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I am submitting herewith a dissertation written by Farshid Shahrokhi entitled "Metalic Loose-Parts Detection and Characterization." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Nuclear Engineering.

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METALIC LOOSE-PARTS DETECTION AND CHARACTERIZATION

A Dissertation

Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

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This dissertation is dedicated to my children, Siminne and Shahram.

ABSTRACT

A theoretical and experimental research program was conducted to provide basic information and guidelines for a comprehensive loose-parts monitoring system suitable for industrial use. This work is an attempt to bring together theoretical work on impact and elastic wave propagation with the current needs of loose parts characterization in an industrial environment.

The pertinent work developed by many on the theory of impact and wave propagation over the past century is discussed. The experimental work for impact location and characterization was performed using modern transient signal analysis techniques. The experiments were performed and techniques developed first on a simple flat plate. The methods were further improved using the Experimental Gas Cooled Reactor (EGCR) structure at Oak Ridge National Laboratory (ORNL) as the test bed.

Several impact location techniques were developed and explored extensively. Their effectiveness and accuracy are demonstrated on the flat plate and the EGCR pressure vessel.

Furthermore, various impact characterization techniques were developed utilizing the time dependent RMS and the relative power spectrum of the impact signals.

The overall performance of the impact location and characterization methods developed proved both useful and effective under noise-free and simulated background noise conditions.

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CHAPTER I

NATURE OF THE PROBLEM AND RELATED BACKGROUND

A. Problem Statement

The occasional presence of metallic loose parts in primary coolant system of today's nuclear reactors is a proven reality.¹ The potential safety significance of these loose parts depends upon the size and location of the part which is one of the factors in continuous safe operation of the power plant.^{2,3} Thus, the characterization of a loose part as to its location, probable size, and an estimate of its origin is valuable information for continuing safe and economical operation of a nuclear power plant.

The metal to metal impact causes the initiation of an impact wave on the surface of the metallic structure. According to the size of the loose part and force of impact the elastic wave patterns vary in their amplitude, wave frequency structure, and duration. This dissertation presents a combination of theoretical insight and practical procedures for detection of the impact wave pattern and characterization of the loose part as to its location of impact and force of the impact relative to a standard.

B. Background Information

The state-of-art in the area of loose-parts monitoring is currently in the infancy stage. The theoretical works in the field of elastic

wave propagation and basic impact theory are at least one hundred years old. The pioneers are Hertz,⁴ Sokolinikoff,⁵ Love⁶ and many others.^{7,8,9,10} These works are basically elaborate mathematical derivation and solution to various stress and strain equations using a spectrum of input assumption and propagation medium simplification. In the past three decades, as the electronic era grew in sophistication many of the purely theoretical works have been put to experimental use. The major problems which many researchers have confronted here are the complications involved in real world application of simplified and purely theoretical results.

The complications which an experimenter is faced with in the application of the theoretical solutions and the experimental results are as follows:

Impact

The concept of impact encompasses a wide range of processes as exemplified by the game of billiards, automobile accidents, the impinging of tidal waves or air blasts upon structures, and even molecular collisions. The complicated process of energy transfer under impact conditions leads to serious problems in the mathematical analysis. Models representing the physical system must be idealized to render them suitable to theoretical treatment, and the postulated dynamic behaviour of such bodies must be verified by suitable experiments. As a consequence, complete solutions have been obtained only for simple geometrical configurations,⁷ utilizing the laws of conservation of mass, conservation of momentum, and mechanical energy balance. Although

many different approaches to the same problem have been recorded,⁸ no general impact theory has been developed to date.

Wave Propagation Path

Approximations have been employed in the wave propagation phase of the impact formulation and solutions. These approximations range from half space assumption to simple geometrical shapes.^{11,12} The difficulties imposed by practical problems on the simplified, yet complicated, solutions of the impact wave propagation are immense. These problems such as: finite thickness plates, weld discontinuity and geometrical irregularity force the experimenter to abandon purely theoretical solutions to empirical solutions and experimental correction factors. The relevant problems of impact characterization associated with propagation path are: wave attenuation¹³ and wave dispersion.¹⁴

Sensor

Probably the most understood part of loose-parts monitoring research is the sensor used to detect the impact. The most widely used sensor is an accelerometer¹⁵ which is also used in structural vibration monitoring. The design of this type sensor was possible after the discovery of piezoelectric effect and material. A piezoelectric material has the property that if deformed by external mechanical pressure electric charges are produced on its surface. This effect was discovered in 1880. The reverse phenomenon, according to which such a material, if placed between two electrodes, changes its form if an electric potential is applied, was discovered soon afterwards (1881). Piezoelectric

material either synthetic or natural crystal is used as the sensing element of the accelerometers. When an accelerometer is attached to a structure, the charge produced by the piezoelectric element is proportional to the surface movement of the structure.

C. Objective and Organization of This Work

There are two objectives in this dissertation.

The first objective is to quantitatively characterize an impact. The characterization consists of impact detection, location and sizing using simulated impacts on a flat aluminum plate and the carbonsteel pressure vessel of the Experimental Gas Cooled Reactor (EGCR) located at Oak Ridge National Laboratory (ORNL).

The secondary objective of this work is to extend the use of normal noise analysis techniques to transient signal analysis. The adapted methods are Root Mean Square (RMS) calculation and Power Spectrum calculation. The normal noise analysis methods are developed for random stationary signals. The impact signals are of a nonstationary, deterministic type. Therefore, the use, modification, and validation of fast Fourier transform, windowing, block averaging, frequency smoothing and digital RMS calculation are reviewed and new ground rules are presented.

The text of this dissertation is organized as follows: Chapter II is dedicated to theoretical formulation of the simplified impacting process and the accelerometer. The two dimensional impact wave propagation studies, where the preliminary impact location and

characterization is developed in Chapter III. Chapter IV contains further experimental development of loose parts monitoring using the more realistic environment of the EGCR pressure vessel. The final chapter contains the overall conclusions and recommendations for future work.

CHAPTER II

MATHEMATICAL FORMULATION OF AN IMPACT AND THE SENSING DEVICE

A. Introduction

The purpose of this chapter is to formulate the essential parameters in impact generation, propagation and detection processes relevant to loose parts monitoring. The process of impact between two bodies is a complicated matter to mathematically formulate. Essentially the two bodies under the process of impact will experience two states: deformation and restitution. If the restitution equates the deformation no permanent deformation has occurred. If during the impact the dynamic yield stress of a given body is reached and surpassed permanent deformation on the surface of that body has occurred and part of the kinetic energy has gone to deform the surface. Obeying the laws of continuum mechanics several types of waves are started at the point of impact. The surface wave or otherwise known as the impact wave travels on the surface of the structure and can reach long distances before attenuation diminishes the amplitude of the impact wave. The detection process is performed using an accelerometer which is sensitive to surface acceleration. Although no exact formulation for the above processes exists on a realistic structure (pressure vessel) it is attempted to give idealized formulation in the following sections of this chapter for a better understanding of impact generation, propagation and detection.

B. Impact Considerations

Consider a solid body in a given phase space, under the action of forces denoted by the Newton's Law

$$\begin{aligned}\Sigma F &= m \frac{dv}{dt} \\ &= \frac{d}{dt} (mv) = \frac{dG}{dt}\end{aligned}\tag{2.1}$$

where G is the linear momentum of the system. The general cartesian coordinate system is illustrated in Fig. 1. The mass m is time invariant and the coordinate system is fixed. The Eq. 2.1 can be integrated to yield,

$$\begin{aligned}\int_{t_1}^{t_2} (\Sigma F) dt &= G(t_2) - G(t_1) \\ &= \Delta G\end{aligned}\tag{2.2}$$

In addition to relations for linear momentum, an analogous set of relations for angular momentum exists about the fixed axis in Fig. 1

$$\begin{aligned}\Sigma M &= \bar{\mathbf{r}} \times \Sigma \mathbf{F} \\ &= \bar{\mathbf{r}} \times m \frac{d\bar{\mathbf{v}}}{dt} \\ &= \frac{d}{dt} (\bar{\mathbf{r}} \times m \bar{\mathbf{v}}) \\ &= \frac{dH}{dt}\end{aligned}\tag{2.3}$$

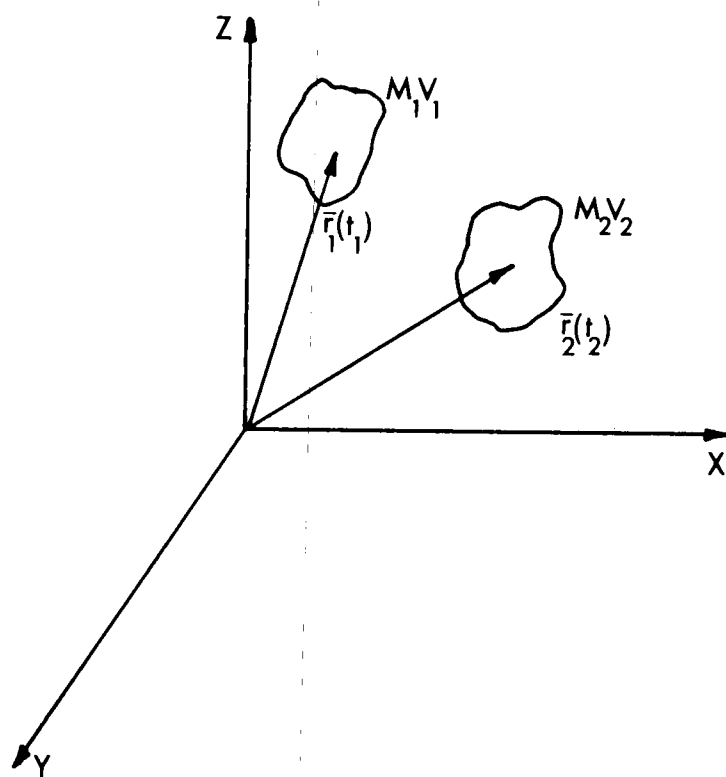


Fig. 1. General 3-dimensional coordinate system.

Hence, using

$$H = m \det \begin{bmatrix} i & j & k \\ x & y & z \\ v_x & v_y & v_z \end{bmatrix}$$

$$\Sigma M = \frac{dH}{dt} \quad (2.4)$$

and

$$\int_{t_1}^{t_2} (\Sigma M) dt = H(t_2) - H(t_1) \\ = \Delta H \quad (2.5)$$

where

$$H(t_2) = \bar{\mathbf{r}}(t_2) \times m \bar{\mathbf{v}}(t_2)$$

$$H(t_1) = \bar{\mathbf{r}}(t_1) \times m \bar{\mathbf{v}}(t_1)$$

If the system under consideration has no externally applied load, i.e., all forces are active-reactive, then the following relations are true,

$$\Delta G = 0$$

$$\Delta H = 0 \quad (2.6)$$

and they express the conservation of angular and linear momentum. It should be noted that momentum, unlike energy, is a vector quantity. The general impulse momentum relation is applicable to all bodies. Since only normal impact is of interest here, one dimensional impact

theory is sufficient. Moreover the impulse momentum relations are written for rigid body models.

Consider particles M_1 and M_2 with velocities v_1, v_2 as illustrated in Fig. 1. By conservation of linear momentum

$$\begin{aligned} M_1 V_{10} + M_2 V_{20} &= M_1 V_{1f} + M_2 V_{2f} \\ &= M_1 V_N + M_2 V_N \end{aligned} \quad (2.7)$$

Physically the momentum equations state that initially the bodies have velocities V_{10}, V_{20} . After contact the force builds as in Fig. 2. This phase terminates when the bodies have a common velocity (V_N). Subsequently a restitution phase take over until the process ends.

A commonly used parameter in this type of analysis is the coefficient of restitution e . By definition

$$e = \frac{\int_{t_a}^{t_d} F dt}{\int_0^{t_a} F dt} \quad (2.8)$$

where F is the contact force between bodies and t_a is the time at which the restitution phase begins in Fig. 2. Based on momentum, an equivalent definition is

$$\begin{aligned} e &= \frac{V_{2f} - V_N}{V_N - V_{20}} \\ &= \frac{V_{1f} - V_N}{V_N - V_{10}} \end{aligned}$$

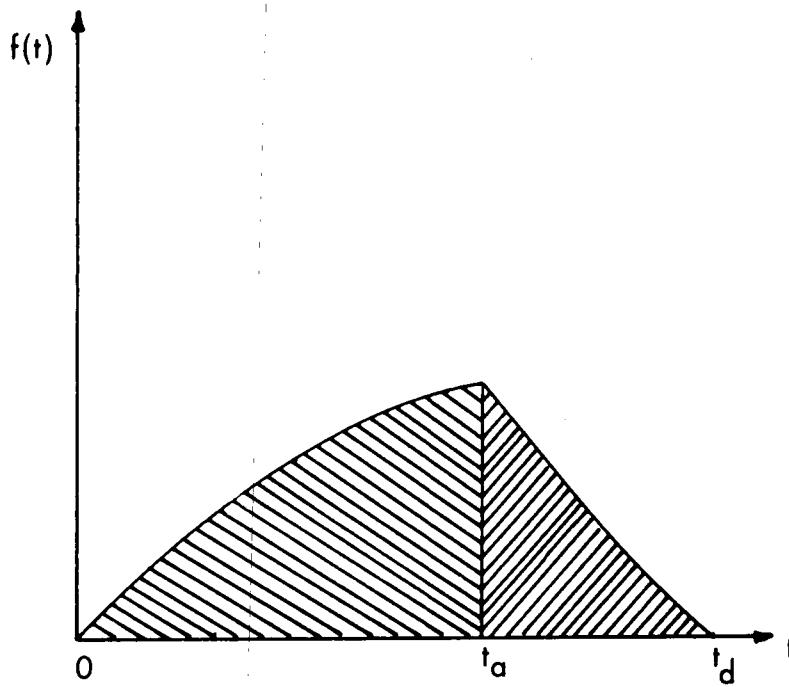


Fig. 2. Time dependent force during impact of two bodies.

$$e = \frac{\text{Relative velocity of separation}}{\text{Relative velocity of approach}} \quad (2.9)$$

An elastic impact is defined by $e = 1$ and a plastic impact has an $e = 0$.

Using the previous definitions the major results of interest can be classified as:

1. Residual velocities

$$\begin{aligned} V_{1f} &= V_{10} - (1 + e) \frac{M_2 V_{10} - M_2 V_{20}}{M_1 + M_2} \\ V_{2f} &= V_{20} - (1 + e) \frac{M_1 V_{10} - M_1 V_{20}}{M_1 + M_2} \end{aligned} \quad (2.10)$$

2. Kinetic energy

The loss of kinetic energy in the system is given by

$$\begin{aligned} \Delta K &= \frac{1}{2} \left(\frac{M_1 M_2}{M_1 + M_2} \right) (1 - e^2) (V_{10} - V_{20})^2 \\ &= \frac{1}{2} M^* V^{*2} \end{aligned} \quad (2.11)$$

where

$$\begin{aligned} M^* &= \frac{M_1 M_2}{1 + \phi} \\ V^* &= (1 - e^2)^{1/2} (V_{10} - V_{20}), \text{ and} \\ \phi &\text{ is the mass ratio } M_1/M_2. \end{aligned}$$

2. Impulse quantity

The total impulse delivered to either body 1 or 2 is the change in the momentum

$$\Delta G = (1 + e) \frac{M_1 M_2}{M_1 + M_2} (V_{10} - V_{20}) \quad (2.12)$$

Consider a one-dimensional impact problem described above and a target of mass M_T (reactor vessel) and a loose part of mass M_L . Given the initial velocity of the vessel to be zero. The residual loose part and vessel velocities V_L , V_T are given by

$$V_L = \frac{M_L - eM_T}{M_L + M_T} V_0$$

$$V_T = (1 + e) \left(\frac{M_L}{M_L + M_T} \right) V_0 \quad (2.13)$$

The total impulse transferred to the vessel is given by

$$G = \frac{1 + e}{1 + \phi} M_L V_0$$

$$= \frac{1 + e}{1 + \phi} G_{INIT} \quad (2.14)$$

where

$$\phi = M_L/M_T$$

V_0 = loose part velocity before impact

G_{INIT} = loose part potential impulse

The total energy delivered to the vessel due to impact is given by

$$E_T = \frac{1}{2} M_T V_T^2$$

$$= \frac{1}{2} M_L V_0^2 \left[\frac{1}{\phi} \left(\frac{1 + e}{1 + 1/\phi} \right)^2 \right]$$

$$= E_{INIT} \left[\phi \left(\frac{1 + e}{1 + \phi} \right)^2 \right] \quad (2.15)$$

where E_{INIT} is the initial energy of the loose part.

C. Impact Wave Propagation

When an elastic medium is strained, the coordinates of a point $P(x,y,z)$ change by components u,v,w while those of a neighboring point $Q(x + \delta x, y + \delta y, z + \delta z)$ change by amounts $(u + \delta u, v + \delta v, w + \delta w)$ respectively, Fig. 3. The displacement components of Q can be expressed in terms of those of P by a Taylor expansion, and if only the first order terms are accepted corresponding to sufficient small values of $\delta x, \delta y, \delta z$ it follows that

$$\begin{aligned}\delta u &= \frac{\partial u}{\partial x} \cdot \delta x + \frac{\partial u}{\partial y} \cdot \delta y + \frac{\partial u}{\partial z} \cdot \delta z \\ \delta v &= \frac{\partial v}{\partial x} \cdot \delta x + \frac{\partial v}{\partial y} \cdot \delta y + \frac{\partial v}{\partial z} \cdot \delta z \\ \delta w &= \frac{\partial w}{\partial x} \cdot \delta x + \frac{\partial w}{\partial y} \cdot \delta y + \frac{\partial w}{\partial z} \cdot \delta z\end{aligned}\tag{2.16}$$

or in operator notation

$$\begin{bmatrix} \delta u \\ \delta v \\ \delta w \end{bmatrix} = \nabla \cdot \begin{bmatrix} u \\ v \\ w \end{bmatrix} \begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix}\tag{2.17}$$

Thus, if the above differential displacements are known ($\partial u/\partial x$, etc.) we can find the relative displacements of all points adjacent to P . For convenience, we will introduce the following quantities

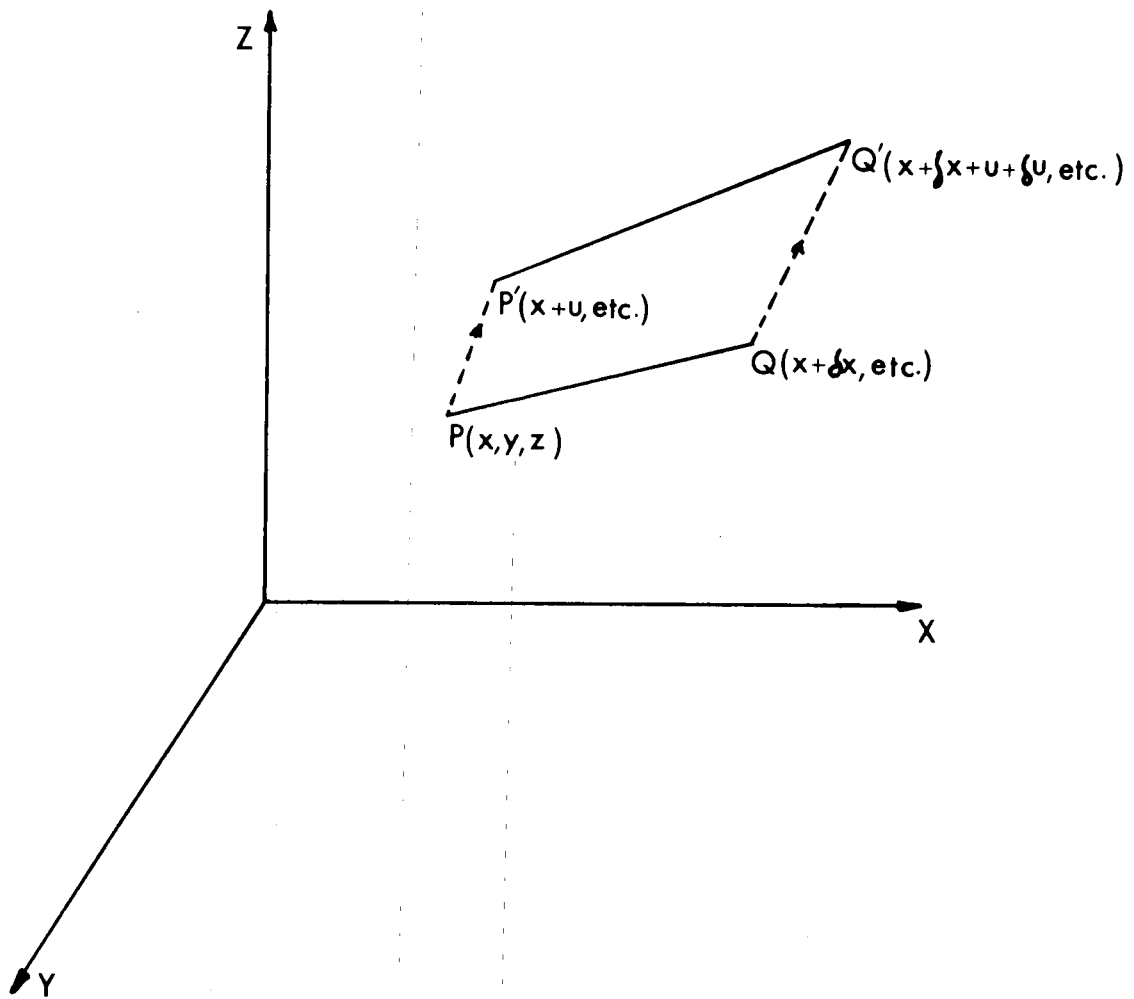


Fig. 3. Displacement of two points P, Q in an elastic medium under strain.

$$\begin{aligned}
\Omega_x &= \frac{1}{2} \left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \right) ; & e_{xy} &= \frac{1}{2} \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \\
\Omega_y &= \frac{1}{2} \left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \right) ; & e_{yz} &= \frac{1}{2} \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right) \\
\Omega_z &= \frac{1}{2} \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) ; & e_{zx} &= \frac{1}{2} \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) \\
e_{xx} &= \frac{\partial u}{\partial x} , & e_{yy} &= \frac{\partial v}{\partial y} , & e_{zz} &= \frac{\partial w}{\partial z}
\end{aligned} \tag{2.18}$$

where e_{xx} , e_{yy} , e_{zz} represent simple extension parallel to x , y , and z axes, or the normal component of strain tensor, and e_{xy} , e_{yz} and e_{zx} are the shear components of the strain tensor.

$$e = \begin{bmatrix} e_{xx} & e_{xy} & e_{xz} \\ e_{yx} & e_{yy} & e_{yz} \\ e_{zx} & e_{zy} & e_{zz} \end{bmatrix} \tag{2.19}$$

From Fig. 4 it may be shown that in yz plane

$$\begin{aligned}
\theta_1 &\approx \tan \theta_1 = \frac{\delta w}{\delta y} : & e_{yz} &= \frac{1}{2} (\theta_1 + \theta_2) \\
\theta_2 &\approx \tan \theta_2 = \frac{\delta v}{\delta z} : & \Omega_x &= \frac{1}{2} (\theta_1 - \theta_2)
\end{aligned} \tag{2.20}$$

Same relations are true for the shear and rotation components in xy and xz plane. Then, rearranging Eq. 2.16 we may write

$$\begin{aligned}
\delta u &= (\Omega_y \delta_z - \Omega_z \delta_y) + (e_{xx} \delta_x + e_{xy} \delta_y + e_{xz} \delta_z) \\
\delta v &= (\Omega_z \delta_x - \Omega_x \delta_z) + (e_{yx} \delta_x + e_{yy} \delta_y + e_{yz} \delta_z) \\
\delta w &= (\Omega_x \delta_y - \Omega_y \delta_x) + (e_{zx} \delta_x + e_{zy} \delta_y + e_{zz} \delta_z)
\end{aligned} \tag{2.21}$$

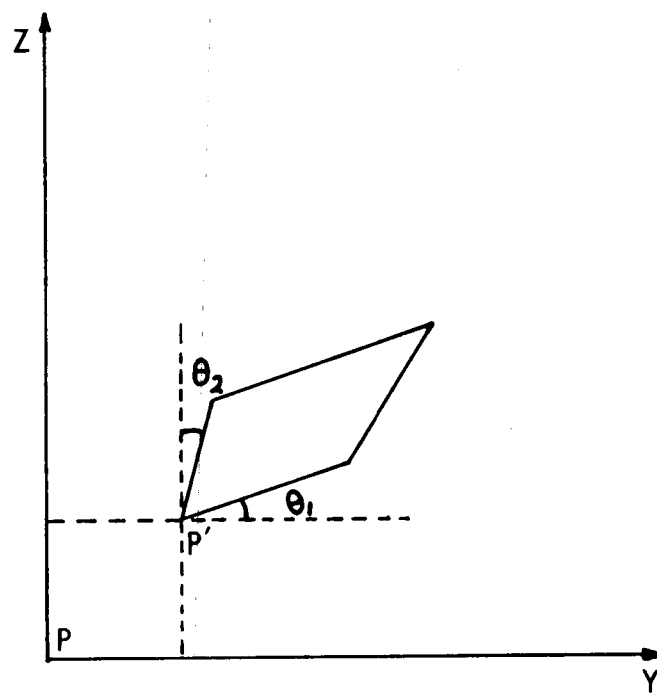


Fig. 4. Shear and rotation in YZ plane.

or in the operator notation,

$$\begin{bmatrix} \delta_u \\ \delta_v \\ \delta_w \end{bmatrix} = \begin{bmatrix} 0 & -\Omega_z & \Omega_y \\ \Omega_z & 0 & -\Omega_x \\ -\Omega_y & \Omega_x & 0 \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \\ \delta_z \end{bmatrix} + \begin{bmatrix} e \\ f \\ g \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \\ \delta_z \end{bmatrix} \quad (2.22)$$

The terms in the first bracket in Eqs. 2.21 and 2.22 correspond to a pure rotation of a volume element (as a rigid body), and when these are all zero the deformation is irrotational and is described as pure strain.

The stresses exerted on an elementary cube of material with its edges along the x, y and z axes (Fig. 5) can be specified in terms of the normal stresses T_{xx} , T_{yy} , T_{zz} and the shearing components T_{xy} , T_{yz} , T_{zx} .

In the generalized form of the Hooke's Law it is assumed that provided the load does not exceed a given value, known as the elastic limit, each of the six components of stress is a linear function of all component of strain. In an isotropic medium the number of elastic constants reduces to the two independent Lamè constants λ and μ . The stress-strain relations may then be written⁵

$$\begin{aligned} T_{xx} &= \lambda\theta + 2\mu \frac{\partial u}{\partial x} ; & T_{zy} &= T_{yz} = 2\mu e_{yz} \\ T_{yy} &= \lambda\theta + 2\mu \frac{\partial v}{\partial y} ; & T_{xz} &= T_{zx} = 2\mu e_{xz} \\ T_{zz} &= \lambda\theta + 2\mu \frac{\partial w}{\partial z} ; & T_{xy} &= T_{yx} = 2\mu e_{xy} \end{aligned} \quad (2.23)$$

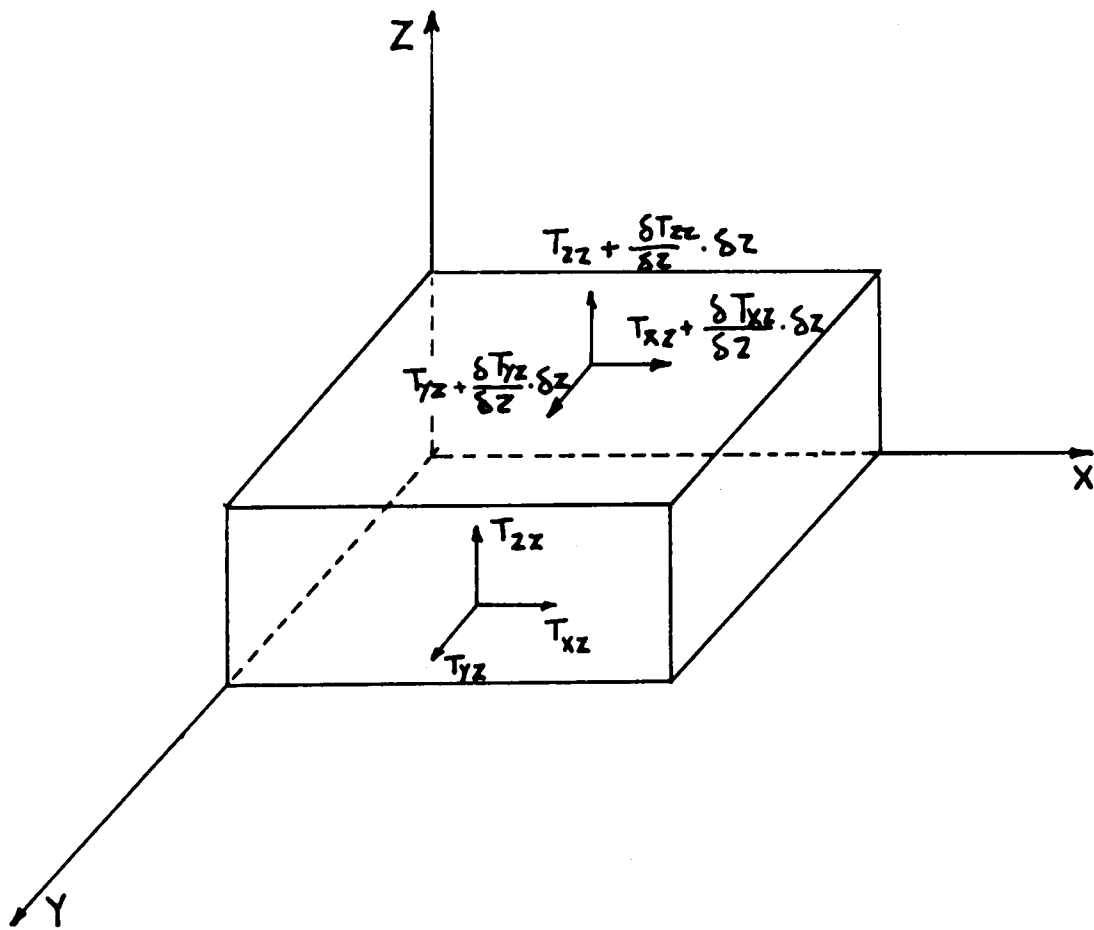


Fig. 5. Stress in an elastic medium.

where the dilatation $\theta = e_{xx} + e_{yy} + e_{zz}$. The relations between the Lamè constants λ and μ and the more familiar Young's modules E , Poisson's ratio σ , and the elastic compression modulus K , are readily shown to be

$$E = \frac{\mu(3\lambda + 2\mu)}{\lambda + \mu} \quad ; \quad \lambda = \frac{E}{(1 + \sigma)(1 - 2\sigma)}$$

$$\sigma = \frac{\lambda}{2(\lambda + \mu)} \quad ; \quad \mu = \frac{E}{2(1 + \sigma)}$$

$$K = \lambda + 2 \frac{\mu}{3} \quad ; \quad \mu = G$$

The rigidity modulus G is identical to Lamè constant μ .

The equations of motion are given by the set of equations.⁶

$$\rho \frac{\partial^2}{\partial t^2} (V) = \nabla \cdot T \quad (2.25)$$

where

$$V = \begin{bmatrix} u \\ v \\ w \end{bmatrix} \quad ; \quad T = \begin{bmatrix} T_{xx} & T_{xy} & T_{xz} \\ T_{yx} & T_{yy} & T_{yz} \\ T_{zx} & T_{zy} & T_{zz} \end{bmatrix}$$

Making use of the elastic relationships in Eq. (2.23) for the stress components in Eq. (2.25), we have (see Appendix A for complete derivation)

$$\rho \frac{\partial^2 V}{\partial t^2} = (\lambda + \mu) \nabla \theta + \mu \nabla^2 V \quad (2.26)$$

The above are the basic equations of motion of an isotropic elastic solid and may be shown to correspond to propagation of two

types of waves through the medium. Elimination of terms involving shear strains (such as $\partial u/\partial y$, etc.) from Eq. (2.26) leads to wave equation for a dilatational (or irrotational or compressional) wave. See Appendix A for details of derivation.

$$\rho \frac{\partial^2 \theta}{\partial t^2} = (\lambda + 2\mu) \nabla^2 \theta \quad (2.27)$$

This indicates that compressional wave is propagated through the medium with a velocity

$$c_d = \left[\frac{(\lambda + 2\mu)}{\rho} \right]^{1/2} = \left[\frac{K + 4\mu/3}{\rho} \right]^{1/2} \quad (2.28)$$

On the other hand, if θ is eliminated from Eq. (2.26) we obtain the wave equations for a torsional or rotational wave, the details are also presented in Appendix A.

$$\begin{aligned} \rho \frac{\partial^2 \Omega_x}{\partial t^2} &= \mu \nabla^2 \Omega_x \\ \rho \frac{\partial^2 \Omega_y}{\partial t^2} &= \mu \nabla^2 \Omega_y \\ \rho \frac{\partial^2 \Omega_z}{\partial t^2} &= \mu \nabla^2 \Omega_z \end{aligned} \quad (2.29)$$

In addition, if we impose the further restriction that $\theta = 0$, we obtain the wave equations for transverse or shear waves

$$\begin{aligned} \rho \frac{\partial^2 u}{\partial t^2} &= \mu \nabla^2 u \\ \rho \frac{\partial^2 v}{\partial t^2} &= \mu \nabla^2 v \end{aligned}$$

$$\rho \frac{\partial^2 w}{\partial t^2} = \mu \nabla^2 w \quad (2.30)$$

Waves of this type are propagated with a velocity

$$c_t = \sqrt{\mu/\rho} \quad (2.31)$$

Any plane wave propagated through an isotropic elastic medium must travel with one of the velocities c_d or c_t and it is important to realize that both types can be propagated in a solid, but note that for an ideal fluid $\mu = 0$ and only compressional waves can be propagated. Although only the above types of elastic wave can be propagated in an unbounded isotropic solid, elastic surface (e.g., Rayleigh) waves may occur at a boundary surface. The amplitude of these surface waves decreases rapidly with depth into the solid and their velocity of propagation, c_s , is less than the transverse wave velocity, c_t . If the Poisson's relation $\lambda = \mu$ ($\sigma = 1/4$) holds, then $c_s = 0.9194 c_t$. The associated displacements are in directions normal and parallel to the surface, the latter component being parallel to the direction of propagation.

We have shown that the wave equation for a compressional or a transverse wave is of the form

$$\frac{\partial^2 \epsilon}{\partial t^2} = c^2 \nabla^2 \epsilon = c^2 \left(\frac{\partial^2 \epsilon}{\partial x^2} + \frac{\partial^2 \epsilon}{\partial y^2} + \frac{\partial^2 \epsilon}{\partial z^2} \right) \quad (2.32)$$

where ϵ stands for θ , Ω , or u , and $c = c_d = [(\lambda + 2\mu/\rho)]^{1/2}$ for a transverse or rotational wave.

In practice, the deformation is often a function of only one coordinate x , say, then the equation becomes

$$\frac{\partial^2 \epsilon}{\partial t^2} = c^2 \frac{\partial^2 \epsilon}{\partial x^2} \quad (2.33)$$

The steady-state solution of this equation for the case where ϵ is simple harmonic is then

$$\begin{aligned} \epsilon &= \epsilon_0 \exp(j\omega t) \exp(-j\omega x/c) \\ &= \epsilon_0 \exp[j\omega(t - x/c)] \end{aligned} \quad (2.34)$$

Attenuation of the wave would be expressed by an additional multiplying term in this equation of the form $\exp(-\alpha x)$, where α represents the attenuation constant.

