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Measurement Techniques for Electrothermal-Chemical Gun Diagnostics

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December 1993

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1. INTRODUCTION

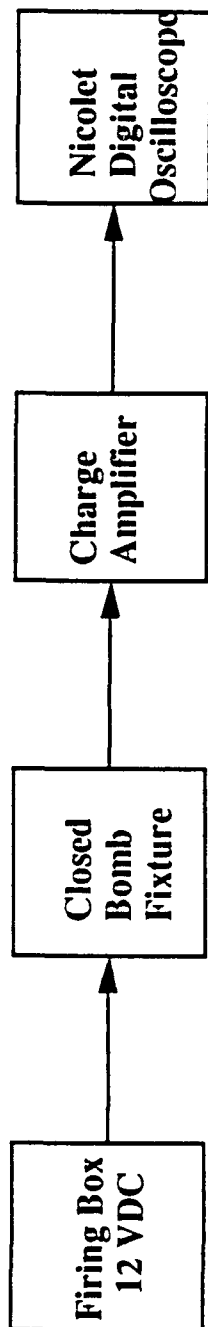
Methods of acquiring experimental data including pressures, pulse forming network (PFN) currents, and voltages with a minimum of electrical noise that are critical to electrothermal-chemical (ETC) ballistic and combustion experiments are described. Measurements are performed in a 30-mm ETC gun facility that is driven by a 130-kJ (maximum) pulsed-power supply and a 50-cm³ closed chamber facility using a 300-kJ power supply, both of which are located at the Army Research Laboratory (ARL), Aberdeen Proving Ground, MD. Strict attention is devoted to grounding of measurement and data-recording devices, as well as in shielding of measurement electronics, data lines, and high-power modulator components with "Faraday" enclosures.

Tests are performed that compare fiber-optic measurements with directly measured signals. A design of a third-order, low-pass filter is given, and its attenuation effect on high-frequency noise is demonstrated both analytically and experimentally. The use of ferrite rings on data lines and 60-Hz power lines is frequent and fiber optical links are used for electrical isolation between data recording equipment and high-voltage components. The experimental arrangements and resulting data are presented and a discussion of the data and conclusions are included.

2. BACKGROUND

The recording of experimental measurements in an ETC environment is complicated by the presence of a large, noise-producing source, namely, the PFN. The block diagram (Figure 1) can be used to compare fundamental differences in measurements made in an ETC environment to those made in a conventional ballistic diagnostic facility. The most significant difference between the two arrangements shown in Figure 1 is that of a high-energy PFN in an ETC gun facility. While the PFN is an essential source of electrical energy needed to initiate the combustion process of an ETC combustion event, it is also, unfortunately, the source of large amounts of electromagnetic radiation that can interfere with small signal experimental measurements. In fact, it has been reported in some ETC experiments the plasma generator itself causes electrical disturbances due to the violent electrical ignition of the fuse wire contained within the plasma capillary tube (Oberle 1993). As a result of these problems, much time has been devoted to the arrangement of the data acquisition systems of the ARL's ETC facilities, which are responsible for the measurement of experimental quantities. The following will provide a description of some of the measurement techniques that are used to help obtain reliable, noise-free experimental data.

CONVENTIONAL



ETC

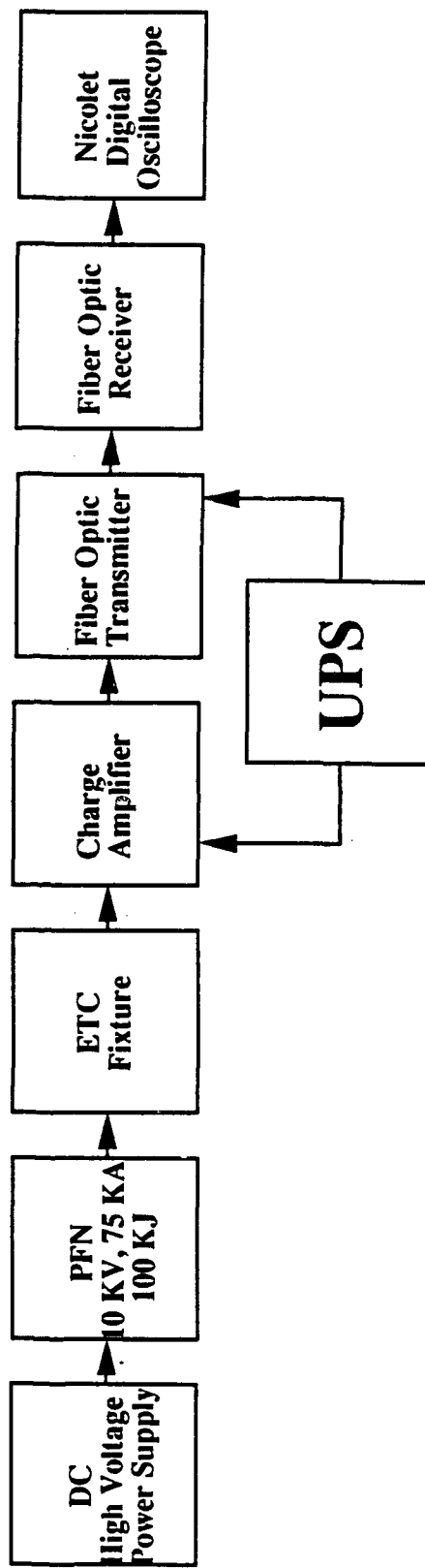


Figure 1. Comparison of ETC to conventional data acquisition systems.

3. PROCEDURE

The experimental arrangement employed in the 30-mm ETC facility, shown in Figure 2, consists of various data acquisition equipment, a grounding system, the electrical power supply (including the high-voltage DC charging supply and the PFN), an ETC diagnostic fixture, and a system of amplifiers and optoelectronics, which are used to transmit pressure measurement data. Nicolet digital oscilloscopes are used for the recording of experimental pressure, voltage, and current measurements, with the feature of digital data storage on 5.25-in floppy disks. As indicated in Figure 2, two separate locations are used for grounding of the oscilloscopes, and, to date, the resulting measurements in each case have provided very reliable experimental data in terms of immunity to electromagnetic interference (EMI) as in the experimental data taken by White et al. (1991). In systems such as this one, in which circuit impedances are measured in milliohms, a major noise-producing mechanism accompanying electromagnetic disturbances is the induction of current flow in measurement cable shields (Burden and Shear 1969). Because this requires a loop surrounding a changing magnetic field, a single point ground is a first requirement. The major system ground (labeled #2 in Figure 2)—actually the massive, heavily reinforced concrete gun mount which extended down 6 feet into moist ground—was accordingly defined. Thus, the oscilloscopes which attach directly to the discharge circuit are grounded only at this ground; isolating plugs are employed to prevent completion of the loop through the power line ground. (Such loops, in which the conductive ground forms part of the path, are called "ground loops.") The charge amplifiers and fiber optic transmitters are, perforce, grounded to the ETC chamber through the shields of the cables from the pressure gages mounted in its walls. While this is not precisely at the system ground, the chamber's outer walls have large conducting area and conduct no massive discharge currents and are thus electrically close to ground. The charges produced by these gages are measured in microcoulombs and the voltages derived are measured in millivolts; consequently, only very small noise voltages are permissible. To achieve these small values, two measures are taken. First, battery operation of the charge amplifiers and optical fiber transmitters is used, the batteries being provided by an uninterruptible power supply (UPS) unplugged from the AC line at shot time. Second, because the capacitance between any device and ground can complete a ground loop, double shielding—essentially Faraday shielding—is used around the signal cables and the electronic units.

Two other grounds are used. The first (labeled #1 in Figure 2) is undesirable but necessary for safety. It is the service ground to the high-voltage power supply as required by the National Electrical Code.

