibration show no significant difference greater than the inaccuracy of the test.

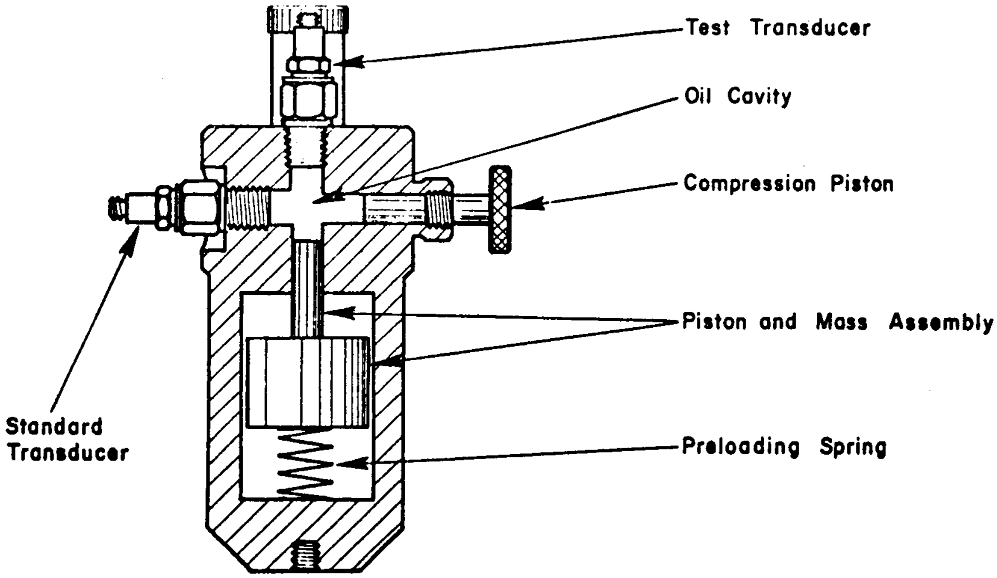


Figure 3. Sinusoidal pressure generator, design principals.

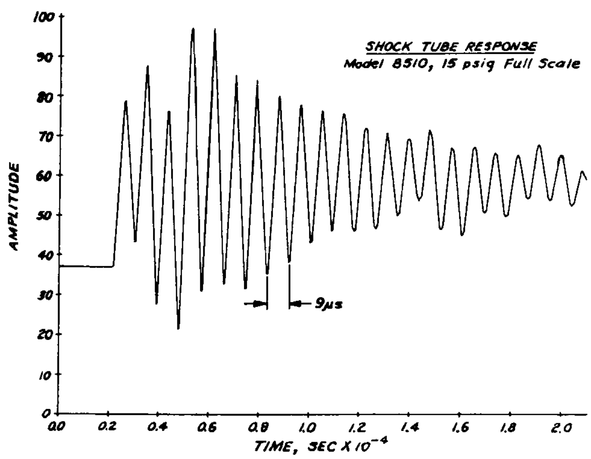


Figure 4. Transducer response from step pressure input/shock tube (Model 8510, 15 psig full scale)

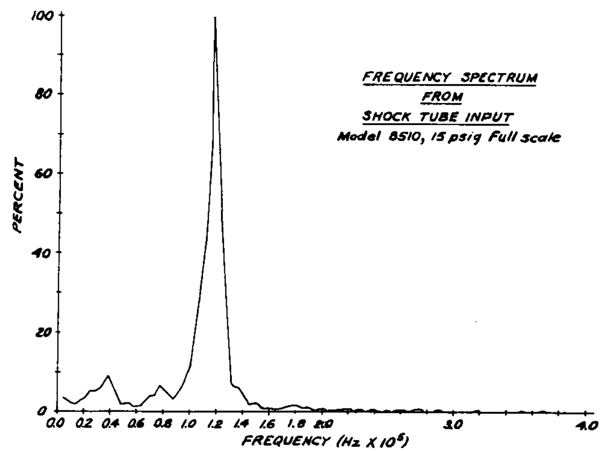


Figure 5. Transducer response spectrum from shock tube input (Model 8510, 15 psig full scale)

