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DETERMINATION OF EQUIVALENT CIRCUIT FOR PVDF SHOCK-PRESSURE GAUGES

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Broadband impedance measurements of a PVDF shock-pressure gauge are used to build an equivalent circuit for the gauge. The essential components are a gauge capacitance and a low-loss transmission line. Component features are consistent with the physical characteristics. With knowledge of this circuit, troublesome oscillations can be anticipated and prevented.

INTRODUCTION

Polyvinylidene fluoride (PVDF) shock-pressure gauges are an interesting subset of piezoelectric devices because of applications as electromechanical transducers.¹ In some applications, an equivalent circuit helps clarify the device operation and extend its range of operation. For piezoelectric devices, such equivalent circuits may be complicated, with multiple stray capacitances and associated inductances required to explain the system response.² Building an equivalent circuit for the PVDF devices used to record shock-pressure waves is a critical step toward understanding electrical resonances that interfere with accurate measurements. We outline our use of the pressure gauges, review the measurement difficulty, develop the equivalent circuit, and show how the circuit accounts for the behavior.

GAUGE BEHAVIOR

Figure 1 shows a PVDF gauge. The two 44-mm-long (after cut to length for use) sputtered Au-over-Pt leads form a lossy transmission line. The two leads are deposited on opposite sides of the 23.1- μm -thick PVDF polymer film. Each lead is 3 mm wide and $>0.2 \mu\text{m}$ thick. At one end the leads form a capacitor with crossover area 9.2 mm^2 and capacitance 44.1 pF at low frequencies. This region is the active area that drives the gauge. As manufactured, the lead resistances add to 9.2 Ω . Each gauge has a serial number (E530H10 here). These data are provided by the manufacturer, Metravib RDS, France.

In a typical application, a shock wave passes from the front to the rear electrode of the capacitor, displacing charge through the piezoelectric effect.³ Increases in the shock stress increase the

Fig. 1. Projected view of PVDF gauge.

displaced charge. The charge propagates down the leads forming the strip transmission line and induces a voltage across a current-viewing resistor (CVR) connected across the open end of the leads in Figure 1. A 50- Ω coax carries this signal to the recorder. The CVR has an accurately measured resistance near 0.01 Ω . Figure 2 shows the record of a typical shock wave and the resulting current in the CVR. The current reaches a 97-A peak, with a 4-ns full-width-at-half-maximum.

Even though the current from the gauge typically maintains the general characteristics in Figure 2, at times the current pulse is quite different. Figure 3 shows spurious oscillations from the electrical-circuit response that interfere with analysis of the pressure data. A Fourier transform of the data in Figure 3 shows a spectral peak near 200 MHz.

EQUIVALENT CIRCUIT FOR PVDF GAUGE

Figure 4 shows an equivalent circuit.⁴ The current produced by the mechanical stress is modeled by a current source in parallel with the capacitance of the gauge active area. The R_m and L_m allow for a large resistance and inductance that may also appear across the active portion. The electrode section is characterized by an inductance L_e , capacitance C_e , and resistance R_e per unit length for the strip transmission line.

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Fig. 2. Pressure wave incident on PVDF gauge and resulting current across CVR. $R_{CVR} = 0.01016 \Omega$, gauge area 9.095 mm^2 .

Fig. 3. Oscillatory current induced into CVR. $R_{CVR} = 0.01986 \Omega$, gauge area 9.050 mm^2 .

Fig. 4. Lumped parameter model for PVDF gauge and associated circuitry.

The R_{ep} allows for the possibility of a small conductivity in the PVDF material between the electrodes forming a resistive shunt path. The CVR resistance is R_p . The L_c , R_c , and C_c are lumped parameters representing the 42-ft-long

cable transmitting the signal to a $50\text{-}\Omega$ load at the digitizer. In many cases, especially for long cables, these lumped parameters are better represented as a transmission line. Here our emphasis is on the components shown in Figure 1.

Several parameters in Figure 4 can be assigned approximate values. From cable characteristics, $C_c = 1 \text{ nF}$, $L_c = 25 \mu\text{H}$, R_c is negligible, $R_p = 0.01 \Omega$. Termination impedance at the digitizer is 50Ω . Remaining parameters characterize the basic gauge in Figure 1.