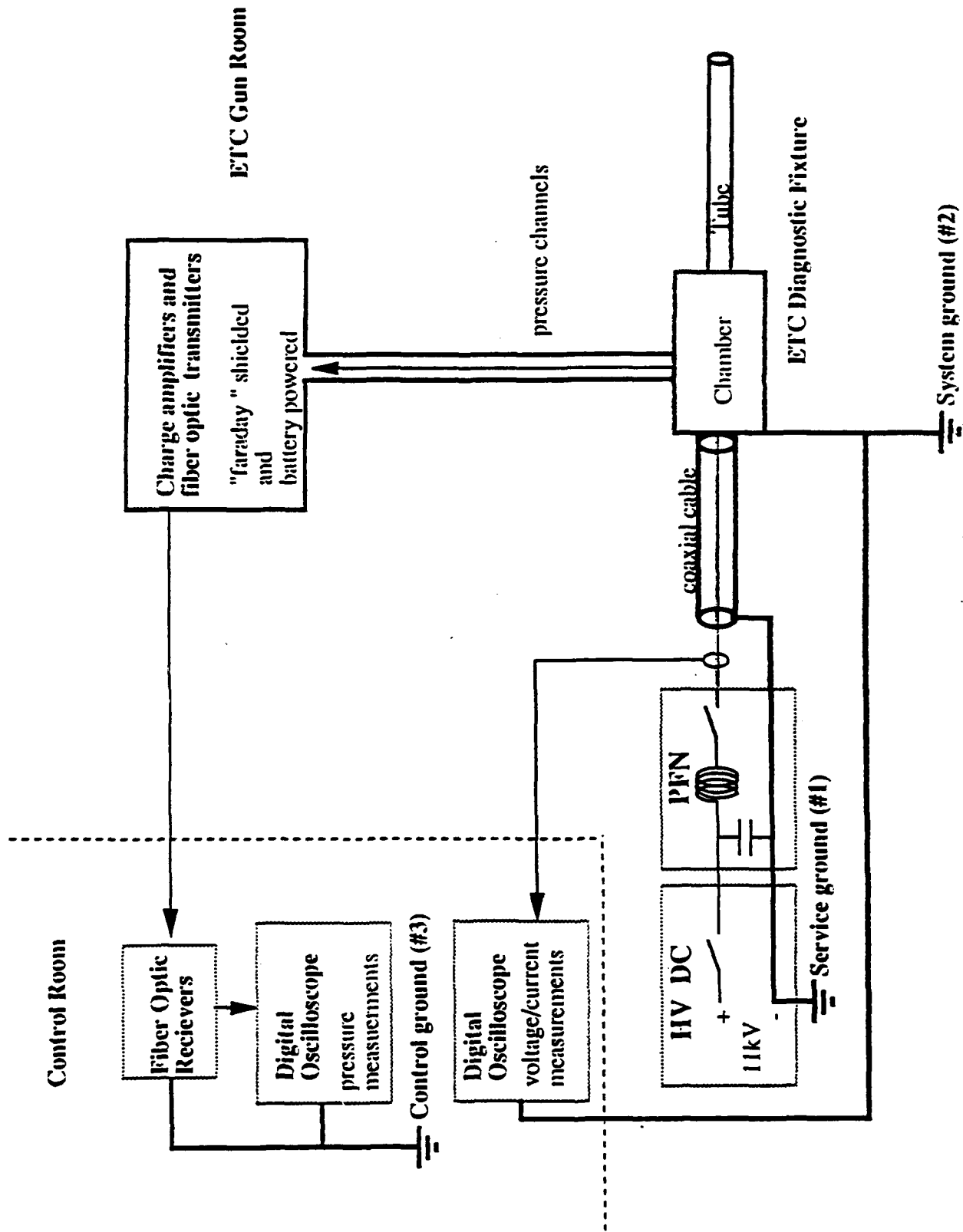


Figure 2. ETC gun diagnostics arrangement.

Because of its comparatively high inductance, it probably carries relatively little current from the discharge; also, the loop includes no signal circuitry so its effect is relatively unimportant. The second (labeled #3 in Figure 2) is the ground for the pressure measurement oscilloscopes. Since the output voltage levels from the optical fiber receivers are relatively high and the only loop of significance (the short link between optical fiber receiver and the oscilloscope) lies entirely in the recording room, a single earth ground, separate from the system ground and isolated from the AC service ground, was used here.

Kistler 607C piezoelectric pressure transducers were used for sensing chamber and gun tube pressures; experience at ARL confirmed the observation of personnel from GT Devices that those transducers containing internal signal conditioning electronics (voltage mode) are more susceptible to electrical noise than are straight (charge mode) piezoelectric transducers. Output from the transducers was converted by Kistler Model 5004 charge amplifiers to a voltage signal that can be recorded with digital oscilloscopes. Powell and Zielinski (1992) at the ARL successfully measured pressure between the anode and cathode of an ablating capillary discharge tube using essentially the same technique except that coupling to the oscilloscope was direct rather than optical.

3.1 Fiber-Optic Link Experiments. Frequency-modulated optical links (Dymec model numbers 6723/6722) are used to provide electrical isolation and are incorporated into each pressure measurement channel. The optical links have an analog bandwidth of DC to 1 MHz, which is more than adequate for the signals that are measured in this application (~50 kHz), and rely on frequency modulation of a 9-MHz carrier signal for data transmission. Because of the frequency modulation technique, the links are inherently less sensitive to attenuation and losses due to optical connectors or other perturbations in the optical fiber. Operational issues that are relevant to this particular application of these optical fiber links have been addressed by Fortier et al. (1992) at the ARL. As indicated in Figure 2, the optical transmitters and the charge amplifiers are located in the interior of a "Faraday," or shielding box, which is used to protect the equipment from electric fields. Each individual piece of equipment inside the Faraday box is physically separated with nonconductive material from the other equipment and the structure of the box itself. Also, each piece of equipment had its electrical power (110 V, 60 Hz) supplied by a single 750-VA UPS. The thought behind the three elements of EMI shielding, single point grounding and the use of a UPS, as previously discussed, is to prohibit the generation of EMI noise and to prevent ground loops or paths which aid in the flow of noise current through grounded wires of data signal paths (Burden and Shear 1969).

The susceptibility of the fiber-optic link to electrical noise has been experimentally tested at the ARL in the 130-kJ/30-mm ETC Diagnostics Laboratory. The purpose of the following test was to determine what grounding and power-source configurations for an optically coupled data acquisition are most successful in terms of acquiring noise-free electrical data. This is done by making comparisons of direct measurements with optically coupled measurements, the latter of which are sensitive to grounding and power supply noise due to the added complexities of their receiver and transmitter electronics. Since, under normal operating circumstances, it is required to make these measurements in the harsh EMI environment of a discharging power supply, this experiment consisted of making measurements during the discharge of the 130-kJ PFN into a fixed 35-milliohm resistive load. The PFN was discharged three times with a different data acquisition arrangement each time (i.e., different primary power and EMI shielding arrangement). During the discharges, measurements were made of the time rate of change of the load current (di/dt) via a Rogowski coil. A current waveform is obtained by performing a numerical integration on the resulting di/dt waveform. The accuracy of the current waveform is dependent upon the di/dt waveform; therefore, it is essential to make extremely accurate di/dt measurements. The output from the Rogowski coil was coupled, in parallel, to separate digital oscilloscopes for each of the three discharges. One measurement is made directly with a Nicolet model 4094 digital oscilloscope while another is optically coupled via a frequency modulated, Dymec fiber-optical system as previously described. A 100-m length of fiber-optic cable was used to connect the optical transmitter with the receiver. With the experimental setup as just described, a comparison between the direct measurements and optically coupled measurements was made. To rule out inconsistencies in noise levels in the laboratory during the test, the initial stored energy level of each discharge is kept constant at 10 kJ.

The setup of equipment in the first discharge is shown in Figure 3. The optical transmitter is placed physically close to the PFN (approximately 0.5 m away from output connection), and it is powered by a 110-V AC receptacle outlet. The receiver is also powered by an outlet; however, the grounding prong on the receiver unit is intentionally disconnected with the use of an adapter plug. The receiver output is terminated at the input of the second 4094 Nicolet oscilloscope, which also has an adapter plug disconnecting the grounding wire. The resulting measurement of di/dt (Figure 4a) as recorded directly with an oscilloscope, was free from noise; consequently, the integrated waveform produced a noise-free load current trace. On the other hand, the measurement obtained with the fiber-optic link (Figure 4b) was very badly distorted, and it does not least resemble the true waveform.