Transient pressure excitation is also used to evalutate pressure transducer response characteristics. The excitation source is a shock tube which has a 2.5 inch diameter cylindrical cross-section with a 15-inch driver end and 60-inch driven end. The tube sections are mechanically coupled by a bolted flange which can be disengaged to enable insertion of a diaphragm material as a separator. Pressurization of the driver section with a gaseous medium causes expansion of the membrane until it establishes sufficient contact with an implanted knife-edge mechanism to rupture. The resultant sudden release of the pressurized air into the lower pressure driven compartment produces a hypersonic shock wave front which impinges the end plate in which the pressure transducer is flush mounted. The transducer diaphragm is thus exposed to a very fast rise time pressure step which has significant high frequency content such that extended frequency response information is available. A transient recorder captures the resulant transducer output and stores it for subsequent playback and analysis. A programmable calculator with fast fourier transform capability accepts the transient waveform and processes it for presentation on a companion X-Y plotter in either time domain or frequency domain format. The time history display of Figure 4 shows the classic response of an extremely underdamped linear second order system to a step function input. The transducer output oscillates about a steady-state deflection corresponding to the magnitude of the input pulse. The predominant ringing frequency represents the transducer resonance, and the envelope of the oscillations generally conforms with a logarithmic decay related to transducer damping factor. Supplementary information is obtained by additional signal processing and analysis. A frequency domain presentation such as that of Figure 5 with its spectral content data indicates the presence or absence, in the measured bandwidth, or minor resonances or other anomalous response, if any, and relative magnitude.

No significant minor resonances or deviations from the theoretical response based on the principal resonances have been detected to 100 000 Hz on any range of the Model 8510.

4.0 EXCITATION REQUIREMENTS

Piezoresistive transducers are passive devices and require an external power supply to provide the necessary current or voltage excitation to operate the transducer. The standard versions of the 8500 Series transducers are designed to operate from constant DC voltage supplies. However, special versions can be produced to operate from constant current, or AC supplies.

The excitation across the piezoresistive elements causes a finite current to flow through each element. The I^2R heating results in an increase in temperature of the elements slightly above ambient which increases the resistance of the elements. Differentials in this effect may cause the output voltage to vary slightly with time until the temperature is stabilized. With 10 Vdc excitation, stabilization usually occurs within a few seconds when tested at standard barometric conditions. To be on the safe side, a 15 second warmup time is specified. With less excitation voltage, the warmup is faster, however, it should be recognized that the response is not instantaneous.

Measurements have also been made at excitations other than 10 Vdc to investigate effects. As a result of these tests, maximum excitation without damage is usually specified at 18 Vdc, and excitations to 15 Vdc might be considered as a technique to provide improved signal-to-noise ratios in some applications. With some transducers, excitation at other than 10 V can change zero output, sensitivity and their shift with temperature. Figures 6-a and 6-b show this effect tested on a sample 5 psig full scale transducer. Because of this, calibrations should be completed using the power supply excitation planned for use in the application.

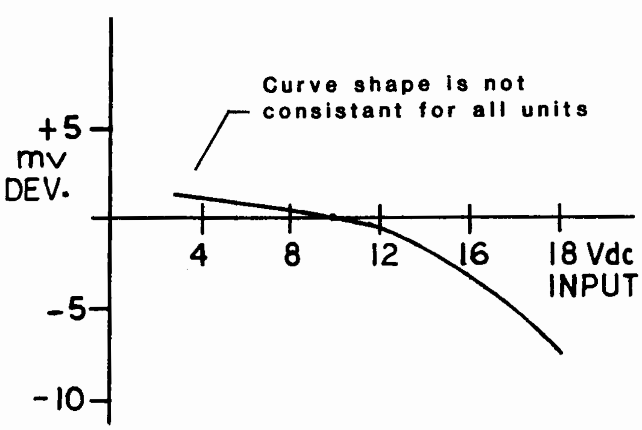


Figure 6-a. Zero change with input voltage change 2-18 Vdc on sample 8510-5.

