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TECHNICAL REPORT BRL-TR-2610

ACCELERATION MEASUREMENTS IN HIGH G ENVIRONMENTS

James O. Pilcher II

November 1984

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US ARMY BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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This report discusses the difficulties encountered in acceleration measurements performed on gun and projectile systems and the techniques used to circumvent these difficulties. Particular points of discussion are the use of mechanical, digital and electronic filtering techniques and their limitations.

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I. INTRODUCTION

Over the past ten years, the Ballistic Research Laboratory (BRL) has been striving to develop accurate means of predicting the dynamic behavior of gun systems. Particularly, the major concerns are those effects that dominate the launch conditions of the projectile and its subsequent terminal performance. The basic objective of the acceleration measurement techniques discussed is to determine the dynamic structural response of guns and projectiles in order to verify theoretical predictions. These measurements are made in real gun systems which impose severe environmental conditions that contain interference phenomena which often dominate the outputs of the measurement system, rendering the measurements useless for their purpose. In spite of the difficulties encountered, viable acceleration measurements can be obtained by addressing the nature of the environmental interference and the structural response.

A. The Measurement Problem

The measurement problem is one of being able to discriminate the significant motion vector from a complex combination of vector components which are generated by various dynamic phenomena including the ones of interest. Unlike well-controlled laboratory experiments designed to separate various physical phenomena, ballistic system measurements are subject to interference from local accelerations generated by stress waves, blast waves, dilatational vibrations, traveling loads, impulses, and impacts at mechanical interfaces. Often the resulting interfering accelerations have a greater magnitude than the measurand.

B. Approach to the Problem

To gain a meaningful acceleration measurement, one must exploit the characteristics of the physical phenomena encountered during the measurement. In this discussion, the global structural motion is paramount. Therefore, emphasis is placed on the low frequency responses of ballistic systems, that is, those below 10 kHz. However, higher frequency responses cannot be ignored or disregarded. The high frequency responses of ballistic systems (generally from 8 kHz to 60 kHz) must be considered for their effect on the transducer system and their pollution of the desired data. The measurand must be considered as a six-degrees-of-freedom phenomenon, and the sensor must be considered to have a multidegree-of-freedom response, depending on the design of the specific sensor used.

Interferences in the measurement from environmental conditions can be eliminated or minimized by numerical, electronic and mechanical filtering techniques. However, these filters must be designed for each specific situation.

The separation of the desired vector components of motion can be achieved through the deliberate design of sensor arrays and their associated data processing algorithms. The theoretical predictions must be cast in the same vector component combinations as the measurement. This technique is enhanced through the selection of matched pairs of sensors.

The following discussion reviews the characteristics of the environment, measurand and sensors, and the applications of filters, sensor arrays and calibrations as well as their requirements and limitations.

II. THE HIGH G ACCELERATION ENVIRONMENT

Before proceeding, a definition is in order. A "G" is defined as one standard gravitational acceleration unit, 32.2 ft/sec^2 or 9.8 m/sec^2.

For modern ballistic systems, accelerations can be expected with measurands ranging from 5 Hz to 10 kHz in the frequency domain and from 0 kG to 50 kG in the magnitude domain. Superimposed on these measurands are interfering accelerations ranging from 10 kHz to 60 kHz in the frequency domain and 2 kG to 10 kG in the magnitude domain. The desired measurands can be reasonably estimated for instrumentation purposes. However, the interfering acceleration environment cannot be readily estimated. Sources of the interfering accelerations are strain waves, impacts and impulses which cause the sensor to resonate, overload, and/or respond nonlinearly. Even if a sensor is not permanently damaged, which is often the case, the output has been modified by sensor-generated baseline shifts and frequency components caused by the nonlinear response of the sensor. This condition often renders the data from the measurement unintelligible. Figure 1 shows the output of a piezoelectric accelerometer which is dominated by stress wave interference.