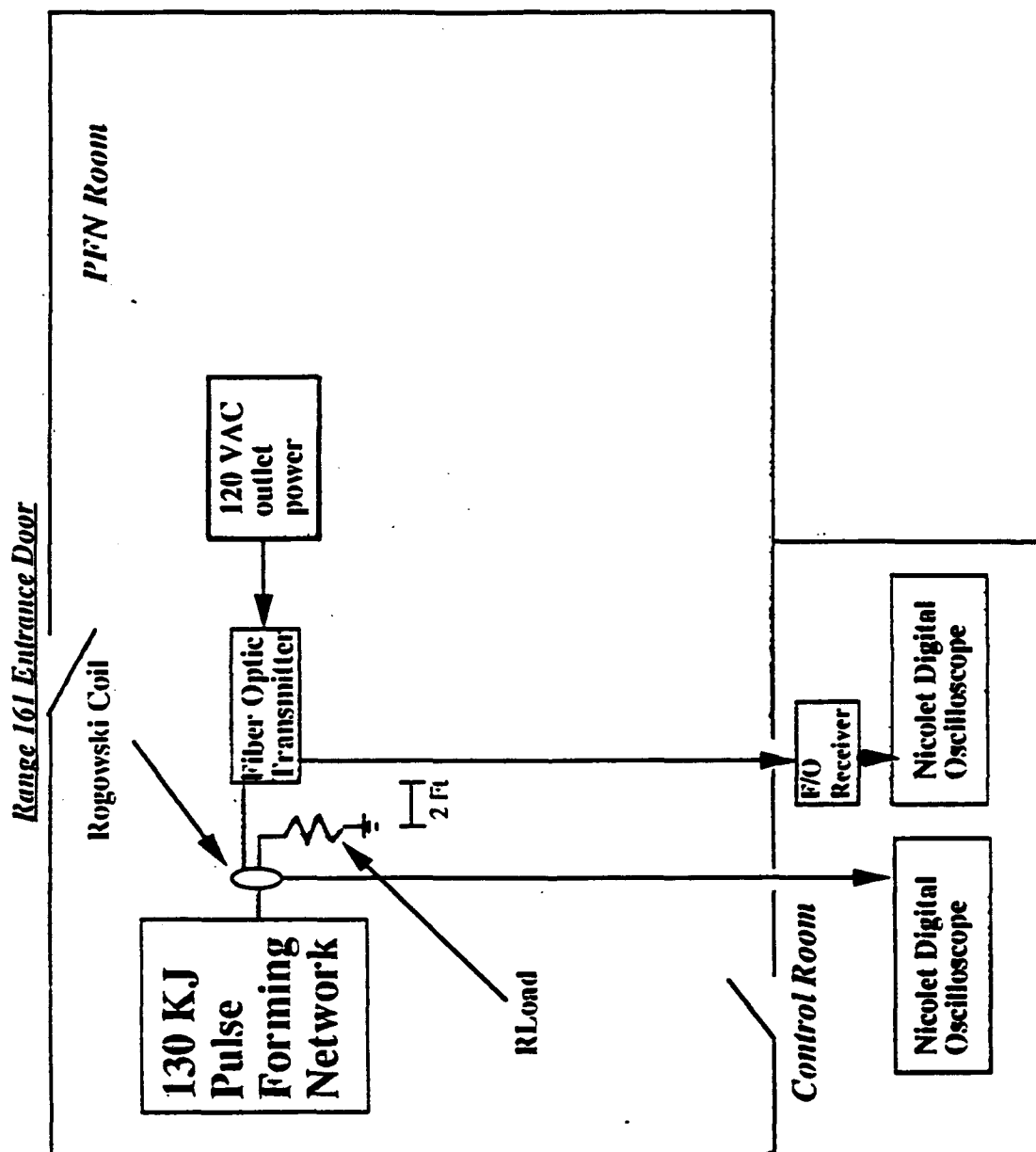
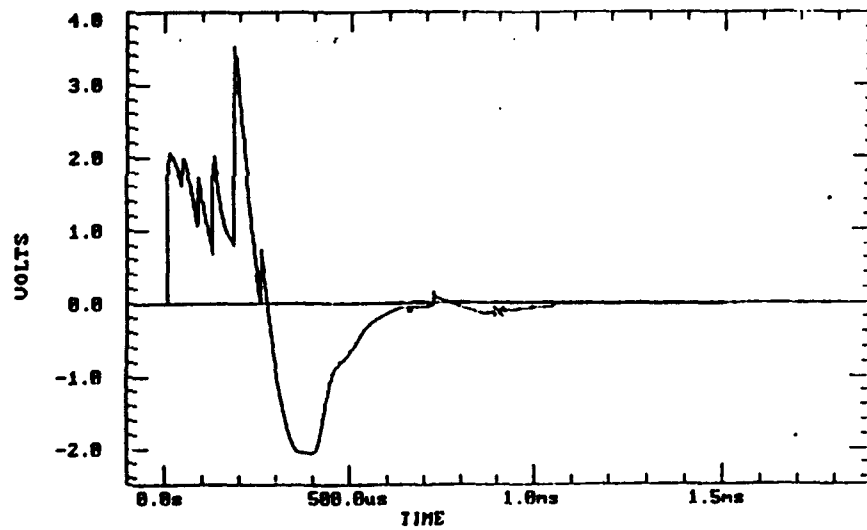
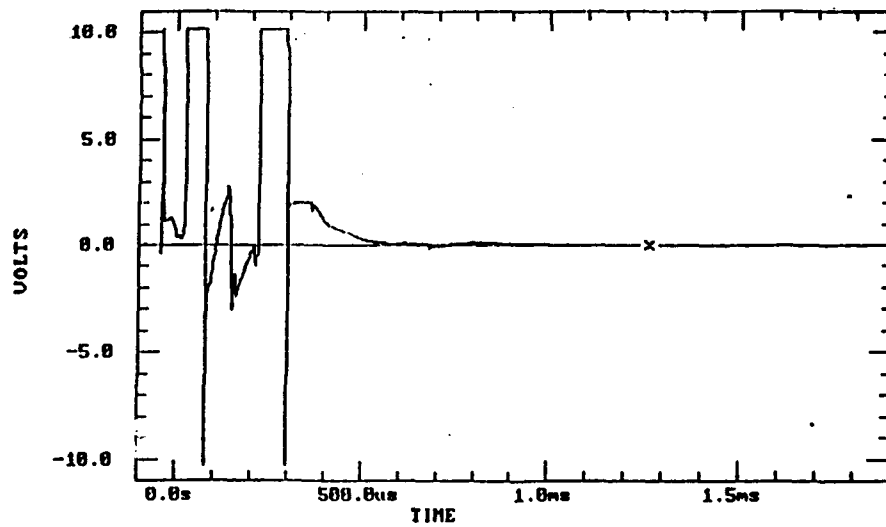


Figure 3. Pressure measurements with oscilloscope grounded at control room ground.



(a) Direct



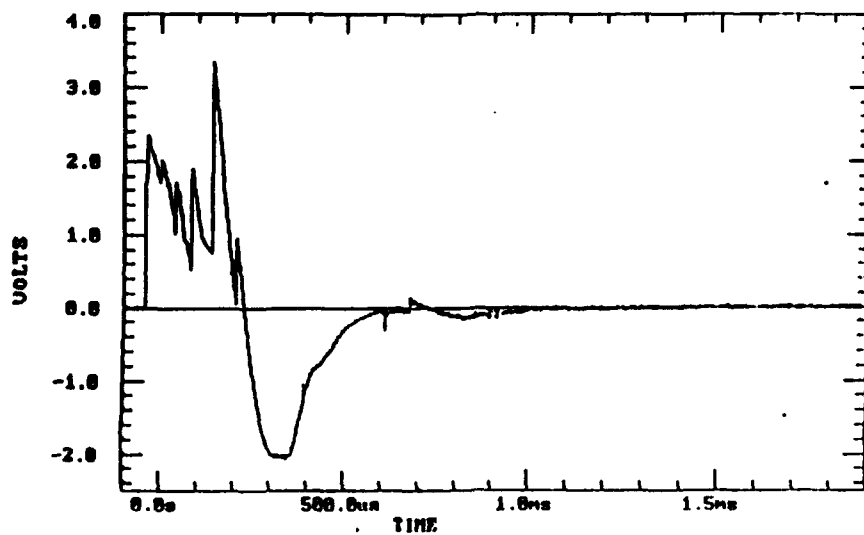
(b) Optical

Figure 4. Load di/dt waveforms for the first discharge, (a) direct and (b) optically coupled.