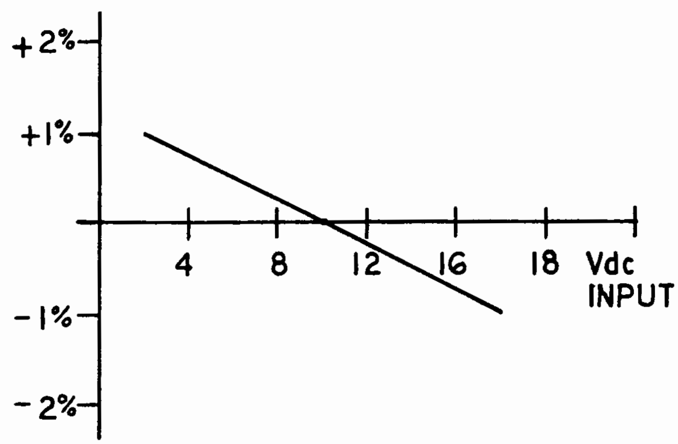


Figure 6-b. Sensitivity shift (mV/psi/input volt) for sample 8510-5 for 2-18 Vdc input

5.0 EFFECT OF AMBIENT TEMPERATURE

Most of the characteristics of the 8500 Series diffused transducers are not appreciably affected by temperature. The piezoresistive strain coefficients and the material resistivity do change, however, and these must be allowed for in the transducers mechanical and electrical design. For example, the stresses imposed by the mechanical attachments of the silicon elements within the transducer can cause further apparent change, either increasing the apparent temperature coefficients or decreasing them. Electrical resistive components can also be placed in the bridge circuit to alter performance. The end result is that each design has a characteristic change in sensitivity, bridge balance, and bridge resistance with temperature.

Because of variations in material properties, processes, and dimensions, the performance of a population of units of a given design will scatter about the nominal. To provide the lowest effect of temperature, the performance can be measured for each transducer during the manufacturing process, and resistance values can be chosen to compensate for change with temperature. The bridge circuit employed in these transducers is shown by Figure 7. The resistance in series is used to reduce the sensitivity variation with temperature. Note that a resistor is placed in both the positive and negative power supply lines; this is done to retain balance to aid in rejection of common mode noise. The resistances in parallel with one arm of the bridge correct for bridge unbalance and balance change (zero shift) with temperature.

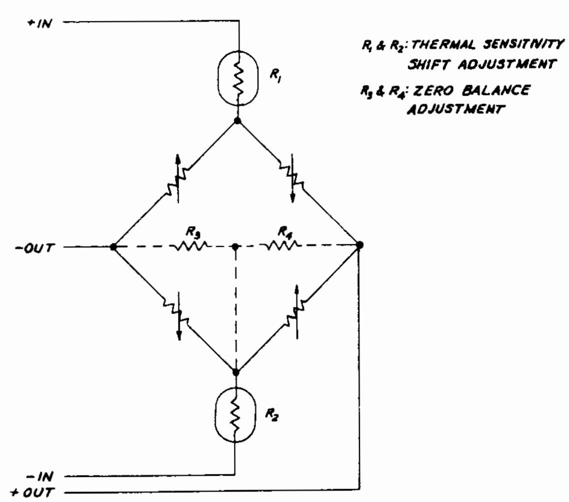


Figure 7. Schematic diagram, 4-arm bridge.

A basic feature of the Model 8510 is that all of the temperature compensation elements are contained within the small 10-32 screw size transducer case. NO external compensation module is necessary. Each unit is tested in the manufacturing process and components selected to optimize performance. The performance capabilities and test results for 8510 transducers are summarized as follows.

Sensitivity - The temperature compensation utilized for standard production units reduces the thermal sensitivity shift to a maximum of ±4% of output at -18°C and +93°C, referenced to room temperature. This temperature error is sometimes also expressed as a maximum of ±.09% of output/°C. Note that on special order tighter specifications can be met; the compensated temperature range can be suppressed, expanded, shifted up or down; also calibration data can be supplied at any specified temperature within the environmental range. The sensitivity variation with temperature for a typical 8510 with and without the series compensation resistance is shown by Figure 8. Uncompensated slope is approximately -.15%/°C and compensated slope about -.03%/°C over most of the temperature range.

