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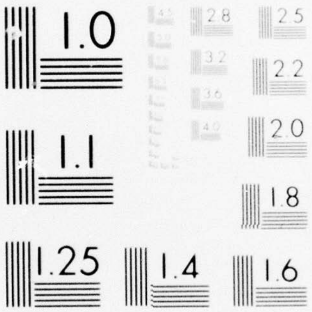

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SELF-CONDITIONING TRANSDUCERS

August 1977

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Air Force Systems Command
Kirtland Air Force Base, NM 87117

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When strain gage signals placed directly on long data lines are received by remote processing systems, they may be so attenuated, distorted and superimposed with noise that they no longer represent the parameter being measured. The author describes two types of signal conditioners which can be placed at the point of measurement to overcome these problems, and includes the advantages and limitations of each device.

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Self-conditioning Transducers

D. J. RAY, Air Force Weapons Laboratory

When strain gage signals placed directly on long data lines are received by remote processing systems, they may be so attenuated, distorted and superimposed with noise that they no longer represent the parameter being measured. The author describes two types of signal conditioners which can be placed at the point of measurement to overcome these problems, and includes the advantages and limitations of each device.

LOW-LEVEL ANALOG DATA generated by strain gage transducers may be obscured by noise voltages induced in long lengths of cable unless the signal amplitude is kept high. Such transducers typically have high source impedance and generate signals in the millivolt range. Since noise levels in long data lines can approach this amplitude, the signals received by remote amplifiers may not accurately represent the parameter being measured. Because of their limited frequency response, long data lines also attenuate and distort the signals they carry.

A typical strain gage transducer contains a piezoresistive bridge which converts such parameters as acceleration, pressure, and structural strain and stress to a voltage proportional to the measured variable. The bridge normally feeds the output signal through a cable to an amplifier which drives either a multiplexer, a control device or a magnetic tape recorder.

The equivalent circuit of the bridge and the cable is shown in Figure 1. The relationship of bridge output V to the measurand A is $V = HA$, where H represents the transfer function from measurand to bridge output. The Thevenin equivalent resistance of the bridge is represented by R. The distributed resistance and capacitance of the cable are shown lumped as R_c and C; cable inductance is not included because its value is not large enough to affect the signal frequencies of interest considered in this article. Noise source V_n represents induced cable noise.

The bridge source resistance and the cable resistance and capacitance place a limit on the signal

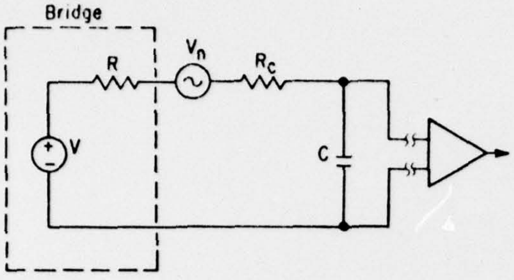

Figure 1. This model of a strain gage bridge transducer/cable combination can help to determine the bandwidth of the system. High values of gage resistance R, lumped cable resistance R_c and capacitance C reduce the frequency response, while cable noise V_n establishes the signal-to-noise ratio of the system.

bandwidth of this system. Using the lumped model, the 3-dB bandwidth BW in hertz is:

$$BW = \frac{1}{2\pi(R+R_c)C}$$

High values of R, R_c or C reduce the frequency response of the system by decreasing its bandwidth; the amplitude of higher frequency signals is thus attenuated to the level of induced cable noise.

As a typical example, a 500-Ω bridge transducer which drives 1,000 m of cable whose parameters are 5 Ω/100 m and 66 pF/m has a 3-dB bandwidth of about 4.38 kHz. Under these conditions, transducer source resistance is more significant than the cable resistance. Cable noise, V_n, is difficult to predict for a given installation, but in this configuration it is added to the signal before amplification. Noise introduced ahead of the first stage of amplification ordinarily establishes the signal-to-noise ratio of any system (Ref. 1).

Since the cable represents a necessary part of the system, unless some type of radio link transmits the signal, a trade-off in cost, bandwidth and noise must be made. The bandwidth can be increased by using expensive cabling which has lower values of R_c and C. However, the source impedance of state-of-the-art piezoresistive transducers is significantly greater than the typical lumped resistance of cable up to 3,000 m long. Referring to the previous example, if the source resistance were zero, the new 3-dB bandwidth would be about 48 kHz.