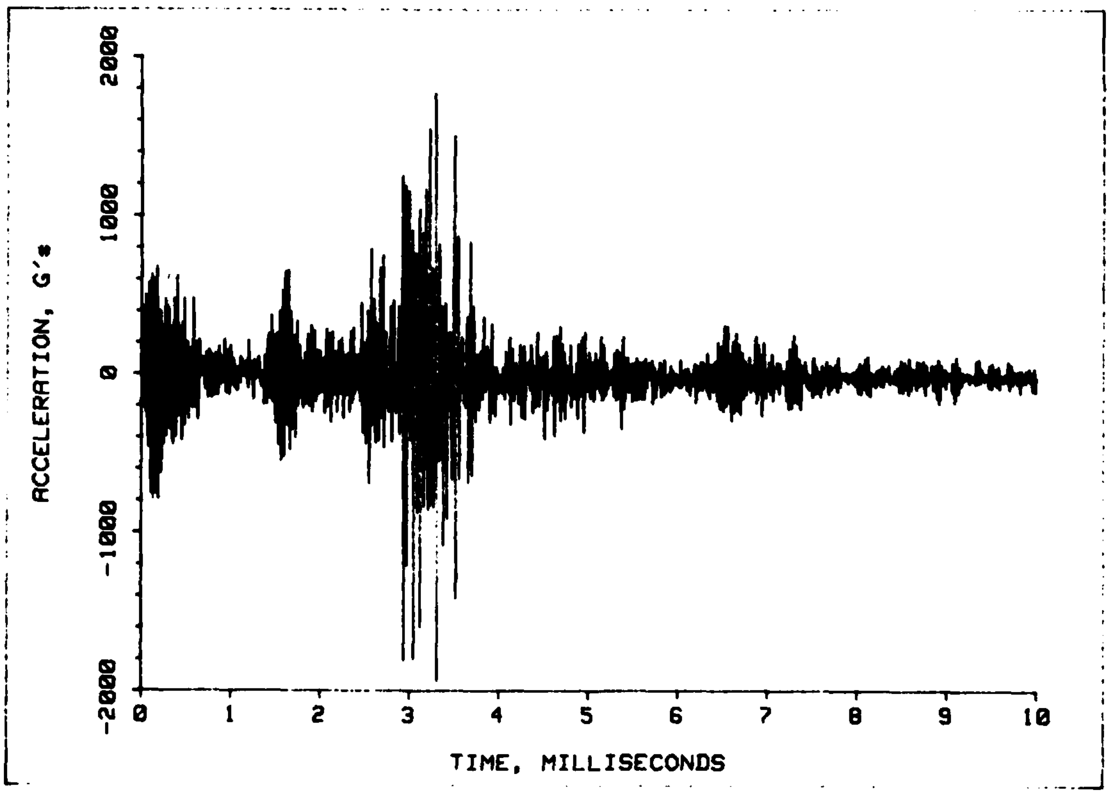

Figure 1. Typical Gun Muzzle Acceleration Signal

In this case, the accelerometer is mounted directly to the muzzle of a 75-mm gun. The bandwidth of the acquisition system is 100 kHz. The linear response of the accelerometer is 6 kHz.

The expected maximum acceleration of the structure is 350 G with significant modes up to 1.5 kHz. This accelerometer was subjected to accelerations in excess of 2000 G peak but did not suffer permanent damage, a fact verified by subsequent recalibration. In this case, baseline shifts occurred due to excitation over the nonlinear range of the accelerometer. Figure 2 shows the normalized amplitude spectrum of the signal in Figure 1.

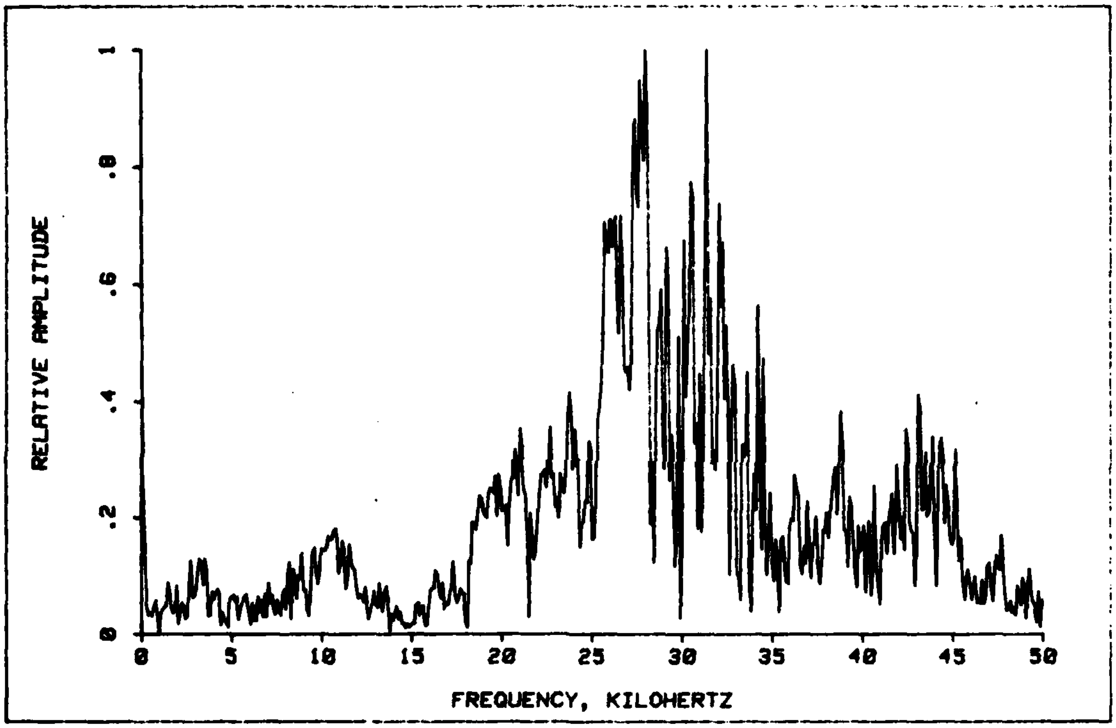

Figure 2. Fourier Spectrum of the Signal in Figure 1

This spectrum shows a reasonable separation of the frequency content of the measurand from the interference. However, merely filtering the output signal numerically or electronically will not remove baseline shifts or spurious frequencies in the range of the measurand frequencies. Figure 3 shows the appearance of the measurand after low pass numerical filtering at 6 kHz. Although the filter removes the high frequency components of the data which masked the measurand, it does not remove the baseline shift and the self-generated low frequencies caused by the nonlinear response of the sensor to the interference.