D. Sensor Formulation

The sensor most widely used in the loose-part monitoring work is a piezoelectric accelerometer, although acoustic emission sensors have been utilized in some cases. The accelerometer is an instrument used to measure shock or vibration. It can simply be described by a mass element connected to the steel casing by a spring and a damping medium. The transducing element produces an electrical output proportional to the displacement of the mass element relative to the case and also proportional to the acceleration applied to the case. Almost all accelerometers can be represented as a single degree of freedom system and are most sensitive only in one axis.

A simplified but accurate model of a typical accelerometer is shown in Fig. 6 where M is the sensitive mass of the accelerometer, K is the spring constant, and C is the dashpot damping coefficient. The basic equation of motion of the mass M is given by

$$-M \frac{d^2 x_1}{dt^2} + C \left(\frac{dx_1}{dt} - \frac{dx_2}{dt} \right) + K(x_1 - x_2) = 0 \quad (2.35)$$

The displacement of M with respect to accelerometer housing is given by

$$x = x_1 - x_2 \quad (2.36)$$

and, therefore, Eq. (2.35) becomes

$$M \frac{d^2 x}{dt^2} + C \frac{dx}{dt} + Kx = -M \frac{d^2 x_2}{dt^2} \quad (2.37)$$

Dividing both sides of Eq. (2.37) by M , and redefining the constant coefficients leads to

$$\frac{d^2 x}{dt^2} + 2\xi\omega \frac{dx}{dt} + \omega^2 x = -a(t) \quad (2.38)$$

where

$\omega = \sqrt{K/M}$, circular natural frequency

$\xi = C/2 \sqrt{1/MK}$, ratio of actual to critical damping

$a(t) = d^2 x_2 / dt^2$, time dependent acceleration input to the
system

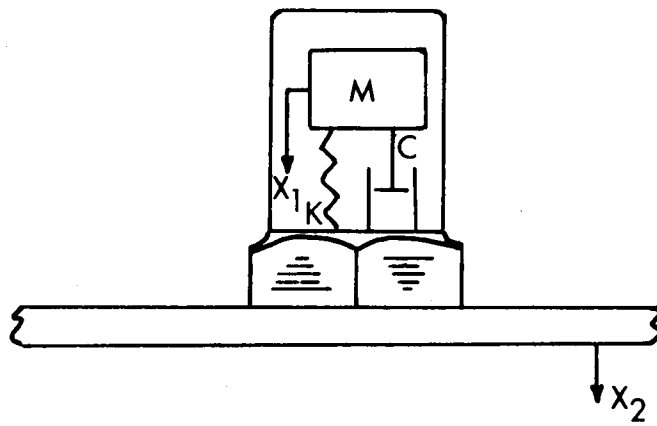


Fig. 6. A simplified accelerometer design.

The relation (2.38) is the governing equation for an accelerometer system with $a(t)$ being the impact acceleration at the sensor location.

The sensitive element of an accelerometer (K in Fig. 6) is a piezoelectric crystal which is in effect a capacitor, that produces a charge, q , across its plate proportional to a force applied to the crystal. The actual circuit diagram of an accelerometer is shown in Fig. 7. The internal resistance and inductance can be ignored when considering the general performance of an accelerometer. The output voltage of the accelerometer is equal to the generated charge by the piezoelectric element divided by the transducer capacitance. A piezoelectric transducer can be used in either voltage or charge sensitive mode. The simplified equivalent circuit for both modes is shown in Fig. 8. The shunt resistance is usually the input resistance of an associated amplifier and the external capacitance C_t is the capacitance of the cable. Since the charge generated by the transducer does not change as the cable capacitance changes (C_t , long and short cables), the charge sensitivity of the accelerometer system remains unaffected. This characteristic explains the practical advantage of a charge sensitive electronics over that of a voltage sensitive system.

Each accelerometer is provided with a voltage, and a charge sensitivity calibration: Q (picocoulombs/g's) and E (millivolts/g's). When using a voltage amplification system the factory voltage sensitivity will change according to the type and length of cable used from the transducer to the amplifier. The following two equations give the new voltage sensitivity of the system.

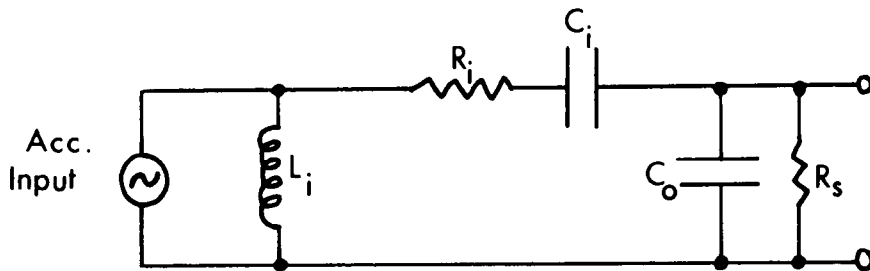


Fig. 7. Circuit diagram of a piezoelectric accelerometer.

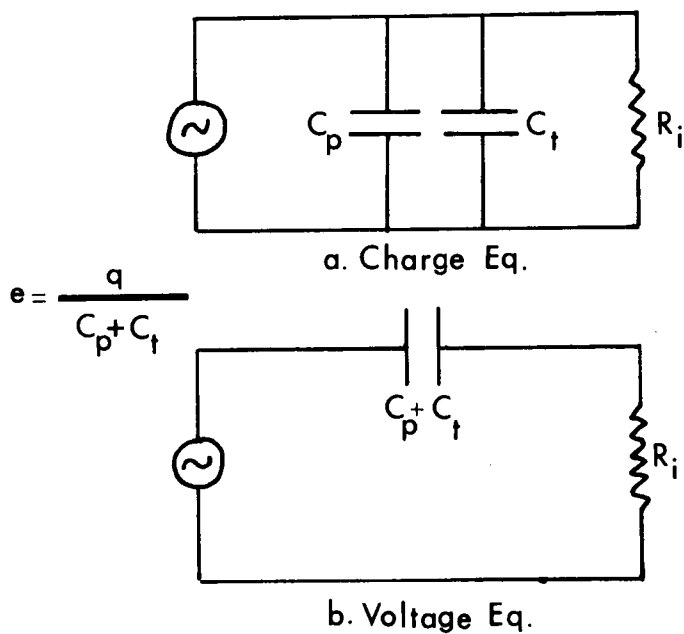


Fig. 8. Equivalent circuits for piezoelectric transducer system.

$$\begin{aligned}
 E &= \frac{Q}{C_p + C_t} \times 1000 \\
 &= E_{cal} \frac{C_p + C_{cal}}{C_p + C_t}
 \end{aligned}
 \tag{2.39}$$

where

- E = new sensitivity being determined, mV/g
- Q = factory supplied charge sensitivity, pe/g
- C_p = transducer internal capacitance, pF
- C_t = total capacitance external to the transducer, pF
- C_{cal} = external capacitance used when calibrated at factory, pF
- E_{cal} = factory supplied voltage sensitivity, mV/g

E. Remarks

The theoretical work indicates that the process of contact between two bodies results in the generation of impact wave (surface wave) which is detected by the accelerometer. The magnitude of the surface wave is related to the momentum of the loose part through the coefficient restitution. This relation will be examined in the following chapter through experiment in conjunction with other aspects of impact characterization.

CHAPTER III

TWO DIMENSIONAL IMPACT WAVE STUDIES

FLAT PLATE EXPERIMENT

A. Introduction

In this chapter, there are three primary objectives. The first is to study several accelerometer mounting methods and identify the effect of the mount on the impact signal. The second objective is to develop and test an impact location method using various triangulation techniques. The final objective is to explore the impact signal in time and frequency domain and obtain a correlation between the signal characteristic and the impact characteristic. In particular the angle between the missile and the target is of particular interest. The relation between the impact angle and the signal characteristic will be investigated, holding the missile impact energy constant.

B. Experimental Facility

The two dimensional impact experiments were conducted in the laboratory on two types of structures. The first was a steel machinist surface plate ($44 \times 64 \times 2$ cm), and the second was an aluminum slab ($122 \times 122 \times 5$ cm). The steel plate was used in the accelerometer attachment studies. The 10-32 threaded stud mount recommended by the accelerometer manufacturer was designated the "reference" mounting technique, and other mounts and mismounts were then compared to this

reference. Table 1 lists the various mounts and mismounts investigated, and Fig. 9 illustrates the geometry of the steel impact plate. The aluminum slab was used in impact location and characterization studies. The slab was provided with hinges on one side and a handle on the opposite side for the angle of impact experiment. The schematic diagram of the aluminum slab and location of the accelerometer stud mounts are shown in Fig. 10. The aluminum slab was positioned on a set of U channels for ground isolation.

Table 1. Accelerometer mounts tested

Mount Designation	Description
0	"Reference"; 10-32 threaded stud torqued to 1.92 J
1	Angle hole stud mismount; hole axis $\sim 10^\circ$ off perpendicular to surface
2	Short (bottomed) hole stud mismount; hole ~ 0.8 mm (1/32 in.) shorter than stud
3	Over-torqued (3.39 J) and under-torqued (1.13 J) threaded stud
4	Cylindrical magnet; holding force ~ 111 N.
5	U-shaped channel magnet; holding force ~ 333 N.
6	Eight-pole castellated magnet; holding force ~ 333 N.
7	Direct pressure mount, with and without silicone grease couplant
8	Commercial 10-32 threaded insulated stud, torqued to 1.92 J

The impacts used were the constant of a free falling steel ball from a magnetic release apparatus which can be positioned over the target plate. A plumb bob is used to site the point of impact.

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PLATE IMPERFECTIONS
(4, 1/2-IN. THROUGH HOLES)

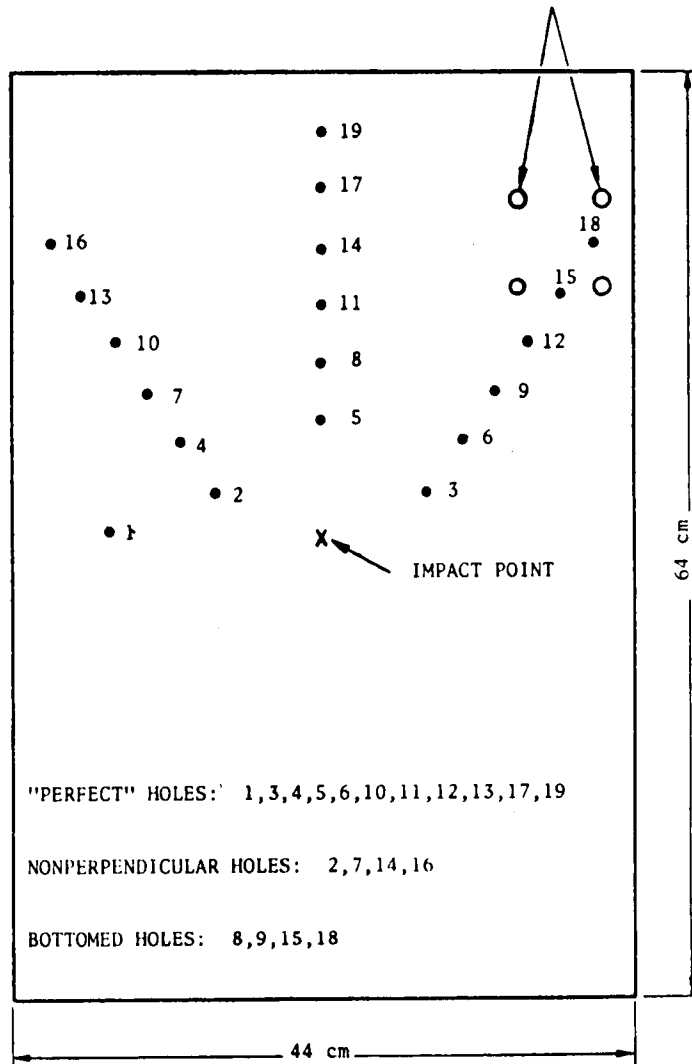


Fig. 9. Accelerometer stud mounting pattern on the steel plate.

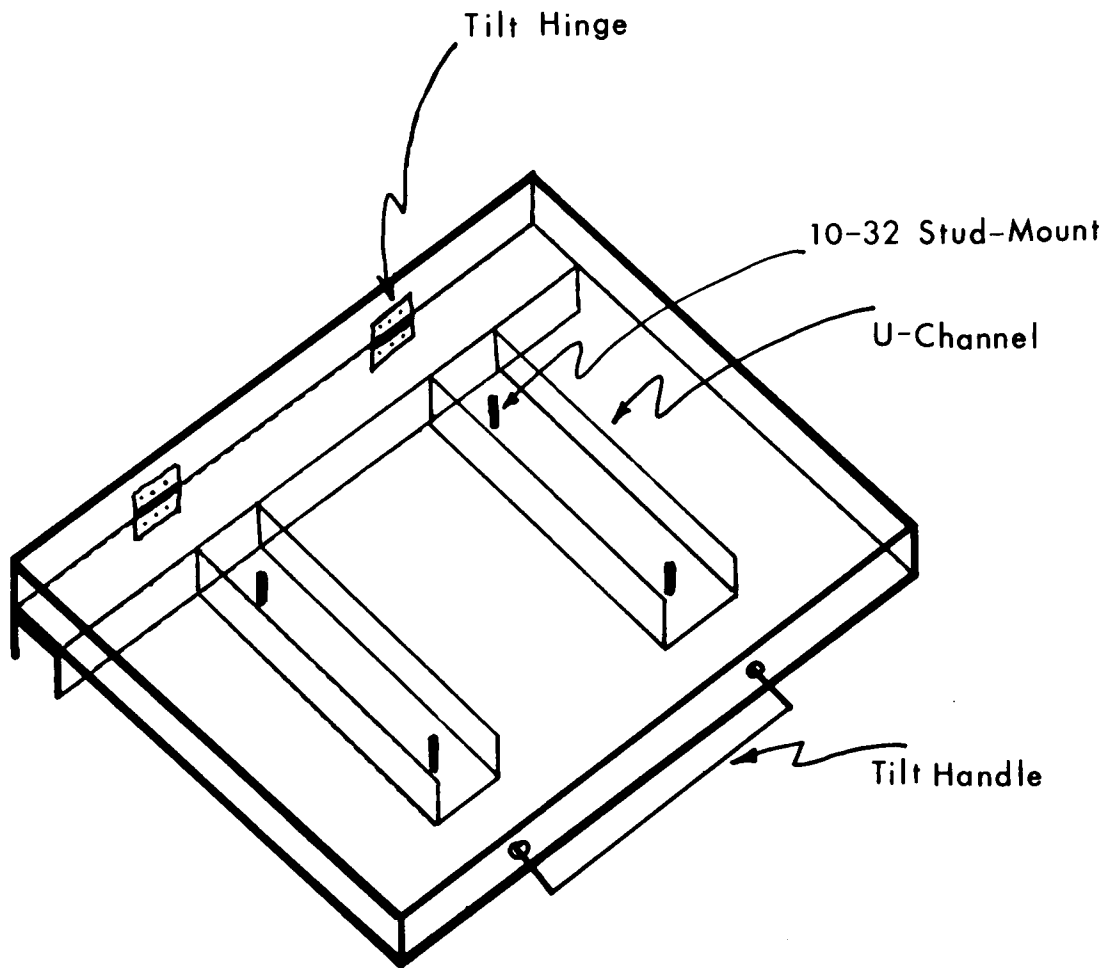


Fig. 10. Schematic of the aluminum slab and the tilt mechanism.

C. Electronic and Data Acquisition System

The electronics and data acquisition system used consists of Endevco Model 2236 accelerometers (charge sensitivity ~ 66.0 PC/g's), Endevco Model 2735 charge amplifiers, Endevco Model 2731 remote charge converter, Princeton Applied Research (PAR) Model 113 voltage amplifiers, and a 4 channel Nicolet Explorer III transient capture oscilloscope with digital data storage. The schematic diagram of the data collection system is shown in Fig. 11. Both types of amplification systems (charge and voltage) were used, no difference was noticed, since the distance between the accelerometer and the amplifiers were relatively short (183 cm). The impact data were stored on digital minidiskettes, and transferred to a PDP 11/20 via a DR11-C module from the NIC Explorer III memory for further processing. Appendix B contains the necessary Fortran callable machine language program for the data transfer.

D. Accelerometer Attachment Studies

The response of an accelerometer due to a surface disturbance highly depends on the attachment method. All the accelerometer manufacturers recommend stud mounting with a given torque, but due to some physical limitations or misinstallation, divergence from the reference (stud mount) installation might occur. The effect of various mounting techniques and mismounting are investigated here. Table 2 lists the tests performed for this purpose. The impacts were the free fall of a 2.04 gram steel ball on the machinists surface plate with

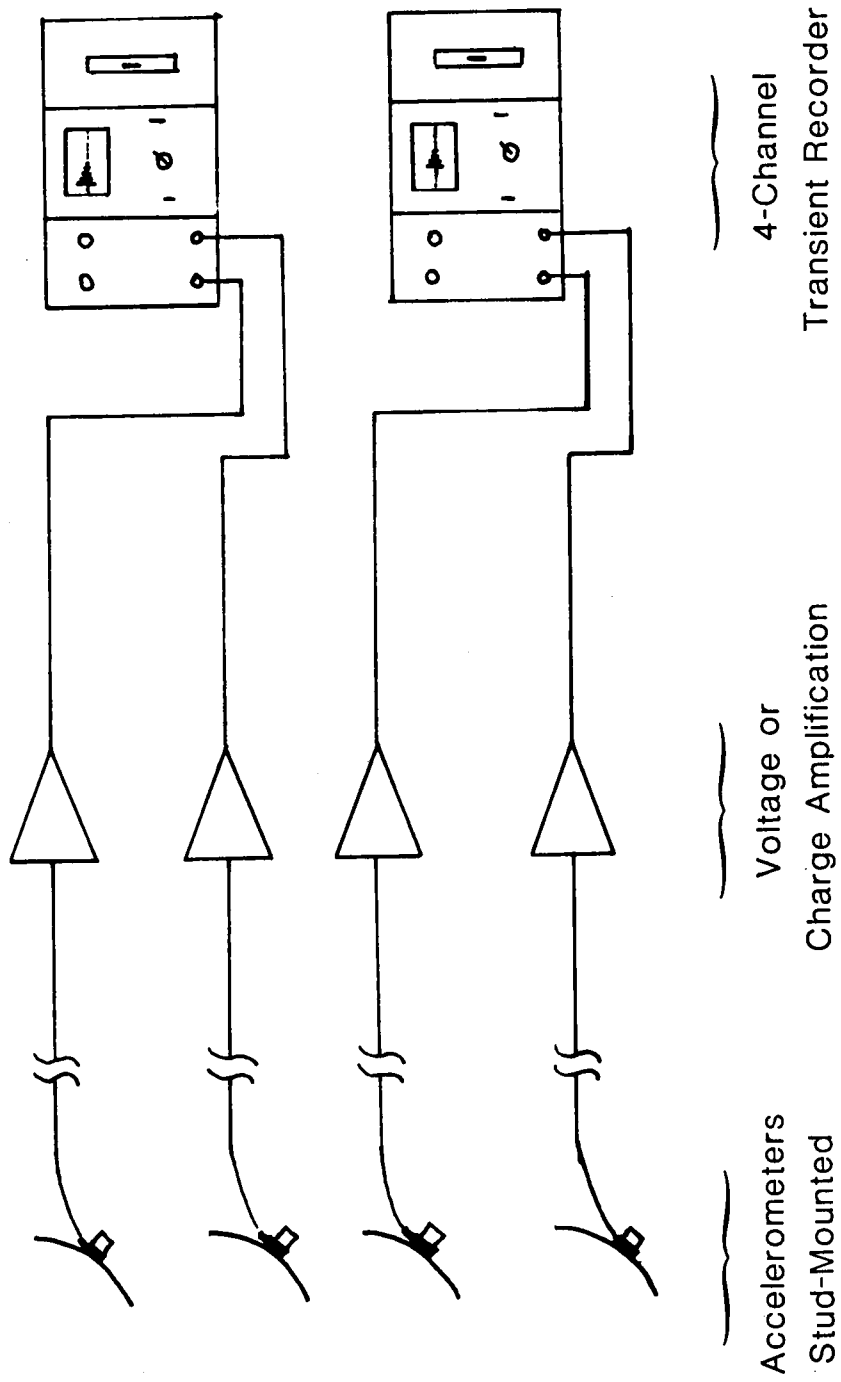


Fig. 11. Schematic diagram of data collection system.

Table 2. List of various impact tests on the steel plate

Impact ^a No.	Accel. Location ^b	Mount Designation ^c	Comments
1	5	0	Reference for impacts 4 and 5
2	14	1	
3	8	2	
4	5	3	Under-torqued stud
5	5	3	Over-torqued stud
6	2	1	
7	3	0	Reference for impact 6
8	13	0	Reference for impact 9
9	15	2	
10	7	1	
11	9	2	
12	{ between 2 and 4	4	Reference was provided by impact 16
13	{ between 2 and 4	5	First orientation
14	{ between 2 and 4	5	Second orientation
15	{ between 2 and 4	6	
16	4	0	For testing symmetry assumption; also reference for impacts 12-15
17	6	0	
18	4	7	5.9 kg (13 lbf) deadweight and grease couplant
19	4	7	11.8 kg (26 lbf) deadweight and silicone grease couplant
20	4	7	5.9 kg (13 lbf) deadweight; no couplant
21	4	7	11.8 kg (26 lbf) deadweight; no couplant
22	4	8	Reference was provided by impact 16

^aSteel ball diameter, 0.793 cm; mass, 2.04 g; and drop height, 73.66 cm. Impact energy, 1.47×10^{-2} J (0.011 lbf); momentum, 7.75×10^{-3} N-s; and impact point, geometric center of plate.

^bSee Fig. 9, page 31.

^cSee Table 1, page 30.

an impact energy of $1.47\text{E}2$ joules. The resultant surface accelerations, with no band pass restriction other than that imposed by the sensor and the amplifier, were digitized (at 2 MHz for time comparison and 100 kHz for frequency comparison) and stored into a single data block of 2048 points per impact.

Figure 12 shows several surface accelerations in nanocoulomb (charge amplification system used) units^a vs time after impact for selected impacts of Table 2. These highly repeatable transient signals were fourier transformed to produce the power spectrum (for example, Fig. 13) of each sensed impact. Typical power spectra, discussed in detail later, are shown in Figs. 14 through 26. They are particularly enlightening when presented in a normalized form, namely, as a ratio of the acceleration spectrum from the mount under test to that from the reference mount at the same relative position on the plate. Deviations from the "reference" response are thus readily apparent in the figures as departures from the dashed horizontal line at an ordinate value of unity. The time- and frequency-domain data contain the same information, but the signal distortions introduced by the various mounts are often more clearly perceived in one form or the other. For example, the time-domain plots show the initial wave passage and the time-varying amplitude of the signal particularly well, whereas the normalized

^aThe traces of Fig. 12 cannot be converted to "g" (9.80 m/s^2) units through the accelerometer's specified charge sensitivity of 66 pC/g, because that figure is applicable only to the accelerometer's "linear" frequency range, namely, 2 Hz-8 KHz for the model 2236. The signals of Fig. 12 are wideband.

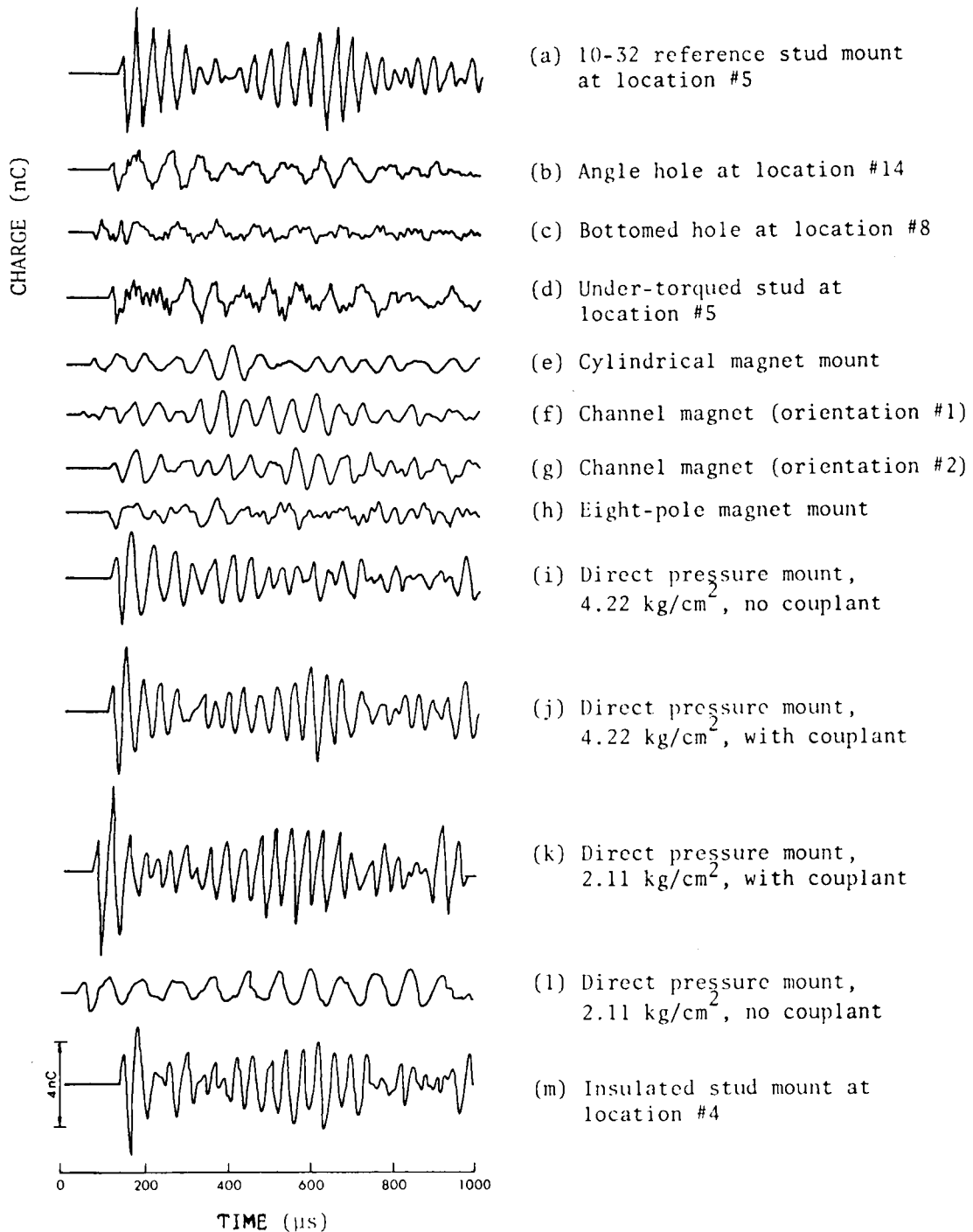


Fig. 12. Time-domain accelerometer responses to the impulse produced by a ball drop, for various accelerometer mounting methods. All traces have the same vertical and horizontal scales.

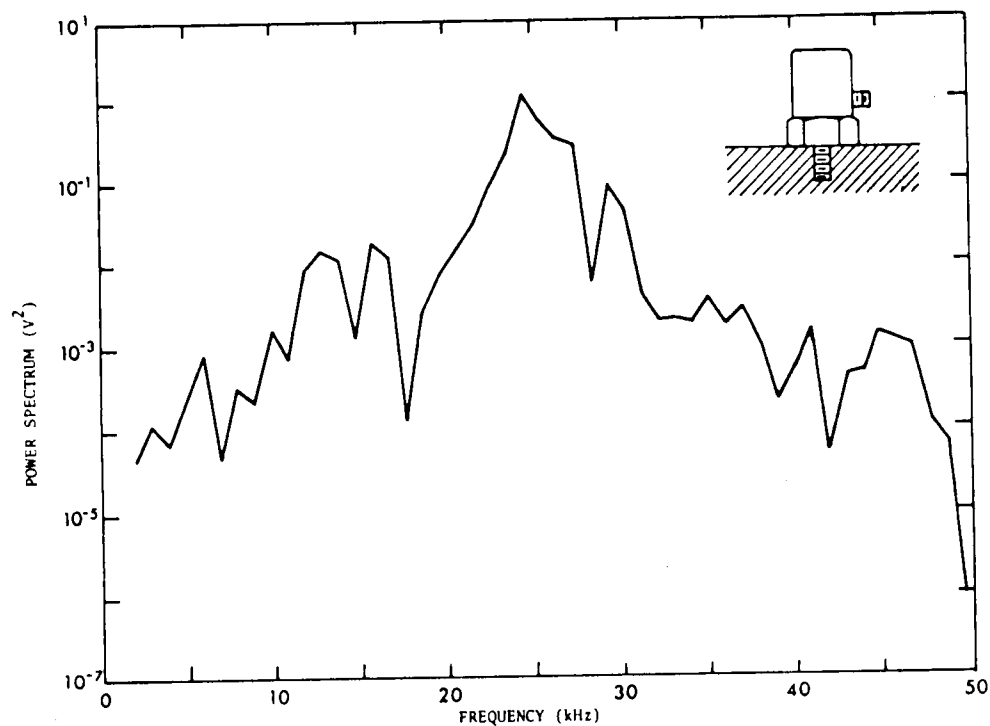


Fig. 13. Accelerometer power spectrum for the reference mounting.

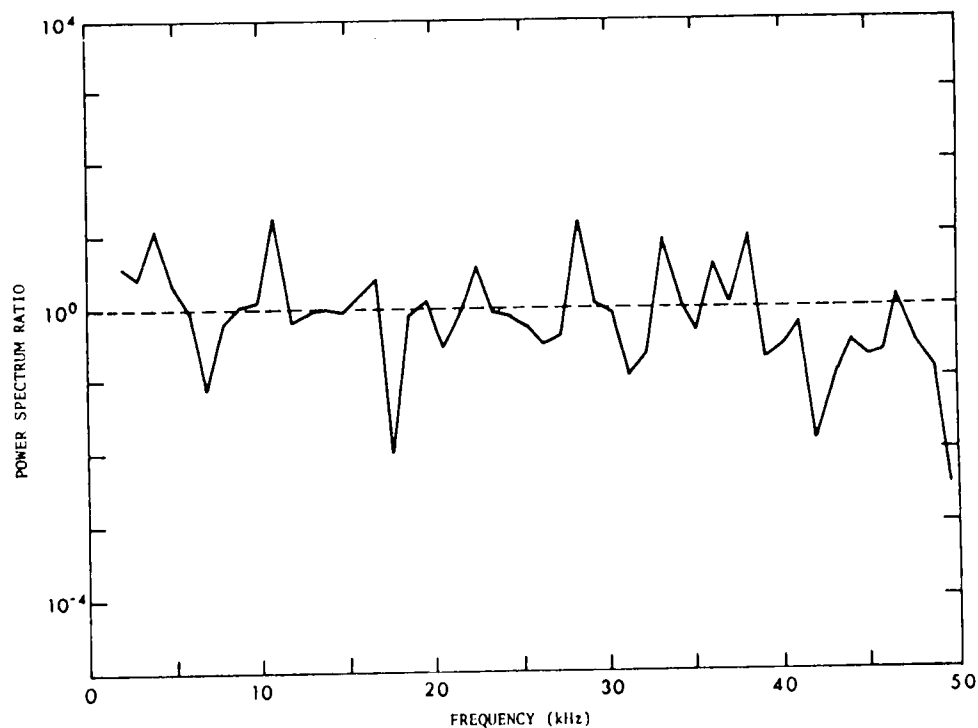


Fig. 14. Ratio of acceleration power spectra at plate positions 4 and 6.

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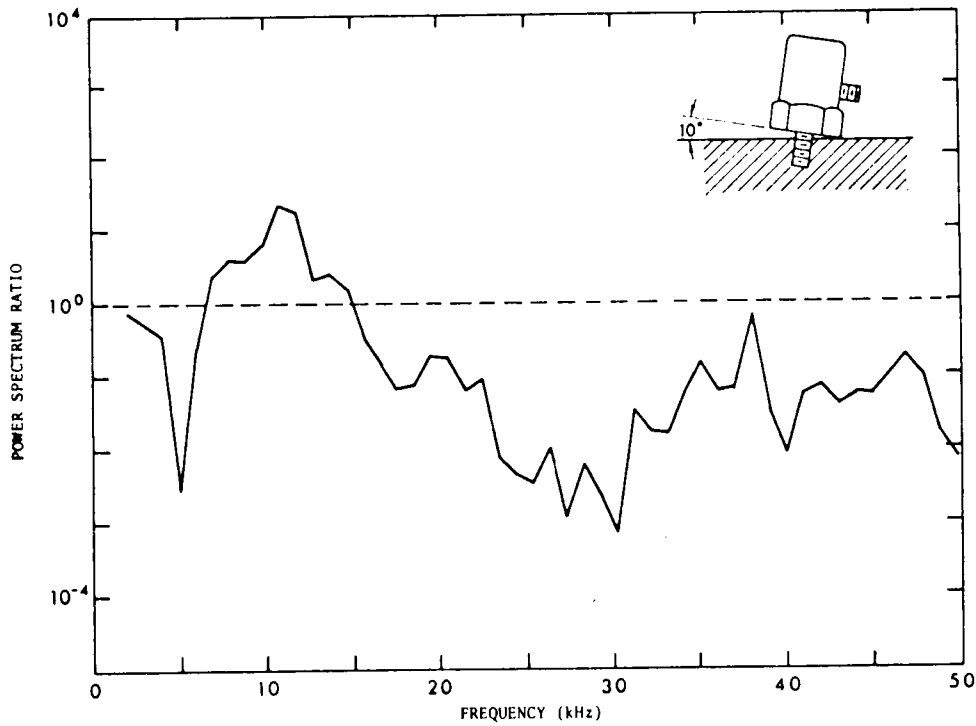


Fig. 15. Response of nonperpendicular hole stud mounting relative to the reference.

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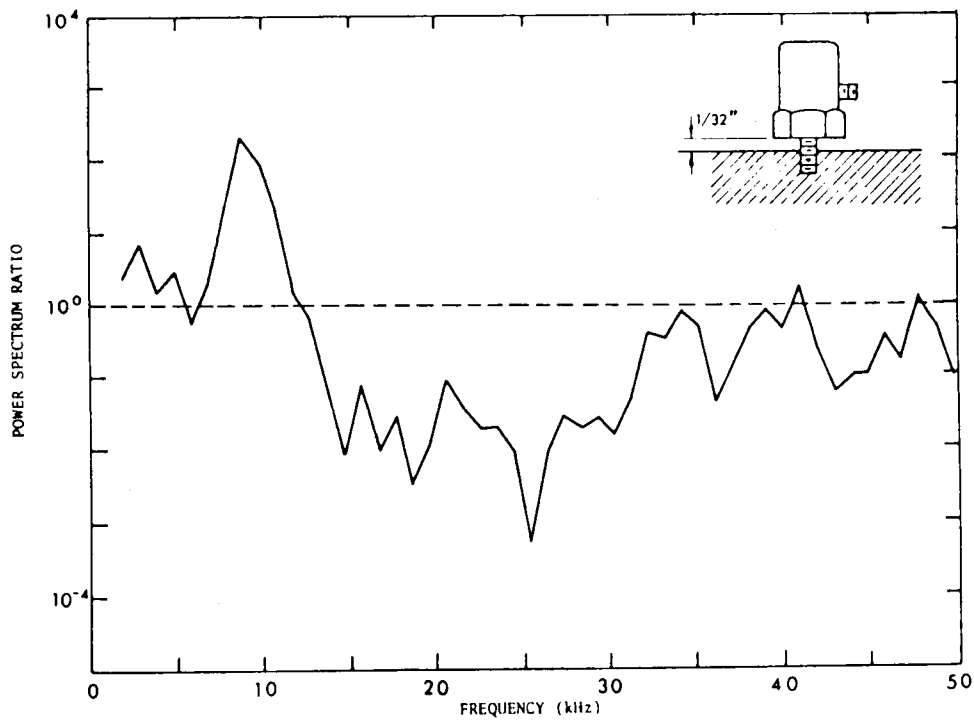


Fig. 16. Response of bottomed hole stud mounting relative to the reference.