The approximate distribution of temperature errors for standard production Model 8510 units is:

% of Units	Maximum Temperature Sensitivity Shift % FSO
100	4.0
75	2.5
50	1.5
25	1.2

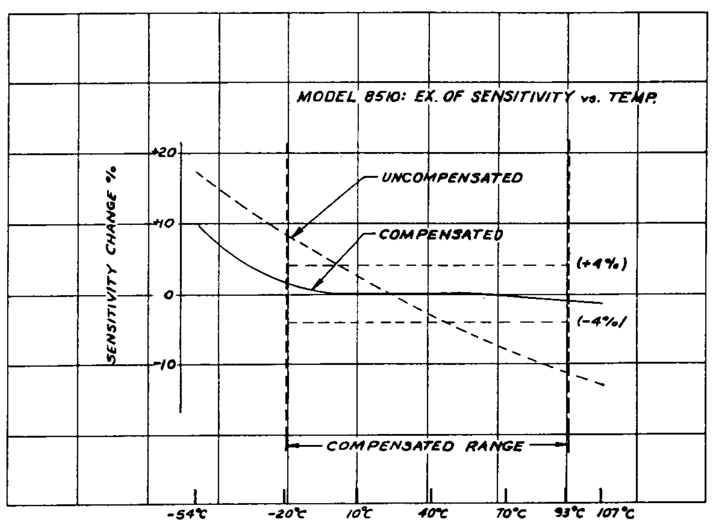


Figure 8. Example of sensitivity, change with temperature for Model 8510.

Zero Measured Output - Similarly, the thermal zero shift is reduced to a maximum of ±3% FSO (full scale output) at -18°C and +93°C, referenced to room temperature by resistive compensation. This corresponds to a maximum of ±.05%/°C. Figure 9 shows a plot of zero shift with temperature for a typical 8510, both uncompensated and compensated. Uncompensated slope is .06%/°C and compensated, it is .015%/°C. If the reference side of the transducer is sealed off (when used as a sealed reference pressure differential pressure transducer), the thermal zero shift is considerably increased in accordance with Boyle's gas law.

The approximate distribution of temperature errors for standard production Model 8510 units is:

% of Units	Maximum Temperature Zero Shift, % Output
100	3.0
75	1.5
50	1.0
25	0.5

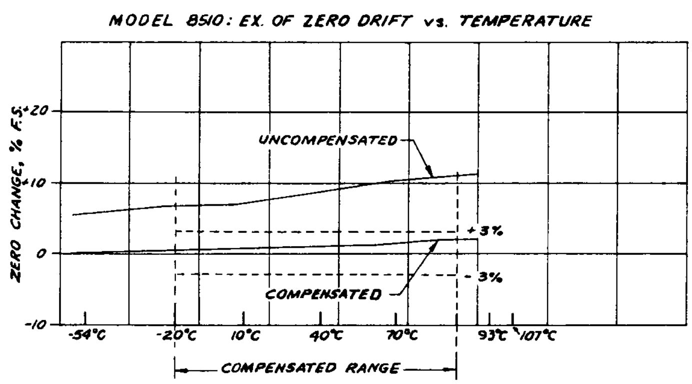


Figure 9. Example of zero shift with temperature change for Model 8510.

Input/Output Impedance - Since the resistance of silicon gages is temperature dependent (as well as components in the temperature compensation circuitry), input and output impedance is likewise affected by temperature. The effect may be of no particular significance to the user, however, the change in resistance is typically -1.7 ohm/°C for input resistance and +1.6 ohm/°C for output resistance.

High Temperature Limit - For the standard Model 8510, high temperature is limited by the PVC jacketed cable. With a silicone or teflon jacketed cable, continuous operation at higher temperatures can be achieved. For operation above 150°C, the unit must be installed into a water-cooled jacket or Endevco can supply an ablative coating over the diaphragm which withstands 2 000°C for short time durations.

Low Temperature Limit - The standard Model 8510 has been specified at the typical low end of the military specifications, -54°C, but some successful tests have been performed at -184°C. For operation below -18°C Endevco can supply calibration data at the temperatures of interest.

6.0 EFFECTS OF TEMPERATURE TRANSIENTS

All Endevco pressure tested are qualification tested per paragraph 6.7 of ISA Specification S37.10. Results are shown on the Specification Sheets.

The photosensitivity of silicon quite often will render silicon diaphragm pressure transducers susceptible to radiation. The resulting transient output can be significant for applications where high intensity light can impinge on the diaphragm (such as in explosions or in engine combustion chambers). Endevco has employed several solutions to this - not the same for all designs. In some cases it is advisable to cover the diaphragm with an opaque material. The diaphragm coating does slightly affect acceleration sensitivity and frequency response, and is not usually recommended for ranges below 100 psi. For low range units (2 to 100 psi) opaque silicon grease over the diaphragm has been found to be quite effective.