Two feasible approaches remain to maintain a high signal-to-noise (S/N) ratio: either use a transducer having a high-level output and low-source impedance or process the signal at the output of the transducer. The method described here employs either voltage-to-voltage or voltage-to-current amplifiers (VVAs or VCAs) to process or condition the bridge signal in what can be referred to as a self-conditioning transducer. Either type of amplifier can raise the signal level considerably over the cable noise level and improve the frequency response of the cable link. Since such signal conditioning amplifiers are now packaged as integrated circuits, they can be placed in the transducer case.

VVAs raise S/N ratio, reduce distortion

Various integrated-circuit differential amplifiers, which have an input impedance of 10^{10} Ω and an output impedance of less than 1 Ω, can perform the voltage-to-voltage function. Some notable VVAs are the AD520/AD521 series by Analog Devices and the 3670/3660 series by Burr Brown. These amplifiers, which may have a gain-bandwidth product as high as 20 MHz, can be cascaded to provide high-level output signals at low output impedance for bridge transducers. The circuit designs of these devices, being relatively straightforward, are published by the device manufacturer.

A piezoresistive gage, however, requires regulated voltage for normal operation; it also may be desirable to shunt calibrate the bridge. As shown in Figure 2, the voltage required by the bridge can be obtained from the amplifier's regulated power supply. The shunt calibration circuit may be a simple, inexpensive field-effect transistor (FET) that switches the calibration resistor across one arm of the bridge. If this shunt resistor is switched very quickly by FET Q1, the step response of the entire instrumentation system, from transducer to playback recorder, can be observed. This information may be useful in analyzing the quality of data produced by the system.

Noise pulses on the FET trigger line should not be able to turn on the calibration circuit. As shown in Figure 2, false triggering can be eliminated by a simple RC filter (R17 and C4) followed by a level-sensing comparator A2 which provides fast turn-on. To prevent capacitive loading on the amplifier (A1) output, series resistor R18 is included.

Wire savings, reduced noise with VCAs

Cabling costs can be reduced by converting the bridge output voltage to current form before transmitting it long distance. As shown in Figure 3, a typical current transmitter includes a voltage-controlled current source represented by gV (conductance or $1/R$ times signal voltage), and a constant