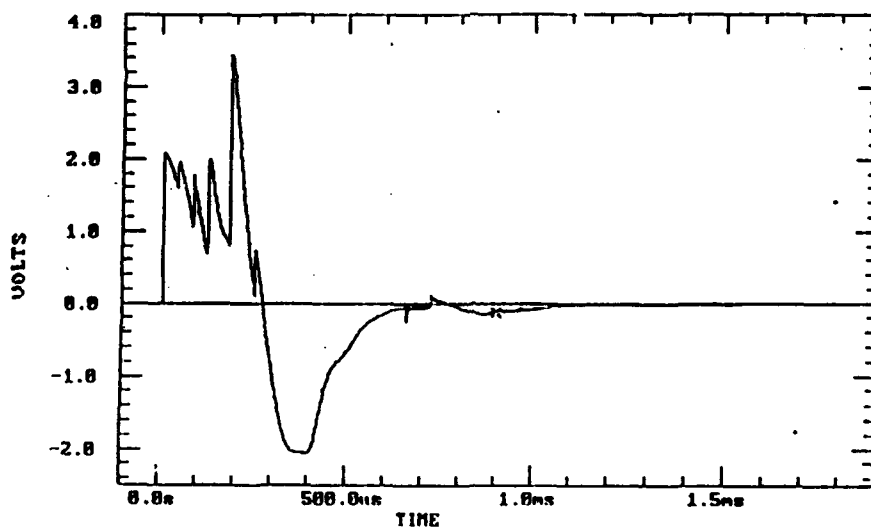
For the second discharge, the fiber-optic transmitter was powered by a UPS. The UPS was disconnected from the utility power system; therefore, it is supplying the transmitter from a converted DC battery supply, which is completely electrically isolated from the utility network. The location of the UPS is in the interior of an ungrounded, metal Faraday enclosure that was located 2 m away from the nearest current-carrying component (prepulse bank ignitron) of the PFN. The UPS is electrically isolated from all parts of the metal enclosure and a household grade extension cord, running parallel to the PFN, is used to connect the UPS to the optical transmitter. This arrangement of the transmitter and UPS is such that all equipment on the measurement, or transmitting side, is ungrounded or left "floating" from the PFN and utility grounds. The AC cord of the UPS is external to the Faraday enclosure, and the fiber-optic receiver and oscilloscope are set up identically as in the first discharge. In this case, the resulting measurements (Figure 5) from both arrangements are free of noise, and, in fact, they are nearly identical when compared directly.

For the third and final primary power arrangement, the experiment was unchanged with the exception of the removal of the UPS from the enclosure to a location just 0.5 m from the PFN load/output connection. The results from this configuration were very similar to the data obtained in the second configuration thus indicating that the power source isolation proved by a UPS or similar unit is highly useful in minimizing electrical noise in data systems. As is illustrated by our efforts with the very sensitive charge amplifiers, the degree to which such means alone are useful will depend upon the circuit arrangements, the relative noise and signal levels, and the sensitivity of the equipment involved. Figure 6 shows a plot of the optical measurement values subtracted from the direct measurement values. Dividing this result by the value of the direct measurement and multiplying by 100 yields the percent error between the two approaches, as illustrated in Figure 7. More will be said about the error in the optical measurement in the discussion section of this report.

3.2 Filter Design Experiment. A transient noise problem associated with the UPS was observed during similar tests. Amplitude peaks or "spikes" in line voltage were introduced into the pressure channels (see Figure 8) by the switching circuitry of the UPS. Figure 8 shows the response of a pressure transducer mounted in the chamber of an unpressurized ETC fixture. The arrangement for this pressure channel is as shown in Figure 2. The UPS was in the battery powered mode, and it is supplying inverted AC power to the charge amplifier and the optical transmitter. It was noticed that with only the UPS operating, transient voltage waveforms with peak amplitudes of about 100 mV are introduced into the pressure channel. Because the transient noise repeats with a 16.7-ms period it is almost certainly a result



(a) Measured di/dt (direct)



(b) Measured di/dt (optical)

Figure 5. Load di/dt waveform for second discharge, (a) direct and (b) optically coupled.

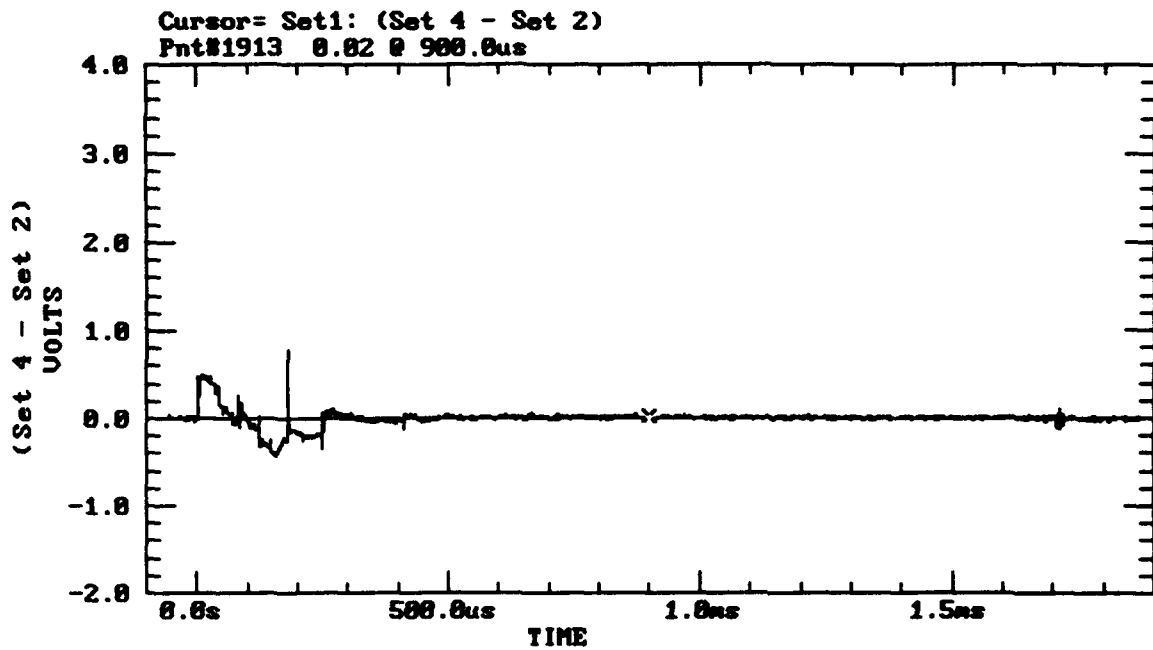


Figure 6. Optically coupled waveform subtracted from direct coupled waveform.