The transducer also responds to thermal transients via conduction through the diaphragm and housing. The standard test method of transferring the unit from a +20°C to +90°C water results in a transient error as shown in Figure 10. Note that the effect on zero balance is extremely

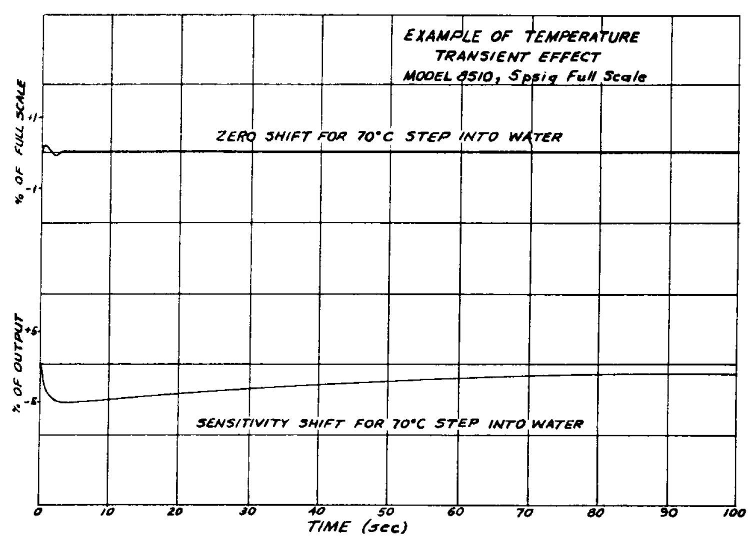


Figure 10. Example of temperature transient effect, Model 8510, 5 psig full scale.

small and short duration. A somewhat larger error results from its change in sensitivity, -5% FSO being a typical error in output when the unit (with uncovered diaphragm) is simultaneously subjected to a full range pressure input and a step temperature change of 70°C. For a more complete discussion of temperature transient input effects refer to Endevco TP279.

7.0 NOTES ON ELECTRICAL RELATIONSHIPS

Loading Effects - An equivalent circuit of a piezoresistive transducer for use when considering loading effect is shown below.

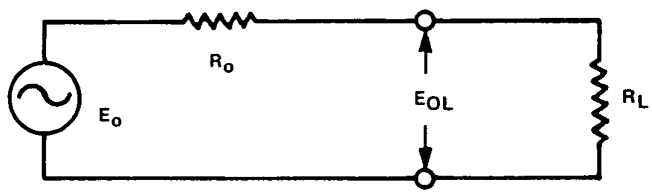


Figure 11. Loading effects.

R_o = output resistance of the bridge, including cable resistance

E_o = sensitivity into an infinite load

E_{OL} = loaded output sensitivity

R_L = load resistance

Using the equivalent circit above and the output resistance, the effect of loading may be directly calculated:

$$E_{OL} = E_o \frac{RL}{R_o + R_L}$$

Because the resistance of the strain gage elements varies with temperature, output resistance must be measured at the operating temperature.

Effect Of Cable On Sensitivity - Each ENDEVCO® piezoresistive transducer is calibrated and supplied with a specified length of cable. When utilizing long cable in a particular application, three effects must be noted:

1. Resistance in the output excitation wires may significantly reduce the excitation voltage at the transducer resulting in a loss of sensitivity. The reduced sensitivity is equal to:

$$E_{IL} = E_O \frac{R_i}{R + 2R_{ci}}$$

where R_i is the input resistance of the transducer and R_{ci} is the resistance of one excitation wire.

This effect may be overcome by using remote sensing leads.

2. Signal attenuation also results from resistance in the output wires. This attenuation may readily be calculated from the relation:

$$E_{OL} = E_O \frac{R_L}{R_O + R_L + 2R_{CO}}$$

where the terms are as defined as for "Loading Effects", and R_{CO} is the resistance of one output wire between transducer and load.

3. RC filtering in the shielded instrument leads may attentuate the high frequency components in the data signal. The stray and distributed capacitance present in the transducer and in a short cable are such that any filtering effect is usually negligible. However, when long leads are connected between transducer and readout equipment, the frequency response at higher frequencies may be significantly affected.

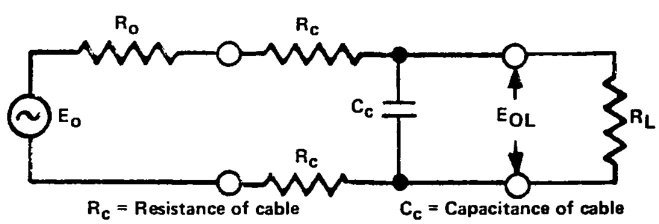


Figure 12. Simplfied circuit with long cable.