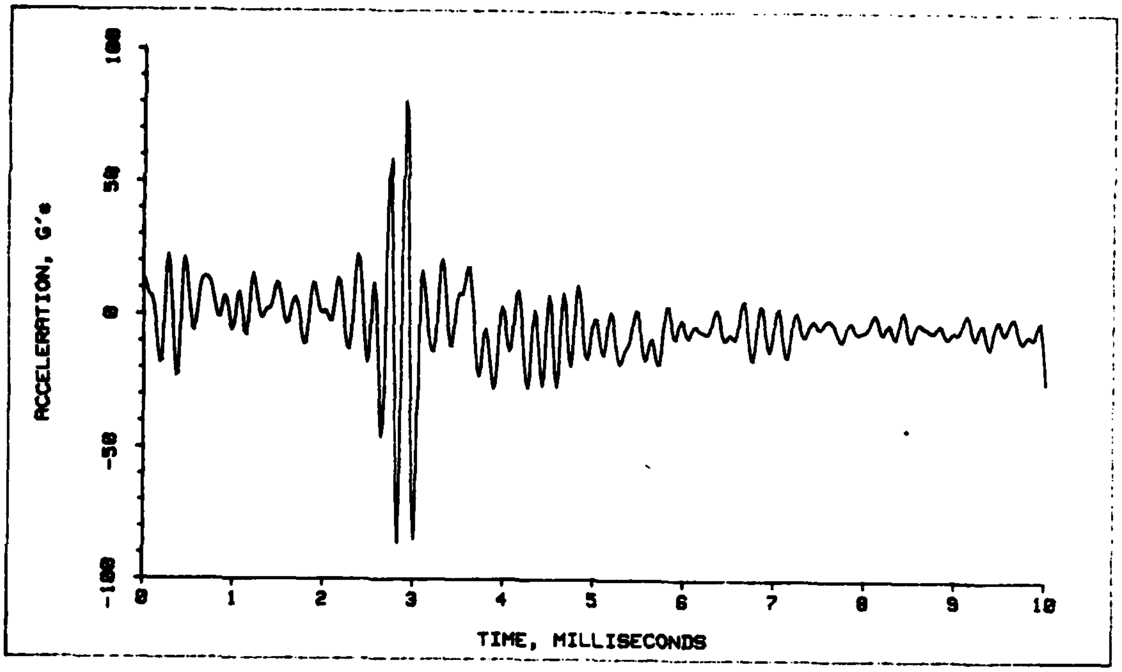

Figure 3. Data in Figure 1 Low-Pass Filtered at 8 kHz

Mathematically, the excitation at the input to the accelerometer can be expressed by the second time derivative of the sensor's position vector, $\mathbf{P} = \mathbf{R} + \mathbf{r}$. The unit vectors of the earth coordinates are U'_x, U'_y and U'_z. The unit vectors of the sensor coordinates are U_x, U_y, and U_z with their origin at the center of gravity of the local structural element. The position vector is diagramed in Figure 4.

The vector **R** is the relative position vector of the origin of the local coordinate system with respect to the earth's coordinate system. The local coordinate system translates and rotates with respect to the earth's coordinate system as a function of time. The vector **r** is the position of the point of observation with respect to the origin of the local coordinate system. Since the local coordinate system undergoes rotation, the first time derivative of the unit vector U is defined as the angular velocity vector, $\boldsymbol{\omega}$.[1] It can be shown that the acceleration vector, **A**, at the point of observation is[2]

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1 S.W. McCuskey, *Introduction to Advanced Dynamics*, Addison-Wesley Publishing Company, Reading, MA, pp 28-33, 1958.

2 J.O. Pilcher II, "Theoretical Consideration in Measuring Six-Degree-of-Freedom Motion of Gun Tubes by Accelerometers," ARBRL-TR-02474, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, February 1983. (AD# A125474)