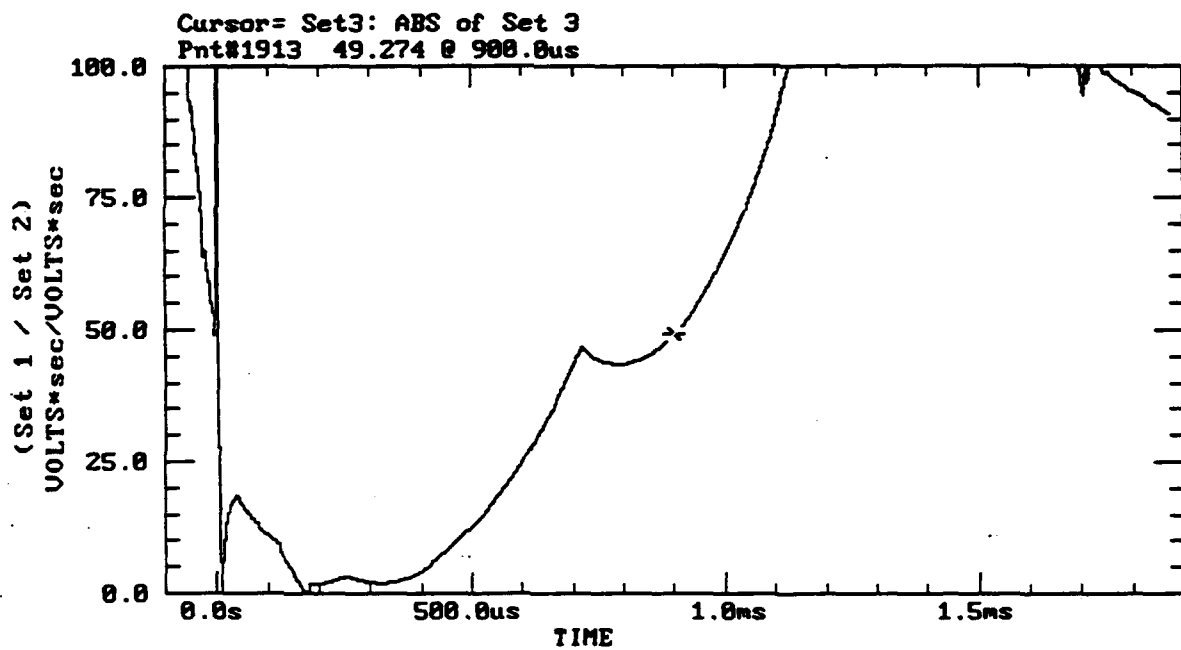


Figure 7. Percent difference of optically coupled and direct coupled waveforms.

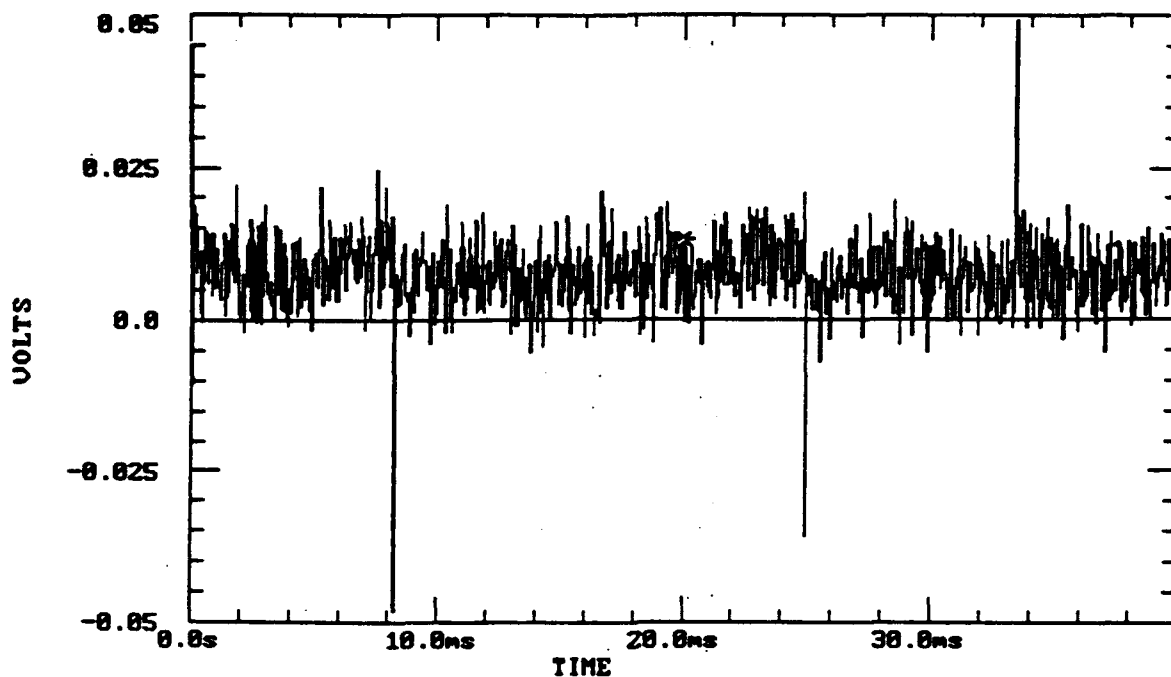


Figure 8. Pressure channel response with transient noise interference.

of the conversion process in the 60-Hertz UPS power source. Further, because the UPS inverter completes a positive and a negative excursion in each cycle, positive as well as negative transients should occur during the 16 ms; this too is evident in the waveform of Figure 8, except that a positive 500-mV spike expected at 16 ms on the plot is missing. This was lost by the oscilloscope because its digital sampling rate was not high enough to capture all the transient portions of the waveform in this particular time window.

One solution to this problem was in the design and implementation of a third-order, low-pass filter with a cutoff frequency of 7.5 kHz. A low-pass filter of this type will allow 60 Hz to pass unattenuated, but it will filter the power supply of noise above the 7.5 kHz cut off (note the 40 kHz transient noise is well above the 7.5 kHz cut off). The diagram of the filter is given in Figure 9. The Laplace transform technique is used to obtain the transfer function of the output voltage with respect to the input voltage

$$L = 220\mu\text{H}$$

$$C = 2\mu\text{F}$$

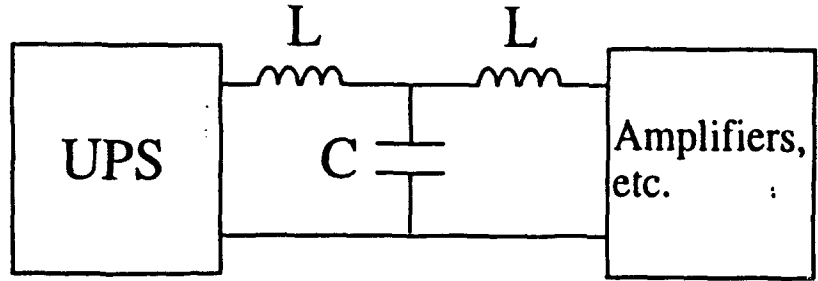


Figure 9. Third-order low-pass circuit diagram.

of the filter ($V_2(S)/V_1(S)$). This is accomplished by replacing all inductance terms (L) with their corresponding Laplace transform (LS) (Hostetter 1984). The same is done for the capacitances, voltages, and currents in the circuit. Now the transfer function can be solved for by simple algebraic techniques, as shown. Using Kirkoff's Voltage Law on the two circuit loops yields the following two equations:

$$V_1(S) = I_1(S)LS + (1/CS)(I_1(S) - I_2(S)); \quad (1)$$

$$V_2(S) = -(1/CS)(I_2(S) - I_1(S)) - I_2(S)LS. \quad (2)$$

In addition,

$$V_2(S) = I_2(S)R. \quad (3)$$

Solving for $I_1(S)$ in Equation 1 and substituting into Equation 2 gives

$$V_2(S) = -(1/CS)(I_2(S) - (V_1(S) + I_2(S)/CS)/(LS + 1/CS)) - I_2(S)LS. \quad (4)$$

Substituting $I_2(S)R$ for $V_2(S)$ into Equation 4 and rearranging yields

$$I_2(S)/V_1(S) = 1/(L^2CS^3 + RLCS^2 + 2LS + R). \quad (5)$$

Finally, multiplying both sides of Equation 5 by R yields

$$V_2(S)/V_1(S) = R/(L^2 CS^3 + RLS^2 + 2LS + R). \quad (6)$$

Equation 6 is the third-order transfer function of the filter that is shown in Figure 9.

The values of $L = 220 \mu\text{H}$ and $C = 2.0 \mu\text{f}$ were chosen to give a cutoff frequency at about 7.5 kHz, based on a load $R = 480 \text{ ohms}$ (the total impedance of the fiber-optic transmitters). These values give a cutoff which is well below the frequency of the transient noise. The resulting gain vs. frequency plot (Bode plot) for this transfer function is shown in Figure 10. By introducing this to output of the UPS, the noise was completely eliminated from the 60-Hz UPS power supply and from the pressure channel trace. Based on the results of this particular test, it is suggested to correct for this problem if any electronics equipment in the data acquisition system is powered by a similar UPS.