Because the resistance and capacitance is actually distributed along the cable, the circuit of Figure 12 only approximates the effect of long wires. It is suggested that each 300 meters of cable be considered as a separate RC network. Terminating a long cable with a load equal to the characteristic impedance of the cable will usually improve system high frequency response. For precise measurement, line filtering action must be determined experimentally as part of the system calibration.

Filtering Out Thermal Zero Drift - Many piezoresistive transducers nave enough signal to be used at one-tenth or less of rated range. The limiting factor is the zero drift with temperature which becomes significant when operating at a small fraction of full range. This temperature shift is, in most cases, essentially a dc phenomenon.

Many applications do not require dc information but do require frequency response down to 1/2 or 1/10 Hz. The solution suggested is a high pass filter into the electronic system so that the dc thermal shift is rejected but the low frequency signal is preserved. The method used is a simple high pass RC filter (see Figure 13) with a cutoff frequency (3 dB down) of:

$$f_c = \frac{1}{2\ RC}$$

where

R = Shunt Resistance

C = Series Capacitor

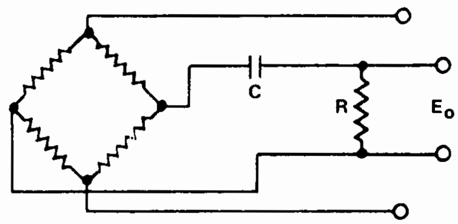


Figure 13. High pass filter.

When an amplifier cannot tolerate a high resistance on the input, the filter can be connected to the output of the amplifier using a suitable value of shunt resistance. The input resistance of the electronic equipment following the amplifier must be included in the calculation of the resistance.

Balancing Zero Measurand Output - Compensation or adjustment of the unbalanced output of a transducer (Zero Measurand Output) can easily be performed in the signal conditioning equipment. For a full-bridge transducer the balance potentiometer R_b is connected across the excitation terminals and a current limiting resistor connected between the wiper arm of the potentiometer and the bridge as shown in Figure 14 below.

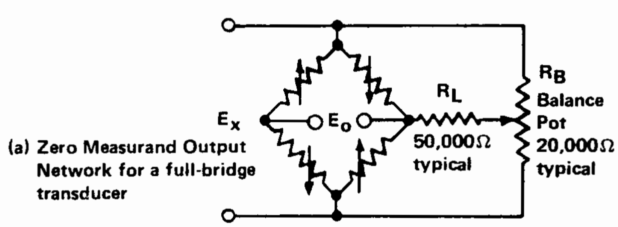
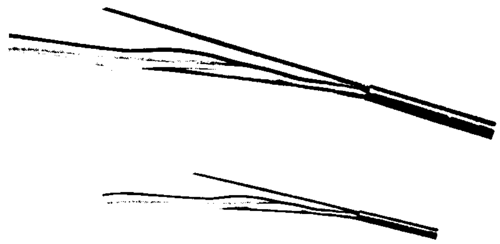
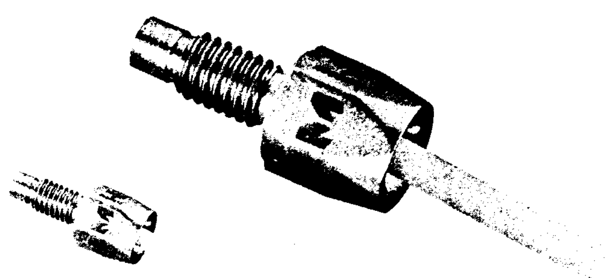


Figure 14. Zero Measurand Output network for a full-bridge transducer.



ACTUAL SIZE

Endevco's Model 8514 ultraminiature pressure transducer.



ACTUAL SIZE

Endevco's Model 8530 absolute reference pressure transducer.