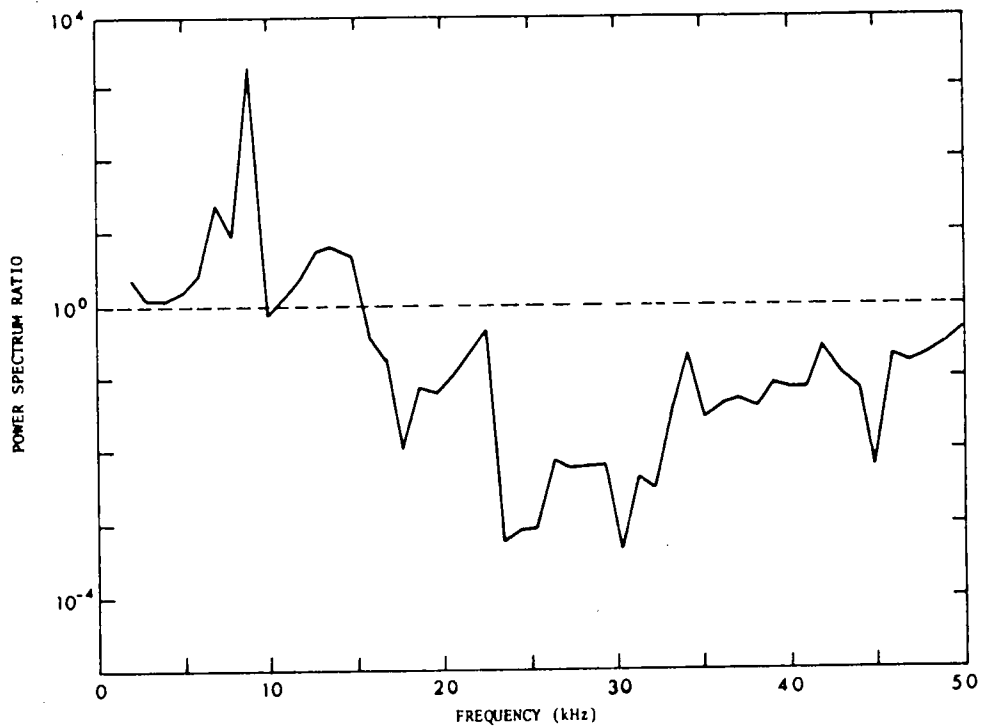


Fig. 17. Response of under-torqued stud mounting relative to the reference.

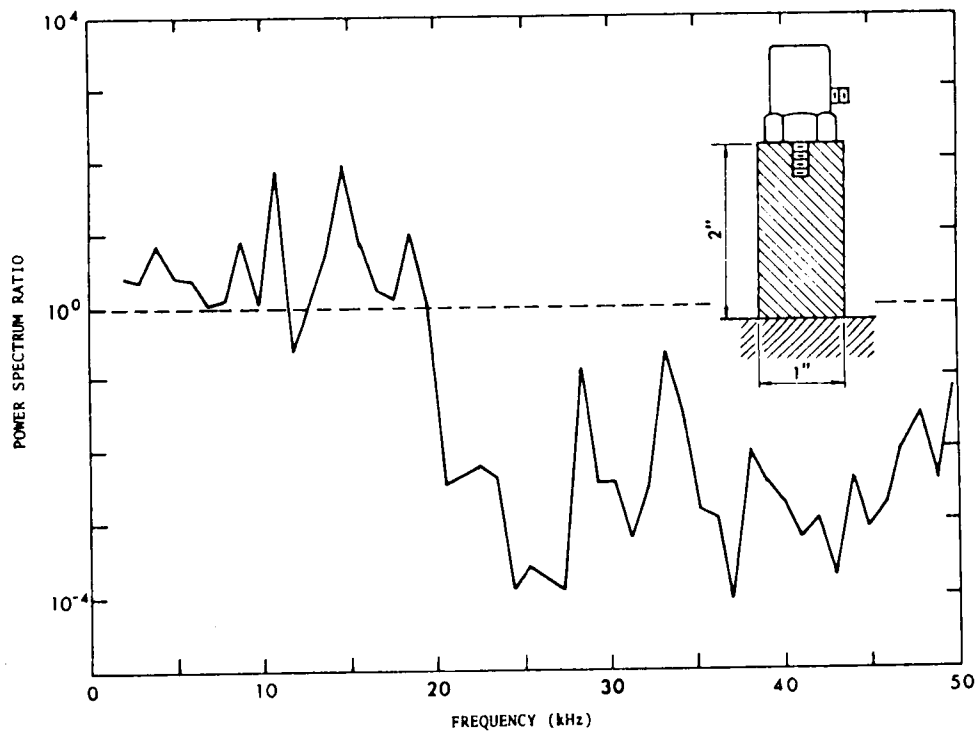


Fig. 18. Response of cylindrical magnet mounting relative to the reference.

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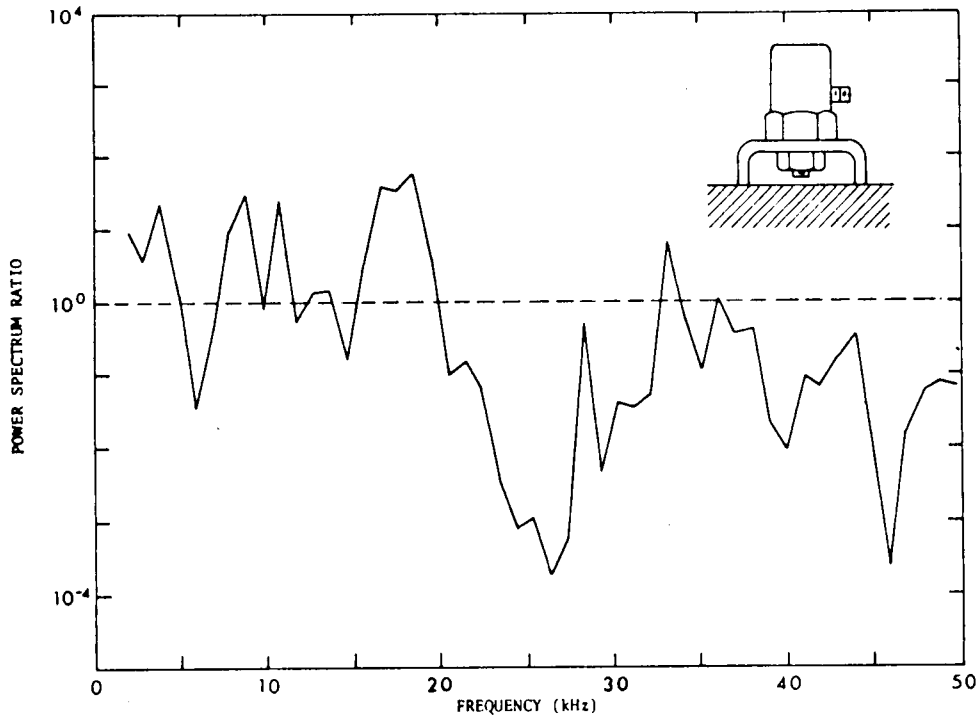


Fig. 19. Response of channel magnet mounting relative to the reference (first orientation).

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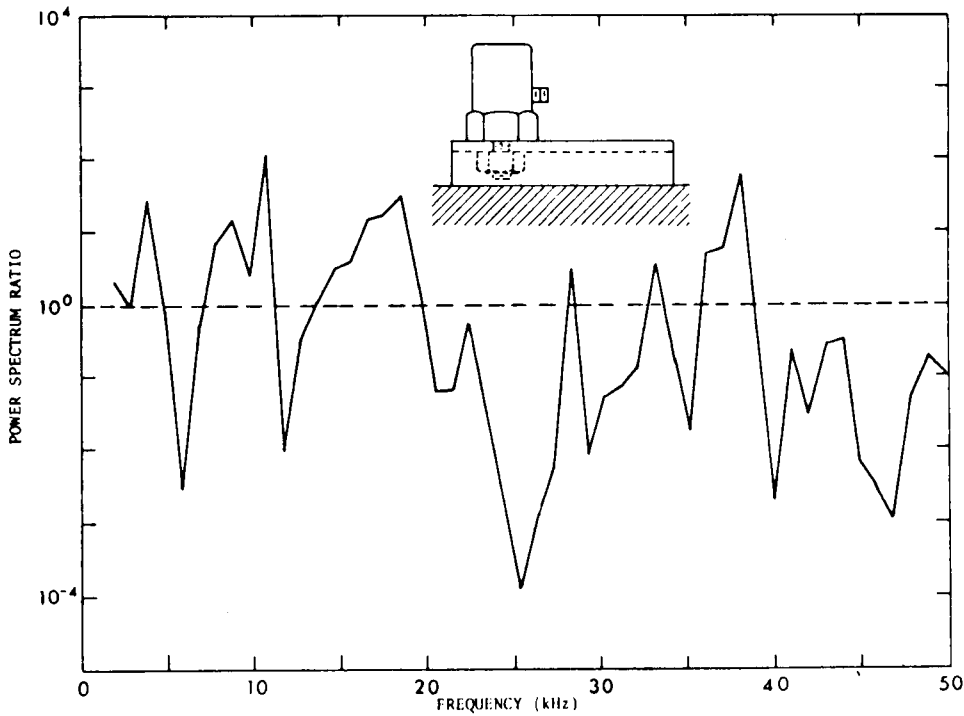


Fig. 20. Response of channel magnet mounting relative to the reference (second orientation).

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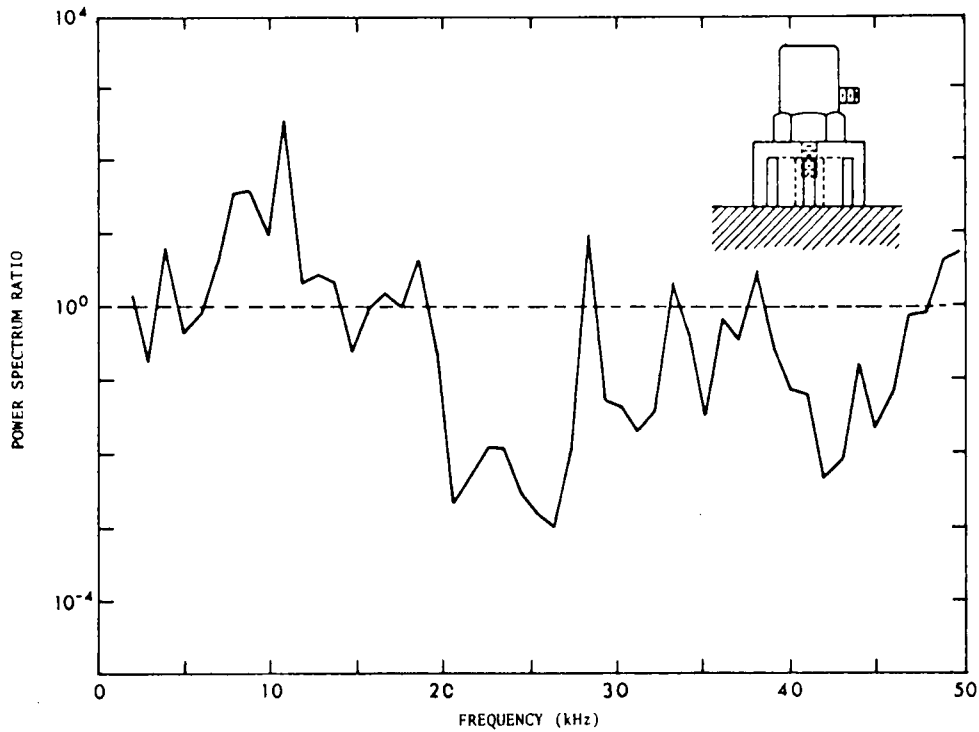


Fig. 21. Response of eight-pole magnet mounting relative to the reference.

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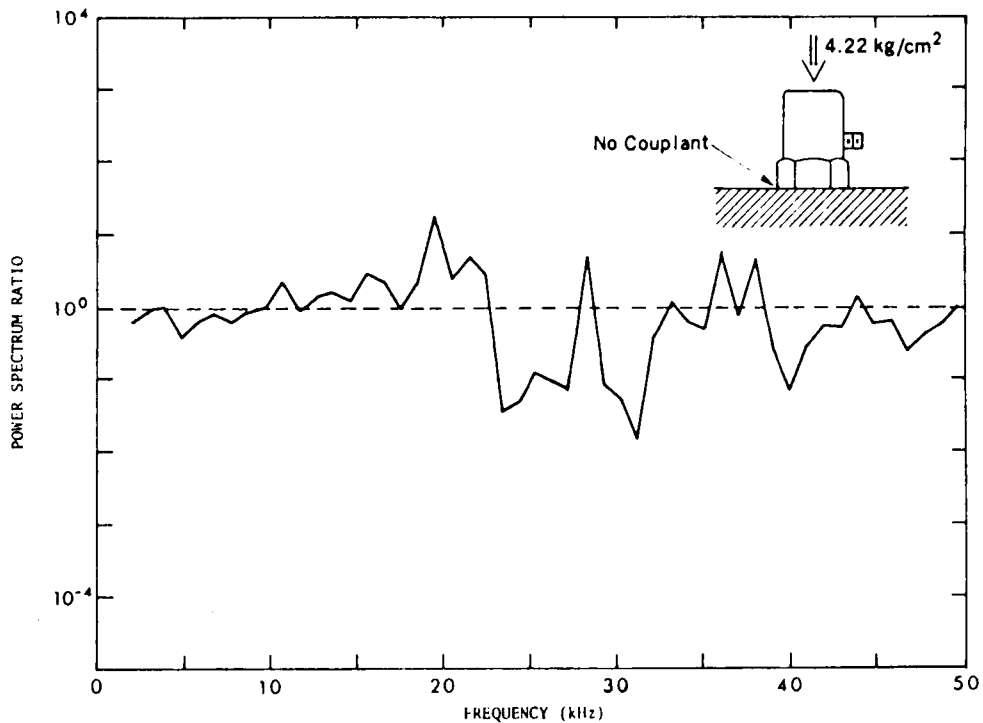


Fig. 22. Response of direct pressure mounting relative to the reference (4.22 kg/cm^2 , no couplant).

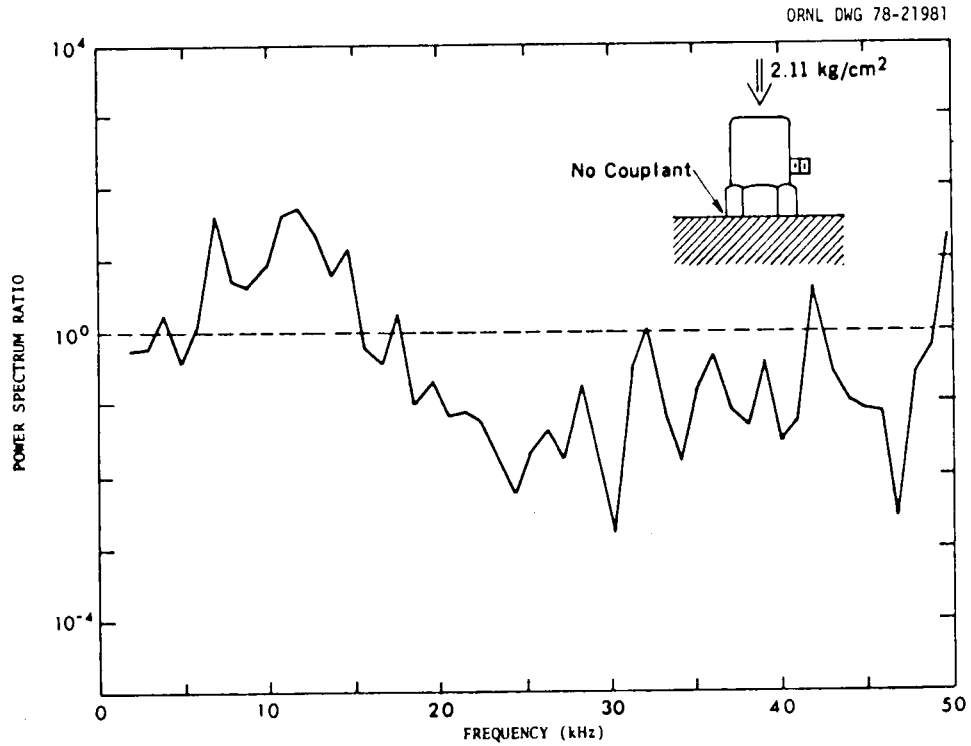


Fig. 23. Response of direct pressure mounting relative to the reference (4.22 kg/cm^2 , with couplant).

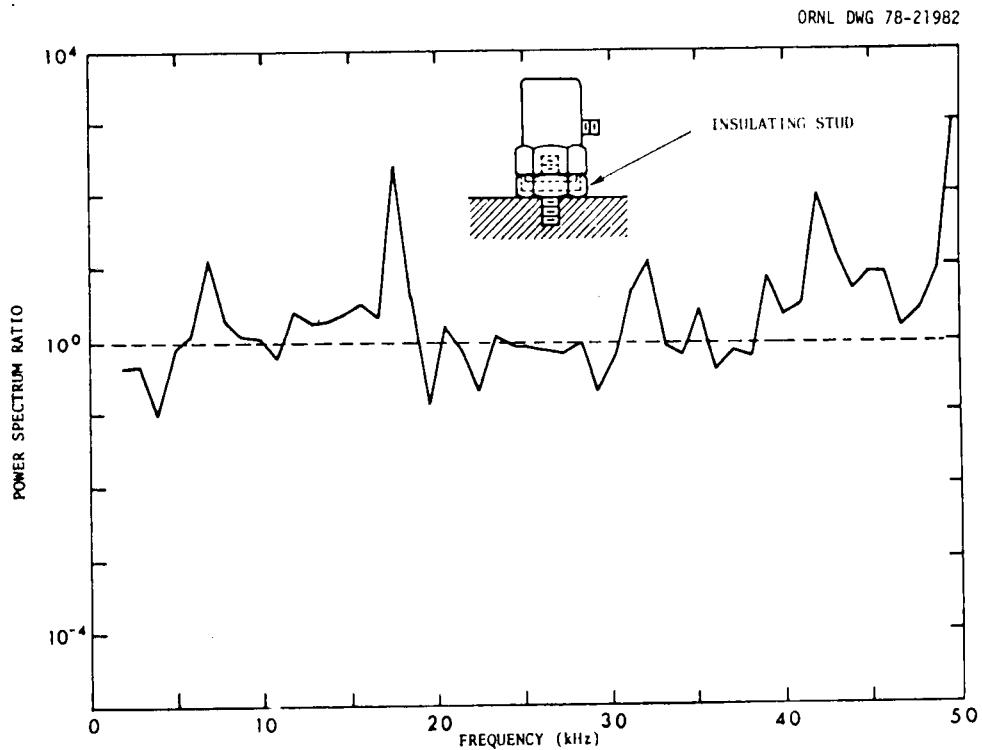


Fig. 24. Response of direct pressure mounting relative to the reference (2.11 kg/cm^2 , with couplant).

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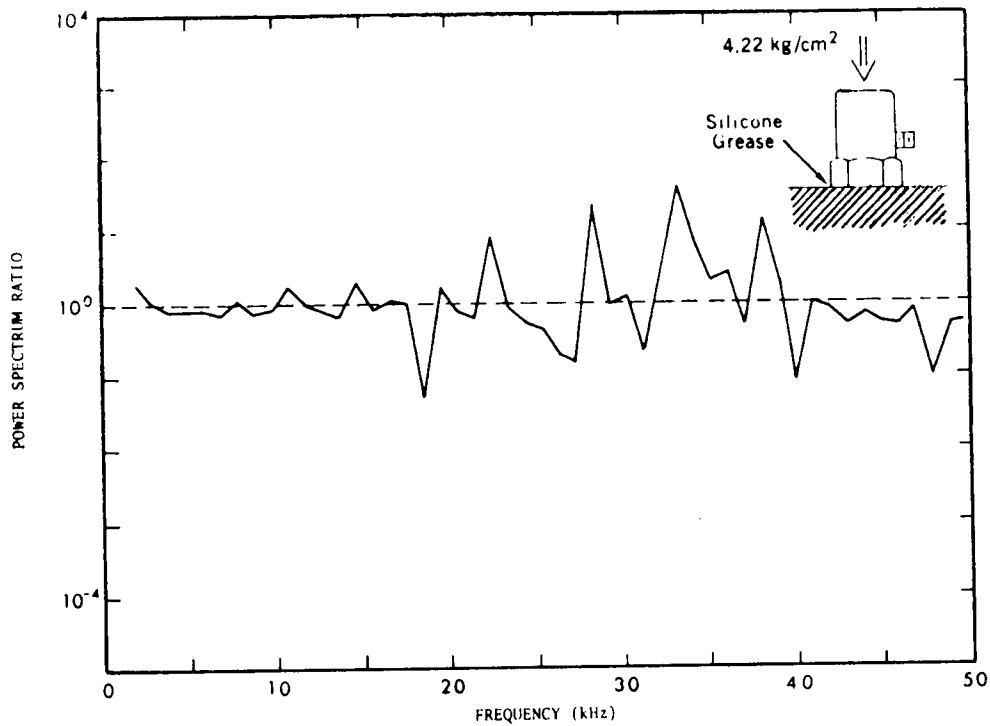


Fig. 25. Response of direct pressure mounting relative to the reference. (2.11 kg/cm^2 , no couplant).

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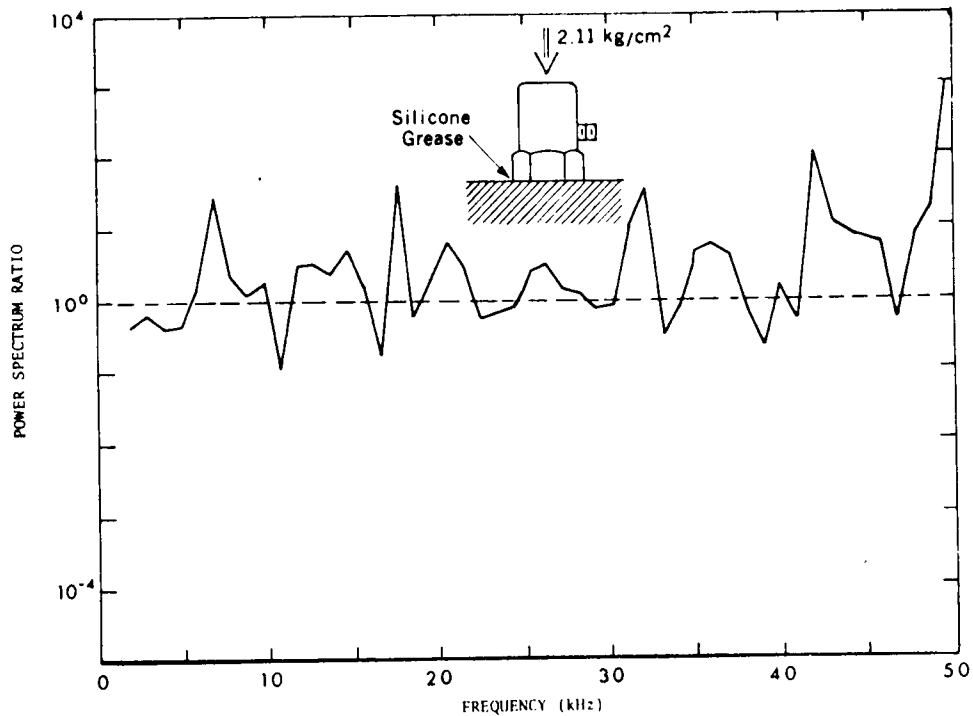


Fig. 26. Response of electrically insulated stud mounting relative to the reference.

frequency spectra show the transfer function (filtration) characteristics of the mount more clearly.

To demonstrate that symmetry can be used to simplify the experimental technique, two impacts were performed at two symmetric positions about the major axis of the plate (impacts 16 and 17), and the surface accelerations were compared. Although the surface plate had some inherent asymmetries (Fig. 9, page 31), the ratio between the power spectra at these two sensor positions was observed to fluctuate more or less randomly between bounds of about 0.1 and 10 (Fig. 14), with a mean value of roughly unity. We concluded that, to the extent required for subsequent comparisons, response symmetry holds.

The dominant feature of the time domain trace from the reference mount was observed to be smoothly damped oscillations having a period corresponding to the accelerometer's natural (resonant) frequency, roughly 25 kHz (see Figs. 12 and 13).

Angle Hole Stud Mismount

A stud angular mismount was tested by drilling the mounting hole at an angle of $\sim 10^\circ$ off perpendicular. This type of mismount can be anticipated in plant backfit situations where the mounting location of the accelerometer on a reactor structure is not easily accessible. The most prominent effects produced by this mismounting (see Figs. 12b and 15) are an overall loss of signal amplitude (a factor of ~ 2) and a shift of sensed signal power to lower frequencies (7 to 20 kHz) relative to the reference (Fig. 13).

Short (Bottomed) Hole Stud Mismount

This type of mismount, wherein the sensitive face of the accelerometer does not make proper contact with the surface to which it is affixed, can also be expected to occur where accessibility to the mounting location is limited. As in the angle hole case, the time-domain signal amplitude is attenuated a factor of somewhat more than 2 (Fig. 12) and a frequency-domain distortion also occurs (Fig. 16), in this case a pronounced low-frequency enhancement in the narrow band of ~ 7 to 12 kHz.

Stud Torquing Mismount

The recommended mounting torque for the model 2236 accelerometer is 1.92 J (17 in.-lbf). We performed several tests in which the accelerometer torque was varied from 1.13 to 3.39 J (10 to 30 in.-lbf) and concluded that over-torquing does not appreciably change the time or frequency characteristics of the surface acceleration sensed, whereas under-torquing (<15 in.-lbf for this accelerometer) is accompanied by a significant signal amplitude loss (Fig. 12d), a marked low-frequency enhancement (Fig. 17), and suppression of the accelerometer's resonant behavior in the 23-27 kHz region.

Cylindrical Magnetic Mount

In reactor installations where direct threaded stud mounting to the component of interest is not practical, it has been industry practice to stud mount the accelerometer on a magnet which, in turn, attaches itself to the reactor component (if it is a ferrous material).

The data from tests of a cylindrical magnet having a holding force of 111 N (25 lbf) show, relative to the reference mount, a loss of signal amplitude (Fig. 12) and a general suppression of the higher-frequency surface accelerations (Fig. 18).

U-Shaped Channel Magnetic Mount

We also tested a U-shaped channel magnet, with the accelerometer bolted to the magnet. The magnet had a holding force of ~ 333 N (75 lbf). Two orientations of the magnet relative to the direction of the wave propagation were examined. The relative magnitudes of the time signals appeared to be similar (Figs. 12f and 12g), but the initial wave passage signal and the frequency content were different for the two orientations (Figs. 19 and 20). Although perhaps not so corruptive as some of the other mountings tested, the U-shaped channel magnet cannot be viewed as providing a faithful acoustic coupling between the structure and the accelerometer.

Eight-Pole Magnet

An accelerometer bolted to an eight-pole magnet (333 N holding force) produced time-domain amplitude characteristics similar to those for the other magnets (Fig. 12h), but the initial wave formation and frequency characteristics were distinct (Fig. 21). Compared to the reference mount, there was a trough in the 20-25 kHz region and a crest in the 7-12 kHz region.

Direct Pressure Mount

Direct pressure mounting of the accelerometer (often accomplished at reactors with taut steel bands or clamps) was also examined (Figs. 12i-12l; 22-25). Since the accelerometer case is not designed to transmit the large forces that would be required to achieve good acoustic coupling between two dry surfaces, the use of a liquid or gel couplant between the accelerometer face and the mounting surface is almost a necessity in this type mounting. Its presence results in signal amplitude and frequency transfer characteristics that closely approach the reference threaded stud mount (Figs. 12j and 12k, 23, and 24). Two pressures, ~ 2.11 and ~ 4.22 kg/cm² (30 and 60 lbf/in.²), were applied by placing a deadweight atop the accelerometer, but the resulting variations in the transfer characteristics were judged to be insignificant, so long as the couplant was present. Without the couplant, however, signal distortion was appreciable, particularly for the lower pressure case (Figs. 12 and 25).

Insulated Stud Mount

Electrically insulated, threaded studs are often used in loose-part detection systems to avoid ground loops. Our tests showed that the distortions introduced by a commercial insulated stud were not pronounced (Fig. 12), except for a slight emphasis of frequencies >40 kHz (Fig. 26).

Remarks

Any obstruction (in the form of an indirect mount) interposed between the structural surface waves and the sensing surface of the

accelerometer acts as a mechanical filter and thus, to some extent, it can be expected to modify the electrical signal produced by the transducer. Depending upon the application, this modification may or may not be important. If the frequency-dependent transfer function of the mount is constant with time and independent of the magnitude of the acoustic wave being sensed, the distortions introduced by the mount can be removed, if desired, by well-known signal processing methods. Alternatively, measurement of the mount's signal transfer function can serve to quality assure the accelerometer installation.

For all mismountings tested, perhaps the most notable effects were (1) a significant loss (~ 2) in peak waveform amplitude, and (2) a selective loss of the higher signal frequencies, often accompanied by an accentuation of certain lower frequency bands. From the standpoint of loose-part detection, the first effect is probably the more important since, for a simple threshold discriminator logic system, mismounting would result in a direct loss of loose-part detection sensitivity, whereas the second effect would most likely degrade only the system's selectivity for metallic impacts. These generalizations apply specifically to *wideband* loose-part detection systems; narrowband systems would conceivably be affected to a lesser degree, depending on the frequency bands selected, and would require analysis on an individual case basis.

Since acoustic couplants can obviously greatly reduce the distortions and signal losses accompanying accelerometer mismounting, the practicality of their use in the high-temperature and high-radiation environments encountered in loose-part detection applications might be worthy of further study.

E. Impact Location

The location of an impact is one of the parameters of interest in loose parts monitoring. The general formulation for impact location on a flat surface in two dimensional cartesian coordinate system is given by

$$[(x - x_i)^2 + (y - y_i)^2]^{\frac{1}{2}} - [(x - x_j)^2 + (y - y_j)^2]^{\frac{1}{2}} = f(\Delta L)_{ij} \quad (3.1)$$

where

(x, y) = coordinate of the impact point

$(x_i, y_i), (x_j, y_j)$ = coordinate of accelerometer i and j

$f(\Delta L)_{ij}$ = a function relating ΔL to a signal parameter

$(\Delta L)_{ij}$ = difference in distance between i and j

The function $f(\Delta L)$ can be expressed either in exact form or it can be approximated. The exact formulation is given by

$$f(\Delta L)_{ij} = \Delta t_{ij} * V \quad (3.2)$$

where

V = impact wave velocity

Δt_{ij} = time arrival difference from j to i

The velocity of impact wave propagation is either known or can be measured and the time difference of the wave arrival can be measured from the time signal. Now, Eq. (3.2) is substituted into (3.1) which

represents the equation of a hyperbole. The impact is located at the intersection of three hyperbolies obtained from the time of arrival difference of three accelerometer signals.

The above impact location method was tested on the steel and the aluminum plate. The impact wave velocity was measured using known impact positions and accelerometer locations, and the time of arrival differences was measured from accelerometers time domain signal at the first major zero crossing.^a The impact wave propagation velocity on the steel was measured at 4213.1 meters/sec ($c_d = 5900$ m/s, $c_t = 3080$ m/s) and for the aluminum plate at 6093.4 meters/sec ($c_d = 6320$ m/s, $c_t = 3230$ m/s). Given the above two velocities a series of impacts at various locations were performed on the steel and the aluminum plate. A computer program was written and used to plot and solve for the three simultaneous hyperbolic equations [Eq. (3.1)] for the coordinates of the point of impact. The numerical results are given in Tables 3 and 4, and a typical computer plot of the hyperbolas are given in Fig. 27. In some cases there might arise an ambiguity of the solution (the three hyperbolas intersect in two places on the plane of interest). This can be resolved using the sign of one or more Δt 's (i.e., if $\Delta t_{12} > 0$ then $t_2 - t_1 > 0$ which indicates impact is closer to accelerometer number 1 and vice versa if $\Delta t_{12} < 0$ the impact is closer to accelerometer number 2). The error in the impact location is systematic and is caused by the digitization rate and is given by

^aOther criteria for Δt measurements were also used with similar success.