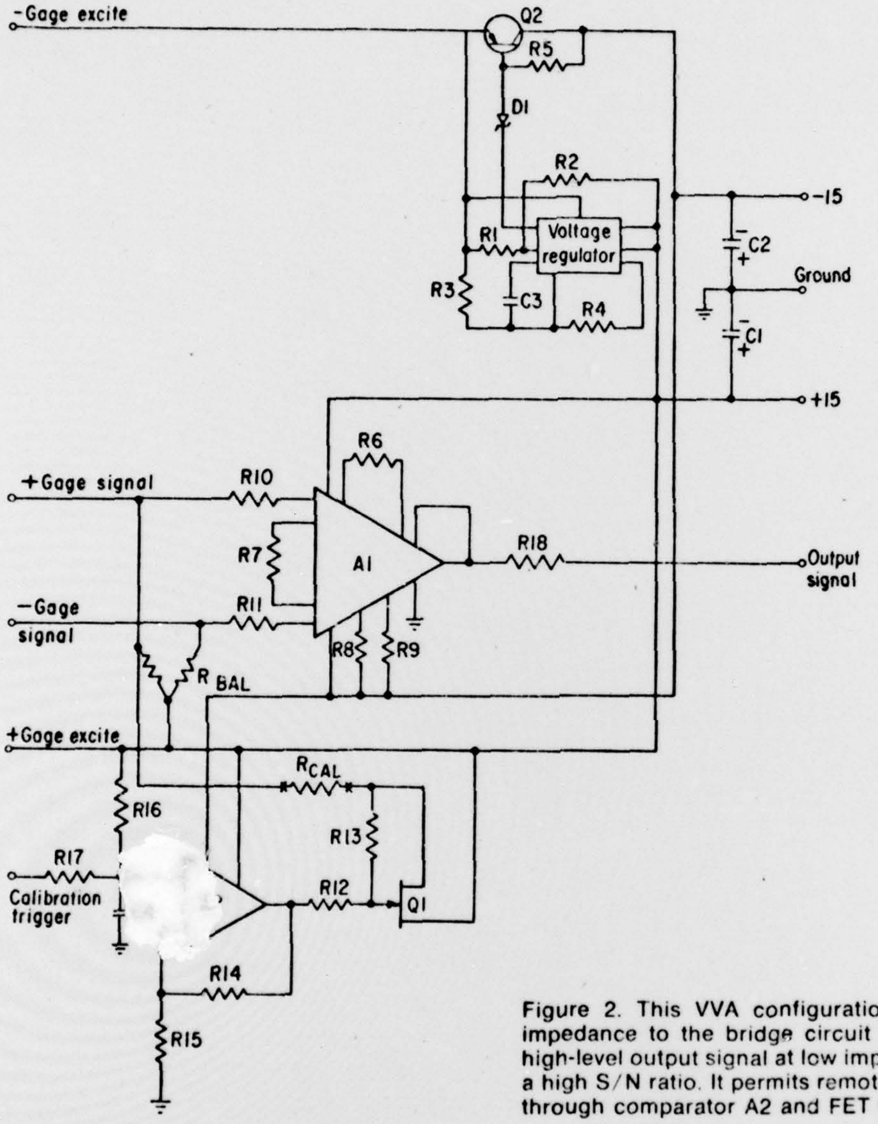

Figure 2. This VVA configuration presents a high impedance to the bridge circuit while generating a high-level output signal at low impedance to maintain a high S/N ratio. It permits remote bridge calibration through comparator A2 and FET Q1.

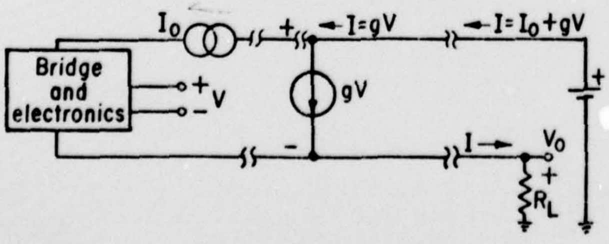

Figure 3. A typical VCA, represented here as gV, generates an output signal which, after being developed across load resistor R_L, returns to the VCA through the power supply. Thus, only two wires are required to power the gage and generate output voltage V_o for a remote data acquisition system.

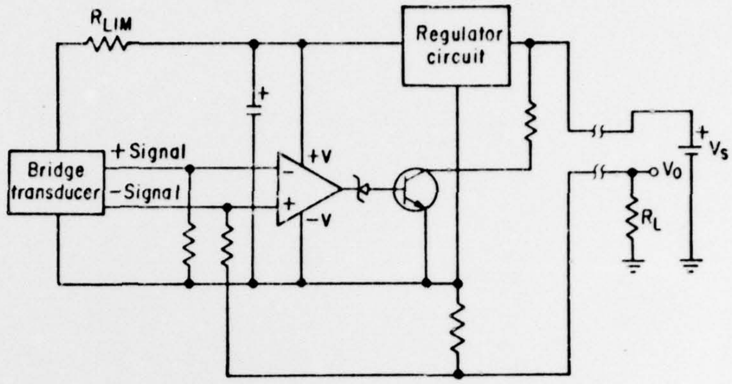

Figure 4. This VCA configuration, suitable for 500 Ω bridge accelerometers may require a limiting resistor, R_{LIM}, in series with the supply line to reduce bridge current drawn from the regulator.

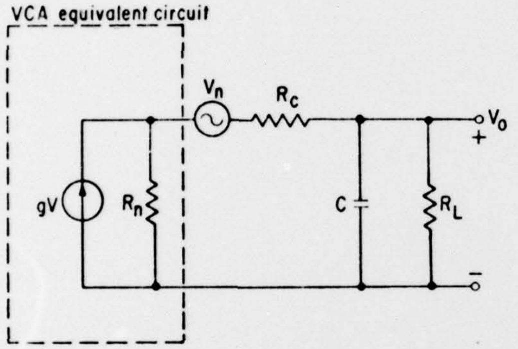

Figure 5. This model of a VCA and its cabling forms the basis for calculating the frequency response of the system. Optimum response is realized when equivalent parallel resistance R_n is maximized.

current source I_o which energizes both the bridge and the amplifier electronics. Since output signal I has a return through the power supply, only two wires are required for both signal and power. The output signal develops across load resistor R_L.

Several two-wire circuit configurations have been published by Burr Brown (Ref. 2); National Semiconductor has integrated two-wire circuitry into its LH0045 transmitter (Ref. 3). Kulite Semiconductor has developed a very stable two-wire design for pressure transducers. The configuration shown in Figure 4, a modified Burr Brown design, can be used with 500-Ω bridge accelerometers (Ref. 4). As discussed previously, shunt calibration of the bridge may be desirable. Unless sophisticated transmitting and receiving circuits are used for calibration, only one additional wire is required for this function.