UNITS OF MEASUREMENT

	psi	kg/cm^2	in. H_2O	cm H_2O	in. Hg	mm Hg	$dyne/cm^2$	Atm.	See *Note*
1 psi =	—	.0703	27.67	70.13	2.036	51.715	68,947	.0680	(10)
1 kg/cm^2 =	14.22	—	393.7	1,000	28.96	735.56	980,665	.9678	(1)
1 in. H_2O =	.03613	.00254	—	2.540	.07355	1.868	2,491	.002458	(2)
1 cm H_2O =	.0142	.001	.3937	—	.02896	.7356	980.64	.0009678	(2)
1 in. Hg =	.4912	.0345	13.59	34.53	—	25.40	33,864	.03342	(3)
1 mm Hg =	.01934	.001359	.5352	1.35	.03937	—	1333	.001316	(3)(4) (8) (9)
1 $dyne/cm^2$ =	1.45×10^{-5}	1.02×10^{-6}	4.015×10^{-4}	1.02×10^{-3}	2.953×10^{-5}	7.5×10^{-4}	—	9.87×10^{-7}	(5)(11)
1 atmosphere =	14.696	1.033	406.8	1,033	29.92	760	1,013,250	—	(6)(7)

Notes:

(1) 1 kg/m^2 = 10,000 kg/cm^2

(2) in. H_2O and cm H_2O are referenced to a temperature of 4°C (39.2°F)

(3) in. Hg, mm Hg, and μHg are referenced to a temperature of 0°C(32°F)

(4) 1 mm Hg = 1000 μ Hg

(5) 1 $dyne/cm^2$ = 1 microbar = 1 X 10^{-6} bar

(6) 1 bar = .987 Atmosphere

(7) Atmospheres are more precisely called normal atmospheres

(8) 1 micron = 10^{-6} metre Hg

(9) 1 Torr = 1 millimetre Hg

(10) 1 psi = 6.895 K Pascal

(11) 1 Pascal = 1 N/m^a = 10 $dyne/cm^2$

Decibel Formulae

Power: $dB = 10 \log \frac{W}{W_0}$

Pressure or Voltage: $dB = 20 \log \frac{P}{P_0}$

$dB = 20 \log \frac{E_1}{E_2}$

Pressure Ratio	dB − ← + →	Pressure Ratio	Pressure Ratio	dB − ← + →	Pressure Ratio
1.000	0.0	1.000	.316	10.0	3.16
.988	0.1	1.012	.251	12.0	3.98
.977	0.2	1.023	.199	14.0	5.01
.966	0.3	1.035	.158	16.0	6.31
.955	0.4	1.047	.126	18.0	7.94
.944	0.5	1.059	.100	20.0	10.00
.891	1.0	1.12	.0316	30.0	31.62
.841	1.5	1.19	.0100	40.0	100
.794	2.0	1.26	.0032	50.0	316
.708	3.0	1.41	10^{-3}	60.0	10^3
.631	4.0	1.58	10^{-4}	80.0	10^4
.562	5.0	1.78	10^{-5}	100	10^5
.501	6.0	2.00	10^{-6}	120	10^6
.447	7.0	2.24	10^{-7}	140	10^7
.398	8.0	2.51	10^{-8}	160	10^8
.355	9.0	2.82	10^{-9}	180	10^9

Pressure vs Altitude

(per N.A.C.A. Report No. 538; based on U.S. Standard Atmosphere)