3.3 Common Mode Rejector. A technique using rings of ferromagnetic material to attenuate the amplitude of noise currents that flow in the shield or grounded conductors of any electrical equipment in the data acquisition system is used. The technique employs a device known as a "common mode rejector" and it is used to attenuate or reject signals traveling in the ground or common conductors of a circuit (Askeland 1985). This technique has been successfully applied to other experimental work including the pressure measurements made in the Electromagnetic Railgun Laboratory of the ARL (Powell and Zielinski 1992). The ferromagnetic rings, or "ferrites," contain iron oxides, and they generally have a high relative permeability. This characteristic of high permeability enables the ferrite to introduce an amplification effect of the magnetic field (or inductance) generated by current-carrying conductors surrounding the material. Common ferrites include NiFe_2O_4 , MnFe_2O_4 , and $(\text{Zn,Mn})\text{Fe}_2\text{O}_4$ (Askeland 1985).

Ferrites are implemented by wrapping the power cords and coaxial data lines of all electronics equipment tightly for several turns around the ferrite material. Figure 11 shows the circuit diagrams of the resulting arrangement, with the addition of a ferrite. The circuit includes a voltage source, the series resistance of the data lines (R_s), the inductances due to the windings around the ferrite, and the load voltage measurement. By examining the circuit closely, it can be seen that for the current flowing from the voltage source, the associated magnetic fields in the ferrite will be equal in magnitude and opposite

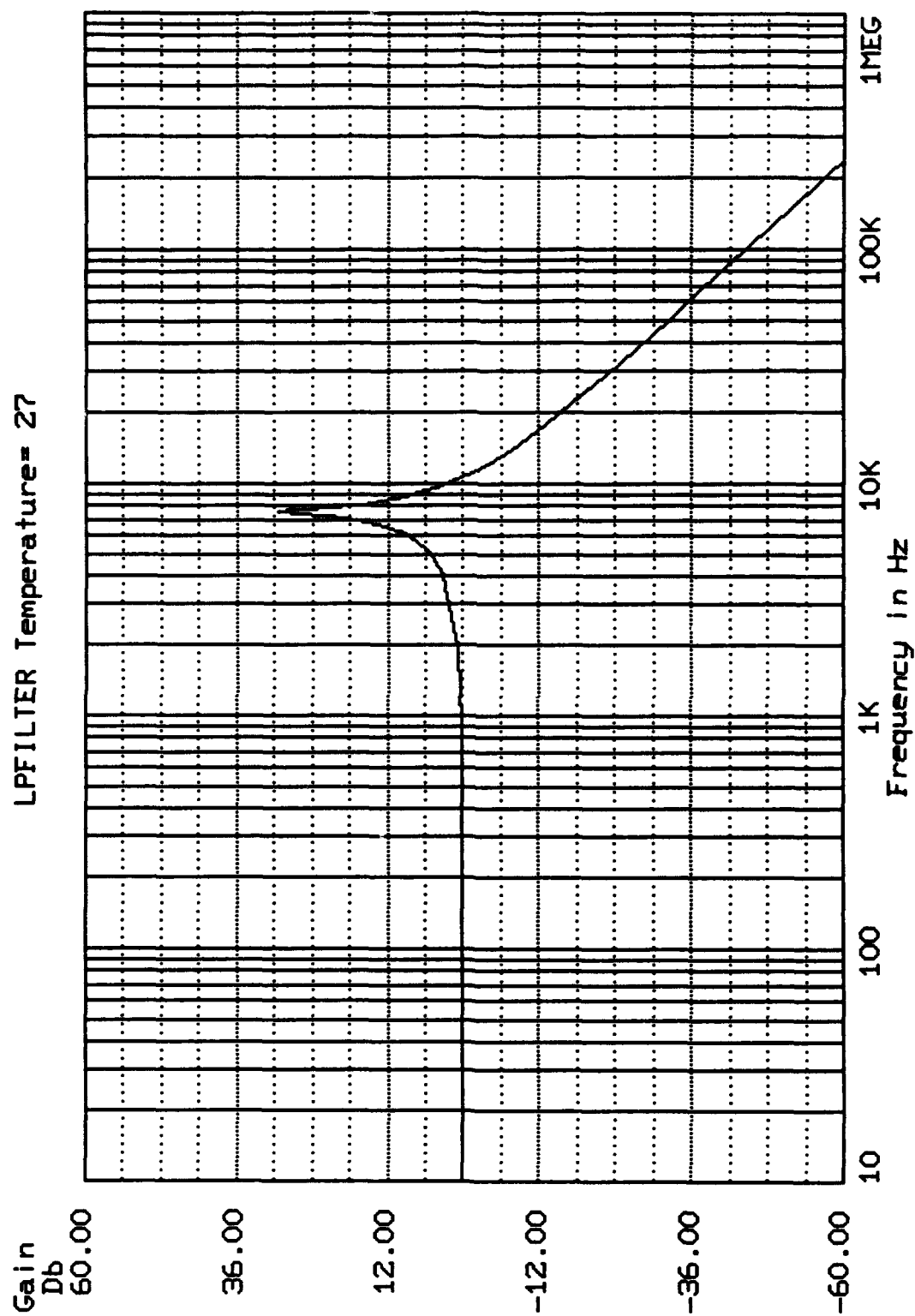


Figure 10. Magnitude vs. frequency plot for low-pass filter used.

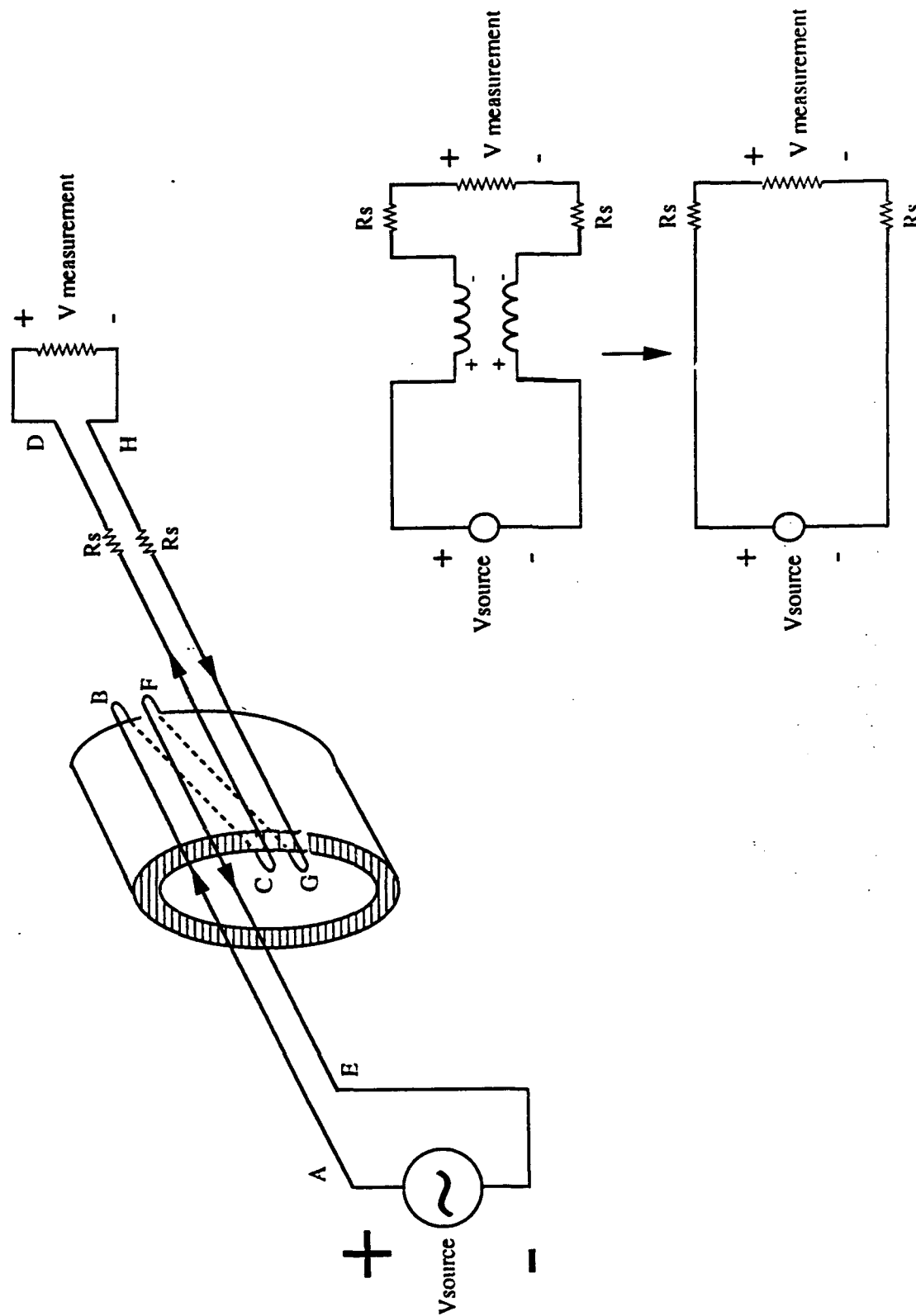


Figure 11. Equivalent circuits for common mode rejector.