Table 3. Results of impact location using Δt method on the steel plate

Impact coordinates		Time diff. measured			Impact location		
		μ_{sec} Δt_{12}	μ_{sec} Δt_{23}	μ_{sec} Δt_{13}			
x-cm	y-cm				x-cm	y-cm	Error ^{cm}
5.0	20.0	2.0	28.5	29.0	5.22	19.81	0.29
7.0	17.0	8.0	34.0	42.5	6.87	17.11	0.17
15.0	15.0	26.0	26.0	52.0	15.30	15.17	0.34
20.0	15.0	35.0	20.0	56.5	20.01	15.3	0.30
30.0	35.0	64.5	-4.0	60.5	30.4	34.7	0.50
40.0	15.0	60.5	1.5	62.0	39.85	14.91	0.17
25.0	40.0	36.5	-2.0	34.5	25.17	40.25	0.30
20.0	50.0	-5.5	-10.0	-15.5	19.92	49.7	0.31

Acc #1 at location #3 $x = 28.76^{\text{cm}}$ $y = 34.98^{\text{cm}}$
 Acc #2 at location #13 $x = 5.07^{\text{cm}}$ $y = 48.64^{\text{cm}}$
 Acc #3 at location #19 $x = 22.00^{\text{cm}}$ $y = 60.58^{\text{cm}}$
 Measured impact wave velocity = 4213.1 m/sec

Table 4. Results of impact location using Δt method on the aluminum plate

Impact coordinates		Time diff. measured			Impact location		
		μ_{sec} Δt_{12}	μ_{sec} Δt_{23}	μ_{sec} Δt_{13}			
x-cm	y-cm				x-cm	y-cm	Error ^{cm}
10.0	10.0	60.0	40.0	100.0	9.74	9.82	0.32
20.0	10.0	55.0	44.0	99.0	20.41	9.75	0.48
30.0	20.0	57.0	42.0	99.0	29.63	20.01	0.37
50.0	20.0	25.5	53.5	79.0	50.30	20.66	0.72
60.0	30.0	3.0	53.5	56.5	59.92	30.18	0.20
80.0	50.0	-50.5	34.5	-16.0	79.90	49.73	0.29
100.0	70.0	-53.5	-23.0	-76.5	100.3	70.21	0.37
110.0	80.0	-53.5	-35.5	-88.5	109.8	80.50	0.54

Acc #1 at location #1	x = 39.37 ^{cm}	y = 39.37 ^{cm}
Acc #2 at location #2	x = 82.55 ^{cm}	y = 39.37 ^{cm}
Acc #3 at location #3	x = 82.55 ^{cm}	y = 82.55 ^{cm}
Measured impact wave velocity = 6093.4 m/sec		

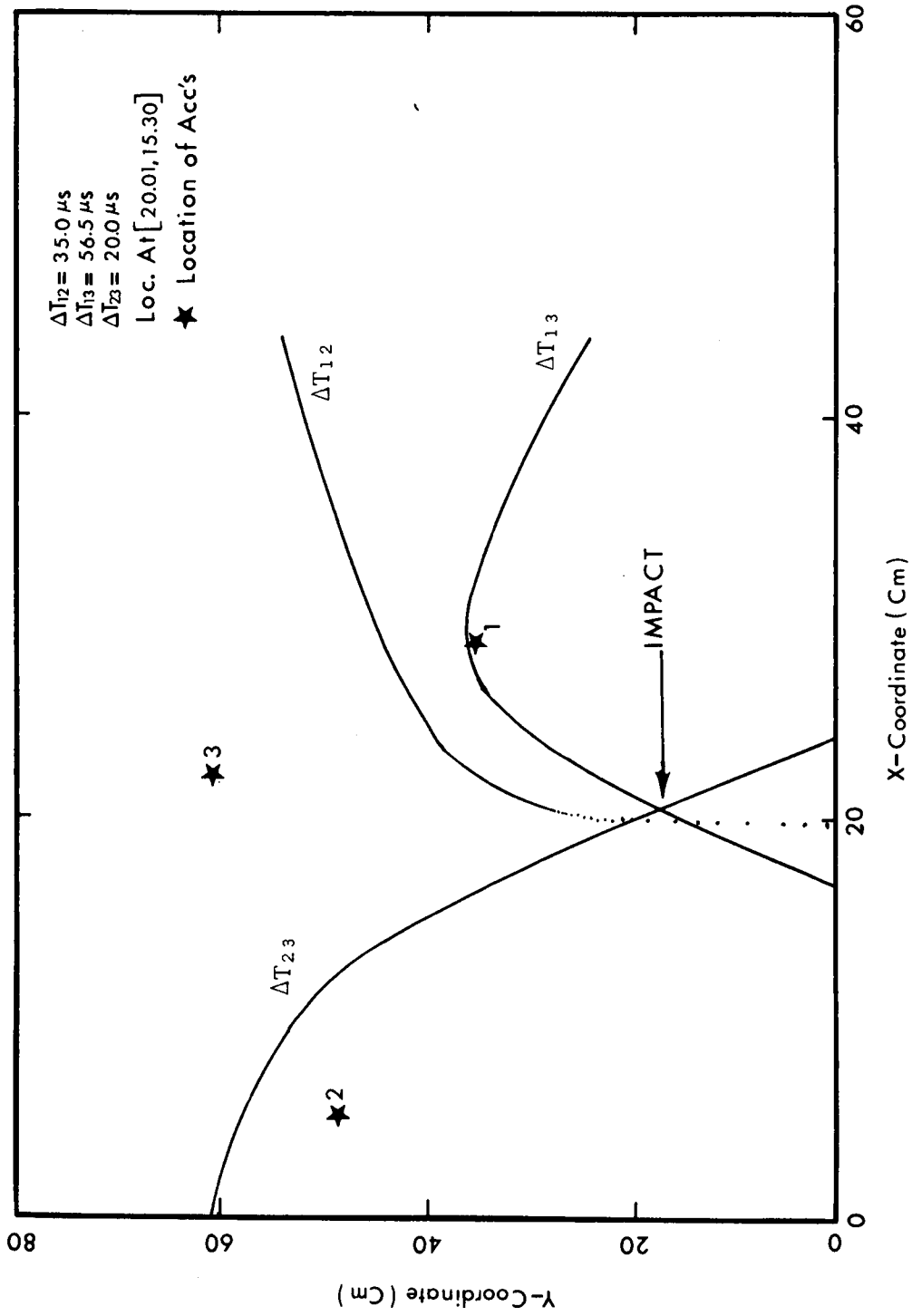


Fig. 27. A typical impact location plot using Δt method.

$$\text{Error} = \pm \frac{2}{\text{SR}} \times \text{velocity} \quad (3.3)$$

where

SR = the sampling rate

For the above cases, a sampling rate of 2 MHz was used so the error for the steel plate is ± 0.421 cm and for the aluminum plate the error is ± 0.609 cm.

The approximation method for impact location is given by

$$A_i = A_0/L_i \quad (3.4)$$

$$A_j = A_0/L_j \quad (3.5)$$

where

A_i, A_j = peak amplitude or peak RMS at positions i and j .

Using at least four accelerometers 1, 2, 3 and 4 the following ratios can be formulated

$$\begin{aligned} A_1/A_2 &= L_2/L_1 \\ A_2/A_3 &= L_3/L_2 \\ A_3/A_4 &= L_4/L_3 \quad ; \quad A_4/A_1 = L_1/L_4 \end{aligned} \quad (3.6)$$

where

$$L_1 = \sqrt{(x - x_1)^2 + (y - y_1)^2}$$

$$L_2 = \sqrt{(x - x_2)^2 + (y - y_2)^2}$$

$$L_3 = \sqrt{(x - x_3)^2 + (y - y_3)^2}$$

$$L_4 = \sqrt{(x - x_4)^2 + (y - y_4)^2}$$

Equations (3.6) can be solved for the coordinate of the impact (x,y). Results of eight impact location tests on the aluminum plate are tabulated in Table 5 and a typical plot of the surface of convergence is shown in Fig. 28. The double peak nature of the surface of convergence indicates multiresolution of Eq. (3.6), which turns out to be a set of quadratic equations. The true solution (location of the impact) is the x and y coordinates associated with the highest peak of the convergence surface shown in Fig. 28.

F. Impact Characterization

The purpose of impact characterization is to observe the transient signal and relate one or more signal parameters to a known impact parameter. In particular the following will be studied both in time and frequency domain: the angle of impact, relation between impact force and the signal amplitude or signal RMS, relation between similar impacts on opposite sides of a structure, and the general frequency characteristic of a transient impact signal.

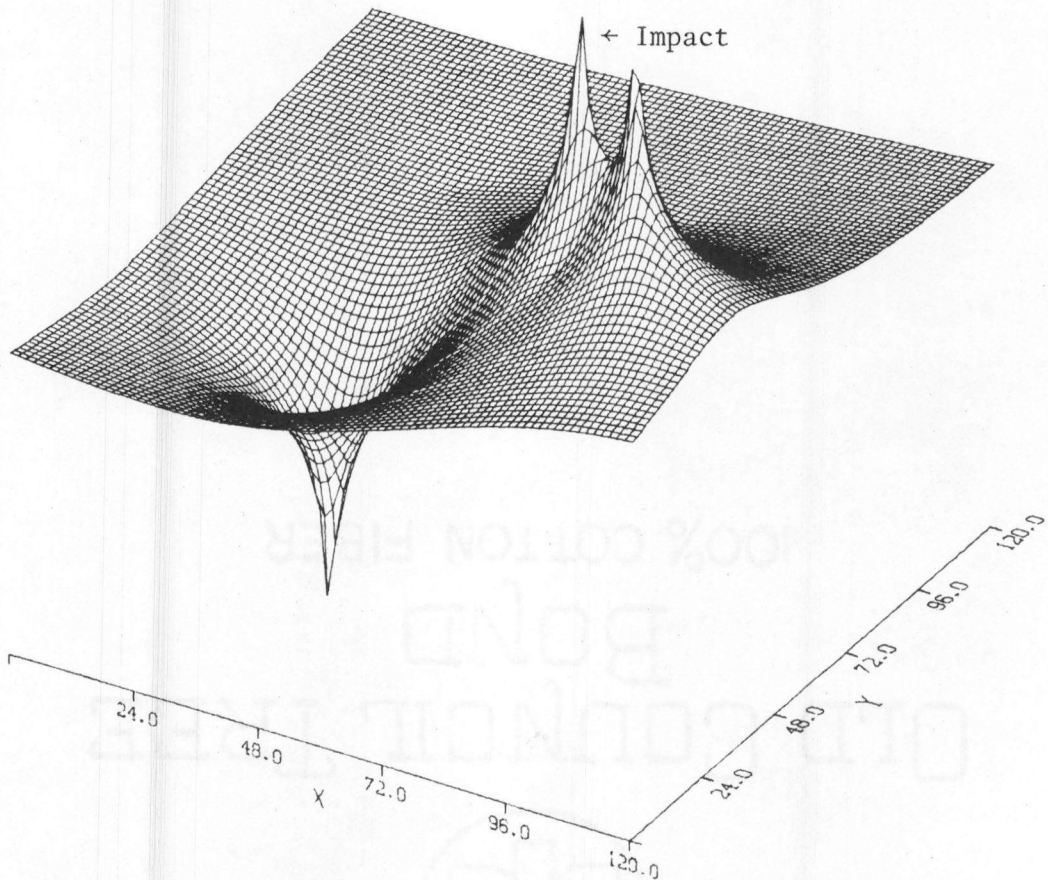
As the first step toward impact characterization the relation between the sensor response as a function of vertical or azimuthal angle of impact with the plane of the target was studied. The aluminum plate was used in these tests and the vertical angle of impact was varied by lifting the plate via a chain hoist. The azimuthal angle was varied by simply impacting around the sensor at various angles. The

Table 5. Results of impact location on a flat surface
using 1/L attenuation model

Impact coordinates		Peak RMS (volts)				Impact location		Error
X-cm	Y-cm	RMS ₁	RMS ₂	RMS ₃	RMS ₄	X-cm	Y-cm	cm
10.0	10.0	0.048	0.026	0.019	0.026	9.0	10.5	1.12
20.0	20.0	0.073	0.029	0.021	0.027	22.5	21.0	2.69
30.0	20.0	0.146	0.056	0.038	0.050	28.5	21.0	1.80
50.0	20.0	0.156	0.093	0.050	0.055	49.5	19.5	0.71
60.0	30.0	0.112	0.104	0.044	0.045	60.0	31.5	1.50
80.0	50.0	0.129	0.518	0.166	0.104	81.0	49.5	1.12
100.0	70.0	0.064	0.123	0.197	0.070	102.0	70.5	2.06
110.0	80.0	0.077	0.126	0.219	0.087	112.5	79.5	2.55

RMS FOR ACC# 1 - 0.129 VOLTS
RMS FOR ACC# 2 - 0.516 VOLTS
RMS FOR ACC# 3 - 0.166 VOLTS
RMS FOR ACC# 4 - 0.104 VOLTS

IMPACT COORDINATES
X- 81.00
Y- 49.50



IMPACT LOCATION MAP

Fig. 28. A typical impact location plot using $1/l$ attenuation model.

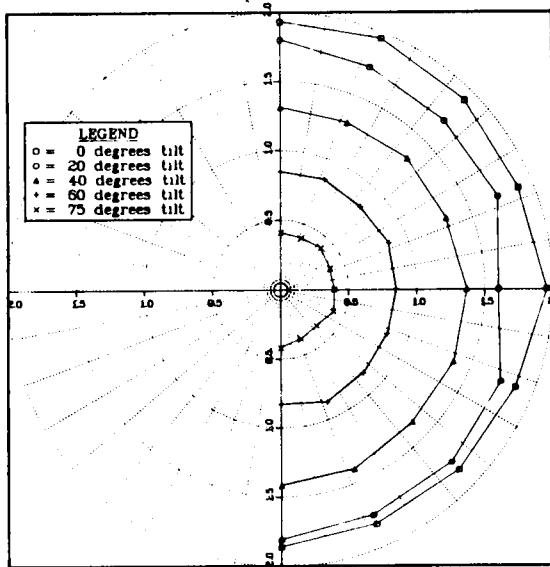
missile was a small (0.8727 cm in diameter, 2.7135 gram) steel ball magnetically released from a constant distance of 73.66 cm from the release point to the impact point. Several accelerometer response functions were used to determine the relative merits of each. Table 6 lists the various response measures used.

Table 6. List of response measures

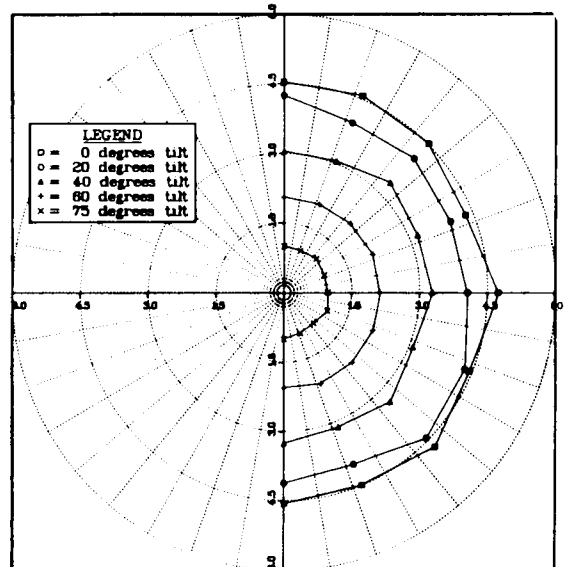
Function	Notes
First arrival RMS	Acc. impact wave response Root <u>M</u> ean <u>S</u> quare excluding the side reflections
Peak amplitude	Peak voltage of the impact signal
Low frequency RMS	DC-7 kHz RMS of impact signal
Wide band RMS	DC-50 kHz RMS of impact signal

Figure 29a,b,c, and d shows various measurements listed in Table 6 both as a function of vertical tilt angle and the azimuthal target angle around the sensor. It can be seen that all the response function except for the low frequency (DC-7 kHz) RMS are uniform with respect to the azimuthal target angle. The low frequency RMS function on the other hand is a more sensitive indicator. The asymmetric position of the sensor and the targets with respect to the edge of the plate shown in Fig. 30 is the cause of the skewness of low frequency RMS which is not apparent in the other response functions. The functional dependence of the angle of tilt is shown in Fig. 31 in a normalized fashion. This graph was plotted using all the response functions in Table 6,

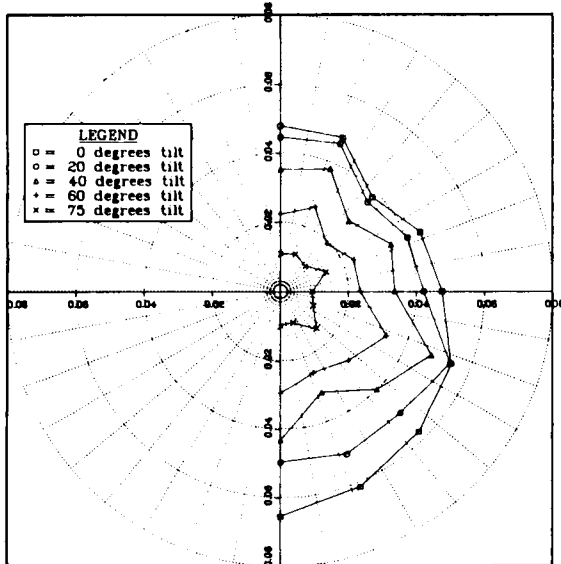
A. First Arrival RMS



B. Peak Voltage



C. RMS Dc to 7 KHz in Volts



D. RMS Dc to 50 KHz in Volts

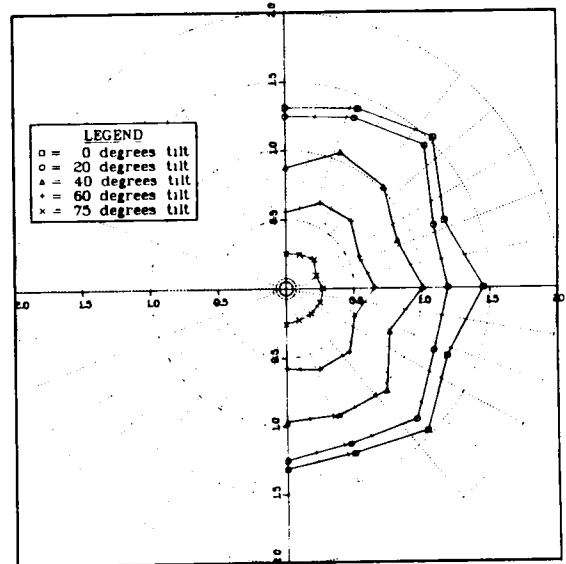


Fig. 29. Accelerometer response as a function of vertical and azimuthal angles. (A) First arrival RMS, (B) peak amplitude, (C) low frequency RMS, (D) wide band RMS.

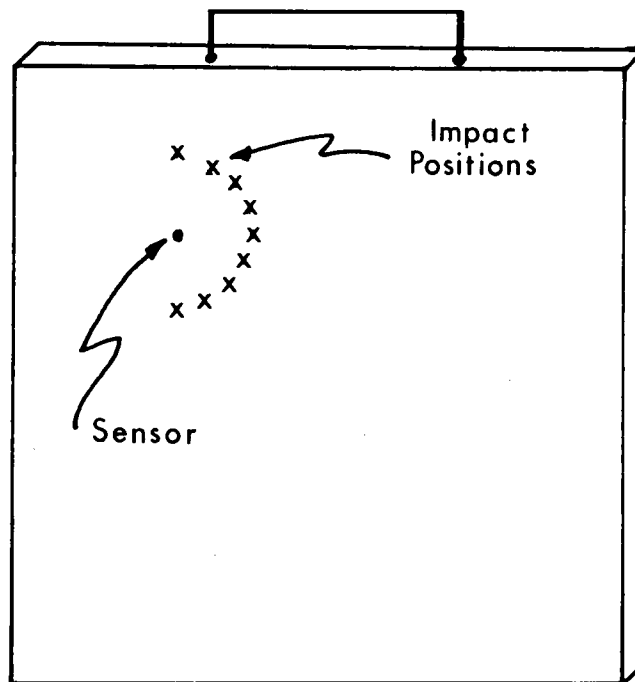


Fig. 30. Target-sensor arrangement for the angle of impact study.

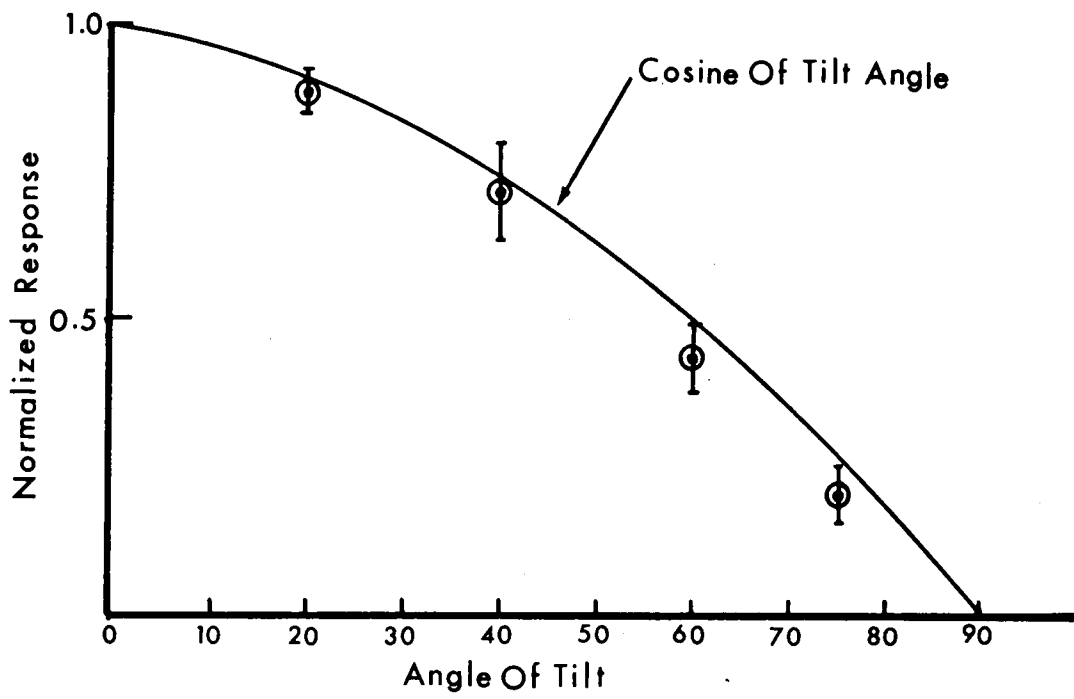


Fig. 31. Normalized average response as a function of tilt angle.

normalizing each to the corresponding response at the zero angle of tilt according to the following formula.

$$R(\theta) = \bar{r}(\theta) = \frac{1}{4} \sum_{i=1}^4 \frac{r_i(\theta)}{r_i(0)} \quad (3.7)$$

where

$r_i(\theta)$ = functions in Table 6 ($i = 1$ to 4)

θ = angle of tilt

It can be seen that the functional dependence of the responses is the cosine of the angle of tilt.

The correlation between impact momentum and various sensor response functions listed in Table 6 was studied next. A series of impacts was performed using a 0.793 cm in diameter steel ball freely falling from various heights on the aluminum slab. Data was recorded on magnetic disk using the transient recorder, both in high (DC-50 kHz) and low (DC-7 kHz) frequency range. The data were further analyzed and various responses were plotted vs drop height, Fig. 32(a,b,c,d). This indicated that all the responses were a linear function of drop height (or impact momentum), although all the impacts made some surface deformation. Further examination of the relationship between the impact energy and response was conducted using an assortment of steel balls dropped from various heights. The results are plotted in Fig. 33. In this figure the peak response was plotted versus the impact energy using three steel ball sizes. This type of representation indicates the linear and the nonlinear portion of the response versus the impact

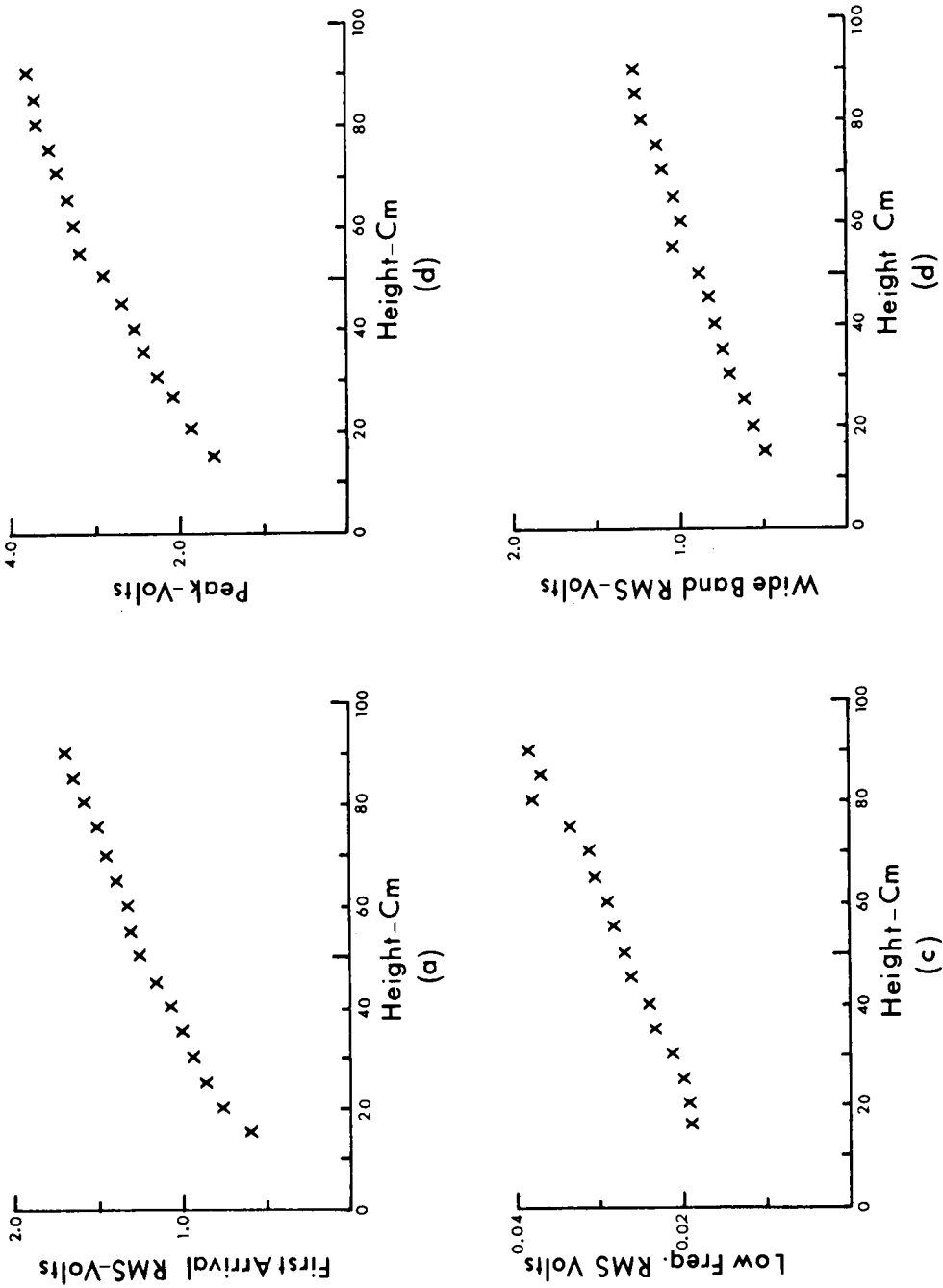


Fig. 32. Accelerometer response as a function of impact energy.
 (a) First arrival RMS, (b) peak amplitude, (c) low frequency RMS,
 (d) wide band RMS.

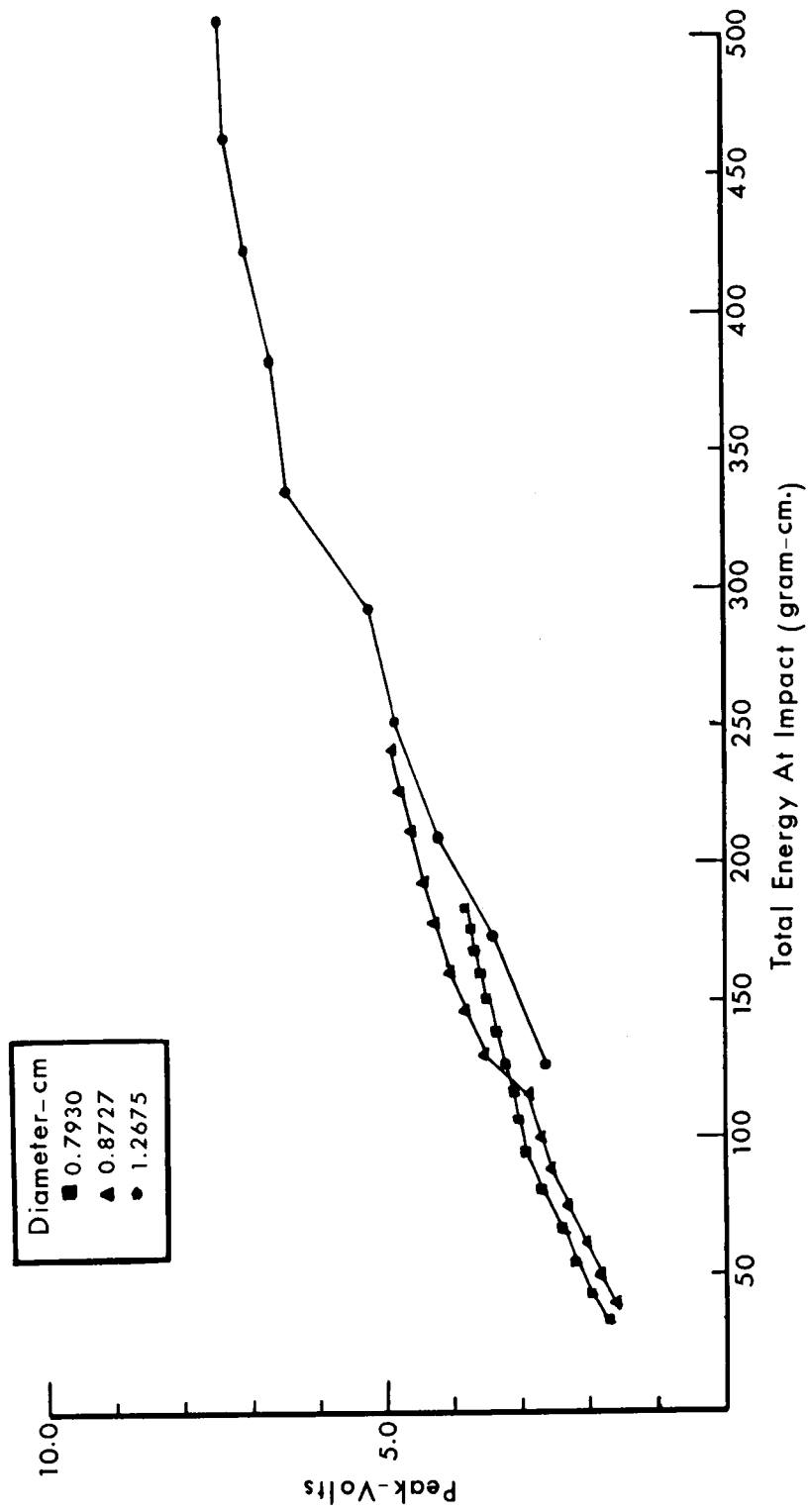


Fig. 33. Peak amplitude versus impact energy for an assortment of steel balls.

energy which is related to the elastic (linear portion) and the inelastic (nonlinear portion) nature of the contact between the steel ball and the aluminum plate.

The impact-sensor arrangement on the opposing side of the aluminum plate indicated that the results are identical to that of impact and the sensor on the same side of the plate both in the frequency and the amplitude characteristics. The noticeable difference was the 180° phase shift between the signals.

Further analyses were performed on the impact signals in the frequency domain. The power spectrum^a of the transient impact signals as a function of frequency were used to represent frequency characteristics. A typical power spectrum plot of a ball impact is given in Fig. 34. The relative change in the power spectrum at each frequency as the impact momentum increases is shown in Fig. 35(a,b). The change in power level is very noticeable at several frequencies around the resonance frequency of the accelerometer (17, 20, 22, 25, 30 kHz). The change in the power spectrum is further illustrated in Figs. 36, 37 and 38 where the change in power level at two frequencies of interest (22 kHz and 25 kHz) and the integral over the 50 kHz band wide of the relative power spectrum is plotted against the drop height (or the impact momentum). In order to have the ability to compare results each quantity was normalized to their corresponding value in the reference impact (drop from 15 cm height). The results show the linearity of various

^aPower spectrum is obtained from the magnitude square of the complex fourier coefficients.

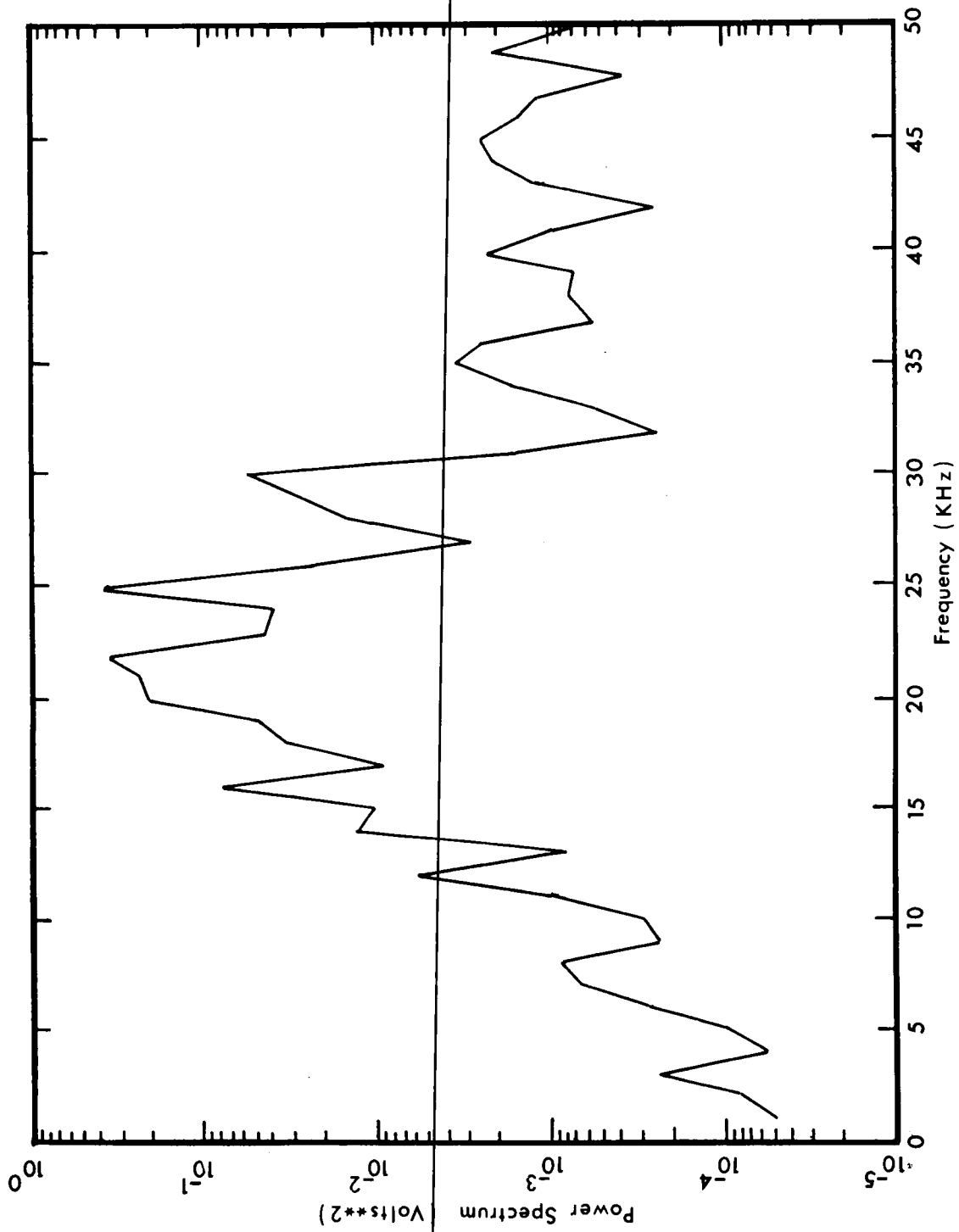


Fig. 34. A typical power spectrum plot of ball impact on the aluminum plate.