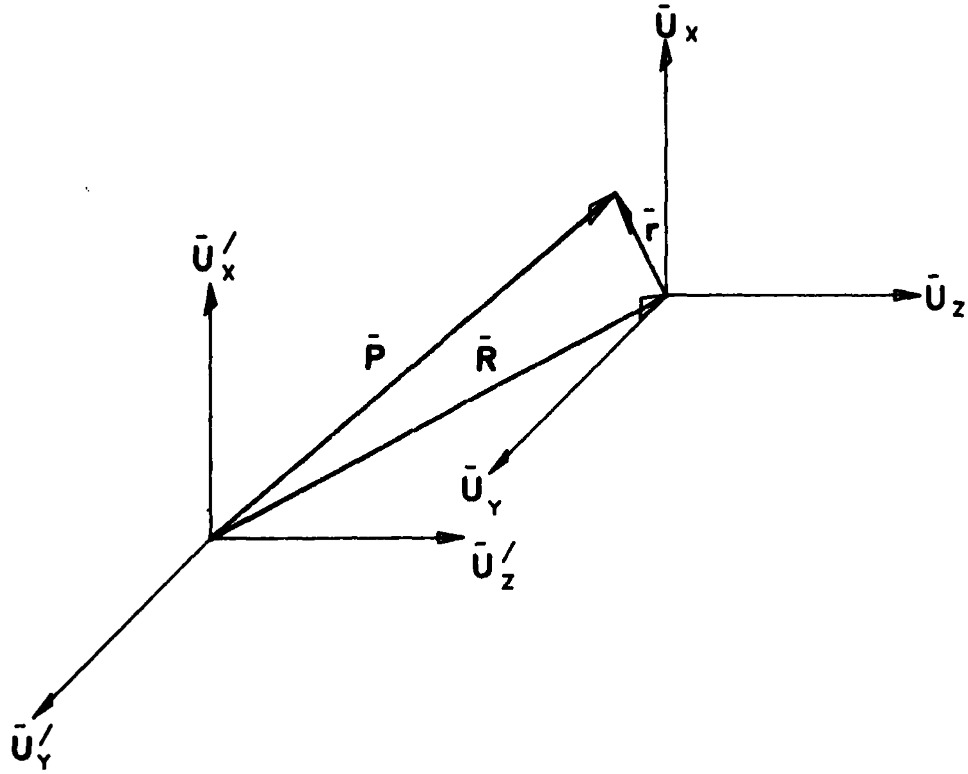

Figure 4. Position Vector

$$A = \frac{d^2P}{dt} = [\ddot{R} + 2\,(\omega\times\dot{R}) + (\omega\cdot(R+r))\omega-(\omega\cdot\omega)(R+r) + \dot{\omega}\times(R+r)] + [\ddot{r}+2(\omega\times\dot{r})]. \tag{1}$$

The terms in the first bracket in Eq. (1) represent the accelerations due to rigid-body motion of the element. The vectors $\ddot{R}$ and $\dot{\omega}$ are usually the desired measurands but are not generally separable from the remaining terms. The terms in the second bracket represent the accelerations due to local deformations. The frequency domain of these accelerations corresponds to the band of higher frequencies shown in Figure 2. In the case of gun tube measurements, the magnitudes of the local deformation accelerations are one to two orders of magnitude greater than the magnitudes of the rigid-body accelerations.

III. MECHANICAL FILTERING

In spite of the difficulties encountered, mechanical filtering offers the most viable approach to eliminating the high frequency accelerations from the measurement. However, this technique cannot be blindly applied. A preliminary measurement must be made without filtering to determine the filter requirements. Once these requirements have been established, the design of the filter can proceed. The operation of the filter must be verified through appropriate testing done over the ranges of magnitudes before it is used for measurement purposes. This is particularly necessary since mechanical filter design is based on approximate theory and is still an art at best.

A filter design used at the BRL is based on the viscoelastic and attenuation properties of felt, which is the medium for the spring and damping elements of the filter. It is designed as a parallel transfer impedance filter.

$$\frac{1}{Z_C} = \frac{1}{Z_R} + \frac{1}{Z_{WC}} + \frac{1}{Z_{WS}} + \frac{1}{Z_{WT}} , \qquad (2)$$

where Z_C = the characteristic impedance, and of the filter;

Z_R = the rigid body impedance;

Z_{WC}, Z_{WS}, Z_{WT} = the wave effect impedance due to compression, shear and torsion, respectively.

Z_R is determined by the classical theory of vibrations and Z_{WC}, Z_{WS}, Z_{WT} are determined by computing the wave impedances.

$$Z_C = \frac{Z_R Z_{WC} Z_{WS} Z_{WT}}{Z_{WC} Z_{WS} Z_{WT} + Z_R\left(Z_{WC} Z_{WT} + Z_{WS} Z_{WT} + Z_{WS} Z_{WC}\right)}. \qquad (3)$$

The wave impedances can be estimated for simple geometries by the models tabulated in Table 30.3 on pages 30-53 of reference 3. Figure 5 shows one of the physical embodiments of a filter. Figure 6 shows the characteristics of the filter in Figure 5 compared with the characteristics of a similar filter using an elastomeric material instead of felt. The fibrous structure of the felt contains numerous scattering surfaces which enhance the attenuation of high frequencies. In this case, the cutoff frequency is designed to be 3 kHz. Figure 7 shows a comparison of the mechanically filtered and mechanically unfiltered shock pulse measure during operational tests of the filter.[4]

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[3] *C.M. Harris and C.E. Crede, Shock and Vibration Handbook Vol. 2, McGraw-Hill Book Company Inc., New York, Chapter 30, p. 53, 1961.*

[4] *J.O. Pilcher, "Application of Mechanical Filters to Ballistic Measurements," Ballistic Research Laboratory, Aberdeen Proving Ground, MD, forthcoming.*