A coax test lead (connector) was soldered to the open gauge leads in Figure 1, and this configuration was probed by an impedance analyzer over the range 1 MHz to 1 GHz. To ensure that the results represent the geometry, separate measurements were made for the connector, the connector plus gauge strip leads, and the connector, gauge leads, and the gauge capacitor all assembled. The connector behaves as a 1-pF capacitor.

The gauge leads are represented by a coplanar-strip parallel-wire transmission line with leads of width $w = 3 \text{ mm}$ separated by distance $b = 1 \text{ mm}$, embedded in a material with effective relative dielectric constant $\epsilon_r(f)$. The leads have a characteristic impedance (Reference 5)

$$Z_0 = 120\pi \frac{K(k)}{K(\sqrt{1-k^2})} \frac{1}{\sqrt{\epsilon_r}},$$

where K is the complete elliptic integral of the first kind, ϵ_r is the relative dielectric constant of the surrounding medium, and $k = b/(b+2w) = 1/7$.

When the connector and lead measurements are made, the connector is in parallel with the input impedance of the transmission line. For a line of length l with an open-circuit termination (for the leads alone) and with characteristic impedance Z_0 , the input impedance is⁶

$$Z(l) = Z_0 \left(\frac{1 + e^{-j2\beta l}}{1 - e^{-j2\beta l}} \right).$$

The $j\beta$ is the imaginary portion of the propagation constant. At low frequency, $\beta l \ll 1$, and $Z(l) = Z_0/(j\beta l)$ for a lossless line and for $2\beta l < 0.05$. Assuming quasi-TEM propagation,

$$\beta = 2\pi f \sqrt{\epsilon_r}/c,$$

where c is the speed of light in free space. Removing the connector contribution from the connector and leads measurement gives data for $Z(l)$. Using the low-frequency $Z(l)$ and neglecting losses, the expression for Z_0 allows the effective relative dielectric constant, ϵ_r , to

be evaluated: $\epsilon_r = 1.53$. This gives the gauge strip transmission line a characteristic impedance $Z_0 = 141.8 \Omega$ and a phase velocity $c/(\epsilon_r)^{1/2} = 2.43 \times 10^8$ m/s. These values provide estimates for the transmission line parameters, C/l and L/l . From $Z_0 = \sqrt{L/C}$ and phase velocity $= 1/\sqrt{LC/l^2}$, we find $L/l = 0.583 \mu\text{H/m}$ and $C/l = 29.0 \text{ pF/m}$.

Figure 5 shows measurements for the three connected components (gauge active region, gauge strip leads, and connector). At low frequency, the circuit reacts as a 1-pF capacitor in parallel with 21 pF from the gauge capacitance. At 230 MHz, the gauge strip-lead inductance contributes to form an impedance minimum, characteristic of a series RLC network. As in Figure 4, a lumped-parameter model can account for this resonance, but the model would be valid only in a narrow frequency band centered at the resonance. Additional elements would be needed to generate the parallel-circuit resonance near 800 MHz. As we will see, **the only components needed to match the measurements are the connector capacitance, gauge strip transmission line, and gauge capacitance.** With analysis, circuit parameters are identified that are consistent with the problem geometry and the measurements. Stray elements are not required to represent the gauge (because it is sufficiently isolated from surrounding connectors).

Fig. 5. Measured and calculated impedances for the connector, leads, and driving capacitor of Sample E530H10.

Circuit Resistance, Losses

Figure 5 shows an impedance minimum near 15 Ω . For a series RLC network at resonance, this value is the resistance, R . Gauge data suggest 9.2 Ω for the total gauge-lead resistance. The circuit losses are modeled by including loss in the propagation constant ($j\beta$ is replaced by $\alpha + j\beta$). The

attenuation constant, α , is the sum of two contributions—conductor loss and dielectric loss.