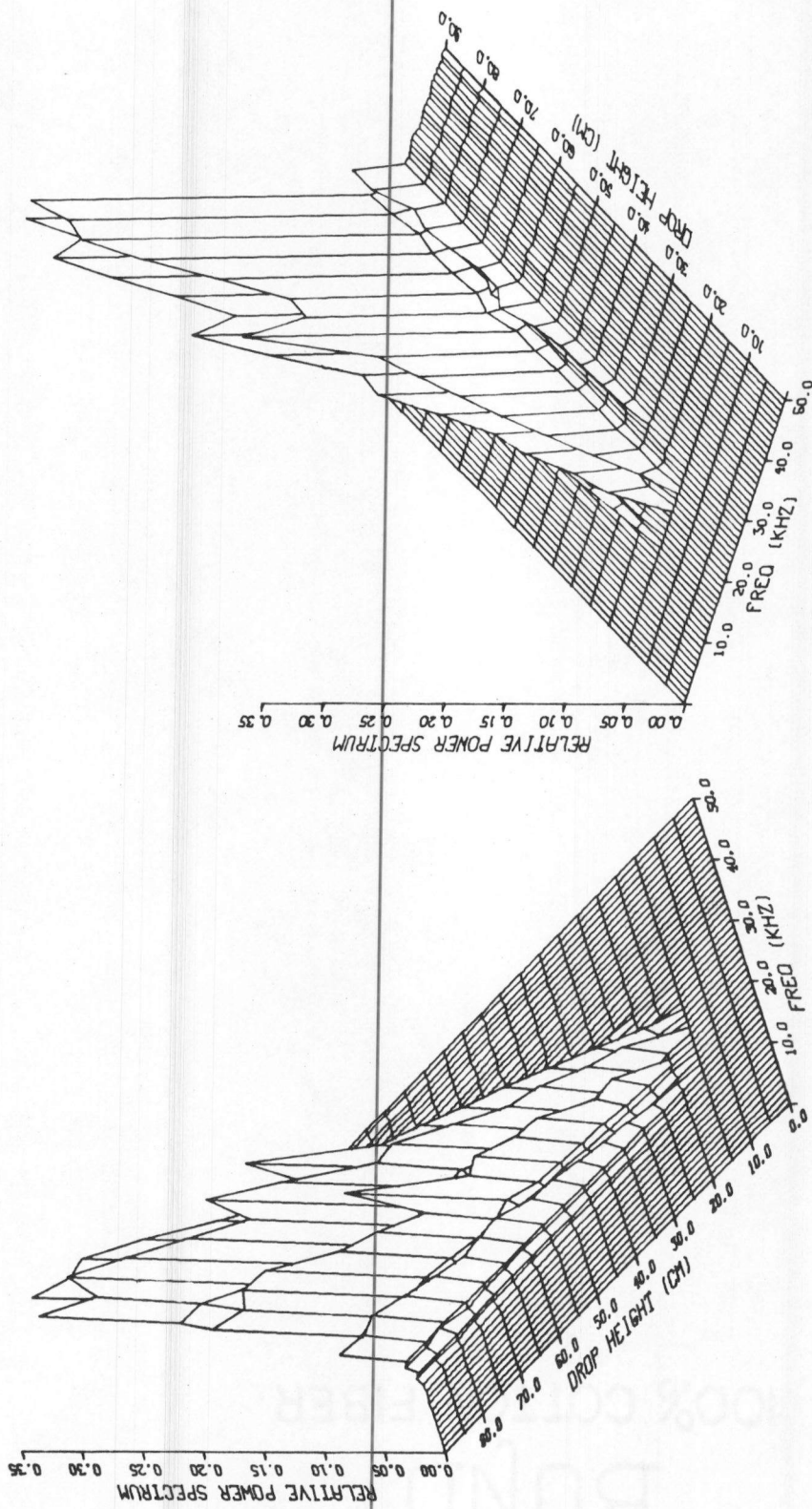


Fig. 35. Relative power spectrum as a function of frequency and drop height.

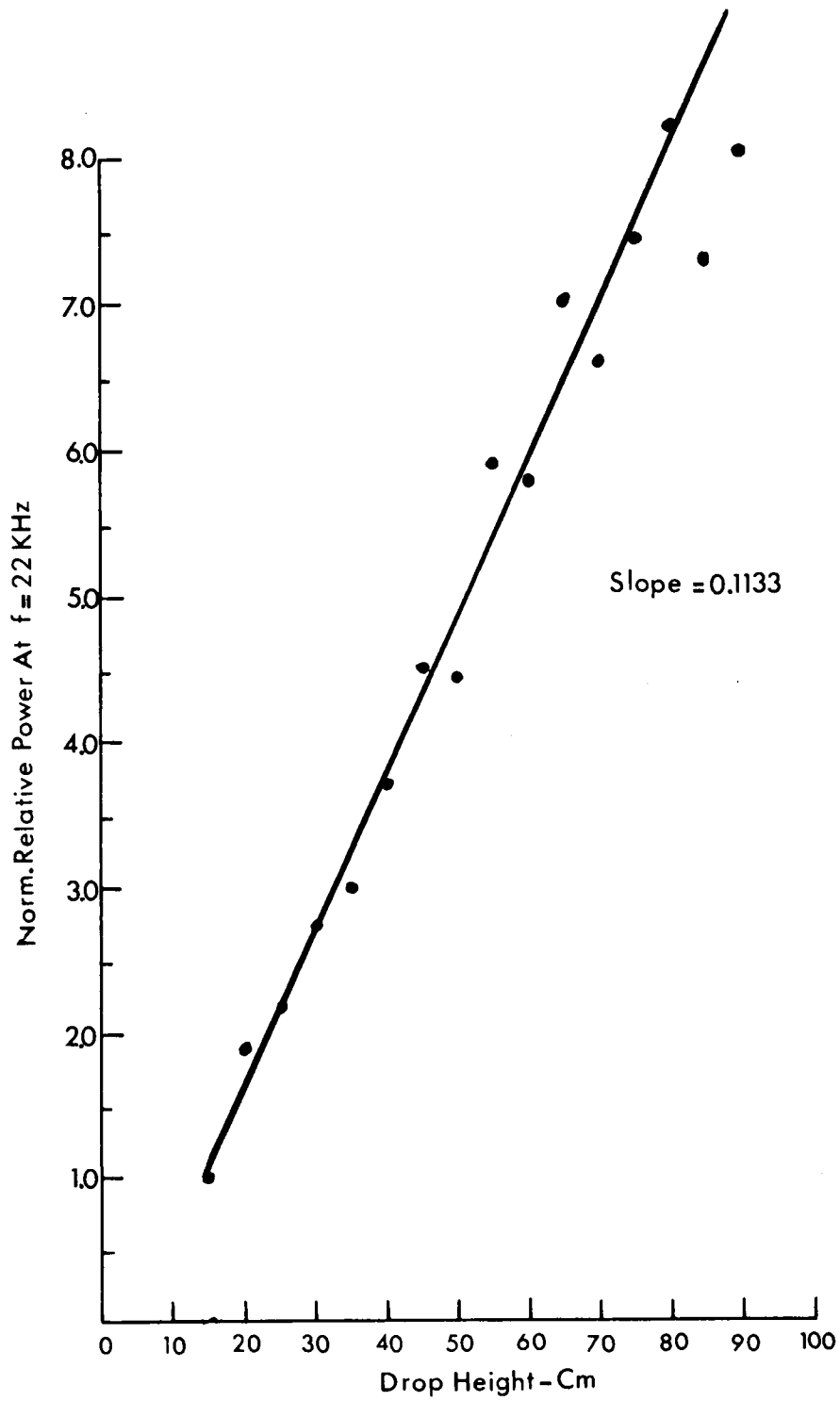


Fig. 36. Normalized relative power spectrum as a function of drop height at 22 kHz.

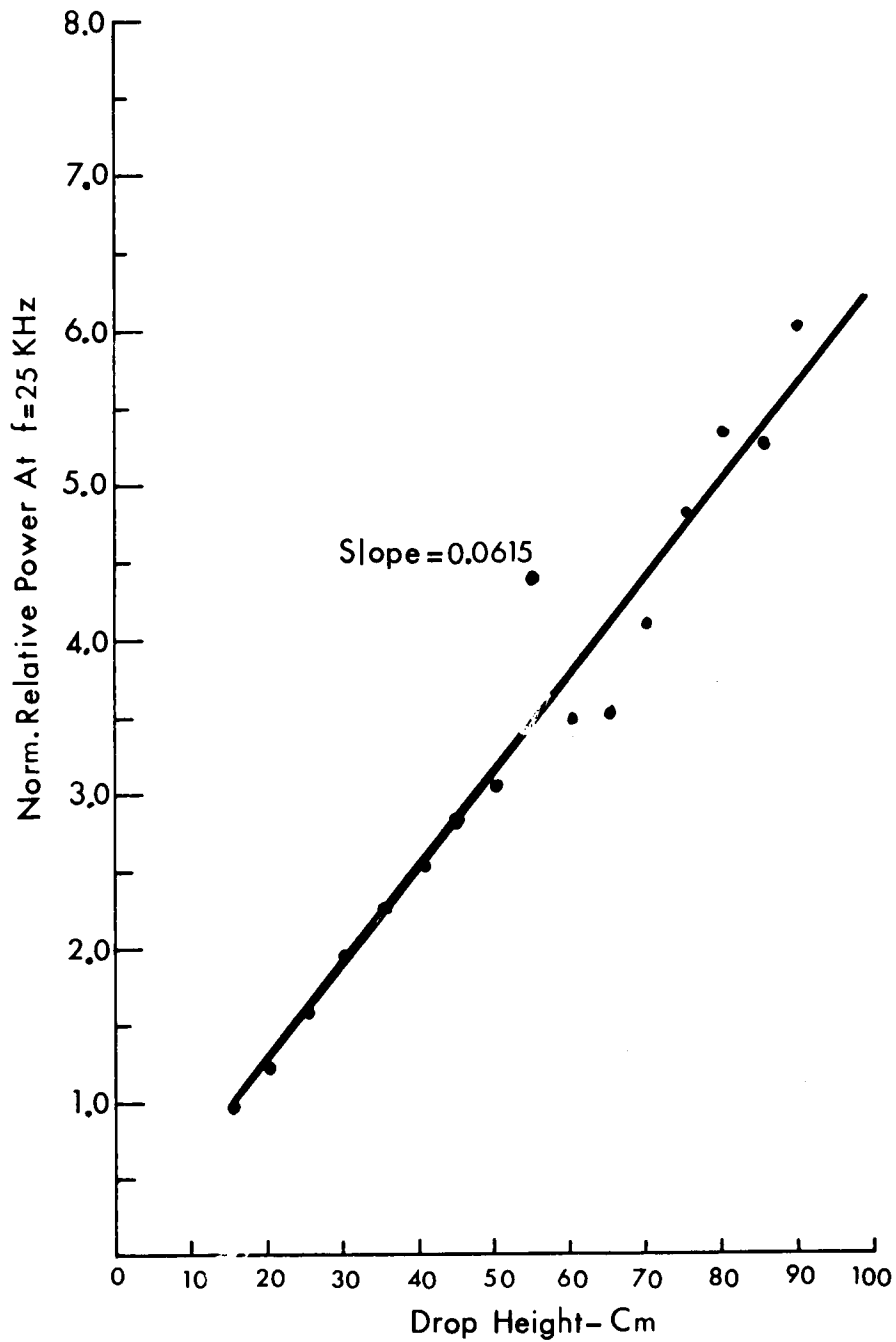


Fig. 37. Normalized relative power spectrum as a function of drop height at 25 kHz.

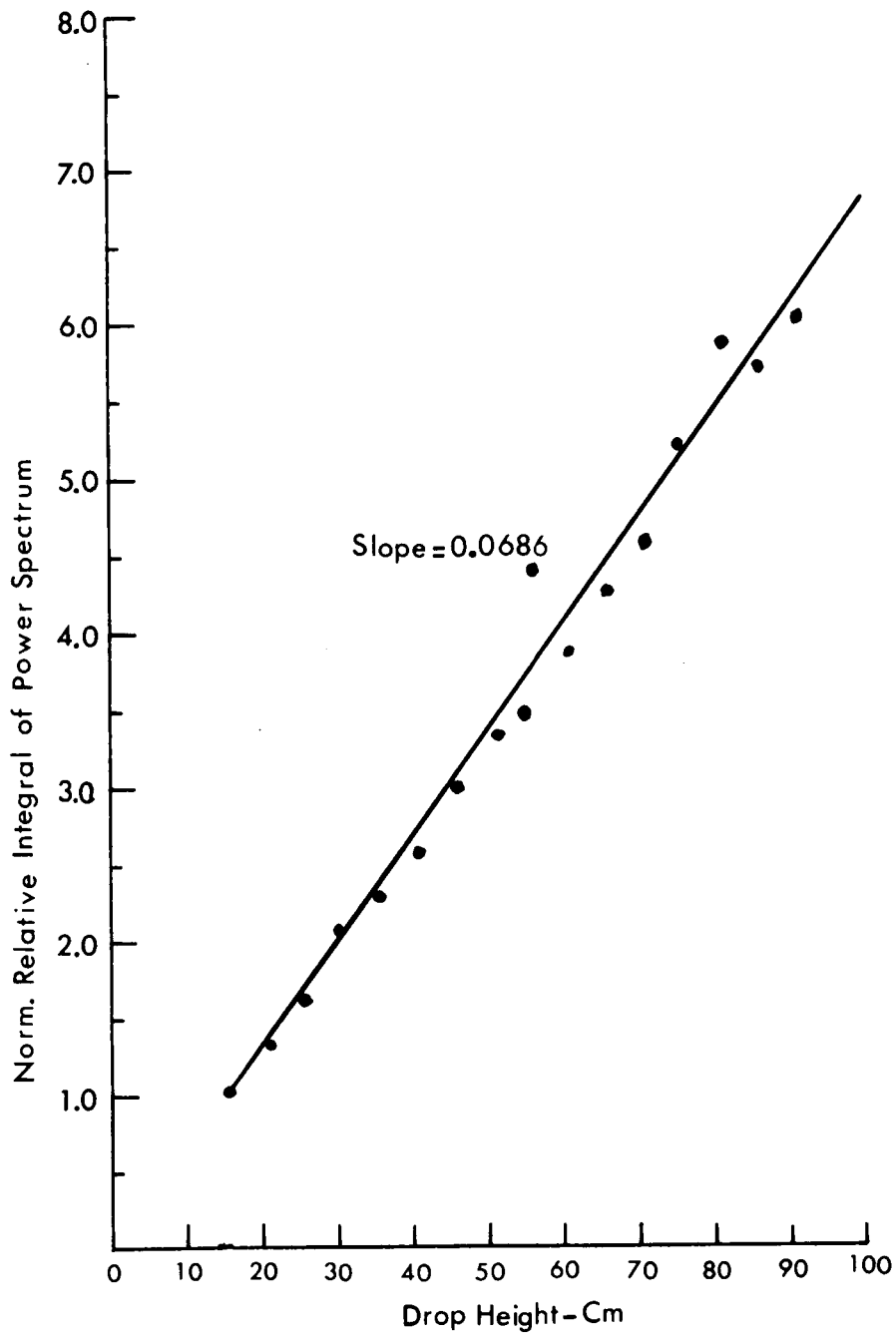


Fig. 38. Normalized relative integral of the power spectrum as a function of drop height.

frequency dependent quantities as the function of increasing impact momentum. This is in agreement with findings of the previous section.

The above frequency analysis method along with the various response function techniques provides several methods for elastic impact characterization. These methods will be tested and modified on a more realistic structure in the following chapter.

CHAPTER IV

THREE DIMENSIONAL IMPACT WAVE PROPAGATION EXPERIMENT

EGCR PRESSURE VESSEL STUDIES

A. Introduction

The methods of impact location and characterization described in the previous chapter are put to test in a more realistic environment in this chapter. The purpose here is to identify the usefulness and the shortcomings of the various time and frequency domain techniques on a structure similar to a commercial power reactor. The Experimental Gas Cooled Ractor was chosen for this purpose, because of availability and the ease of access both to the inside and the outside of the pressure vessel.

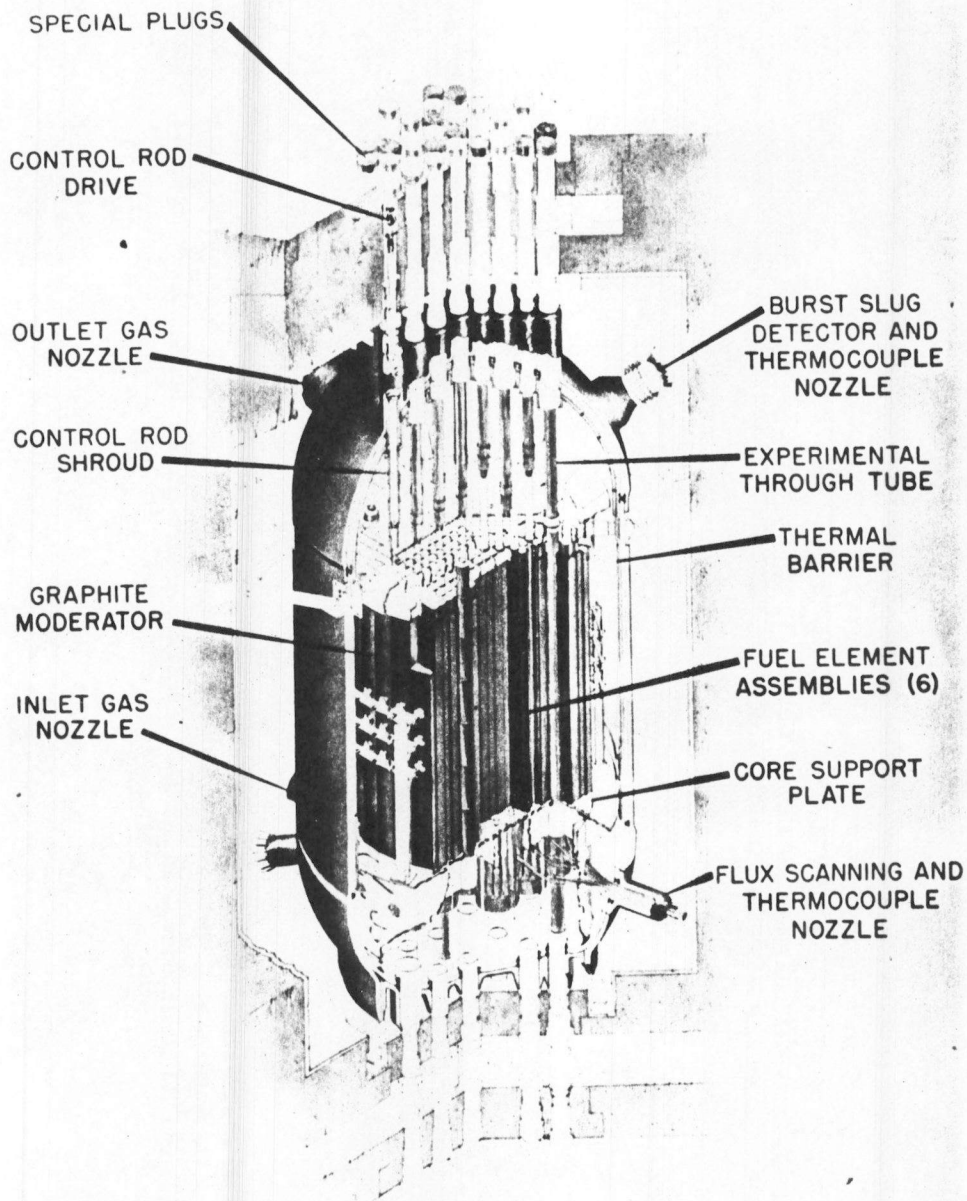
A description of the EGCR test environment and loose parts monitoring electronic is presented first followed by the results of various methods for impact location and impact characterization in time and frequency domain.

B. EGCR Facility and the Accompanied Electronics

EGCR is a decommissioned 34 MWe experimental helium gas cooled reactor which was never fueled due to technical and financial difficulties. The carbon steel pressure vessel of the reactor has a 6.5 centimeter thick cylinder wall with the top and the bottom head section 11.0 centimeters thick. The composite of the reactor vessel with the

internal assembly section is shown in Fig. 39. The obstructions and the discontinuities on the pressure vessel consists of fuel loading ports on the bottom head, four instrumentation outlet bundles, two gas coolant inlet pipes on the lower half of the vessel and two gas outlet pipes and four instrumentation outlet bundles on the top half of the vessel. The top head of the reactor vessel is provided with control rod penetration ports. The reactor vessel has 15.0 cm (6.0 in.) asbestos thermal insulation which is held against the vessel via wire mesh and a series of 1.27 cm in diameter and 15.0 cm long steel rods. The asbestos insulation was removed at six positions 60° apart on the lower head of the vessel for the purpose of the direct accelerometer attachment which is shown in Fig. 40. Access to the inside of the vessel is possible through two manholes on the inlet coolant pipes. The obstruction and the piping sizes on the bottom head are given in Table 7.

A total of nine Endevco model 2236 isobase accelerometers were used for the EGCR experiment. Two types of accelerometer attachment were used. The first type was the direct stud mount to the bottom head of the pressure vessel where three 10-32 by 1/4 in. deep stud taps were drilled into the vessel wall 120° apart. Others were stud mounted on a 2.54 cm cube of stainless steel. The accelerometer and the block assembly was then strap mounted to the fuel charging pipes on the bottom head of the pressure vessel. Approximate location of the accelerometers are shown in Figs. 41 and 42. Voltage amplification electronics described in the previous chapter was used throughout these experiments. For low frequency (0-7 kHz) studies of impact waves a set of Rockland



EXPERIMENTAL GAS-COOLED REACTOR

Fig. 39. The composite of the EGCR reactor vessel with the internal assembly.

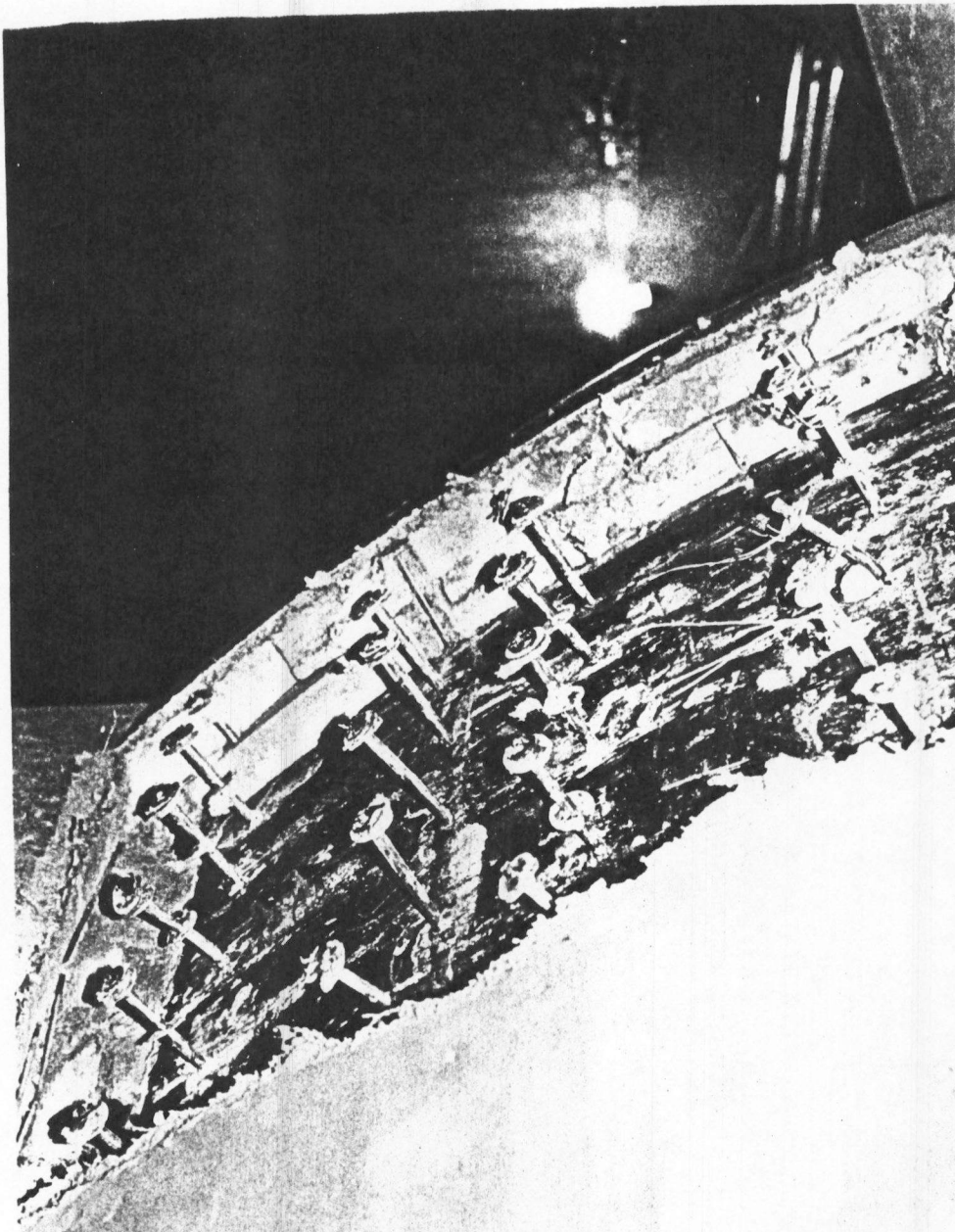


Fig. 40. EGCR pressure vessel and the removed asbestos insulation.

Table 7. List of bottom head nozzle

Quantity	ID (cm)	Service
12 (a,b,c,f,j,k,o,r,v,w,x,y) ^a	42.8625	Fuel charge nozzles
9 (g,h,i,l,m,n,s,t,u)	31.4325	Fuel charge nozzles
2 (p,q)	20.0025	Experimental loop nozzles
1 (d)	31.4325	Experimental loop nozzle
1 (e)	31.4325	Emergency cooling loop
2	29.2100	Thermocouple nozzles
2	29.2100	Thermocouple and flux scanner nozzles
2	55.8800	Reactor coolant inlet

^aNozzle ID letter see Fig. 42.

filters were used. The 48 db/oct rolloff characteristics of these filters provides sharp discrimination against the 25 kHz resonance frequency of the accelerometers.

Three types of impact were used for the purpose of location and characterization: (a) ball bearing impact, (b) stud tap, (c) solenoid discharge action.

Ball Bearing Impact

This type of impact although not reproducible in magnitude, had frequency content similar to ball drop impacts used in the flat plate studies.

Stud Tap

The studs provided for holding down the insulation on the pressure vessel (Fig. 40) were impacted upon with a steel bar. This introduced distinct impact frequencies in the pressure vessel.

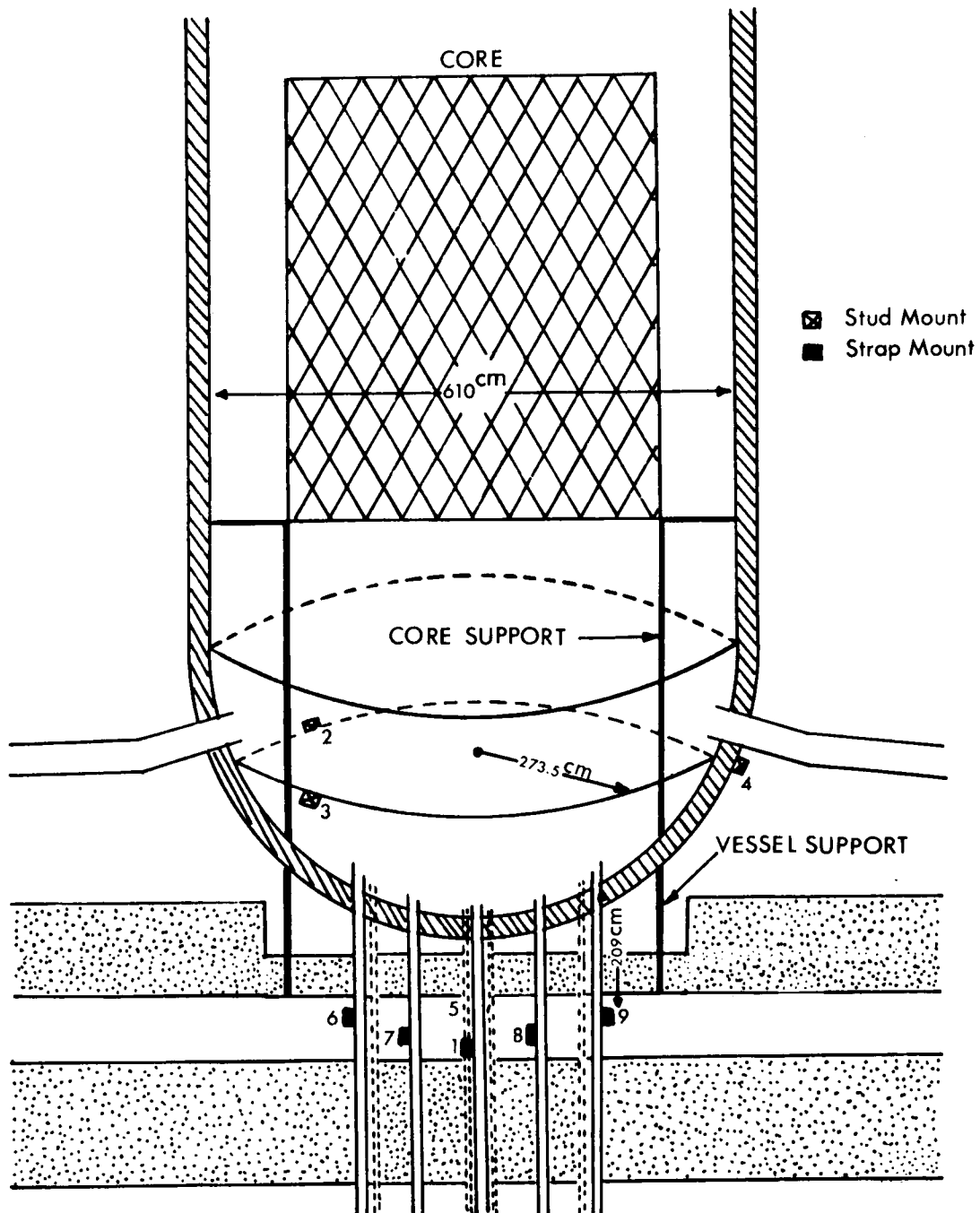


Fig. 41. Vertical view of the accelerometer locations 1 through 9 on the EGCR pressure vessel.

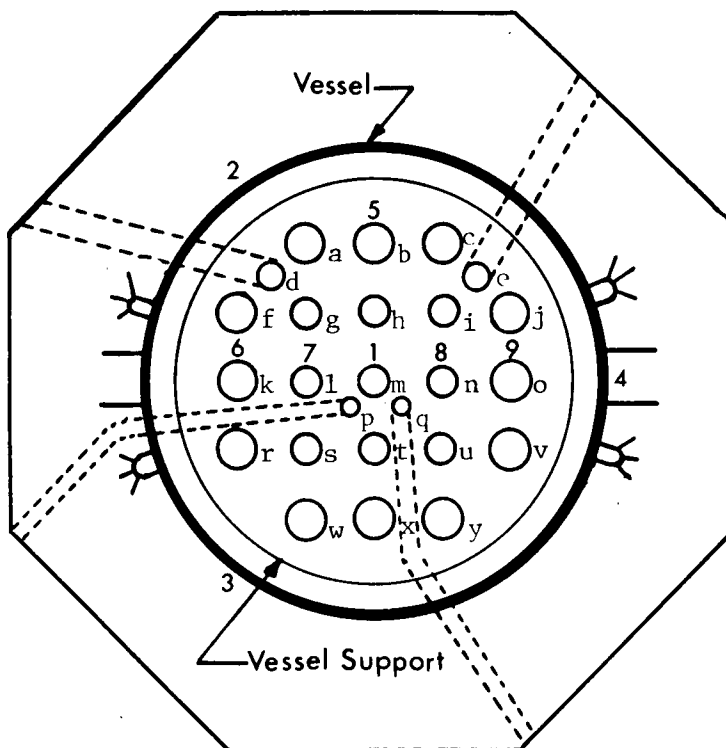


Fig. 42. Horizontal view of the accelerometer locations 1 through 9 on the EGCR pressure vessel.

Solenoid Discharge Action

The need for an automatic and reproducible impactor proved essential for this type of exploratory studies. Therefore, a commercially available solenoid impactor^a was provided by TEC^b (see Fig. 43). A capacitor discharge power supply was then designed^c to provide DC voltage ranging from 0 to 30 volts at 2 amperes. The circuit diagram for this power supply is given in Appendix C.

C. Impact Location Methods

In this section several impact location methods are tested. A description of each method is presented first followed by the actual test results on the EGCR reactor vessel. The basic principals behind the location methods here are similar to the ones described in the previous chapter. The difference being the complication imposed by the geometrical structure of the EGCR vessel and the obstructions, and the various nozzles (Figs. 41 and 42) in the path from the impact to the sensors. The impact location techniques used in this section are divided into two categories: deterministic and heuristic.

The deterministic methods of impact location are based upon the knowledge of the speed of impact wave propagation. The theoretical formula for the velocity of impact wave is given in Chapter II, but in

^aTEC model 1082-A2-100.

^bTechnology for Energy Corporation, 10770 Dutchtown Road, Knoxville, Tennessee.

^cBy O. C. Cole (ORNL), and F. Shahrokhi (UT).



Fig. 43. The solenoid impactor, TEC model 1082-A2-100.

practice one must determine this parameter experimentally. This is warranted due to nonideal condition of practical structures such as surface conditions, material thickness and obstructions. Similar to an impact of a rain droplet in a calm swimming pool, a missile impacting against a structure initiates a system of wave patterns. Several strategically positioned accelerometers can detect the arrival of the impact wave. Knowing the speed of propagation and the time of impact wave arrival at several positions, a simple triangulation should locate the impact.

Tests were conducted to determine the speed of the impact wave propagation on the EGCR pressure vessel. Accelerometer configuration of Figs. 41 and 42 were used utilizing accelerometers 1, 2, 3, and 4. Two types of impact were used: ball drop and automatic impactor. Results are tabulated in Table 8. Each velocity estimate is an average of ten similar impacts. The error in each estimate is less than 10%. The velocities were constructed from the combination of four

Table 8. Wave speeds inferred from time of signal arrival difference

Sampling rate	V_{12}^a	V_{13}^a	V_{14}^a	V_{24}^a	V_{34}^a
100 kHz	2601	2657	5778	3175	3228
50 kHz	2515	2503	7025	3177	3164
20 kHz ^b	2710	2751	6017	3088	2918
100 kHz ^b	2695	2615	6914	3190	3204

^aVelocities are given in meters/second.

^bBall impact using 100 kHz sampling rate.

accelerometers knowing the shortest path difference and measuring the time of arrival difference on a digital scope. Three sampling rates of 20, 50, and 100 kHz were used for data collection. The apparent nonuniformity is obvious, but close observation indicates that similarly positioned accelerometers result in uniform velocities (i.e., acc #2, 3, 4). This indication was further proved using time of energy arrival difference, which is when the short term RMS of the signal rises above the background. Also, the same was true using the time difference associated with the peak of time dependent RMS of each accelerometer. The above observation indicates that the deterministic methods of impact location involving impact wave velocities are in general slow and their accuracy depends upon several factors. The first being the proximity of the sensor to the point of impact. This results in a sharp rise in the accelerometer signal and consequently a good measurement of impact signal arrival time. Second is the dependence on an accurate and unique measure of impact wave speed on a given structure. This requires fast sampling rate, similarly positioned sensors, and prior knowledge of the distance from the calibration impact point to all the sensor locations.

The heuristic impact location methods are based upon the fact that given several monitoring positions on the reactor pressure vessel and an unknown impact upon the vessel; the sensor closest to the impact has the highest response. Three types of heuristic location techniques were used here, where all utilized the above basic principal but differ in the method of triangulation.

The first so-called vector summation method is a technique whereupon a minimum of three sensors is required on the bottom head of the pressure

vessel. A vector system is constructed originating from the center of a circle passing through the three sensors with the vector magnitudes proportional to the response and the vector direction toward each respective accelerometer. Furthermore, the magnitude of the maximum response vector is set to the radius of the circle and all other response vectors are then normalized accordingly. A vector summation of the above vector system will approximately locate the source of the impact. Table 9 lists the numerical values of the peak time dependent RMS's normalized according to the procedure outlined in Fig. 44, which illustrates the results of eight typical impact locations using the above technique. The three accelerometers used were at position 2, 3, and 4. The impacts were at positions 2', 3', 4' on the same circle encompassing accelerometer 2, 3, and 4.