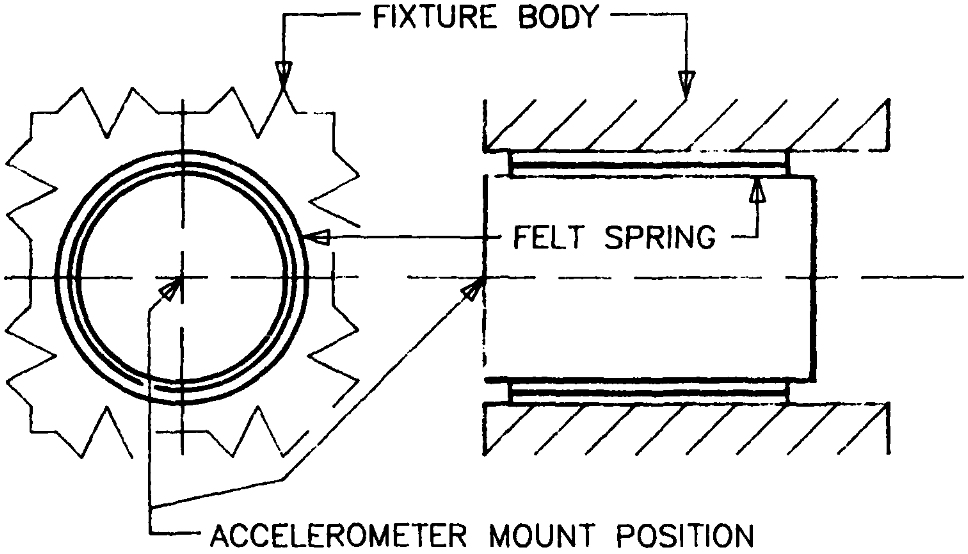

Figure 5. Typical Mechanical Filter

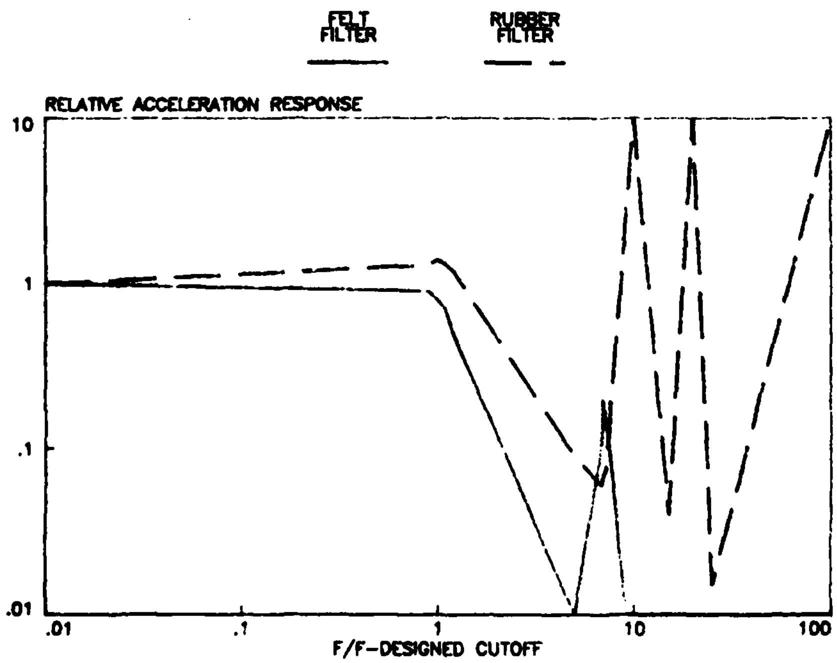

Figure 6. Comparison of Filter Characteristics

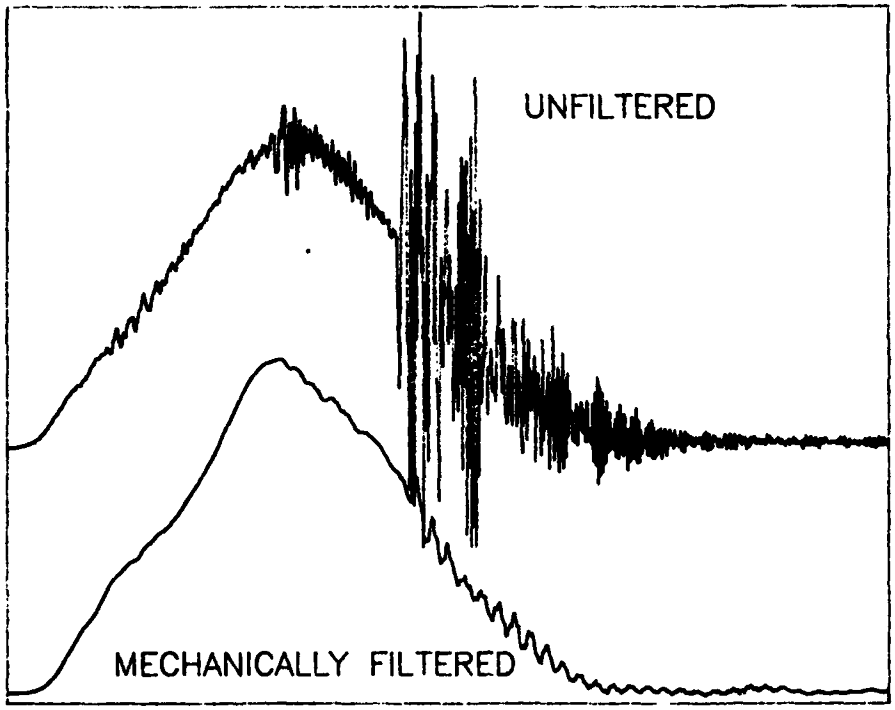

Figure 7. Shock Test Verification of Filter Operation

IV. SPATIAL ARRAY TECHNIQUES

Once the high frequency interference has been eliminated or reduced to an insignificant level, the measuring system must be designed to resolve various vector components. Certain combinations of sensors must be used depending on the primary purpose of the data to be collected. This requires an examination of the accelerometer response to the imposed motion. The accelerometer response can be expressed as a vector, **G**.

$$\mathbf{G} = a\mathbf{U}_x + b\mathbf{U}_y + c\mathbf{U}_z \qquad (4)$$

where a,b, and c are the response coefficients along the local unit vectors.