in direction and will, therefore, cancel each other. As a result to the current that flows in this data signal loop, the effect of the ferrite is negligible. However, any current traveling unidirectionally with respect to the ferrite (typical of noise current from a ground loop, see Figure 12) will generate net magnetic field (inductance) through the ferrite. Consider the equivalent circuit shown in Figure 12. V_{noise} may be generated by the inductive loop made up of the ground path and the leads connecting V_{source} to $V_{measurement}$. Depending on the source and measurement impedances, a V_{noise} signal will be developed across one of the R_s resistances that may not be canceled by the signal developed across the other R_s . This then will show up in $V_{measurement}$. However, with the presence of the inductive impedance (reactance) given by the ferrite core, this will be in series with R_s and is shown in the equivalent circuit in Figure 12. The addition of the inductance generated in this path will, like the addition of impedance to any circuit path, have a tendency to decrease the current amplitude and hence the V_{noise} developed across R_s (see Figure 11). Although this is a desirable situation if a ground loop is introduced into the measurement system, its effectiveness is limited by the frequency of the noise current. This is because the impedance introduced by the ferrite is proportional to the product of frequency and inductance, given by

$$XL = j\omega L = 2 * \pi * f * L. \quad (7)$$

In Equation 7, f is the frequency of the applied signal in Hz, L is the inductance in henrys (H), and π is a constant given as 3.14159. As an example, the impedance offered by a typical inductance at 100 kHz can be as much as 1,256 ohms, which will have a pronounced effect on current traveling in a ground loop having an impedance of fractions of an ohm (typically, $R_s = 0.1$ ohm). However, the same inductance will produce only 12.56 ohms of impedance for the same current at 1 kHz. Even so, the attenuation effect of a common mode rejecter on lower frequency signals can be seen experimentally. Figure 13 shows the result of noise coupled into a pressure channel (in the absence of pressure) during a PFN discharge into the 35-milliohm resistive load. The difference between the two arrangements is that in 13b the pressure channel circuit contains a 20-turn ferrite whereas the circuit of 13a has no ferrite. It is seen from Figure 13 that the frequency of the unwanted noise pickup is on the order of 1–2 kHz, possibly due to the magnetic field pick up from the discharging PFN which is on the order of 0.5 to 1 ms. As described above, this frequency pickup can be effectively reduced by the ferrite common mode rejecter.

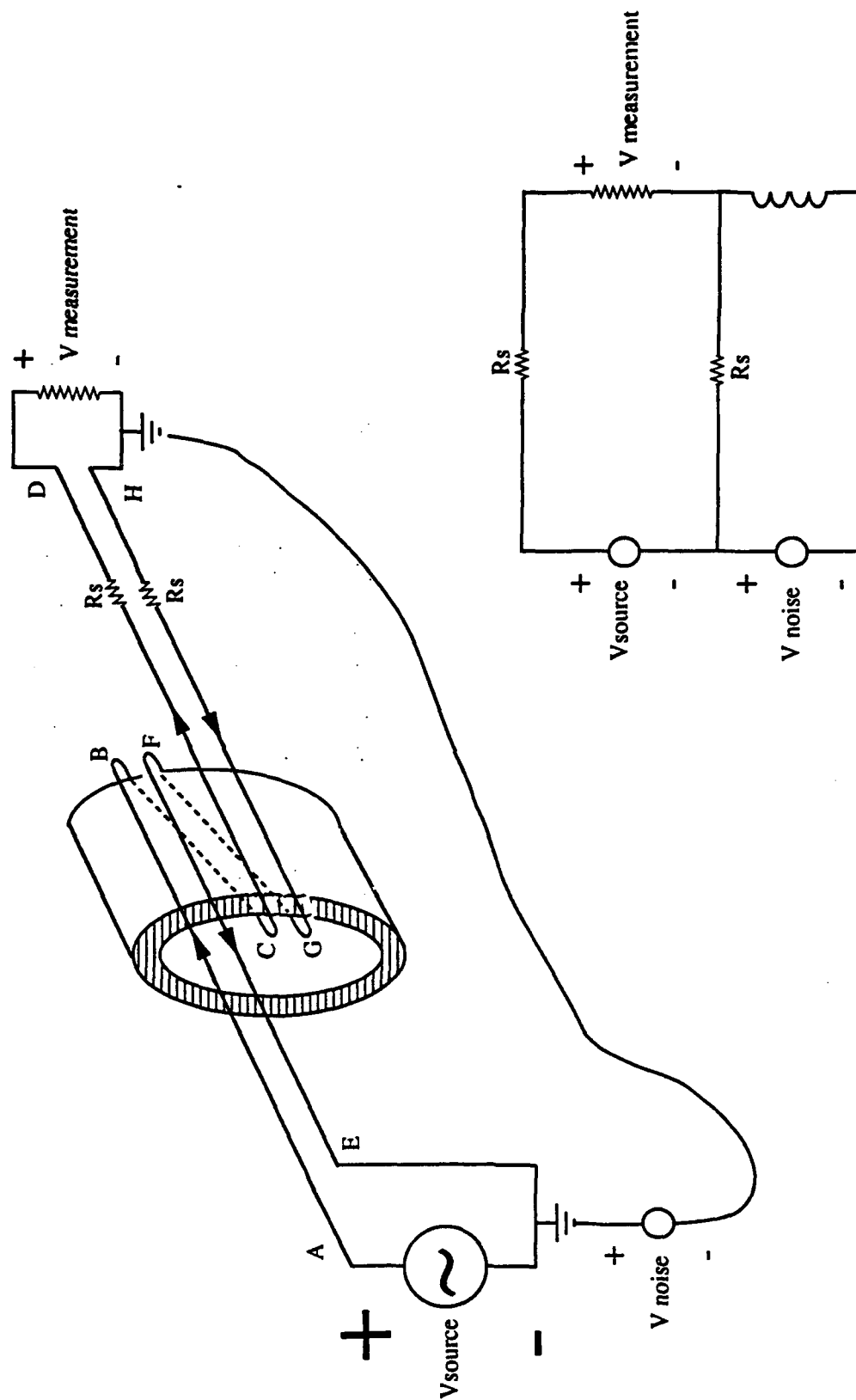
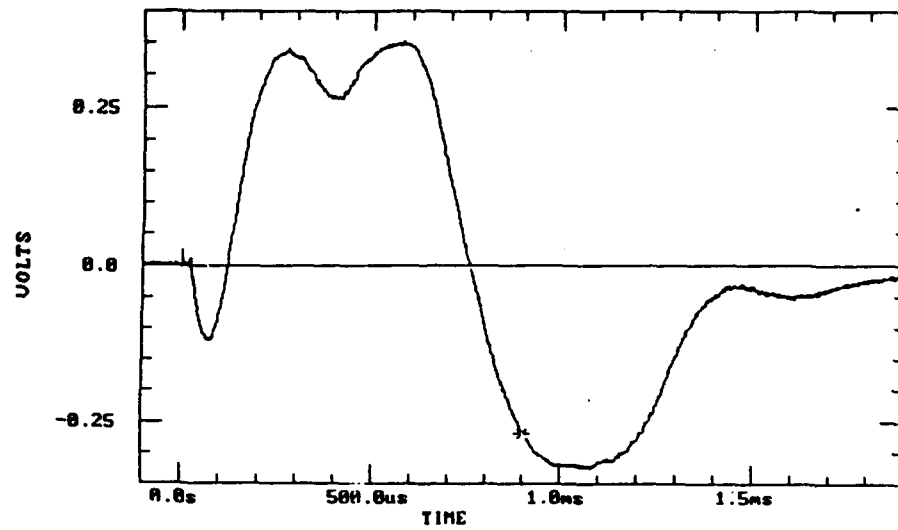
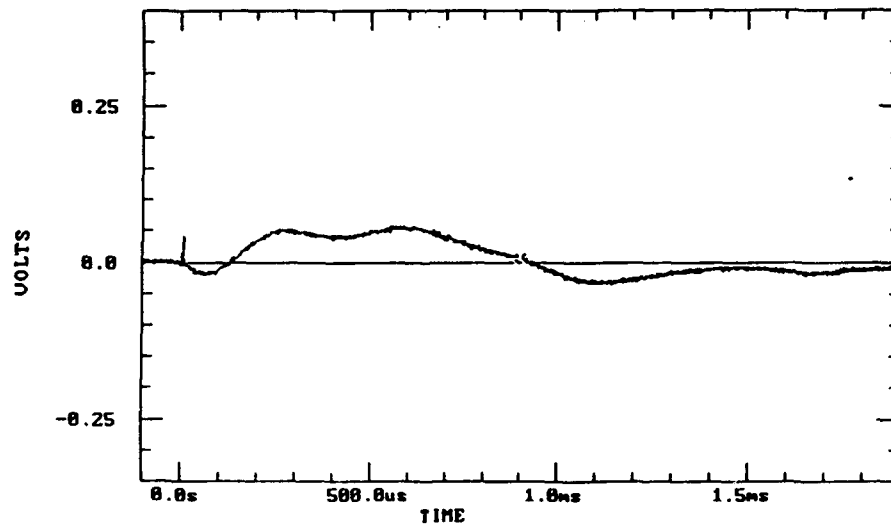