Table 9. Normalized peak of time dependent RMS response

Impact	Impact at	Peak RMS at #2 (norm.)	Peak RMS at #3 (norm.)	Peak RMS at #4 (norm.)
A	2'	0.4095	0.9877	1.000
B	2'	0.5220	0.9846	1.000
C	3'	0.9590	0.4726	1.000
D	3'	1.000	0.5016	0.8648
E	4'	1.000	0.8934	0.5360
F	4'	0.9557	1.000	0.4880

It can be seen from Fig. 44 that the resultant vectors $\bar{A}$ through $\bar{F}$ have a generally correct direction for location but the magnitudes are off by a factor of two. The reason for this is that the original method was suggested for triangulation on flat surfaces, but it has been

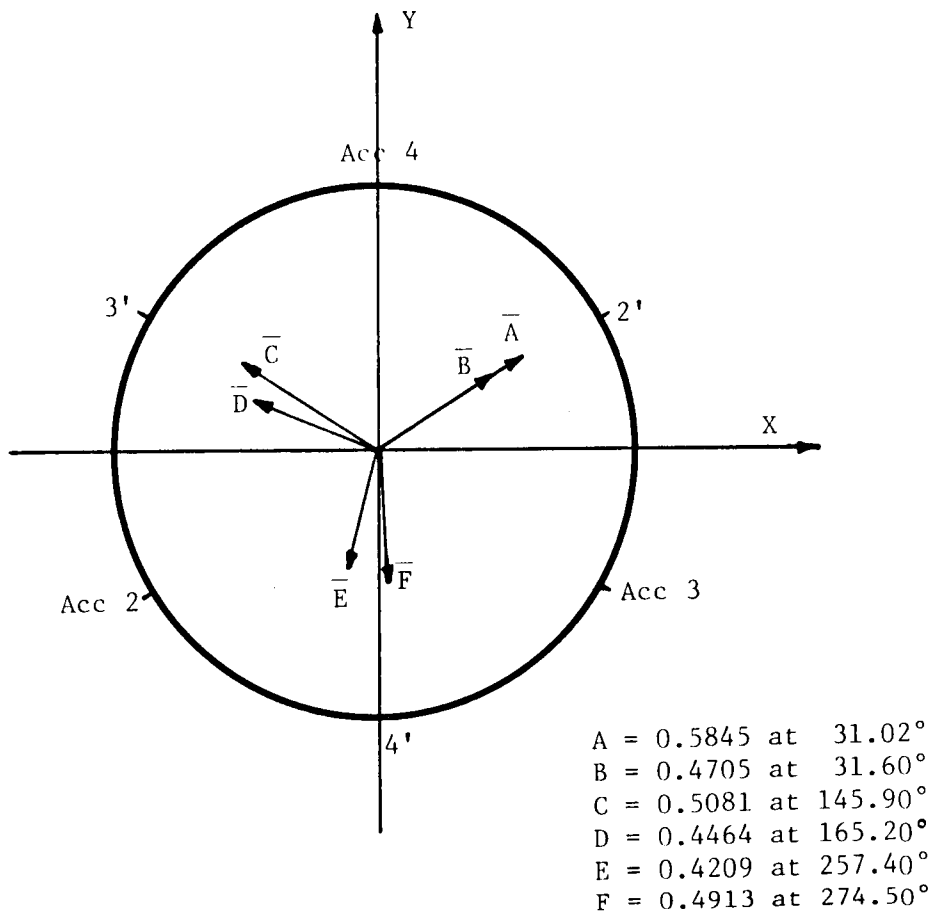


Fig. 44. Impact location using vector summation for eight separate impacts A through F at location 2', 3', and 4'.

demonstrated here that it has limited use on a complicated structure at EGCR pressure vessel. The limitations of this method are severe, but its simplicity is attractive as a quick but not an accurate impact location method.

The second and a more sophisticated method of impact location is based upon a preassigned signal attenuation model such as:^a

$$A_i = \frac{A_0}{|\bar{r}_i|^J} \quad (4.1)$$

where

A_i = response of accelerometer i

$\bar{r}_i$ = a vector from point of impact to accelerometer i

J = attenuation power

A_0 = impact constant

From Fig. 45 the vector $\bar{r}'$ is given by

$$\bar{r}' = |\bar{r}| \cos \eta \hat{i} + |\bar{r}| \sin \eta \hat{j} \quad (4.2)$$

and

$$\bar{R}_i = R \cos \phi_i \hat{i} + R \sin \phi_i \hat{j} \quad (4.3)$$

For simplicity we assume all sensors are on one plane, although this is not required, then we get

$$|\bar{r}_i| = [R^2 + r'^2 - 2Rr' \cos (\phi_i - \eta)]^{1/2} \quad (4.4)$$

^aSuggested by Mr. Ron Canada, TEC.

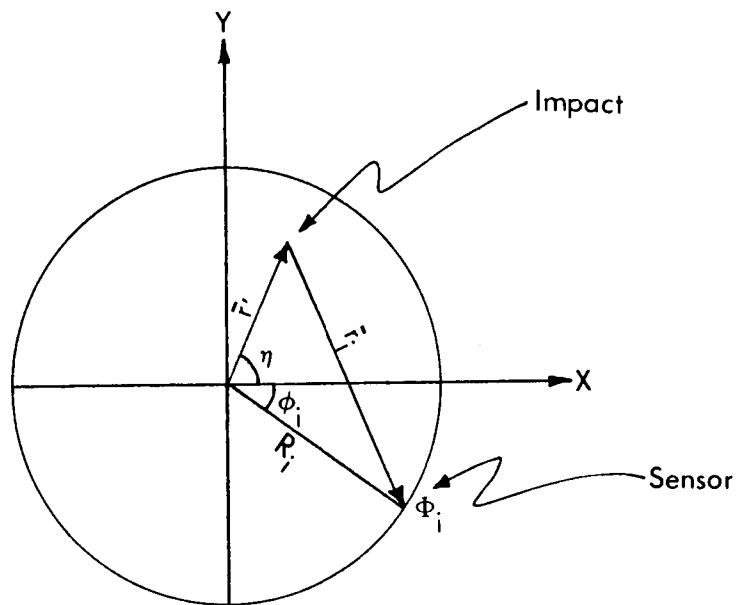


Fig. 45. Impact location using a given attenuation model.

Therefore,

$$A_i = \frac{A_0}{[R^2 + r'^2 - 2Rr' \cos(\phi_i - \eta)]^{J/2}} \quad (4.5)$$

Now given A_i for $i = 1, 2, \dots, N$ sensors and R and ϕ_i for $i = 1, 2, \dots, N$, then find r' and η . To do this we sort A_i 's in descending order and form the following set of quotients,

$$1, \frac{A_2}{A_1}, \frac{A_3}{A_1}, \dots, \frac{A_N}{A_1} \quad (4.6)$$

and denote A_i/A_1 by B_{i-1} for $i = 2, 3, \dots, N$. Then we substitute Eq. (4.5) in (4.6) appropriately to get,

$$B_i = \left[\frac{R^2 + r'^2 - 2Rr' \cos(\phi_1 - \eta)}{R^2 + r'^2 - 2Rr' \cos(\phi_{i+1} - \eta)} \right]^{J/2} \quad i = 1, 2, \dots, N-1 \quad (4.7)$$

It can be seen that $B_1 > B_2 > B_3 \dots > B_{N-1}$.

Finally the following least square formula can be written from the above set of B_i 's.

$$E(r', \eta) = \sum_{i=1}^{N-1} \left[B_i - \left(\frac{R^2 + r'^2 - 2Rr' \cos(\phi_1 - \eta)}{R^2 + r'^2 - 2Rr' \cos(\phi_{i+1} - \eta)} \right)^{J/2} \right]^2 \quad (4.8)$$

Assuming $J = 2$ we must find the minimum of E varying the independent variables r' and η . A simple computer program was written to find the minimum of $E(r', \eta)$ using the method of direct variation of the independent variables r' and η . Table 10 lists the impact

Table 10. Impact location using the combination of vector summation and least squares for the attenuation power of $J = 2$

Impact	RMS	RMS	RMS	Impact at $r', \eta^0 \alpha$	Location $r', \eta^0 \alpha$	Error	Comments
A (2,3,4)	0.5311	1.2810	1.2970	257.43 / 30	257.43 / 30.6	0 /	0.6 outside
B (2,3,4)	0.6797	1.2820	1.3020	257.43 / 30	257.43 / 30.8	0 /	0.8 outside
C (2,3,4)	0.6051	0.2982	0.6310	257.43 / 120	257.43 / 118.8	0 /	1.2 outside
D (2,3,4)	1.0840	0.5437	0.9374	257.43 / 120	257.43 / 122.4	0 /	2.4 outside
E (2,3,4)	1.0700	0.9559	0.5735	257.43 / 270	257.43 / 267.6	0 /	2.4 outside
F (2,3,4)	0.8362	0.8750	0.4270	257.43 / 270	257.43 / 271.2	0 /	1.2 outside
G (3,5,9)	1.415	1.228	0.7940	210 / 270	82.3 / 276	127.8 /	6.0 inside
H (3,5,9)	0.1949	0.1558	0.1019	210 / 270	185.9 / 256.5	24.2 /	13.5 inside
I (3,5,9)	0.1351	0.0870	0.0760	210 / 270	173.7 / 234.0	36.4 /	36.0 inside
J (3,5,9)	1.5150	0.1565	0.0982	246 / 270	149.5 / 193.5	96.5 /	76.5 outside
K (3,5,9)	1.1520	0.2141	0.1260	240 / 270	234.7 / 193.5	5.3 /	76.5 outside
L (3,5,9)	0.7200	0.1180	0.1222	281 / 82	234.7 / 96	46.3 /	14.0 outside
M (3,5,9)	0.8459	0.2614	0.3227	281 / 82	274.3 / 136	6.7 /	54.0 outside

^aRadius are in centimeters and angles are in degrees.

location results using three accelerometers and the above technique. The peak of the time dependent RMS was used as the sensor response.

The apparent success of this method on the impacts A through F of Table 10 is misleading since the impacts were on the same horizontal plane of the accelerometers. The impacts G through M used the accelerometers and the impacts on different horizontal planes and here the accuracy of the method is diminished. The reason for this inaccuracy is that the method approximates the path of the impact wave by the vector $\bar{r}_i$ (Fig. 45) which is the straight line approximation of the actual curved path. This approximation poses varied degrees of inaccuracy depending upon the degree of the curvature which the vector $\bar{r}_i$ must approximate.

The third method of impact location is developed specifically for spherical surfaces. The attenuation model is similar to the previous model.

$$A_i = \frac{A_0}{[l_i]^J} \quad (4.9)$$

The definition of the terms in the above equation are the same as that of Eq. (4.1). The difference is the definition of l_i . In Eq. (4.9) l_i is the actual distance from the point of impact to the accelerometer i. The distance l_i is given by:

$$l_i = \widehat{\Phi_i} S_0 \quad (4.10)$$

where

ϕ_i = location of accelerometer i with coordinate $\phi_i(x_i, y_i, z_i)^{-1}$

S_0 = location of impact with coordinate $S_0(x_0, y_0, z_0)^{-1}$

The arc length in Eq. (4.10) is given by

$$\widehat{\phi_i S_0} = \frac{\pi R \theta_i}{180} \quad (4.11)$$

where:

R = radius of the sphere

θ_i = smallest angle between two vectors $\overline{O\phi_i}$ and $\overline{OS_0}$ (O is the center of the sphere)

Also it is known that the cosine of the smallest angle between any two vectors is given by

$$\cos \theta_i = \frac{\overline{O\phi_i} \cdot \overline{OS_0}}{|\overline{O\phi_i}| |\overline{OS_0}|} \quad (4.12)$$

Using Eq. (4.12), and the coordinates of the n accelerometers the following equation can be derived.

$$\theta_i = \cos^{-1} \left[\frac{x_0 x_i + y_0 y_i + z_0 z_i}{R^2} \right] \quad i = 1, 2, 3, \dots, n \quad (4.13)$$

Also using Eqs. (4.10) and (4.12) the following can be written.

$$A_i = \frac{A_0 \times 180^J}{(R \theta_i)^J} \bigg|_{i=1,2,3,\dots,n} \quad (4.14)$$

Now, we sort Eq. (4.14) in descending order of (A_i) 's where

$$A_1 > A_2 > A_3 > A_4 \dots > A_n \quad (4.15)$$

and form the following quotients

$$\frac{A_1}{A_2}, \frac{A_1}{A_3}, \frac{A_1}{A_4} \dots \frac{A_1}{A_n} \quad (4.16)$$

Now we substitute Eqs. (4.13) and (4.14) in (4.16) and solve for θ_1 .

For $n = 4$ (four accelerometers case) we form the following null functions.

$$f_1(x_0, y_0, z_0) = \left[\cos^{-1} \left(\frac{x_0 x_1 + y_0 y_1 + z_0 z_1}{R^2} \right) \right]^J - \frac{A_2}{A_1} \left[\cos^{-1} \left(\frac{x_0 x_2 + y_0 y_2 + z_0 z_2}{R^2} \right) \right]^J = 0 \quad (4.17a)$$

$$f_2(x_0, y_0, z_0) = \left[\cos^{-1} \left(\frac{x_0 x_1 + y_0 y_1 + z_0 z_1}{R^2} \right) \right]^J - \frac{A_3}{A_1} \left[\cos^{-1} \left(\frac{x_0 x_3 + y_0 y_3 + z_0 z_3}{R^2} \right) \right]^J = 0 \quad (4.17b)$$

$$f_3(x_0, y_0, z_0) = \left[\cos^{-1} \left(\frac{x_0 x_1 + y_0 y_1 + z_0 z_1}{R^2} \right) \right]^J - \frac{A_4}{A_1} \left[\cos^{-1} \left(\frac{x_0 x_4 + y_0 y_4 + z_0 z_4}{R^2} \right) \right]^J = 0 \quad (4.17c)$$

From the above equations we can form the following squared null function.

$$F(x_0, y_0, z_0) = \sum_{i=1}^4 \left[f_i(x_0, y_0, z_0) \right]^2 = 0 \quad (4.18)$$

The unknowns in Eq. (4.18) are the coordinates of the impact point x_0, y_0, z_0 . An efficient optimization method known as Rosenbrock Hillclimb method^a is used to minimize Eq. (4.18) given the following constraints on the coordinates of the impact point.

$$-R \leq x_0 \leq R, \quad -R \leq y_0 \leq R \quad \text{and} \quad -R \leq z_0 \leq R \quad (4.19)$$

with an implicit variable P where

$$P = x_0^2 + y_0^2 + z_0^2 \quad (4.20)$$

The constraint on P is

$$|P - R^2| \leq (3*d)^2 \quad (4.21)$$

where d = thickness of the reactor shell.

The Rosenbrock Hillclimb optimization method developed by Yancey and Spear starts with a user supplied initial guess which satisfies all the explicit and the implicit constraints. The process continuously changes the explicit variables toward the optimum value of the functional $F(x_0, y_0, z_0)$ of Eq. (4.18). The convergence is achieved when the function F of Eq. (4.18) does not change appreciably ($< \epsilon = 0.1\%$ of best estimate of F) for ten consecutive iteration stages. This helps to circumvent the local maxima and local minima. A listing of the Rosenbrock Hillclimb fortran program and a sample problem is presented in Appendix D.

^aComputer code developed by C. B. Yancey and R. C. Spear, Naval Weapons Center, China Lake, California.

A multitude of impact tests were performed on the EGCR pressure vessel ranging from impacts on the outside of the vessel to the impact from the inside of the vessel. Table 11 lists the coordinates of the selected positions of the impacts in the cartesian system with the center of the bottom head hemisphere as the origin. Due east as the positive Y axis, due south as the positive X axis, and straight up as the positive Z axis. The location of the accelerometers in the same coordinate system is given in Table 12. All the impacts were then further processed constructing the time dependent RMS^a plot for each impact. Figures 46 and 47 show a typical impact time domain signal and its corresponding time dependent RMS representation. The peak RMS was then recorded for use in the Rosenbrock Hillclimb location scheme. A typical location process is illustrated in Fig. 48, where each "dot" represents the best estimate of the location of the impact after each stage of the optimization. The "box" is the final converged location position and the "X's" are the accelerometers in use. The z coordinate is not shown in this figure because of the two-dimensional nature of the plot, but is incorporated in the location process.

The results of impact location using in core impacts at locations I1, I2, and I3 (see Table 11 for coordinates), and combination of various accelerometers are presented in Table 13. An impact at above three location can be located within 131.28 cm to 91.25 cm of the impact.

^aMore about the time dependent RMS construction and use in the next section.

Table 11. Coordinates of the selected impacts

Impact	X-cm	Y-cm	Z-cm	Comments
I1	40.8	40.8	-299.3	Inside middle of pipes h, i, m, n ^a
I2	-122.4	-40.8	-276.15	Inside middle of pipes k, l, r, s
I3	122.4	-40.8	-276.15	Inside middle of pipes n, o, u, v
I4	-257.43	0.0	-163.19	Outside opposite o Acc 4
I5	128.70	222.94	-163.19	Outside opposite to Acc 3
I6	128.70	-222.94	-163.19	Outside opposite to Acc 2
I7	-178.70	222.94	-163.19	Outside at Acc 2
I8	-128.7	-224.94	-163.19	Outside at Acc 3
I9	257.43	0	-163.19	Outside at Acc 4

^aSee Fig. 42, page 78, for nozzle identification letters.

Table 12. Coordinates of the accelerometers

Accele #	X-cm	Y-cm	Z-cm	Comments
1	0	0	-304.8	Strap mount on pipe m ^a
2	-128.7	222.94	-163.19	Stud mount on vessel
3	-128.7	-222.94	-163.19	Stud mount on vessel
4	257.43	0	-163.19	Stud mount on vessel
5	0	163.19	-257.43	Strap mount on pipe b
6	-163.19	0	-257.43	Strap mount on pipe k
7	-81.59	0	-293.68	Strap mount on pipe l
8	81.59	0	-293.68	Strap mount on pipe n
9	163.19	0	-257.43	Strap mount on pipe o

^aSee Fig. 42, page 78, for nozzle identification letters.

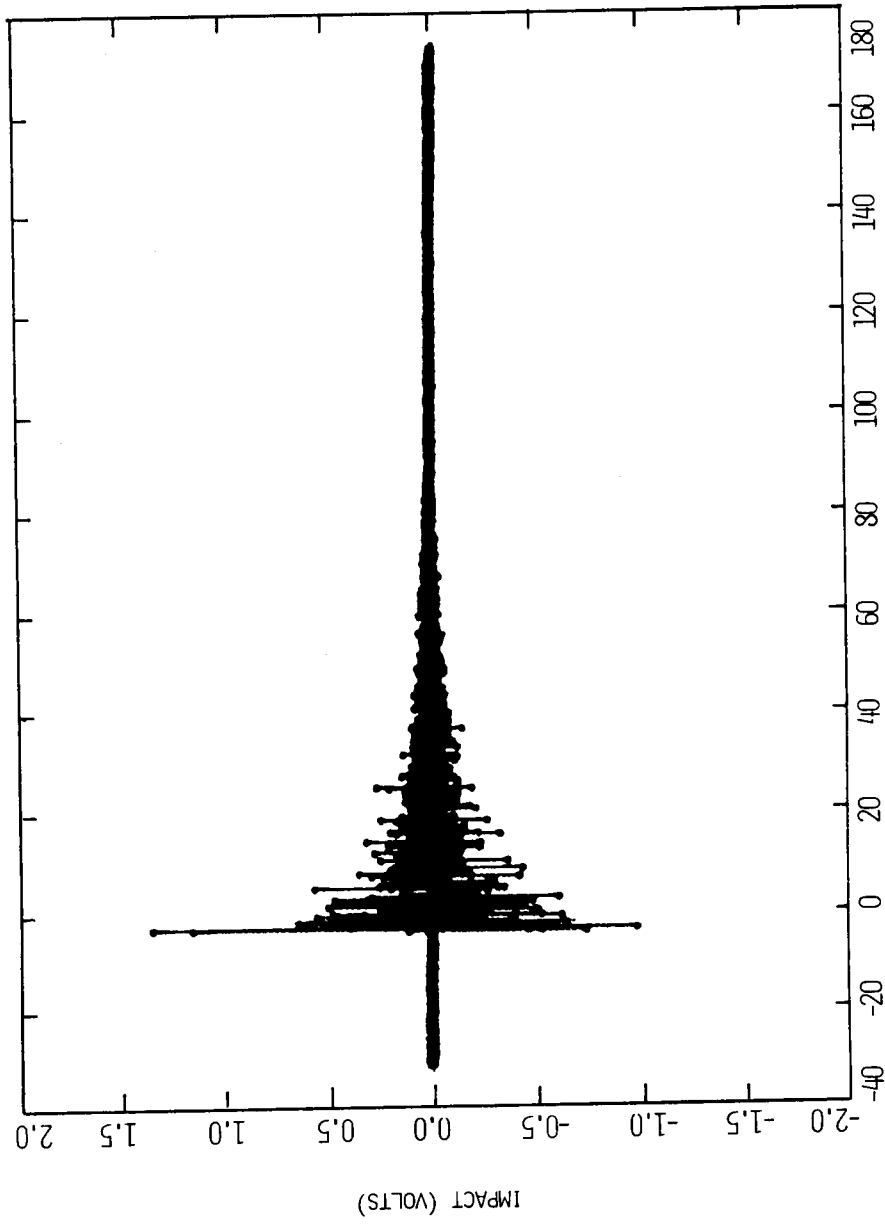


Fig. 46. A typical time domain impact signal.

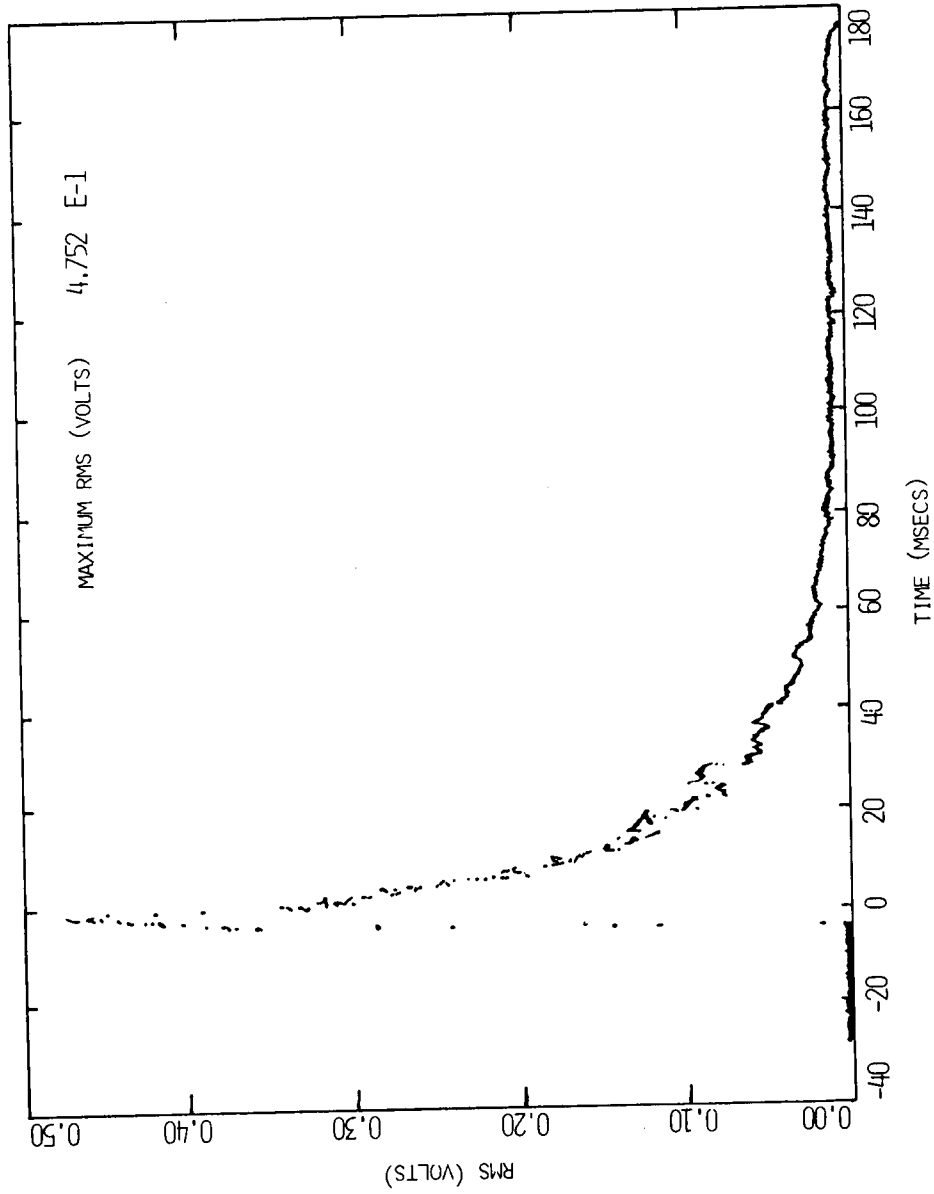


Fig. 47. A typical time dependent RMS of an impact signal.

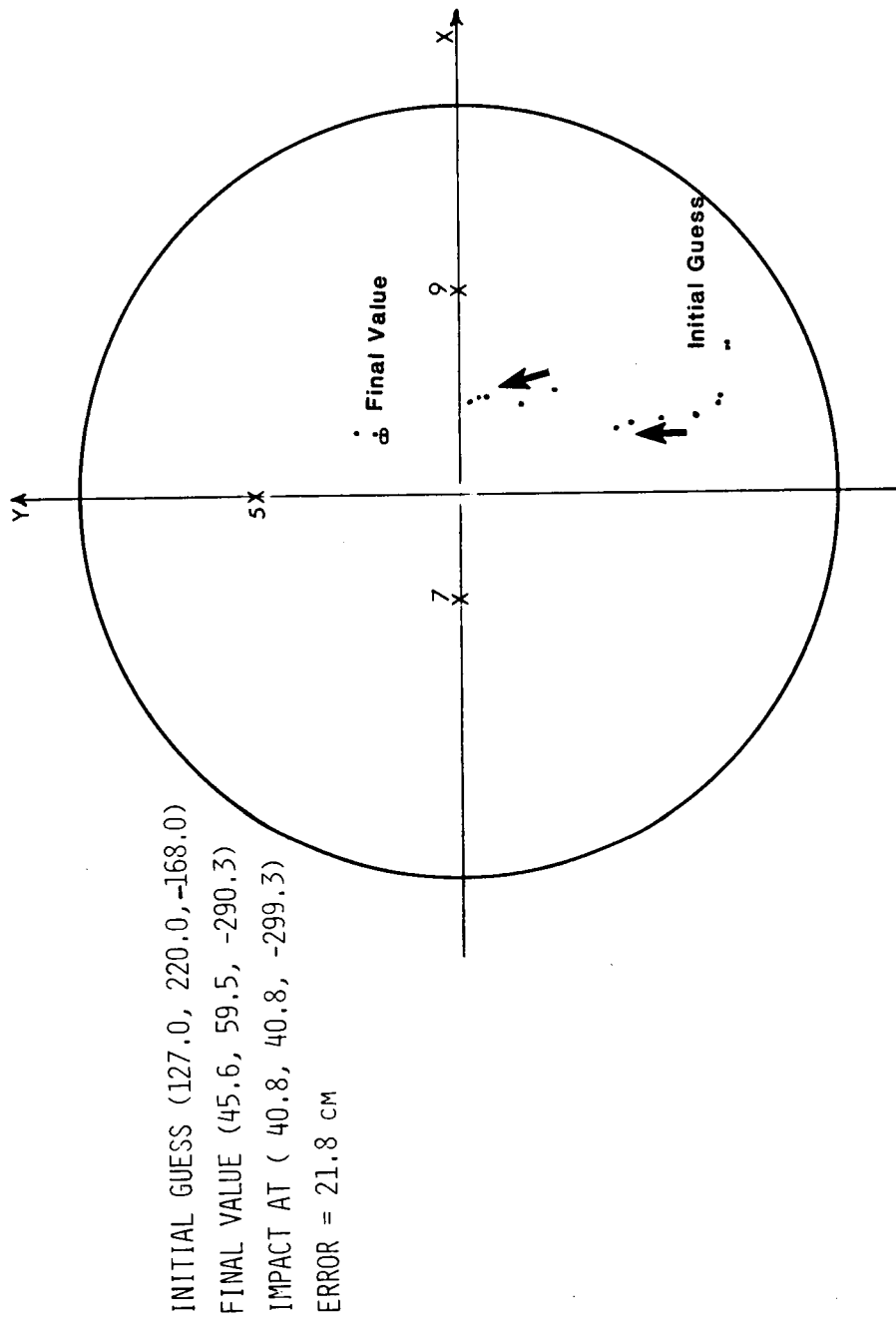


Fig. 48. A typical plot of the impact location process.

Table 13. Impact location error analysis

Impact at	Acc's in use	Error in arc length (cm)	Error in arc length (cm with correction)	Percent improvement	Average error
I3	5, 7, 9	99.83	91.87	7.97	
I3	5, 7, 9	99.80	92.23	7.59	
I3	7, 9, 3	128.52	101.12	21.32	
I3	7, 9, 3	111.79	52.73	50.82	
I3	5, 9, 3	96.70	75.13	22.30	
I3	5, 9, 3	98.45	93.24	5.29	
I3	2, 3, 4	46.36	40.28	13.10	
I3	2, 3, 4	36.65	30.15	17.74	
I3	1, 3, 4	75.13	71.96	4.23	
I3	1, 3, 4	63.02	54.69	13.22	
I3	1, 2, 3	137.01	55.12	59.77	a
I3	1, 2, 3	101.75	51.28	49.60	
I2	2, 3, 4	137.95	108.53	21.32	
I2	2, 3, 4	178.51	156.95	12.08	
I2	2, 3, 1	13.06	22.38	-71.36	
I2	2, 3, 1	9.42	22.71	-141.08	
I2	1, 3, 4	209.17	67.41	67.77	b
I2	1, 3, 4	239.57	40.26	83.20	
I1	2, 3, 4	69.85	64.01	8.36	
I1	2, 3, 4	56.92	24.71	56.58	
I1	2, 3, 1	111.71	60.66	45.70	
I1	2, 3, 1	141.76	60.22	57.52	
I1	3, 4, 1	141.98	71.04	50.31	
I1	3, 4, 1	173.66	71.12	59.02	
I1	2, 4, 1	88.24	84.02	4.74	c
I1	2, 4, 1	83.34	74.12	11.06	

^a Without correction	91.25 ± 30.6
With correction	67.43 ± 23.38
^b Without correction	131.28 ± 98.89
With correction	75.60 ± 57.88
^c Without correction	108.43 ± 40.85
With correction	63.94 ± 17.62

This error can be attributed to two causes: (a) systematic errors, and (b) model error. The systematic error is caused by the extra paths induced by the twenty-five fuel charging nozzles on the bottom head of the pressure vessel (see Table 8, page 81, for nozzle sizes). A correction process was then incorporated in the optimization program to approximate the extra paths. This correction has drastically reduced the error, where after the correction the above impact was located within 63.74 cm to 67.43 cm (see Table 13). The exact correction of extra paths (the intersection of a cylinder and a hemisphere) could further improve the error.

The error attributed by the $1.0/(\text{Distance})^{2.0}$ attenuation model is also indirectly related to the nozzles which are welded to the bottom of the reactor. Correction for this type error depends upon the type of weld and the amount of weld in the path of the impact wave and thus judged to be out of the scope of this work.

The ex-core impact was located with more precision, because of limited and unique impact positions which in turn cause less interaction with the bottom head nozzles. This point is better illustrated in Table 14 where according to the selection of accelerometer combinations the correction for the pipe interference can help or impair the location results. A closer look at the accelerometer combinations used in Table 14 indicates that if one selects a set of accelerometer where the nozzles on the bottom head section of the pressure vessel does not interfere with the impact wave in an effective manner the correction process is not needed and vice versa.

Table 14. Impact location results using ex-core impacts

Impact at	Acc's in use	Error (cm)	Error (cm) Correction	Comments
I4	2, 3, 7	11.6	63.35	Correction has impaired the location process
I5	2, 4, 7	17.34	78.12	
I6	3, 4, 7	22.3	73.4	
I6	3, 4, 7	27.17	68.1	
I4	5, 6, 7	190.3	16.1	Correction has helped the location process
I4	5, 6, 7	193.3	21.8	
I5	4, 5, 6	228.77	14.59	
I5	4, 5, 6	167.10	7.05	
I6	4, 5, 6	185.4	24.7	

The results shown so far have been obtained under essentially zero background noise levels except for the natural electronic noise. This would not be the case with signals from an operating power reactor. In order to test the above impact location technique under the presence of background noise, the signals obtained from the EGCR reactor vessel were digitally mixed with a 50 kHz bandwidth white noise (the same process can be used if a tape recording of the natural noise background of a power reactor was available). Since the noise added was digitally controllable three types of real life conditions were simulated:

(a) all accelerometers in use had the same RMS noise level, (b) all accelerometers in use had a constant signal-to-noise ratio, and (c) all accelerometers in use had varying amount of both signal-to-noise ratio and RMS noise level. The impact location results indicates that if the peak of the time dependent RMS is used in the algorithm, the crucial factor for the accuracy of the location is the minimum signal-to-noise ratio among the set of accelerometers used in location. This

is illustrated in Fig. 49 where the minimum signal-to-noise ratio in a given accelerometer set is plotted against the error difference in impact location from a noise free signal for a given impact. This figure is indicative of an unacceptable added error with signal-to-noise ratios of less than 5 (the noise free case was located within 10 cm of the actual impact point).

The speed and the accuracy with which the Rosenbrock Hillclimb algorithm optimizes the coordinates of an impact have also been studied. The findings are as follows. The more accelerometer signals used the slower is the convergence. This is simply due to added number of equations in the functional. Accelerometers of similar mounting (all stud mounts or all pipe mounts) result in more accurate and sharper peak on the convergence surface. A mix of signals from the above two types of accelerometer mountings results in shallow and flat convergence surface which is directly related to slow convergence. A minimum of three accelerometers are required for unique results but if the three accelerometers favor a particular region of the structure, a multipeak will occur on the surface of convergence with the taller peak being the right answer. Use of more than three accelerometers will alleviate this multipeak problem but the appearance of a shallow peak is the result. The above findings are illustrated in Figs. 50, 51, and 52, where the surface of the convergence (functional F) is plotted for various types and accelerometer selections. The Z coordinate has been dropped from the plot because of the three-dimensional nature of the figure, but every point on the surface has the correct Z coordinate.

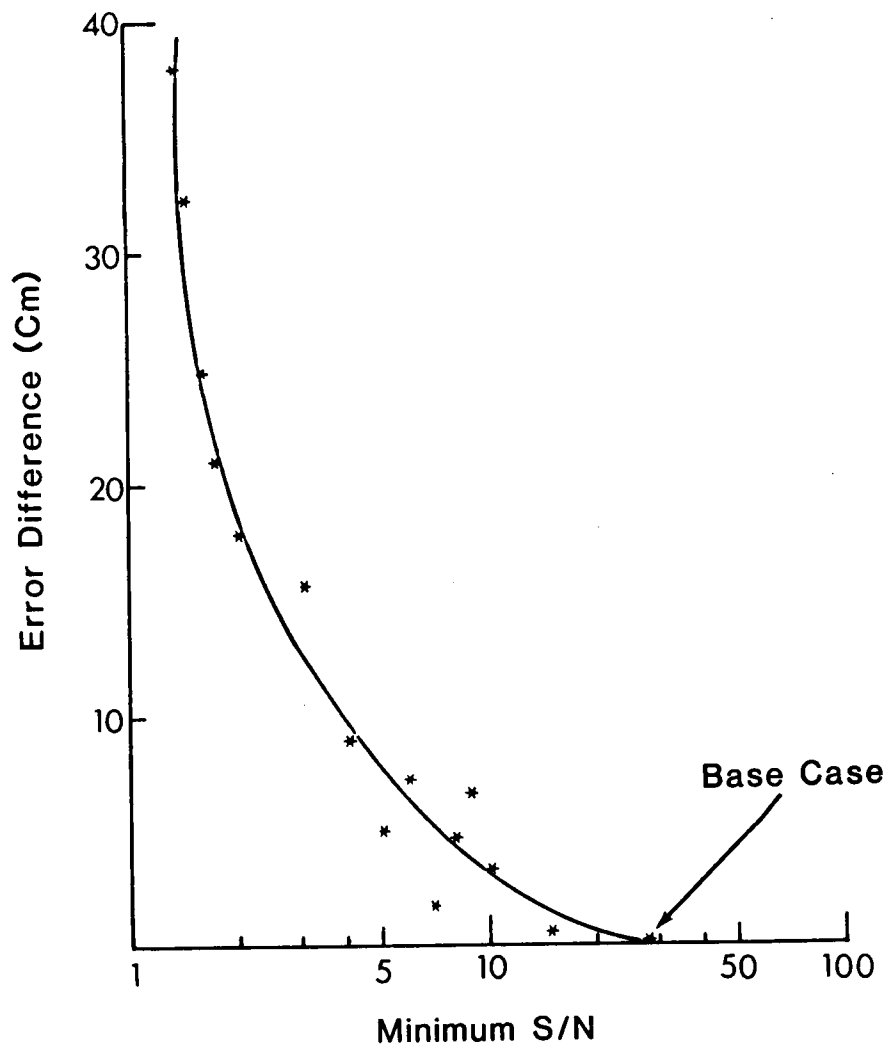


Fig. 49. Effect of minimum signal-to-noise ratio on the accuracy of impact location.