ALTITUDE (Feet)	PRESSURE		
	In. Hg.	Mm. Hg.	P. S. I.
-1,000	31.02	787.9	15.25
- 500	30.47	773.8	14.94
0	29.921	760.0	14.70
500	29.38	746.4	14.43
1,000	28.86	732.9	14.18
1,500	28.33	719.7	13.90
2,000	27.82	706.6	13.67
2,500	27.31	693.8	13.41
3,000	26.81	681.1	13.19
3,500	26.32	668.6	12.92
4,000	25.84	656.3	12.70
4,500	25.36	644.2	12.45
5,000	24.89	632.3	12.23
5,500	24.43	620.6	12.00
6,000	23.98	609.0	11.77
6,500	23.53	597.6	11.56
7,000	23.09	586.4	11.34
7,500	22.65	575.3	11.12
8,000	22.22	564.4	10.90
8,500	21.80	553.7	10.70
9,000	21.38	543.2	10.50
9,500	20.98	532.8	10.30
10,000	20.58	522.6	10.10
10,500	20.18	512.5	9.91
11,000	19.79	502.6	9.73
11,500	19.40	492.8	9.53
12,000	19.03	483.3	9.35
12,500	18.65	473.8	9.15
13,000	18.29	464.5	8.97
13,500	17.93	455.4	8.81
14,000	17.57	446.4	8.63
14,500	17.22	437.5	8.46
15,000	16.88	428.8	8.28
15,500	16.54	420.2	8.13
16,000	16.21	411.8	7.96
16,500	15.89	403.5	7.81
17,000	15.56	395.3	7.64
17,500	15.25	387.3	7.49
18,000	14.94	379.4	7.34
18,500	14.63	371.7	7.19
19,000	14.33	364.0	7.04
19,500	14.04	356.5	6.90
20,000	13.75	349.1	6.75
20,500	13.46	341.9	6.61
21,000	13.18	334.7	6.48
21,500	12.90	327.7	6.34
22,000	12.63	320.8	6.21
22,500	12.36	314.1	6.08
23,000	12.10	307.4	5.94
23,500	11.84	300.9	5.82
24,000	11.59	294.4	5.70
24,500	11.34	288.1	5.58
25,000	11.10	281.9	5.45
25,500	10.86	275.8	5.33
26,000	10.62	269.8	5.22
26,500	10.39	263.9	5.11
27,000	10.16	258.1	4.99
27,500	9.94	252.5	4.88
28,000	9.72	246.9	4.78
28,500	9.50	241.4	4.67
29,000	9.29	236.0	4.56
29,500	9.08	230.7	4.46
30,000	8.88	225.6	4.36
30,500	8.68	220.5	4.27
31,000	8.48	215.5	4.17
31,500	8.29	210.6	4.07
32,000	8.10	205.8	3.98

ALTITUDE (Feet)	PRESSURE		
	In. Hg.	Mm. Hg.	P. S. I.
32,500	7.91	201.0	3.89
33,000	7.73	196.4	3.80
33,500	7.55	191.8	3.71
34,000	7.38	187.4	3.63
34,500	7.20	183.0	3.54
35,000	7.04	178.7	3.46
35,332	6.93	175.9	3.40
35,500	6.87	174.5	3.375
36,000	6.71	170.4	3.296
36,500	6.55	166.4	3.22
37,000	6.39	162.4	3.14
37,500	6.24	158.6	3.067
38,000	6.10	154.9	2.994
38,500	5.95	151.2	2.925
39,000	5.81	147.6	2.852
39,500	5.68	144.1	2.798
40,000	5.54	140.7	2.72
40,500	5.41	137.4	2.66
41,000	5.28	134.2	2.595
41,500	5.16	131.0	2.535
42,000	5.04	127.9	2.47
42,500	4.92	124.9	2.415
43,000	4.80	122.0	2.36
43,500	4.69	119.1	2.304
44,000	4.58	116.3	2.25
44,500	4.47	113.5	2.195
45,000	4.36	110.8	2.14
45,500	4.26	108.2	2.094
46,000	4.16	105.7	2.042
46,500	4.06	103.2	1.997
47,000	3.97	100.7	1.948
47,500	3.873	98.38	1.90
48,000	3.781	96.05	1.858
48,500	3.693	93.79	1.813
49,000	3.605	91.57	1.772
49,500	3.52	89.41	1.729
50,000	3.436	87.30	1.689
51,000	3.276	83.22	1.610
52,000	3.124	79.34	1.533
53,000	2.978	75.64	1.463
54,000	2.839	72.12	1.395
55,000	2.707	68.76	1.33
56,000	2.581	65.55	1.269
57,000	2.460	62.49	1.208
58,000	2.346	59.58	1.152
59,000	2.236	56.80	1.098
60,000	2.132	54.15	1.048
61,000	2.033	51.63	1.000
62,000	1.938	49.22	0.952
63,000	1.847	46.92	0.906
64,000	1.761	44.73	0.865
65,000	1.679	42.65	0.825
66,000	1.601	40.66	0.786
67,000	1.526	38.76	0.748
68,000	1.455	36.95	0.714
69,000	1.387	35.23	0.681
70,000	1.322	33.59	0.649
71,000	1.261	32.02	0.619
72,000	1.202	30.53	0.590
73,000	1.146	29.10	0.562
74,000	1.093	27.75	0.536
75,000	1.041	26.45	0.512
76,000	0.993	25.22	0.488
77,000	0.946	24.04	0.465
78,000	0.902	22.92	0.443
79,000	0.860	21.85	0.423
80,000	0.820	20.83	0.403

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