Figure 12. Equivalent circuits for rejector used in a circuit having a ground loop.



a) Without rejector



b) With 20-turn rejector

Figure 13. Response of pressure channel, (a) without rejector (b) with addition of rejector.

4. DISCUSSION

The percent error calculation shown in Figure 7 reveals very large errors in areas where the functions are near to zero and reasonable error ($< 5\%$) elsewhere. The large error observed in areas of small signal magnitude is due to the signal-to-noise (S/N) ratio of the optical links. In support of this claim, Figure 14 shows the optical and direct measurements from the third discharge, discussed earlier, with an expanded vertical scale. The figure illustrates the large difference and, consequently, large percent error between the two functions in regions of relatively low signal levels. The large difference between the two signals is due to background noise introduced by the optically coupled signal. In Figure 14, for example, the data point on the direct signal (solid line) at $950 \mu\text{s}$ is about -0.05 V , compared to -0.02 for the optical signal (dotted line) giving a percentage difference of 60%. Again, this large difference is caused from noise introduced into the fiber-optic measurement due to the very low S/N in this region. In fact, the manufacturer of the fiber-optic links clearly state the minimum S/N as 40 db. For the data points $950 \mu\text{s}$, the calculated S/N ratio is 3.98 db or about one tenth the minimum value required by the manufacturer.

On the other hand, for larger signals (see Figure 14), the S/N ratio is larger and thus the agreement between the two functions is much improved. It is important to mention that the peak current values obtained from the numerical integration of the signals have very good agreement. In fact, the comparison of peak current values obtained from the two signals (direct and optically coupled) reveals a relatively small percent difference of 2.7%. In addition, the percent difference of the calculated energy obtained from the integral of the current squared multiplied by the load resistance for each signal is only 3.2%, again quite good.

Reasoning as to why good agreement is obtained for overall energy and peak current measurements can be deduced from current and energy profiles in addition to Figures 7 and 14. The energy and current traces for this PFN discharge indicate that most of the current and energy are delivered to the load up to approximately $500 \mu\text{s}$ in time; this is the region of very good agreement between the two signals as seen in either of the two figures as stated. As a result, one would expect a small percent difference between the two values since there are relatively small discrepancies between the di/dt signals obtained.

Some of the error between the two peak currents and calculated energy may be introduced from the numerical integration program, although this is, in most cases, probably quite small as long as the

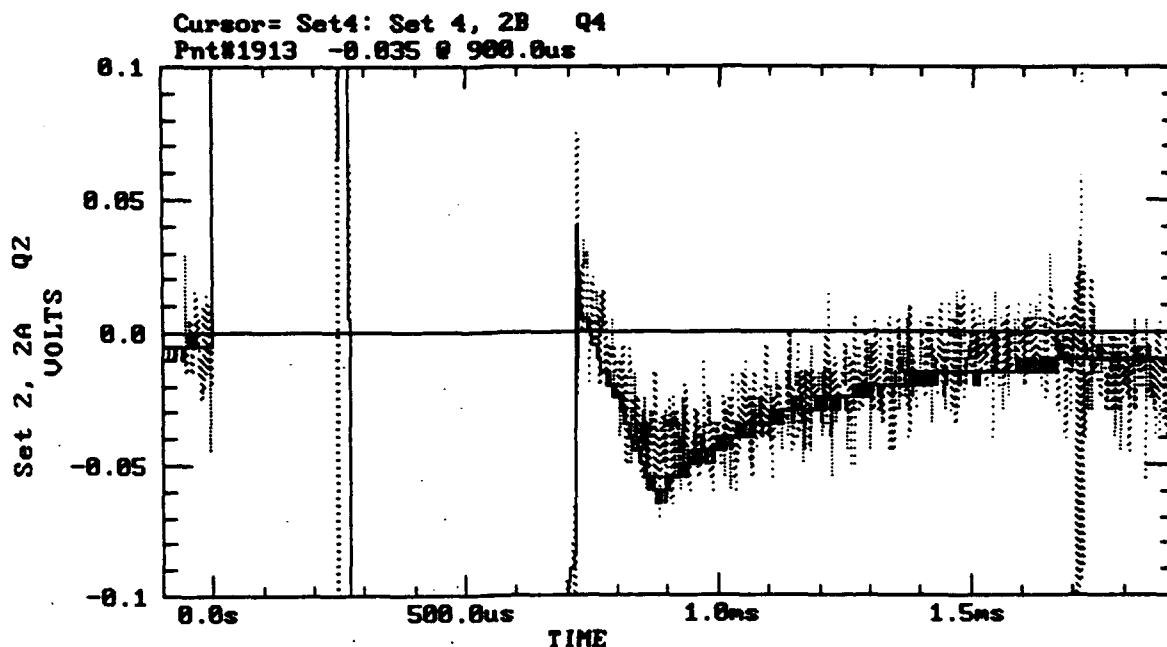


Figure 14. Common mode rejector with circuit having a ground loop.

digitization period of these signals is small compared to the integration window. In summary, as long as the measured signals meet the required S/N ratio plus any obvious specifications of the fiber-optic links, the resulting measurements can be expected to be within about 3% of the accuracy of signals obtained through direct or passive techniques.

5. CONCLUSIONS

A data acquisition system that has allowed for reliable, noise-free experimental measurements in the ETC diagnostic environment at the ARL has been designed and experimentally tested to provide reliable measurements. This includes a system of shielded pressure channels, optoelectronic equipment, a UPS, digital oscilloscopes, and a multi-point grounding system. Tests have been performed to determine a sound arrangement for grounding and for supplying power to a particular type of optoelectronic and amplifier equipment.

It has been determined that the optical equipment provided data to within 3% accuracy of directly acquired data of current and energy delivered to a resistive load. Also, a filter design has been offered for the elimination of voltage "spikes" that are introduced by the switching elements of a UPS. Finally, a technique involving common mode rejectors (ferrites) used to attenuate ground loop currents has been described and experimental data showing its effectiveness were put forward.

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