The coefficients of Eq. (4) are the principal gage factor and the two orthogonal cross-axis gage factors. The equation can be expressed in terms of the principal gage factor, P, and the ratios of the cross-axis gage factors to the principal gage factor, k_1 and k_2 (usually expressed in percent in the literature). For a specific gage arrangement, where the principal axis is along $\mathbf{U}_x$,

$$\mathbf{G} = P\,(\mathbf{U}_x + k_1\mathbf{U}_y + k_2\mathbf{U}_z). \qquad (5)$$

The output, O, is the dot product of the gage response vector, G, with the local acceleration vector, A (given in Eq. (1)).

$$\begin{aligned} O = G \cdot A = P \{ [& \ddot{R}_x + \omega_x\omega_y(R_y+r_y) + \omega_x\omega_z(R_z+r_z) \\ & - (R_x+r_x)(\omega_y^2+\omega_z^2) + 2\omega_y\dot{R}_z - 2\omega_z\dot{R}_y \\ & + \dot{\omega}_y(R_z+r_z) - \dot{\omega}_z(R_y+r_y)] \\ & + k_1[\ddot{R}_y + \omega_y\omega_z(R_z+r_z) + \omega_y\omega_x(R_x+r_x) \\ & - (R_y+r_y)(\omega_z^2+\omega_x^2) + 2\omega_z\dot{R}_x - 2\omega_x\dot{R}_z \\ & + \dot{\omega}_z(R_x+r_x) - \dot{\omega}_x(R_z+r_z)] \\ & + k_2[\ddot{R}_z + \omega_z\omega_x(R_x+r_x) + \omega_z\omega_y(R_y+r_y) \\ & - (R_z+r_z)(\omega_x^2+\omega_y^2) + 2\omega_x\dot{R}_y - 2\omega_y\dot{R}_x \\ & + \dot{\omega}_x(R_y+r_y) - \dot{\omega}_y(R_x+r_x)]\} \quad . \end{aligned} \tag{6}$$

The complicated equation above can be simplified by using matched pairs of accelerometers mounted in symmetrical arrays about the origin of the local coordinate system. Matched accelerometers have the same cross-axis sensitivity. Figure 8 shows the schematic layout for a six accelerometer col-linear array for measuring the local motion of a gun tube. All six accelerometers lie on the same axis. Accelerometers 1 and 3 have their principal axes along U_x; accelerometers 5 and 7 have their principal axes along U_y; accelerometers 9 and 11 have their principal axes along U_z. Vector components for this array can be discriminated using the following algorithms.

$$M_x = \left(\frac{G_1-G_3}{2}\right) - k_1\left(\frac{G_5-G_7}{2}\right) - k_2\left(\frac{G_9-G_{11}}{2}\right)$$

$$= \ddot{R}_x + \omega_x\omega_y R_y + \omega_x\omega_z R_z - R_x\left(\omega_y{}^2+\omega_z{}^2\right) + 2\omega_y R_z - 2\omega_z R_y + \dot{\omega}_y R_z - \dot{\omega}_z R_y \; ;$$

$$M_y = \left(\frac{G_5-G_7}{2}\right) - k_1\left(\frac{G_9-G_{11}}{2}\right) - k_2\left(\frac{G_1-G_3}{2}\right)$$

$$= \ddot{R}_y + \omega_y\omega_z R_z + \omega_y\omega_x R_x - R_y\left(\omega_x^2+\omega_z^2\right) + 2\omega_z R_x - 2\omega_x R_z + \dot{\omega}_z R_x - \dot{\omega}_x R_z \; ;$$

$$M_z = \left(\frac{G_9-G_{11}}{2}\right) - k_1\left(\frac{G_1-G_3}{2}\right) - k_2\left(\frac{G_5-G_7}{2}\right)$$

$$= \ddot{R}_z + \omega_z\omega_x R_x + \omega_z\omega_y R_y - R_z\left(\omega_x^2 + \omega_y^2\right) + 2\omega_x R_y - \omega_y R_x + \dot{\omega}_x R_y - \dot{\omega}_y R_x \; ;$$

$$\left(\omega_y^2+\omega_z^2\right) = \frac{1}{r_1}\left[-\left(\frac{G_1+G_3}{2}\right) + k_1\left(\frac{G_5+G_7}{2}\right) + k_2\left(\frac{G_9+G_{11}}{2}\right)\right] \; ;$$

$$\left(\omega_y\omega_x+\dot{\omega}_z\right) = \frac{1}{r_5}\left[\left(\frac{G_5+G_7}{2}\right) - k_1\left(\frac{G_9+G_{11}}{2}\right) - k_2\left(\frac{G_1+G_3}{2}\right)\right] \; ; \text{ and}$$

$$\left(\omega_z\omega_x-\dot{\omega}_y\right) = \frac{1}{r_9}\left[\left(\frac{G_9+G_{11}}{2}\right) - k_1\left(\frac{G_1+G_3}{2}\right) - k_2\left(\frac{G_5+G_7}{2}\right)\right] \quad , \qquad (7)$$

where $G_i = \frac{O_i}{P_i}$.