Conductor loss is caused by lead resistance and by the reduced effective cross-sectional area resulting from the skin effect. The skin depth of Au is 2.5 μm at 1 GHz, a factor of 10 greater than the lead thickness, consistent with the earlier thin-lead approximation. However, the 3-mm width, which is significant relative to a skin depth, causes current concentration at the edges as frequency increases. When the skin effect dominates, this increases the resistance by a factor proportional to $\sqrt{f}$.

Because the dielectric loss is not explicitly known, $Z(l)$ data are used to generate α . Results are shown in Figure 6. The unit Np (neper) is the natural logarithm of the attenuation factor. At 10^8 Hz, attenuation of the 44-mm transmission line is $\exp(-0.4 \text{ Np/m} \times 0.044 \text{ m}) = 0.9826$. Because losses are small at low frequencies, the previous analysis assuming lossless dielectric behavior of the strip line is still valid.

At low frequencies, the slope in Figure 6 suggests that α is proportional to f^n . A value of $n = 1/2$ is an obvious effect of skin depth. However, the exponent is closer to 5/3. Dielectric loss of the strip transmission line dominates, even at the lower frequencies in Figure 6.

Fig. 6. Frequency variation of attenuation coefficient for transmission-line leads, S/N E530H10.

Gauge Capacitance

The final problem is to identify an equivalent circuit for the PVDF gauge active area. The device geometry suggests modeling simply as a parallel-plate capacitor. This capacitance is extracted from the measurements of the overall system while compensating for the impedance of the strip transmission line and the connector. $C_m = 20.0 \text{ pF}$ gives a reasonable match to data for

$1 \times 10^6 \leq f \leq 1 \times 10^9$ Hz. The change in slope of the impedance at ~ 5 MHz in Figure 5 suggests that dielectric constant decreases as frequency increases. Reference 7 verifies this behavior for poled PVDF at constant pressure in frequency range $1 \leq f \leq 20$ MHz. The ratio of dielectric constant at 1 kHz to its value at 10 MHz is 2.2,⁷ the same as that of the low-frequency capacitance, 44 pF, to the 20 pF we found appropriate for our high-frequency model.

Complete Model of Gauge Measurements

The essential components are identified in Figure 7: a capacitor for the active area, a transmission line for the strip leads, and a capacitor for the connector. Figure 5 shows good agreement between the modeled and measured impedance. Some discrepancy does exist in resonant frequency and shape of the resonance. A more appropriate model would include frequency variation of the PVDF film between the capacitor plates.

Fig. 7. Schematic model for PVDF gauge, its strip transmission line leads, and the connector needed for impedance measurements.

The presented model is appropriate for the initial state of the gauge, while stresses remain low. During actual use, the capacitance is time dependent as the shock wave compresses the active dielectric and reduces the plate separation. Shock pressures of 20 GPa, with shock velocities ~ 5 km/s, compress the $23.1\text{-}\mu\text{m}$ PVDF to 60% of its original thickness within a few nanoseconds. The dielectric constant also increases as the shock pressure increases.⁸ Thus, the compression increases the capacitance and reduces the resonant frequency as time progresses. But a dynamic model awaits another report.

CONCLUSIONS

A technique is presented to model a PVDF shock-pressure gauge in a realistic manner over a large frequency range. This is realized by identifying the appropriate subcomponents and ex-

tracting their parameters from measurements consistent with their physical characteristics. The three components are the connector, strip-line leads, and PVDF active area. The model estimates agree with the measurements and predict device resonances. We presented data for a 9-mm^2 gauge. PVDF gauges with areas $\sim 1\text{ mm}^2$ have also been analyzed, with the same model agreement. Different PVDF geometries can be analyzed by inserting the appropriate subcomponent parameters and model into the overall model. Design tradeoffs then allow optimization of the response for applications. In particular, circuit alterations (such as a simple $100\text{-}\Omega$ resistor in series with strip-line leads) can prevent a deep minimum in impedance variation with frequency and inhibit troublesome oscillations from interfering with measurements.

ACKNOWLEDGMENTS

This work, performed at Sandia National Laboratories, was supported by US DOE under contract DE-AC04-76DP00789. R.P. Reed of SNL/NM furnished helpful discussions and manuscript review.

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