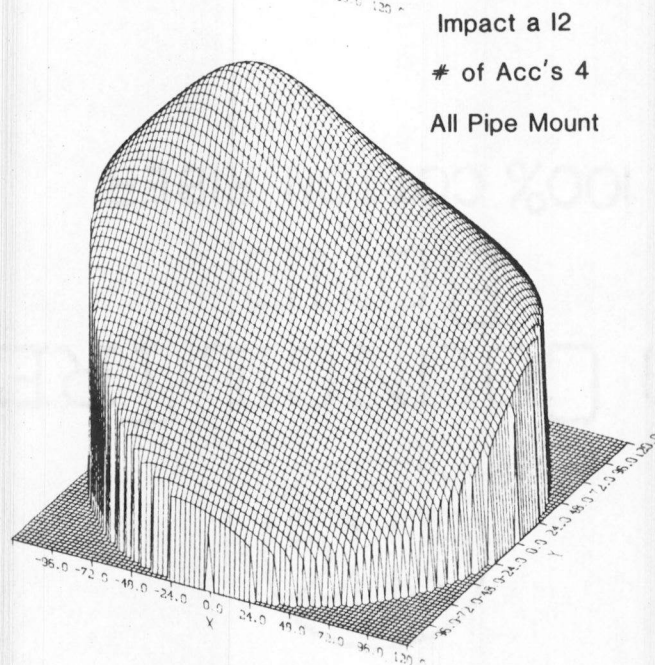
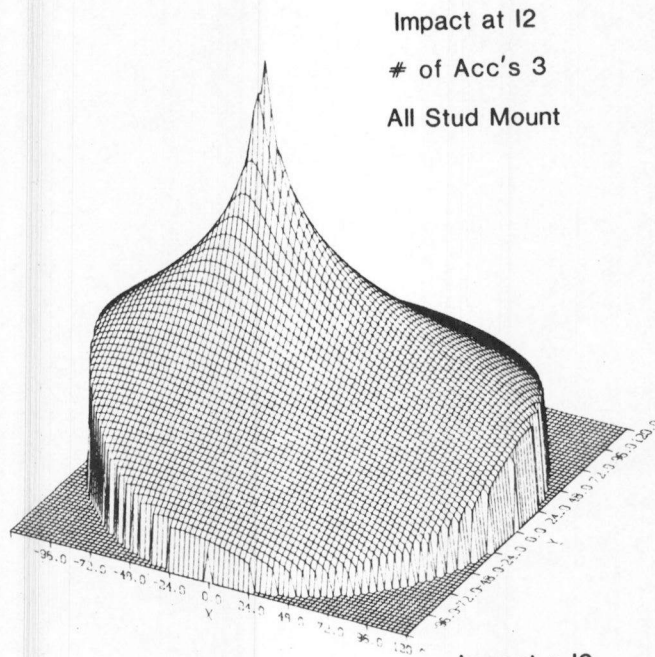
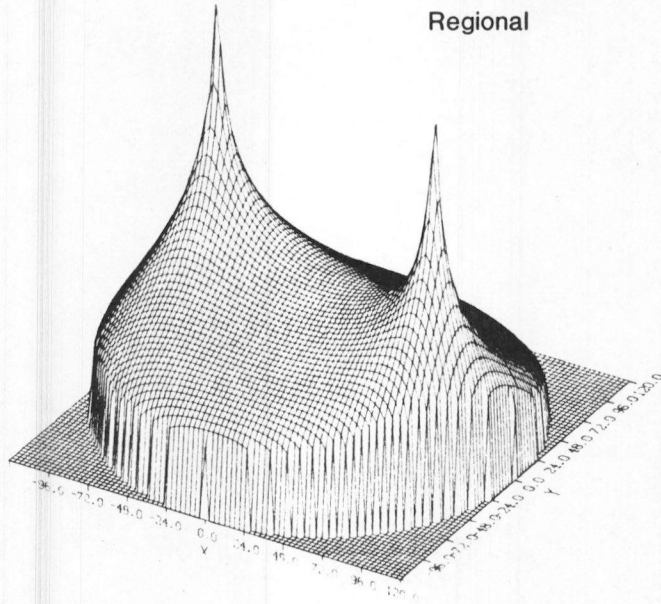


Fig. 50. Convergence plane of an impact at location I2, with use of three and four accelerometers for location.

Impact at I2

of Acc's 3

Regional



Impact at I5

of Acc's 3

Mixed Stud & Pipe Mount

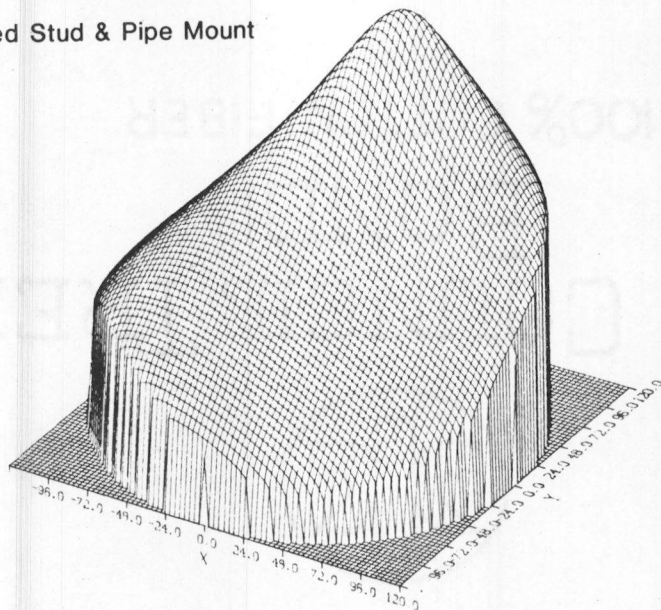


Fig. 51. Convergence plane of regionally located accelerometers; also an impact at I5 and location with a mix of stud and pipe mount accelerometers.

Impact at I5
of Acc's 3
All Pipe Mount

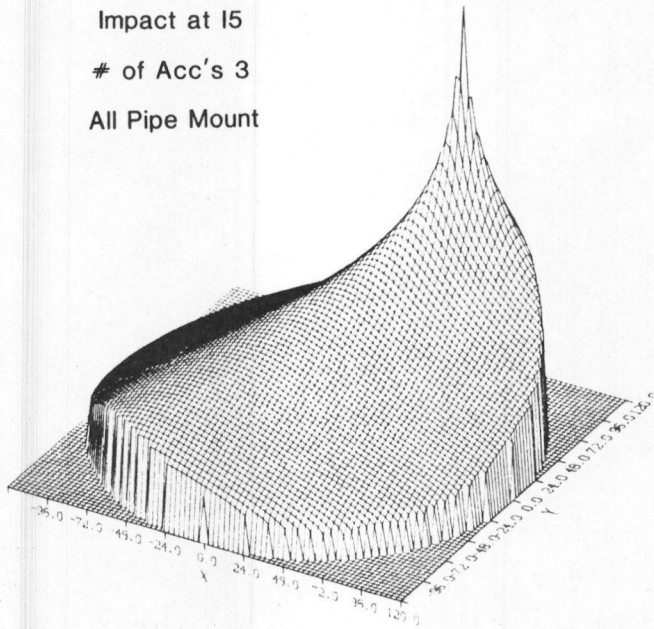


Fig. 52. Convergence plane of an impact at I5 and location with all pipe mount accelerometers.

D. Impact Characterization Methods

The ability to characterize an impact one step further than location as to its probable size and shape is also an objective of this work. Two types of analyses are the basic tools to achieve these goals: time dependent RMS (Root Mean Square) analysis and transient relative frequency analysis. In this section the ideas of impact characterization are presented first followed by experimental results using data from known impacts on the EGCR pressure vessel. Basic computational procedures used in this section are as follows: fast Fourier transform, windowing, frequency smoothing, power spectrum calculation, block averaging, power spectrum manipulation such as addition, subtraction and division, and finally digital time dependent RMS calculation. The mechanics of the above calculational procedures are detailed in Reference 12.

An alternate way of presenting transient time data is the time dependent Root Mean Square representation. Contrary to stationary time signals, the RMS of the transient signals are time dependent. The time dependent RMS can be obtained digitally or by using analog electronic circuits. In this study all the time dependent RMS's were obtained digitally using the following formula,

$$\text{Mean Square } (t_i, \tau) = \frac{[N \cdot \text{MS}(t_{i-1}, \tau) - x^2(t_{i-N}) + x^2(t_{i+N})]}{N} \quad (4.22)$$

where

$$i = 2, 3, \dots, N$$

$$\text{MS}(t_i, \tau) = \sum_{i=1}^N x^2(t_i) / N$$

$$\text{RMS}(t_i, \tau) = \sqrt{\text{MS}(t_i, \tau)} \quad (4.23)$$

where

τ = averaging time

$x(t_i)$ = i th time estimate of the raw signal

N = number of time estimates in τ

The τ dependence in Eq. (4.23) is an important parameter to be considered. It can be seen in Fig. 53 the effect of the averaging time on the shape and characteristics of an impact with mixed-in background noise. Small averaging time (0.5 msec in this case) causes difficulty in peak detection and overall instability in the shape of the time dependent RMS. As the averaging time increases stability in the background noise suppression appears and the peak of the time dependent RMS tends to be more prominent and easier to detect and identify. On the other hand, as the averaging time gets too large (above 8.0 msec for this impact), the double peak character of the time dependent RMS (believed to be impact wave reflection from a nearby nozzle) disappears. This would cause errors in the impact location process which uses the peak of the time dependent RMS. The optimum value of the averaging time depends upon the locality of the accelerometer and the possible strong reflection impact signal arrival in conjunction or close to the main impact wave arrival. In this particular case either two or four msec averaging time was acceptable.

The time dependent RMS is also used in impact characterization besides its use in impact location. As an example consider the

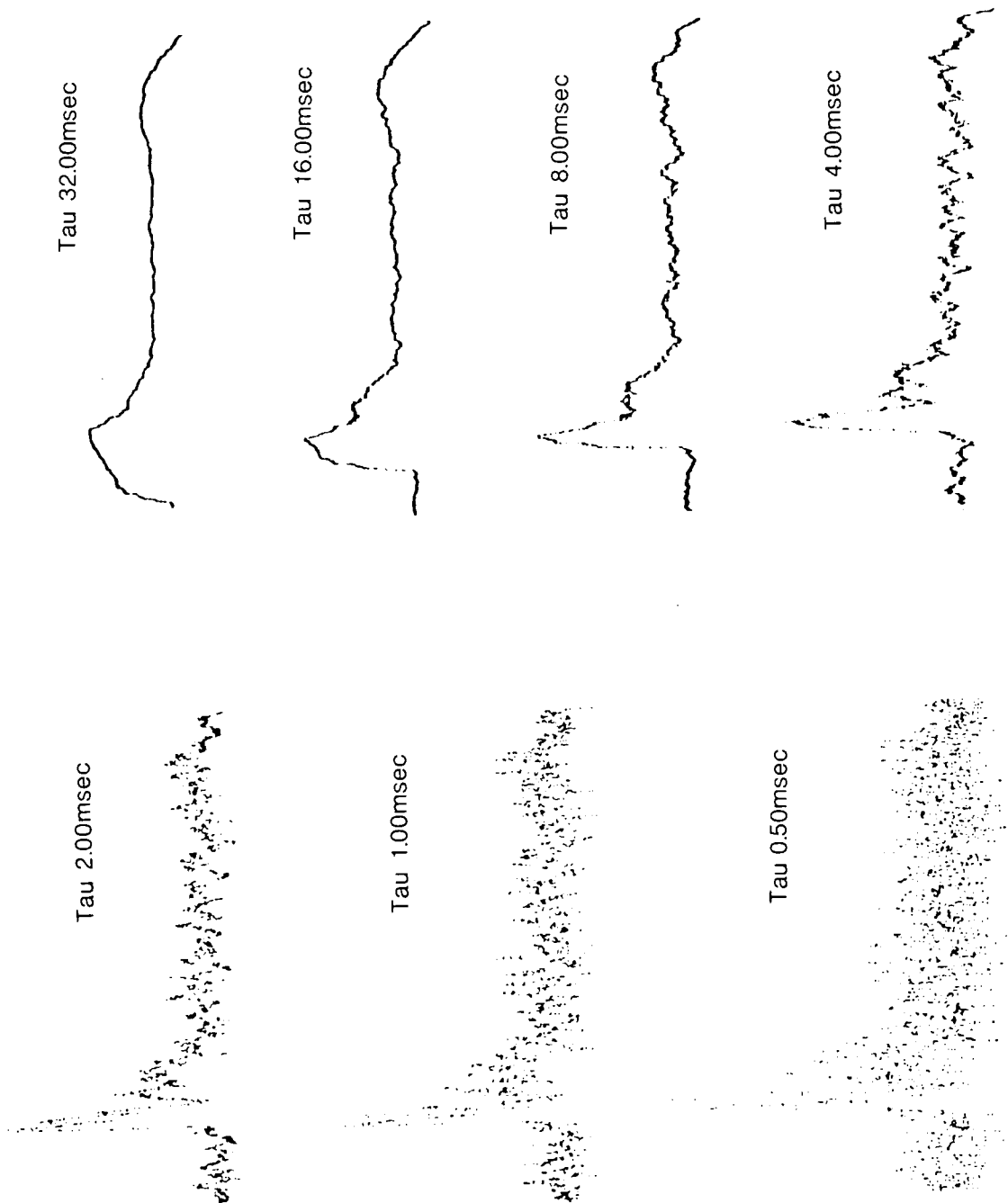


Fig. 53. Effect of averaging time (τ , tau) on the shape of the time dependent RMS ($S/N = 3$).

comparison of in-core and ex-core impacts detected with an ex-core accelerometer. Figure 54 shows the time dependent RMS of two impacts using the solenoid automatic impactor positioned at location I4 (see Table 11, page 94). The first impact was inside the pressure vessel and the second impact on the outside wall of the EGCR vessel. The similarities are obvious (rise time, duration, decay and general shape of the curves). The slight difference in peak amplitude (approximately 11%) can easily be due to differences in impacting surfaces (concave vs convex), surface texture, and solenoid mounting difficulties although care was taken to prevent the above differences.

The time dependent RMS can also be applied in the impact wave path identification and comparison. Figures 55 and 56 show impacts of similar magnitude at accelerometer locations 2, 3, and 4 (Impacts I7, I8, and I9). The time dependent RMS's indicate that the path from accelerometer 2 to accelerometer 4 ($\overline{24}$) is identical to that of $\overline{34}$, and the path $\overline{23}$, although the same distance, is not the same as $\overline{24}$ or $\overline{34}$. A physical examination of the EGCR structure indicates that indeed the path $\overline{24}$ and $\overline{34}$ are symmetric and the path $\overline{23}$ although the same distance is not the same as $\overline{24}$ or $\overline{34}$ due to the inlet coolant gas pipe in the impact wave path.

Further characterization is possible looking at the rise time of the time dependent RMS. A fast rise time indicates a short contact time between the missile and the target, and a slow rise time is indicative of extended contact time. This is illustrated in Fig. 57 where the RMS of a scratch (with a screw driver) and the impact of a pendulum ball at the same location are plotted.

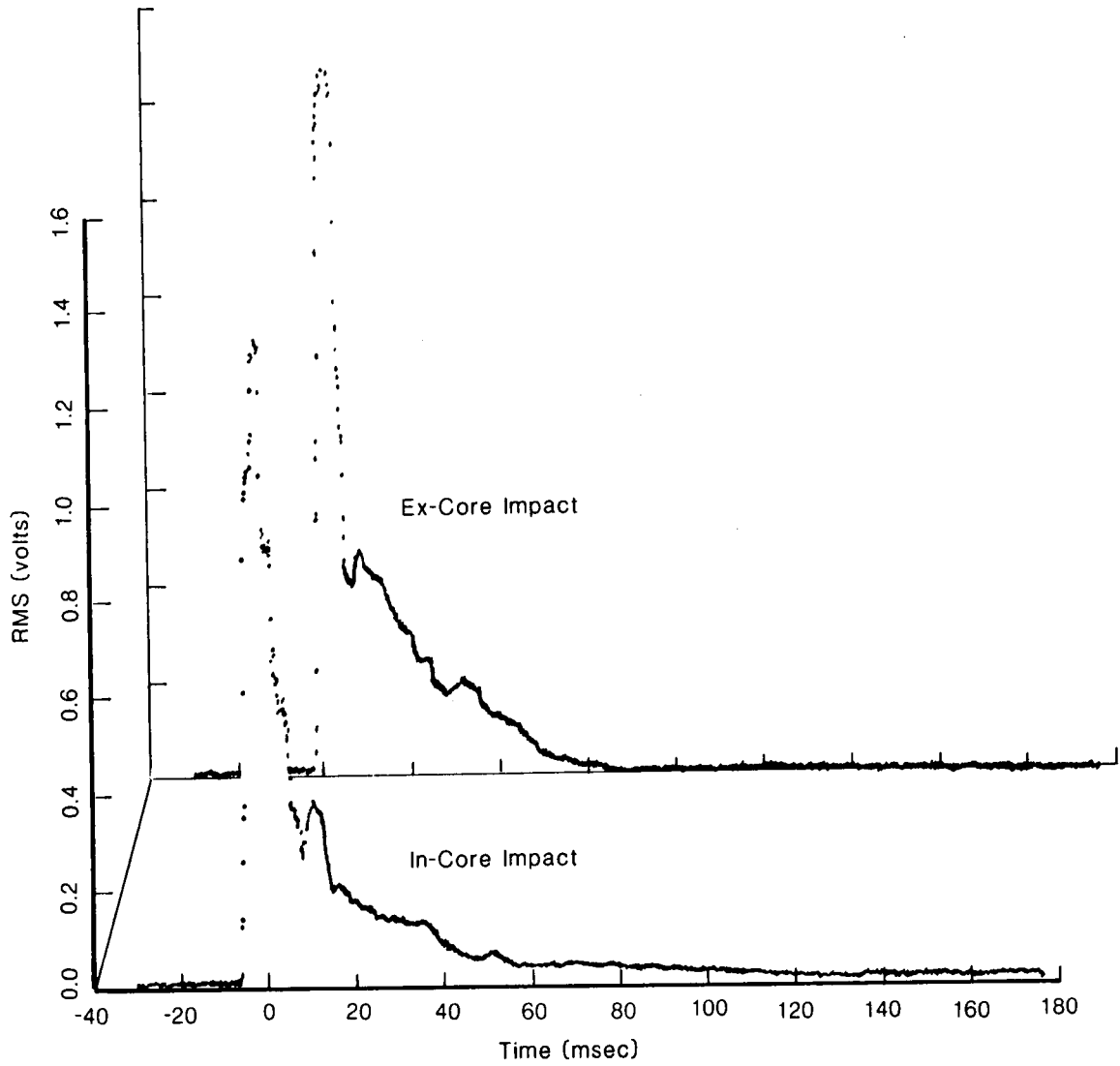


Fig. 54. Comparison of in-core and ex-core impacts using time dependent RMS.

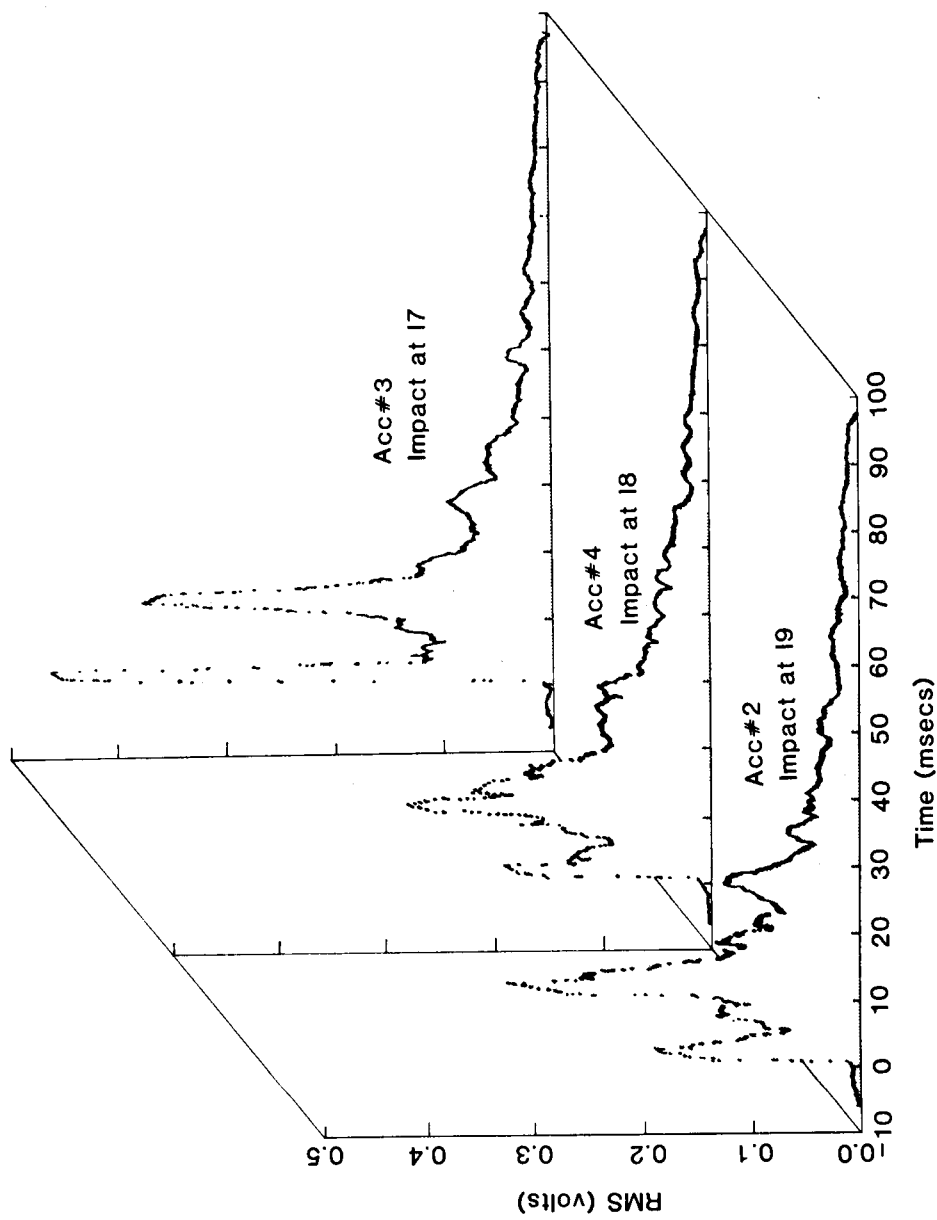


Fig. 55. Time dependent RMS for impacts at I9, I8, and I7.

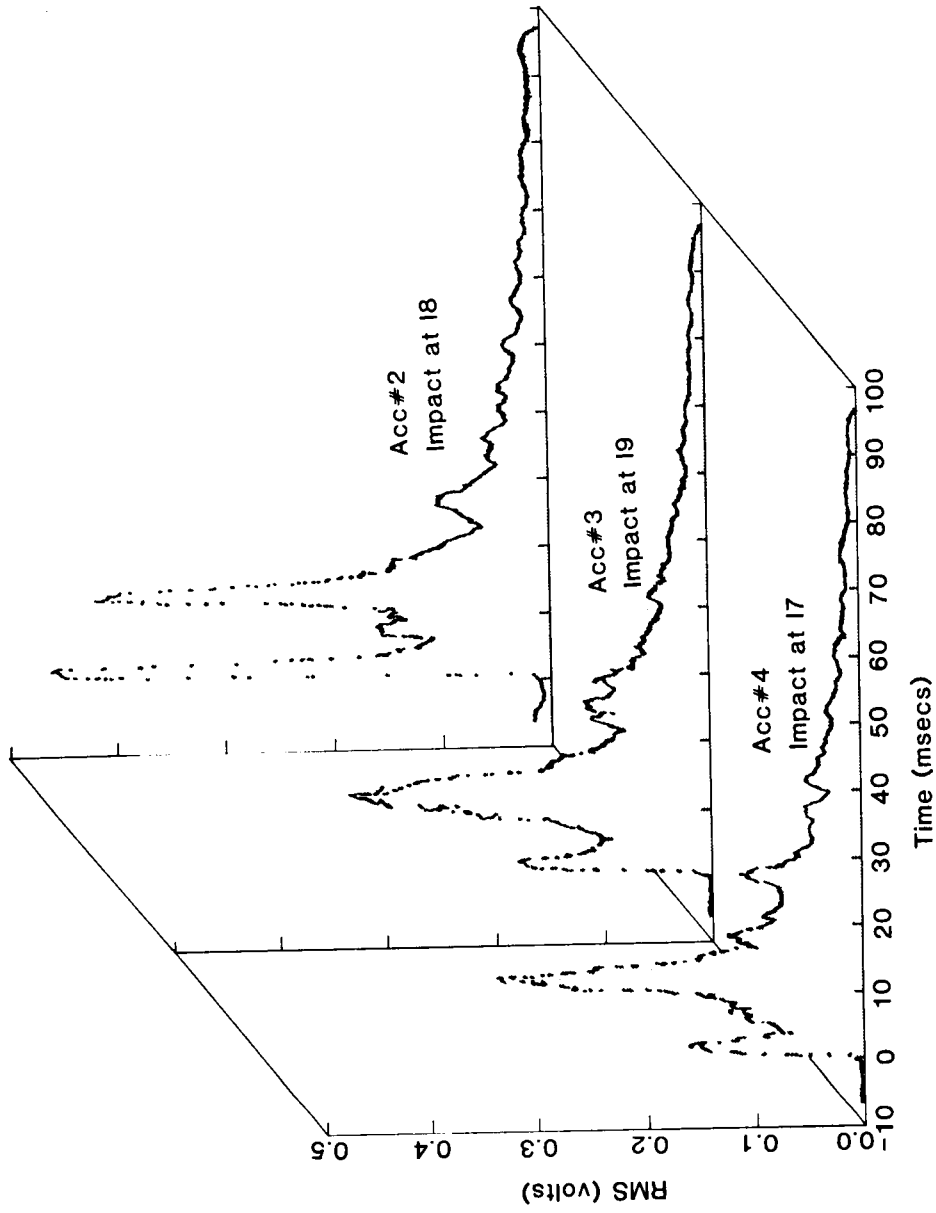


Fig. 56. Time dependent RMS for impacts at I7, I9, and I8.

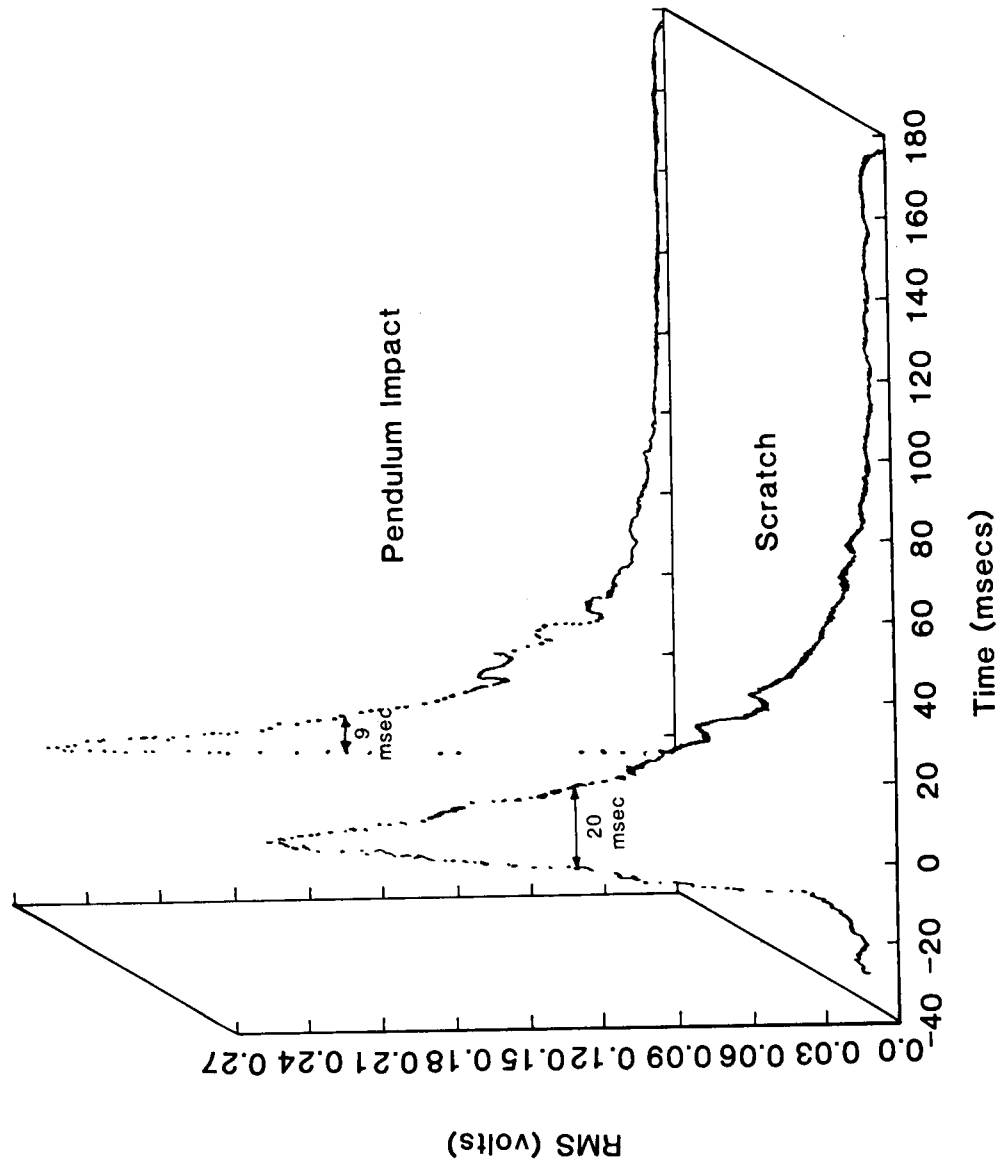


Fig. 57. Comparison of a screwdriver scratch signal with a pendulum ball impact in the time dependent RMS domain.

Frequency domain analysis of impact signals is also used for further characterization of an impact. The impact wave signals are of transient deterministic nature. Therefore, no Fourier coefficient averaging is required, a box-car window is used if the entire wave form is contained in the time window, and frequency averaging is recommended for smoothing the power spectrum curves. The power spectrum which is the magnitude squared of the complex fourier coefficient of the time signal is usually shown to present the frequency contents of an impact.

In theory an impact wave traveling in a structure carries with it information of two types: (a) characteristic of the contact between the missile and the target and (b) the characteristic of the path from the point of impact to the sensor. The sensor (in this study an accelerometer) detects surface acceleration, but as it was explained in Chapter II, it is a resonating system and if it is confronted with a pulse of short duration the response is the resonance of the accelerometer at its preferred frequency (approximately 25 kHz). The frequency analysis pursued in this study has been performed on the analysis of the resonance frequency of the accelerometer. The reason for this so-called high frequency analysis being the lack of low frequency component which is due to quiet background conditions (no pump, no flow, no vibration).

A typical power spectrum of a ball drop impact is shown in Fig. 58. Notice the use of the aliasing (see reference 12) to translate 20-25 kHz frequency range to 0-5 kHz. This was possible because of the lack of significant frequency component of the power spectrum below 20 kHz.

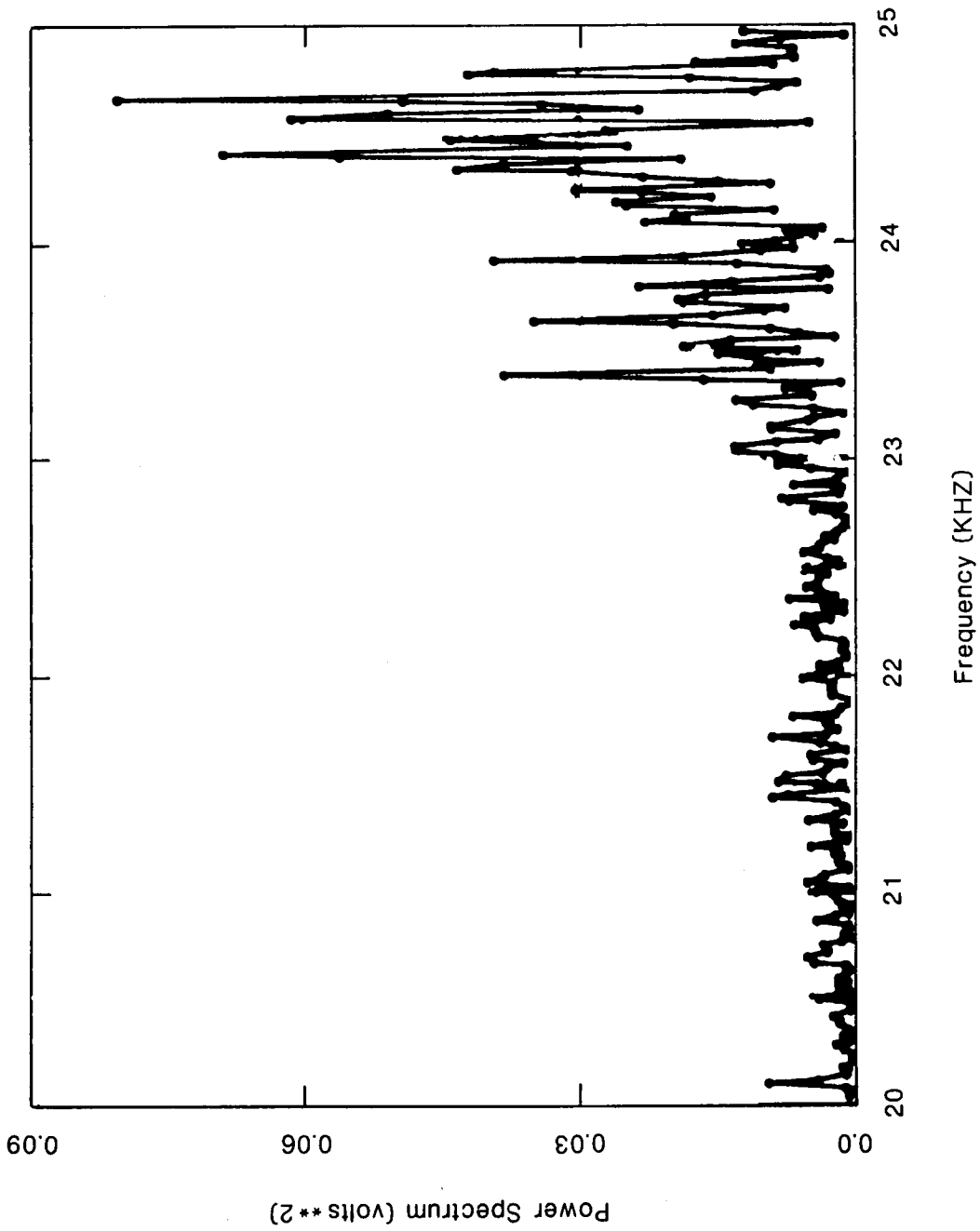


Fig. 58. A typical power spectrum of a ball drop impact on the inside of the EGCR vessel.