Equations (7) are derived in Reference 2.

These equations demonstrate the complexity of the content of the acceleration measurements. Particularly, they show that single components such as R_x are not separable from the data. This is a situation that must be addressed when the purpose of the measurement is to verify model

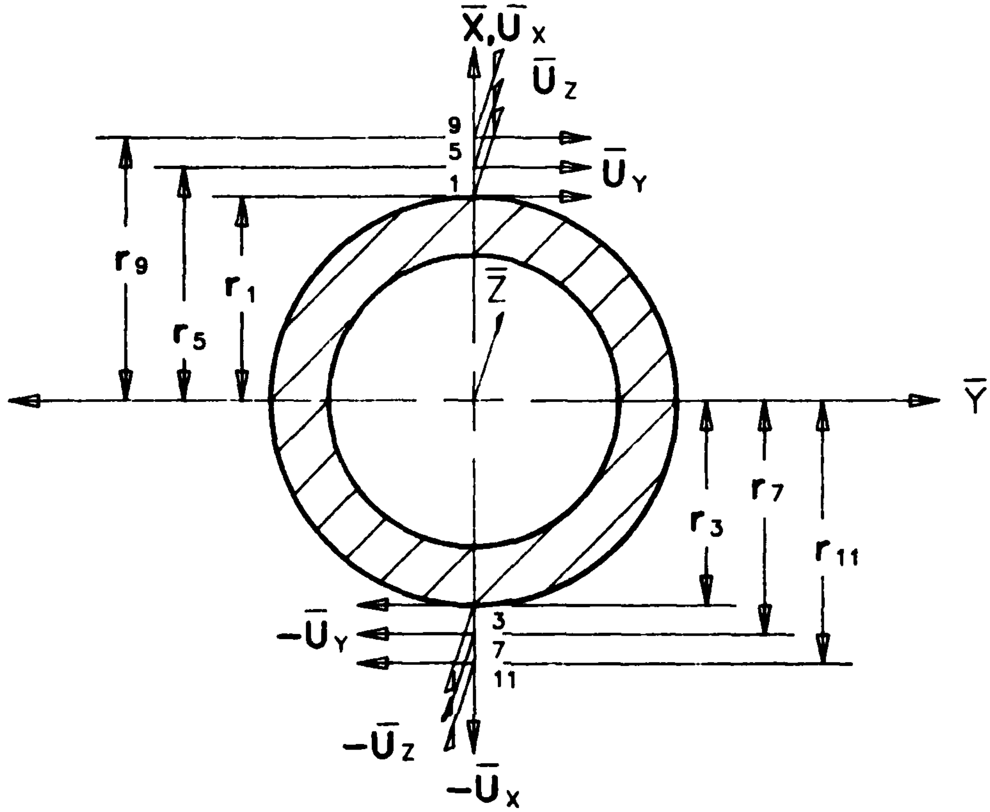

Figure 8. Collinear 3-Pair Accelerometer Array

predictions. Another important consideration is the establishment of the measurement system bandwidth. When vibratory modes are estimated, one must consider that the terms such as $\omega_x \omega_y R_y$ will create frequencies which are the sum of the frequencies in the represented vectorial components. As a rule of thumb, one can expect frequencies up to the third harmonic of the highest mode excited. In addition, the spectrum will be filled with the intermediate frequencies of the vector products.

V. ELECTRONIC AND NUMERICAL FILTERING

It is common practice to provide electronic filtering between the sensor and the data acquisition system to create improved signal-to-noise ratio, and minimize FM/FM recording distortion. Filtering is also provided to prevent aliasing during digitizing for numerical analyses. These filtering applications should be carried out using constant time delay or constant phase filters.[5,6] In dynamic measurements, phase shifts become more significant than amplitude error and must be kept to a minimum. Although these types of filtering are often necessary, they present a dilemma to the experimenter in that they often hide difficulties caused by the sensor itself. If the whole sensor/acquisition system has insufficient bandwidth, one will see baseline shifts and sensor-created frequencies due to nonlinearity and overranging, but not the high frequencies causing these problems. In addition, the output signal will be modified to the point that it cannot be reliably analyzed by Fourier transform techniques. It has been our experience that this condition has been the most common source of difficulty in diagnosing sensor problems in ballistic measurements. What is generally required, but often most difficult to obtain, is an instrumentation checkout test of the experiment with wide system bandwidths that allow complete observation of the event to determine the adequacy of the instrumentation's measuring range functioning.

VI. REQUIREMENT FOR CALIBRATION AND SENSOR CAPACITY

In order to utilize the powerful mathematical techniques available for analyzing accelerometer measurements, more extensive calibration information is required than is generally provided. In addition, more stringent requirements should be placed on the accelerometer for both survival and measurement capabilities.

A. Calibration Requirements

Calibration requirements generally extend the information available in both the space and frequency domain.

1. A complete vector description of accelerometer sensitivity requires a calibration of the sensor sensitivity in two mutually orthogonal planes as shown in Figure 9.