The frequency response of VCAs is quite naturally a function of the overall gain required for a specific type of transducer. If the two-wire circuit includes an operational amplifier, as shown in Figure 4, the response depends on its gain-bandwidth product and on the gain of the optional output transistor. A series resistor, R_{LIM}, can be inserted in the supply voltage line to the bridge to limit the current drawn from the regulator circuit. However, this reduces the level of the transducer output signal; the increased amplifier gain may reduce the frequency response to an unacceptable level.

The frequency response of a VCA and its cabling may be determined by modeling the system, as shown in Figure 5. The value of Norton's equivalent parallel resistance R_n must be maximized for optimal response.

If the sum of R_n and R_c can be made much larger than the value of load resistor R_L, then the frequency at which the output voltage V_o is attenuated approximately 3 dB is given by:

$$f_{3dB} = \frac{1}{2\pi R_L C}$$

This expression indicates that the frequency response can be improved by reducing the value of R_L and C. However, the amplitude of V_o is also dependent on R_L as expressed by: $V_o = R_L gV$. If gV is 8 mA for example, then $R_L = 125\ \Omega$ with V_o at 1 V. The bandwidth for 3-dB attenuation, based on the original 1,000 m cable having a capacitance value of 66 pF/m, is now 21.2 kHz.

To determine if 1 V across R_L is enough to achieve a high S/N ratio, the noise at R_L must be examined. Noise voltage induced in the cable is shown in Figure 5 as V_N. Disregarding for the moment that cable capacitance reduces the noise bandwidth, noise output is expressed as:

$$N_o = \frac{R_L V_N}{R_n + R_L + R_c}$$

If R_n can be made much larger than R_c and R_L, the denominator of the above expression becomes approximately equal to R_n; noise output N_o is therefore proportional to V_N times R_L / R_n. Thus only a small portion of V_N appears at the output if the value of R_n is much greater than R_L. The combination of R_L and C reduces the noise bandwidth slightly, but the effect is negligible in the frequency range of interest.

Hardware limitations of signal conditioners

One obvious drawback of any self-conditioning transducer is the possibility of failure after installation. The probability of such failures can be reduced by burning in the electronic circuits before placement. In addition, overvoltage protection devices can be placed in the cabling at an accessible point as close to the electronics as possible.

Temperature drift, slewing response and other nonlinearities in VVA circuits are essentially those inherent in the instrumentation amplifier or strain gage elements of the transducer itself. These limitations do not appreciably affect the quality of signals generated at the VVA output during most routine measurements.

Current transmitting VCA circuits, on the other hand, may exhibit various types of nonlinearities in amplitude and frequency response of the output signal. The primary cause of nonlinearity in VCAs is temperature variation. Temperature shifts may occur during the generation of the output current changes. The amplifier gain is sensitive to such thermal changes and may cause the signal amplitude to vary in a nonlinear manner. Such variations in heat dissipation may be minimized by reducing the value of ΔP in the following expression:

$$\Delta P = (I_2 - I_1)\ [V_s - R_L(I_1 + I_2)]$$

where ΔP is the change in device power to be dissipated for a current change from I_1 to I_2, which are the minimum and maximum output currents, respectively. V_s represents the supply voltage. The maximum total power P_T required by the system is: $P_T = V_s V_m / R_L$ where V_m is the maximum voltage across R_L. For example, for a system which requires a 28-V supply and has a 15.5 V_m and a 125 Ω load resistor, P_T is 3.47 W, of which 1.55 W is dissipated in the VCA and 1.92 W in R_L. (In this case, the sum of I_1 and I_2 would have to be 224 mA to make ΔP equal to zero. The power dissipated in the VCA must be sinked to the surrounding environment to prevent overheating and possible component damage.

A significant portion of the power dissipation problem results from gage current flowing through the load resistor. The total power required can be reduced considerably by using gage elements which have high resistance.

If the amount of cabling required for a test measurement must be limited, the VCA appears to hold the advantage; however, if the sensors are mounted near each other, one set of VVA power, ground and calibration leads can serve several units. For example, three transducers with VVAs located in close proximity would require seven leads—two power, one ground, three output and one calibration; the VCA-based transducers need five leads—three output, one power and one calibration. Figures 2 and 4 show the power and output connections of typical VVA and VCA signal conditions.

It appears that for bridge type gages of less than 500 Ω resistance, VCA converters must dissipate more power than VVA converters. In addition, the VCA converter produces a lower level signal and a larger offset voltage than the VVA.

Further design improvements and high resistance transducers will help to overcome present limitations of VCA circuits so that designers can take full advantage of the reduced noise levels and wire savings they provide. Several VVA circuits now available provide high frequency response, high signal levels and excellent linearity. For either high- or low-resistance bridge transducers, the VVA offers a simpler approach at the present time.

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