2. A complete description of the nonlinear sensor sensitivity requires sufficient data points over the whole range of measurement to adequately determine the coefficients for at least a third order description.[7] The process is required for both the principal axis of sensitivity and the cross axes of sensitivity.

3. The frequency response of both the principal and cross axes is required for ballistic environments; it is reasonable to assume that the cross-axis environment is going to be the same order of magnitude as the principal-axis environment with the exception of on-board projectile

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[5] *J.N. Walbert, "Application of Digital Filters and Fourier Transform to the Analysis of Ballistic Data," BRL Technical Report ARBRL-TR-02347, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1981. (AD# A102890)*

[6] *P.L. Walter, "Deconvolution as a Technique to Improve Measurement System Data Integrity," Experimental Mechanics, Vol. 21, No. 8, August 1981.*

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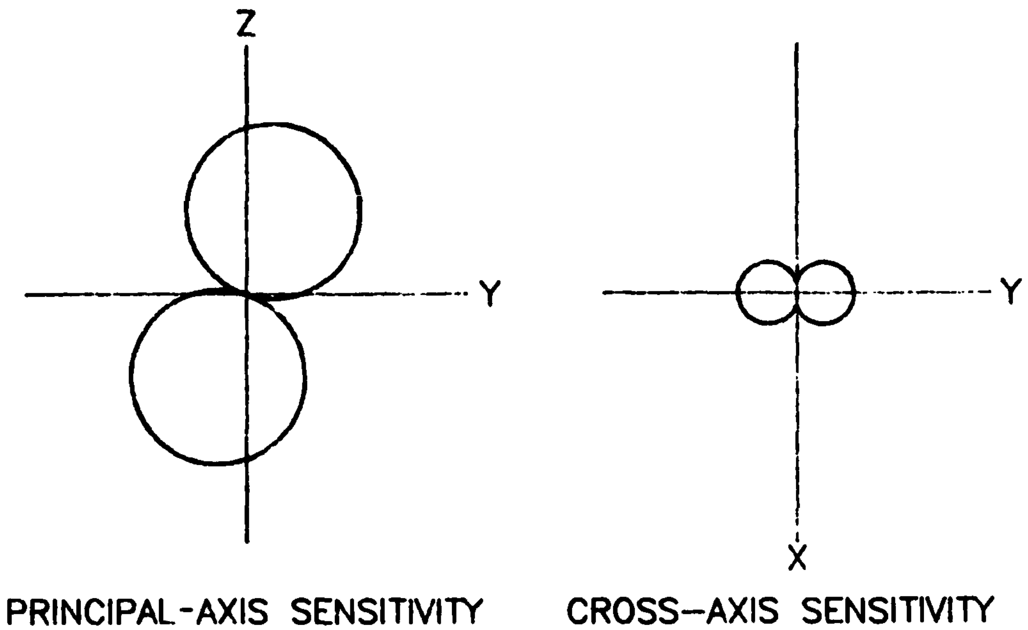

Figure 9. Orthogonal Sensitivity Properties

measurements where the cross-axis environment can be several orders of magnitude greater than the principal-axis environment, depending on sensor orientation.

B. General Response Requirements

The accelerometer must survive and provide a sufficient range of measurement in the ballistic environment. Local mechanical filters and fixtures will have to be employed to ameliorate the strain wave effects. Wherever possible, these filters and fixtures should be included as part of the sensors in the calibration. However, accelerometers must have the following properties.

1. Linearity. Linearity should be within 1% absolute over the range of measurement.

2. Frequency Response. The frequency response should be within plus or minus 1% from .01 Hz to 10,000 Hz.

3. Amplitude Requirements. Amplitude ranges are

for guns - 2,000 G, and
for projectiles,
current - 20,000 G, and
future - 50,000 G.

4. Cross-Axis Sensitivity. Maximum cross-axis sensitivity should be less than 1%.

5. <u>Matched Accelerometers</u>. The difference between cross-axis sensitivities for a matched pair of accelerometers should be less than 0.1%.

6. <u>Volume and Mass Properties</u>. The volume and mass of the accelerometers must be as small as possible with respect to the structure on which they are mounted.

C. User Responsibility

The above requirements can be provided by a vendor, but must be verified by the user. The main problem is that the vendor cannot predict the mounting and environmental condition in which his sensor will be used. The user must either recalibrate the sensor in-house or collaborate with the vendor to obtain a suitable calibration under realistic conditions of use. This is probably the most difficult procedure to practice and the most ignored. The lack of realistic calibration conditions presents the largest source of measurement error, particularly in the ballistic environment.

VII. SUMMARY

- The acceleration environment for real ballistic systems is beyond our ability to accurately predict due to strain wave effects.
- At this time, mechanical filtering appears to be the most viable solution to the strain wave interference problem.
- The complexity of acceleration fields requires that an array of matched pairs of accelerometers be used to determine principal vector components. Predictive model outputs must be tailored to the measurement, taking into account array geometry and vectorial sensitivity.
- Electronic and digital filtering techniques must be used with caution; at a minimum, system bandwidths must be opened up sufficiently to examine the overall measurement system performance during the initial phase of any given test series.
- Calibrations must be extended to encompass the spatial and frequency behavior of the sensor. In addition, calibrations must include the mounting and environmental conditions of the actual measurement.

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