In other words frequencies appearing at say 24 kHz range now show up (aliased) at 4 kHz range and so on. The use of aliasing is common in other areas of signal analysis such as zoom process.

Further, more study indicates that relative change in power spectrum between two accelerometers or the relative change in the power spectrum of two impacts is a sensitive indicator which can be utilized in characterization. The above two indicators can be formulated as follows:

$$P = \frac{PS_a - PS_b}{PS_b} \quad (4.22)$$

where

PS_a = power spectrum of accelerometer a

PS_b = power spectrum of accelerometer b

The P spectrum above is an indicator of impact wave travel path similarity and an indicator of frequency dependent amplitude dispersion of a given impact.

The second indicator is the I spectrum which is given by

$$I = \frac{PS_{a1} - PS_{a2}}{PS_{a2}} \quad (4.23)$$

where

PS_{ai} = power spectrum of accelerometer a for impact i.

The I spectrum is a frequency dependent indicator of variations between two impacts (1 and 2) detected at accelerometer position a.

Also, the area under the P or the I pseudo-spectrum can be thought of as a combined measure of the differences, accumulating the individual frequency differences. The use of P and I pseudo-spectrum or the area under them must be combined with impact location process described in the previous section, since the individual power spectrums (frequency dependent) change magnitude according to the proximity of the impact to the sensor and the obstructions between the impact and sensor.

The use of the I pseudo-spectrum is demonstrated in the following example. Figure 59 shows two I pseudo-spectrums, the lower graph is the I spectrum of two pendulum impacts on the inside wall of the EGCR pressure vessel where the angle of deflection on the pendulum was 30 degrees. Notice that there are no significant activity appears (similar impacts), and the area under the curve is relatively small ($14.28 \text{ v}^2/\text{sec}$). The area under the curve should have been zero if the two impacts were exactly equal. The upper graph is the I spectrum of two pendulum impacts, the first with a 30 degree angle of deflection and the second with 15 degrees angle of deflection. The area under this curve is relatively significant ($93.38 \text{ v}^2/\text{sec}$). The I spectrum shows relative change in the resonance frequency range between the two similar impacts but with different impacting force. The difference between the impact energy of the 30 and 15 degrees pendulum shots were 262.4 gr-cm or 0.019 ft-lb.

The P pseudo-spectrum renders the frequency dependence of the different paths which an impact wave travels to reach an accelerometer location. Since the various paths which an impact wave travels impose

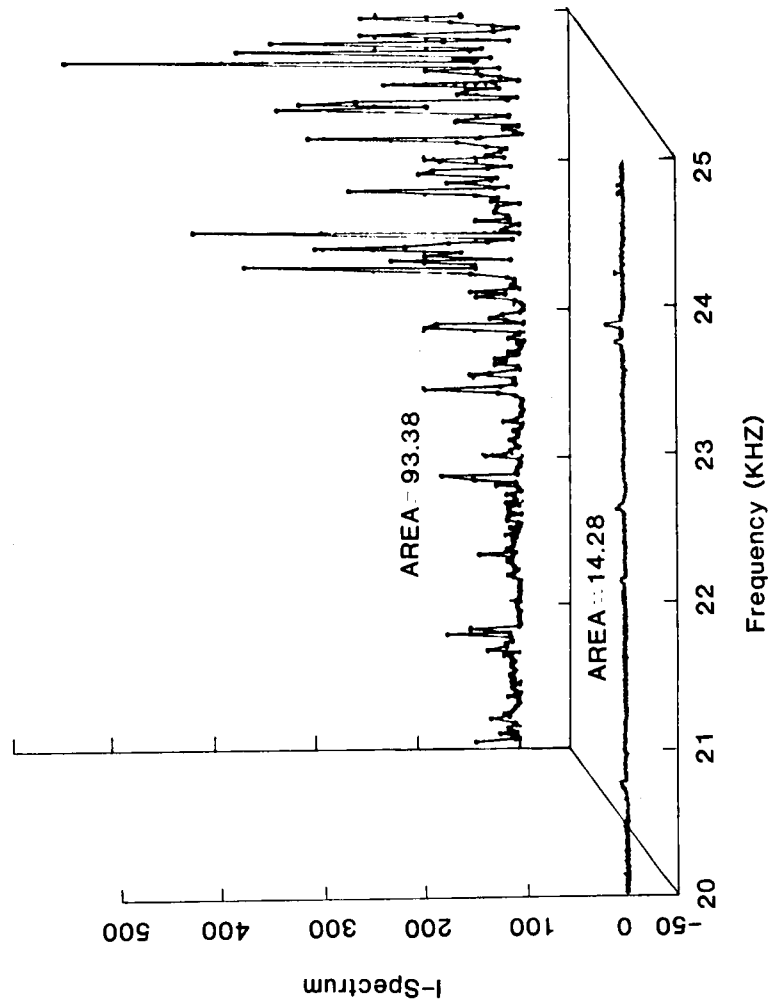


Fig. 59. The use of I-pseudo-spectrum for impact characterization.

a unique frequency characteristic, a general conclusion could not be reached from looking at various P spectrums of the EGCR impacts. The only conclusive results are as follows: (a) similar impact wave travel paths result in zero or near zero area under the P spectrum curve, but the shape of the P spectrums may or may not be similar. This is due to the fact that two impacts are rarely inflected in the same manner. (b) Two types of path variations could be identified, the first being path difference caused by distance; the two path lengths were similar in the structural characteristics but different in length only. The P spectrum showed activity in the resonance frequency range (24-26 kHz). The second type of path variation identified was caused not only by distance but also by the structural differences in the pathway. This type of anomaly causes the P spectrum to show activity in a wider frequency range around the resonance (20-30 kHz). The above two are illustrated in Fig. 60.

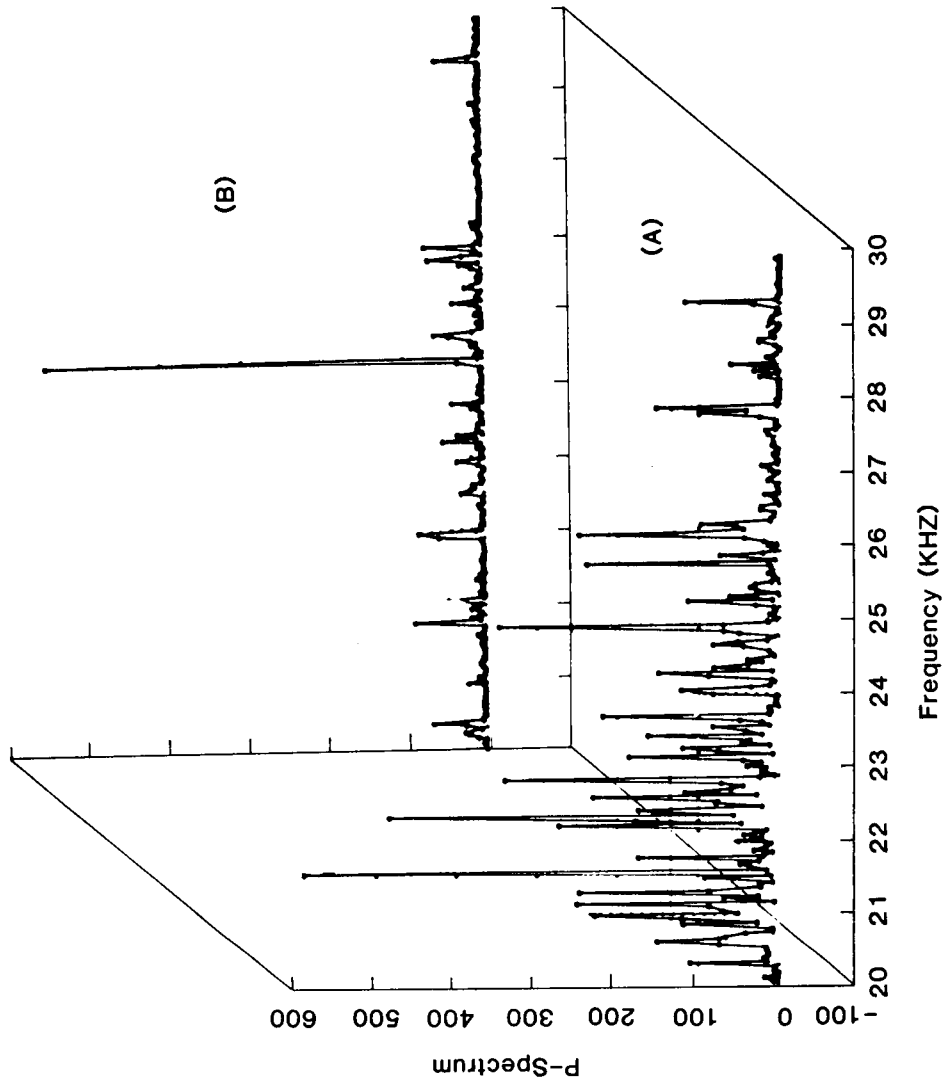


Fig. 60. The use of P-pseudo-spectrum for impact characterizations. (A) Structural and path difference and (B) pure path difference.

CHAPTER V

OVERALL CONCLUSIONS AND RECOMMENDATIONS

A. Summary

A combined theoretical and experimental research effort was launched to develop new techniques for detection, location and characterization of metallic loose parts in a nuclear reactor primary or secondary coolant system.

The formulation for impact formation, wave propagation and the detection sensor were presented. The theoretical work provides understanding of impact wave generation based on elastic and inelastic contact theory and the concept of restitution. The impact wave propagation was then presented using elastic wave propagation theory of stress and strain caused by an impact in a structure. The theory of the accelerometer mechanical concept and use concluded the theoretical part of this study.

Experimentally, two flat plates (steel, and aluminum) were used in conjunction with a set of accelerometers for impact studies under ideal laboratory conditions. The subjects under study here were accelerometer attachments and attachment anomalies, various impact detection systems, impact location using time of arrival or amplitude attenuation. The experiment was then transferred from the idealized laboratory conditions to a relatively large power reactor pressure vessel. Here, the impact experiments were conducted under a more

realistic condition considering the complexity of the vessel. New methods of impact location were then studied and tested followed by development of several mathematical procedures for impact characterization.

In the next section specific conclusions which were reached during the course of this study are presented.

B. Conclusions on Impact Location

Two methods of impact location determination were studied: deterministic and heuristic. The deterministic approach involves the knowledge of surface wave effective velocity in the structure under study. The determination of surface wave effective velocity in a complicated structure is a tedious and unreliable task which deters the use of this technique.

The heuristic method which involves modeling the impact wave attenuation process was found to be an accurate method of impact location. A 1.0/L and attenuation model were found to be effective on the flat plates and the EGCR vessel. As an extension to this model an optimization technique was utilized to determine the location of an impact using the peak RMS of a minimum of three accelerometer transient signals. The effect of background noise on the impact location was also studied, and the results indicated that the minimum signal-to-noise ratio is the controlling factor in the accuracy of this impact location method.

C. Conclusion on Impact Characterization

In theory an impact wave traveling in a structure carries with it information of two types: the impact itself and the characteristic of

the structural path which it travels to reach the sensor position. The impact leaves behind two types of information: the mode of impact (elastic or inelastic) and the restitution information of the loose part. Thus, absolute characterization is not practical in the absence of detailed contact data and examination of the impact area at the time of impact. So, relative characterization of comparative type must be used. Time and frequency domain analysis were developed to perform this relative characterization.

The time dependent RMS was proved to bear such characteristic information as the geometric shape of the loose part at the point of contact. For example, sharp edges result in a fast rise time in the time dependent RMS curve, and sustained impacts (scratch) result in wide peaks in the RMS curve. Also, the peak of the RMS curve is related to the magnitude of the impact.

The relative frequency domain analysis proved sensitive to variations in impact energy and path length difference. Two types of frequency dependent pseudo-spectrum were developed. The P pseudo-spectrum which utilizes two accelerometers detecting an impact describes path length difference and frequency dependent amplitude difference which is also due to dispersion of the impact wave. The I pseudo-spectrum, on the other hand, is a frequency dependent indicator of changes in the energy of impact between two separate impact detected at a given accelerometer location. For example, an energy of impact difference of 262.4 gr-cm (0.019 ft-lb) was shown to be easily detectable. The accelerometer resonance frequency band (20-30 kHz) was used for frequency characterization throughout these studies.

D. Recommendations

This work has shown that time and frequency analyses method developed here are effective for metallic loose-parts detection, location, and relative characterization. The following refinements are thus recommended to further improve the accuracy of impact location and effectiveness of impact characterization.

1. The effect of water in the pressure vessel.
2. The effectiveness of methods presented here under strong low frequency structural vibration.
3. Limited tests where conducted here indicated that accelerometer response is related to impact momentum. More extensive tests are recommended to clarify and quantify this point.

LIST OF REFERENCES

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1. "Development of Vibration Systems for Light Water Nuclear Reactors," Proprietary Progress Report, General Electric Company, NEDC-10780-1, 2, 3, 4.
2. Hamstad, M. A. and R. G. Patterson, "Consideration for Acoustic Emission Monitoring of Spherical Kerlar/Epoxy Composite Pressure Vessels," Lawrence Livermore Laboratory, UCRL-79356, 1977.
3. "Impact Calibration for Loose Parts Monitoring System at St. Lucie I," Internal Report, Combustion Engineering, System Integrity Services, 1977.
4. Hertz, H., "Über die Berührung fester elastischer Körper," *J. reine angew. Math. (Crelle)*, 92, 1881, 155.
5. Sokolnikoff, I. S., "Mathematical Theory of Elasticity," Brown University, Advance Instruction and Research in Mechanics, Providence, R.I., 1941.
6. Love, A. E. H., "A Treatise on the Mathematical Theory of Elasticity," 4th edition, New York, Dover Publications, 1944.
7. Goldsmith, W., "Impact: The Theory and Physical Behavior of Colliding Solids," Edward Arnold Publishers, Ltd., London, 1960.
8. Timoshenko, S. P., "Vibration Problems in Engineering," 2nd Edition, New York, D. van Nostrand Co., 1937.
9. Schnurmann, R., "Rate of Energy Loss from Rebounding Steel Balls," *Proc. Phys. Soc.*, London, 53, 1941, 662.
10. Lamb, J., "The Theory and Practice of Ultrasonic Propagation," *The Principals and Practices of Nondestructive Testing*, Prentice Hall, 1967.
11. Chao, Chi-Chang, "Dynamical Response of an Elastic Half Space to Tangential Surface Loading," *Journal of Applied Mechanics*, pp. 559-567, Sept. 1960.
12. Bycroft, G. N., "Impact of a Rigid Body on an Elastic Half Space," *Journal of Applied Mechanics*, pp. 227-230, June 1977.
13. Lord, A. E., J. N. Deisher, R. M. Koerner, "Attenuation of Elastic Waves in Pipelines as Applied to Acoustic Emission Leak Detection," *Materials Evaluation*, pp. 49-60, November 1977.

14. Underwood, P., "Transient Response of Inelastic Shells of Revolution," *Computers and Structures*, Vol. 2, pp. 975-989, Pergamon Press, 1972.
15. "Piezoelectric Accelerometers," No. 101, Endevco-Dynamic Instruments Division, 1969.
16. Bendat, J. S., A. G. Piersol, "Random Data: Analysis and Measurement Procedures," Wiley-Interscience, Inc., New York, 1971.
17. Rosenbrock, H. H., "An Automatic Method for Finding the Greatest or Least Value of a Function," *Computer J.*, 3, 175-184, 1960.
18. Rosenbrock, H. H., and C. Storey, "Computational Techniques for Chemical Engineers," Pergamon Press, New York, 1966.

APPENDIXES

APPENDIX A

DETAIL DERIVATION OF VARIOUS TYPES OF WAVE EQUATIONS

The equations of motion in the operator format is given by⁷

$$\rho \frac{\partial^2}{\partial t^2} (V) = \nabla \cdot T \quad (A.1)$$

where

$$V = \begin{bmatrix} u \\ v \\ w \end{bmatrix} \quad \text{displacement components}$$

$$T = \begin{bmatrix} T_{xx} & T_{xy} & T_{xz} \\ T_{yx} & T_{yy} & T_{yz} \\ T_{zx} & T_{zy} & T_{zz} \end{bmatrix} \quad \text{stress tensor}$$

The elastic relationships [Eq. (2.23)] are now substituted in Eq. (A.1), and the x component of Eq. (A.1) is then given by

$$\rho \frac{\partial^2 u}{\partial t^2} = \frac{\partial T_{xx}}{\partial x} + \frac{\partial T_{xy}}{\partial y} + \frac{\partial T_{xz}}{\partial z} \quad (A.2)$$

From Eq. (2.23) we have

$$\left. \begin{aligned} T_{xx} &= \lambda \theta + 2\mu \frac{\partial u}{\partial x} \\ T_{xy} &= 2\mu e_{xy} \\ T_{xz} &= 2\mu e_{xz} \end{aligned} \right\} \quad (A.3)$$

Upon substitution of (A.3) into (A.1) we will get

$$\rho \frac{\partial^2 u}{\partial t^2} = \lambda \frac{\partial \theta}{\partial x} + 2\mu \frac{\partial^2 u}{\partial x^2} + 2\mu \frac{\partial e_{xy}}{\partial y} + 2\mu \frac{\partial e_{xz}}{\partial z} \quad (\text{A.4})$$

From Eq. (2.18) we have

$$\frac{\partial u}{\partial y} = -\frac{\partial v}{\partial x} + 2 e_{xy}$$

$$\frac{\partial u}{\partial z} = -\frac{\partial w}{\partial x} + 2 e_{xz}$$

$$\frac{\partial u}{\partial x} = e_{xx} ; \quad \frac{\partial v}{\partial y} = e_{yy} ; \quad \frac{\partial w}{\partial z} = e_{zz}$$

$$\theta = e_{xx} + e_{yy} + e_{zz} \quad (\text{A.5})$$

If the quantity $\mu \partial \theta / \partial x$ is added to and subtracted from the right hand side of Eq. (A.4), and noting the identities of (A.5) we will get

$$\begin{aligned} \rho \frac{\partial^2 u}{\partial t^2} = & \lambda \frac{\partial \theta}{\partial x} + \mu \frac{\partial \theta}{\partial x} + 2\mu \left(\frac{\partial e_{xy}}{\partial y} + \frac{\partial e_{xz}}{\partial z} \right) + 2\mu \frac{\partial e_{xx}}{\partial x} \\ & - \mu \left(\frac{\partial e_{xx}}{\partial x} + \frac{\partial e_{yy}}{\partial x} + \frac{\partial e_{zz}}{\partial x} \right) \end{aligned} \quad (\text{A.6})$$

Further simplification yields

$$\begin{aligned} \rho \frac{\partial^2 u}{\partial t^2} = & \lambda \frac{\partial \theta}{\partial x} + \mu \frac{\partial \theta}{\partial x} + \mu \frac{\partial^2 u}{\partial x^2} + \mu \frac{\partial}{\partial y} \left(-\frac{\partial v}{\partial x} + 2e_{xy} \right) \\ & + \mu \frac{\partial}{\partial z} \left(-\frac{\partial w}{\partial x} + 2e_{xz} \right) \end{aligned} \quad (\text{A.7})$$

Then

$$\rho \frac{\partial^2 u}{\partial t^2} = \lambda \frac{\partial \theta}{\partial x} + \mu \frac{\partial \theta}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \quad (\text{A.8})$$

Equation (A.8) can also be derived for the w and v component of displacement which is similar to above. A set of equations of (A.8) type in x, y, z direction in operator format is then written as

$$\rho \frac{\partial^2 V}{\partial t^2} = (\lambda + \mu) \nabla \theta + \mu \nabla^2 V \quad (\text{A.9})$$

which is the basic equation of motion in an isotropic elastic solid.

If we set all the shear components of (A.9) to zero (i.e., $\partial u/\partial y$; $\partial u/\partial z$; $\partial v/\partial z$; $\partial w/\partial x$; $\partial w/\partial y$) we will get

$$\begin{aligned} \rho \frac{\partial^2 u}{\partial t^2} &= (\lambda + \mu) \frac{\partial \theta}{\partial x} + \mu \frac{\partial^2 u}{\partial x^2} \\ \rho \frac{\partial^2 v}{\partial t^2} &= (\lambda + \mu) \frac{\partial \theta}{\partial y} + \mu \frac{\partial^2 v}{\partial y^2} \\ \rho \frac{\partial^2 w}{\partial t^2} &= (\lambda + \mu) \frac{\partial \theta}{\partial z} + \mu \frac{\partial^2 w}{\partial z^2} \end{aligned} \quad (\text{A.10})$$

If we take $\partial/\partial x$, $\partial/\partial y$, $\partial/\partial z$ of the above three equations respectively and add the results we will have

$$\begin{aligned} \rho \frac{\partial^2}{\partial t^2} (e_{xx} + e_{yy} + e_{zz}) &= (\lambda + \mu) \left[\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} + \frac{\partial^2 \theta}{\partial z^2} \right] \\ &+ \mu \left[\frac{\partial^2 e_{xx}}{\partial x^2} + \frac{\partial^2 e_{yy}}{\partial y^2} + \frac{\partial^2 e_{zz}}{\partial z^2} \right] \end{aligned} \quad (\text{A.11})$$

Further simplification of (A.11) yields

$$\rho \frac{\partial^2 \theta}{\partial t^2} = (\lambda + 2\mu) \nabla^2 \theta \quad (\text{A.12})$$

which is the compressional wave equation.

If we eliminate θ from (A.9) we will get the torsional wave equation. To do this we will take $\partial/\partial y$ of the z direction of (A.9) and subtract $\partial/\partial z$ of the y direction of (A.9) from it which yields

$$\rho \frac{\partial^2}{\partial t^2} \left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \right) = \mu \left(\frac{\partial^3 w}{\partial x^2 \partial y} + \frac{\partial^3 w}{\partial y^3} + \frac{\partial^3 w}{\partial z^2 \partial y} - \frac{\partial^3 v}{\partial x^2 \partial z} - \frac{\partial^3 v}{\partial y^2 \partial z} - \frac{\partial^3 v}{\partial z^3} \right) \quad (\text{A.13})$$

From Eq. (2.18) we have

$$\Omega_x = \frac{1}{2} \left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \right) \quad (\text{A.14})$$

If (A.14) is substituted in (A.13) we will get after simplification

$$\rho \frac{\partial^2 \Omega_x}{\partial t^2} = \mu \nabla^2 \Omega_x \quad (\text{A.15})$$

Similarly

$$\rho \frac{\partial^2 \Omega_y}{\partial t^2} = \mu \nabla^2 \Omega_y$$

$$\rho \frac{\partial^2 \Omega_z}{\partial t^2} = \mu \nabla^2 \Omega_z$$

APPENDIX B

A LISTING OF PROGRAM DATRAN

A macro subroutine was written to transfer data from the Nicolet Explorer III digital transient recorder to the PDP 11/20 memory via a DR11-C hardware. The following is a listing of this FORTRAN callable subroutine.

TITLE DATRAN

ROUTINE TO TRANSFER DATA FROM EXPLORER TO FDP 11 VIA A DR11-C

FORTRAN CALLABLE

CALL DATRAN(NSIZ, NSTART, NINC, IDATA, INORM, IDMEM)

*** INPUT PARAMETERS ***

NSIZ = TOTAL NUMBER OF WORDS TO BE TRANSFERRED
(512, 1024, 2048, 4096)
NSTART = STARTING ADDRESS IN EXPLORER'S DISPLAY MEMORY
FOR DESIRED DATA (-2048 TO -2041)
NINC = ADDRESS INCREMENT BETWEEN DATA POINTS DESIRED
(1, 2, 4, 8)
IDATA = INTEGER ARRAY FOR STORING THE TRANSFERRED DATA
INORM = INTEGER ARRAY FOR STORING NORMALIZING INFORMATION
(4 WORDS LONG)
IDMEM = INTEGER CONTAINING TWO LETTERS INDICATING MEMORY
GROUP FROM WHICH DATA IS TO BE TAKEN
(Q1, Q2, Q3, Q4, H1, H2, AL)

*** IF ERROR ENCOUNTERED, NSIZ IS SET TO 0 ***

GLOBAL DATRAN

MCALL ... V2 ... REGDEF ... PRINT ... TTYIN ... INTEN

... V2 ...

REGDEF

DRCSR=167760

DROUT=167762

DRIN=167764

DRVEC=310

CSECT

DATRAN: TST (R5)+

MOV (R5), 1ER

; SAVE ADDRESS FOR ERROR INDICATIONS

MOV @(R5)+, NSIZ

; GET CALLING ARGUMENTS

MOV @(R5)+, R2

ASL R2

ASL R2

ASL R2

ASL R2

MOV R2, NSTART

; SA SHIFTED 4 BITS LEFT

MOV @(R5)+, R2

ASL R2

ASL R2

ASL R2

ASL R2

MOV R2, NINC

; INCREMENT LEFT-SHIFTED 4 BITS

	MOV (R5)+, IDATA	; ADDRESS OF DATA ARRAY
	MOV (R5)+, INORM	; ADDRESSES OF NORMALIZING WORDS
	MOV @(R5)+, IDMEM	; ID FOR MEMORY BLOCK
	MOV #IDRINT, @IDRVFC	; SET INTERRUPT VECTOR
	CLR @IDROSR	; CLEAR DR11 STATUS
DIALG:	MOV #MS1, R0	; READ DATA FROM EXPLORER
	. PRINT	
	MOV #RESP, R1	; RESPONSE BUFFER
TTY:	. TTYIN (R1)+	; INPUT A CHARACTER
	CMPB #12, R0	; EVERYTHING IN?
	BNE TTY	
	CMPB RESP, #116	; NO?
	BNE TXFER1	
EXERR:	CLR @IDROSR	
	CLR @IER	; TRANSFER NOT POSSIBLE
	RTS PC	
RSTATE:	MOV #MS2, R0	; EXPLORER IN INAPPROPRIATE STATE
	. PRINT	
	BR DIALG	; TRY AGAIN
TXFER1:	TST @IDROSR	; CHECK STATUS OF EXPLORER
	BPL RSTATE	; STATUS NOT RIGHT?
TXFER2:	TSTR @IDROSR	; I/O FLAG=READY
	BPL RSTATE	
	MOV #12, @IDROSR	; SET I/O ACTIVE=1
	CLR @IDROUT	; ID-W/R, AC1, AC2, DISK/PI=0
	MOV @IDRIN, R0	; READ DISKETTE TRACK SELECTOR
	COM R0	
	RTC #177770, R0	
	BNE NOFIX	
	ADD #8, R0	
NOFIX:	ADD #40, R0	; STORE VALUE IN MS3
	MOVB R0, @ITRK	; ID-W/R, AC1, AC2, DISK/PI=1
	MOV #17, @IDROUT	; READ MEMORY GROUP SELECTOR
	MOV @IDRIN, R0	
	COM R0	
	RTC #177770, R0	
	ASL R0	
	MOV R0, R1	
	ADD #MTAB, R0	
	MOV R0, R1	; SAVE FOR CHECKS
	MOVB (R0)+, MEM	; STORE VALUE IN MS3
	MOVB (R0), MEM+1	
	MOV #MS3, R0	; TELL WHERE DATA RESIDES IN
	. PRINT	; THE EXPLORER
	CMPB (R1), #101	; MEMORY SELECTOR=ALL
	BEQ AOK	
	CMP (R1), IDMEM	; MEMORY SELECTOR=MEMORY REQUESTED
	BEQ AOK	
	CMPB (R1), IDMEM	; IS 1ST LETTER SAME?
	BGE ERM	

```

        INC R1
        MOVR IDMEM+1, R3
        CNPB R3, #62
        BLE CHK
        SUB #7, R3
CHK:     CNPB (R1), R3
        BEQ AOK
ERM:     MOV #MS4, R0
        PRINT
        JMP EXERR
AOK:     MOV #KNORM, R3
        MOV #16, N16
        MOV NS17, R4
        MOV #7, R5
DIV2:    ASR R4
        DEC R5
        BGT DIV2
        MOV R4, NW
        MOV NSTART, R1
        MOV IDATA, R2
DLOOP:   MOV R1, R0
        ADD NINC, R1
        COM R0
        MOV R0, @#DROUT
        INC @#DROCSR
        DEC @#DROCSR
TST1:    TSTB @#DROCSR
        BPL TST1
        INC @#DROCSR
        DEC @#DROCSR
TST2:    TSTB @#DROCSR
        BPL TST2
        MOV @#DIRIN, (R2)
        COM (R2)
        ASR (R2)
        ASR (R2)
        ASR (R2)
        ASR (R2)+
        ROL R5
        TST R4
        BLE CONT
        ROR R5
        ROR (R3)
        DEC N16
        BGT CONT
        DEC R4
        TST (R3)+
        MOV #16, N16
CONT:    DEC NS17
        BGT DLOOP
; MEMORY BLOCK REQUESTED CANNOT
; BE ACHIEVED
; TEMP STORAGE FOR NORM. BITS
; 16 BITS PER WORD
; CALC. NUMBER OF
; NORMALIZING BITS TO STRIP
; DIVIDED BY 16
; SET SA FOR TRANSFER
; ADDRESS FOR DATA
; MOV TRANSFER ADDRESS TO R0
; INCREMENT TO NEXT TRANSFER ADDRESS
; COMPLEMENT FOR NEGATIVE LOGIC
; SET ADDRESS FOR TRANSFER
; PULSE I/O STEP
; HAS EXPLORER RECEIVED ADDRESS
; PULSE I/O STEP
; IS EXPLORER DATA READY?
; READ DATA INTO POP MEMORY
; COMPLEMENT DATA
; SHIFT DOWN 4 BITS
; SAVE NORMALIZING BIT IF PRESENT
; HAVE ALL NORMALIZING BITS
; BEEN STRIPPED
; STORE NORMALIZING BIT
; INTO KNORM AREA
; COMPLETED A WORD
; BUMP TO NEXT WORD
; COMPLETED TRANSFER?
; DO THE NEXT ONE!

```

```

; NOW PUT NORMALIZING BITS INTO 4 WORDS AND CHECK EXTRA BITS
MOV #16, NN16
MOV %KNORM, R2          ; ADDRESS OF NORMALIZING BITS
MOV INORM, R3           ; DESTINATION FOR 4 NORMALIZING WORDS
MOV NW, R4              ; CALC. NO. OF BITS TO CMP & SKIP
ASR R4
ASR R4
DEC R4
MOV R4, NXTRA          ; NO. OF BITS TO SHIFT
BGT NLOOP              ; NEED TO CHECK EXTRAS
MOV (R2)+, (R3)+       ; MOVE HNORM
MOV (R2)+, (R3)+       ; MOVE VNORM
MOV (R2)+, (R3)+       ; MOVE HZERO
MOV (R2)+, (R3)+       ; MOVE VZERO
JMP FIN2
NLOOP: ROR (R2)          ; ROLL BIT INTO C
      BCS NLP0
      ROR (R3)          ; ROLL C INTO NORMALIZATION ARRAY
      CLR R5            ; TEMPLATE FOR SKIPPED BITS
      BR NLP1
NLP0:  ROR (R3)          ; ROLL C INTO NORMALIZATION ARRAY
      MOV NXTRA, R5      ; TEMPLATE FOR SKIPPED BITS
NLP1:  DEC NN16
      BGT NLP2
      MOV #16, NN16
      TST (R3)+         ; BUMP TO NEXT WORD (INORM)
NLP2:  DEC N16           ; BUMP BIT COUNTER (KNORM)
      CLR R0
NLP4:  ROR (R2)          ; SKIP THIS BIT
      BCC NLP5
      INC R0
NLP5:  DEC R4            ; READY TO CHECK SKIPPED BITS?
      BGT NLP4
      CMP R0, R5         ; EVERYTHING OK?
      BEQ NLP6
HOMO:  MOV #MS5, R0      ; DATA IS NOT HOMOGENEOUS
      .PRINT
      JMP EXERR
NLP6:  MOV NXTRA, R4      ; RESET NO. OF BITS TO SKIP
      SUB NXTRA, N16
      BGT NLOOP
      TST (R2)+         ; BUMP TO NEXT WORD (INORM)
      MOV #16, N16
      DEC NW
      BGT NLOOP
FIN2:  CLR @DIRCSR       ; CLEAR DIR11 STATUS
      MOV INORM, R0      ; FIX HZERO AND VZERO
      CMP (R0)+, (R0)+   ; IF NEGATIVE VALUES
      BIT #4000, (R0)    ; BIT 11 SET?
      BEQ FIN3          ; NO

```

```

        BIS #170000, (R0)          ;SET BITS 12-15
FIN3:   TST (R0)+
        BIT #4000, (R0)           ;BIT 11 SET?
        BEQ FIN4                  ;NO
        BIS #170000, (R0)         ;SET BITS 12-15
FIN4:   RTS PC
;
;      INTERRUPT ERROR HANDLER
DRINT:  .INTEN 7
        MOV #177777, R0
        HALT
;
;      STORAGE LOCATIONS
NS12:   .WORD 0
NSTART: .WORD 0
NINC:   .WORD 0
IDATA:  .WORD 0
INORM:  .WORD 0
IDMEM:  .WORD 0
IER:    .WORD 0
NW:     .WORD 0
NXTRA:  .WORD 0
N16:    .WORD 16.
NN16:   .WORD 16.
RESP:   .BLKW 10
;
;
;      TABLES
MTAB:   .ASCII /01020304050607080910111213141516171819/
KNORM:  .BLKW 32.
;
;
;      MESSAGES
MS1:    .BYTE 15, 12
        .ASCII /READ DATA INTO EXPLORER MEMORY: /
        .BYTE 200
MS2:    .BYTE 15, 12
        .ASCII /EXPLORER'S STATUS IS NOT RIGHT FOR DATA TRANSFERS!!!/
        .BYTE 15, 12
        .ASCII /(CHECK FOR DISK ERROR, DISK ACTIVE, OR LIVE STATUS)/
        .BYTE 0
MS3:    .BYTE 15, 12
        .ASCII /DATA READ FROM TRACK /
TRK:    .ASCII /1 INTO MEMORY GROUP /
MEM:    .BYTE 40, 40, 0
MS4:    .BYTE 15, 12
        .ASCII /MEMORY BLOCK REQUESTED CANNOT BE ACCESSED DUE TO MEMORY/
        .BYTE 15, 12
        .ASCII / GROUP SELECTION ON MAINFRAME!!!/
        .BYTE 0

```

MS5: .BYTE 15,12
 .ASCII /DATA TRANSFERRED DOES NOT REPRESENT A SINGLE EVENT -- /
 .ASCII /TRY AGAIN!/
 .BYTE 0
 .EVEN
 .END

APPENDIX C

CIRCUIT DIAGRAM OF THE AUTOMATIC IMPACTOR POWER SUPPLY

A capacitor discharge DC power supply was designed and built to deliver 20 volts DC at 2 amps. The circuit diagram of the power supply and its internal components is shown in Fig. C-1.

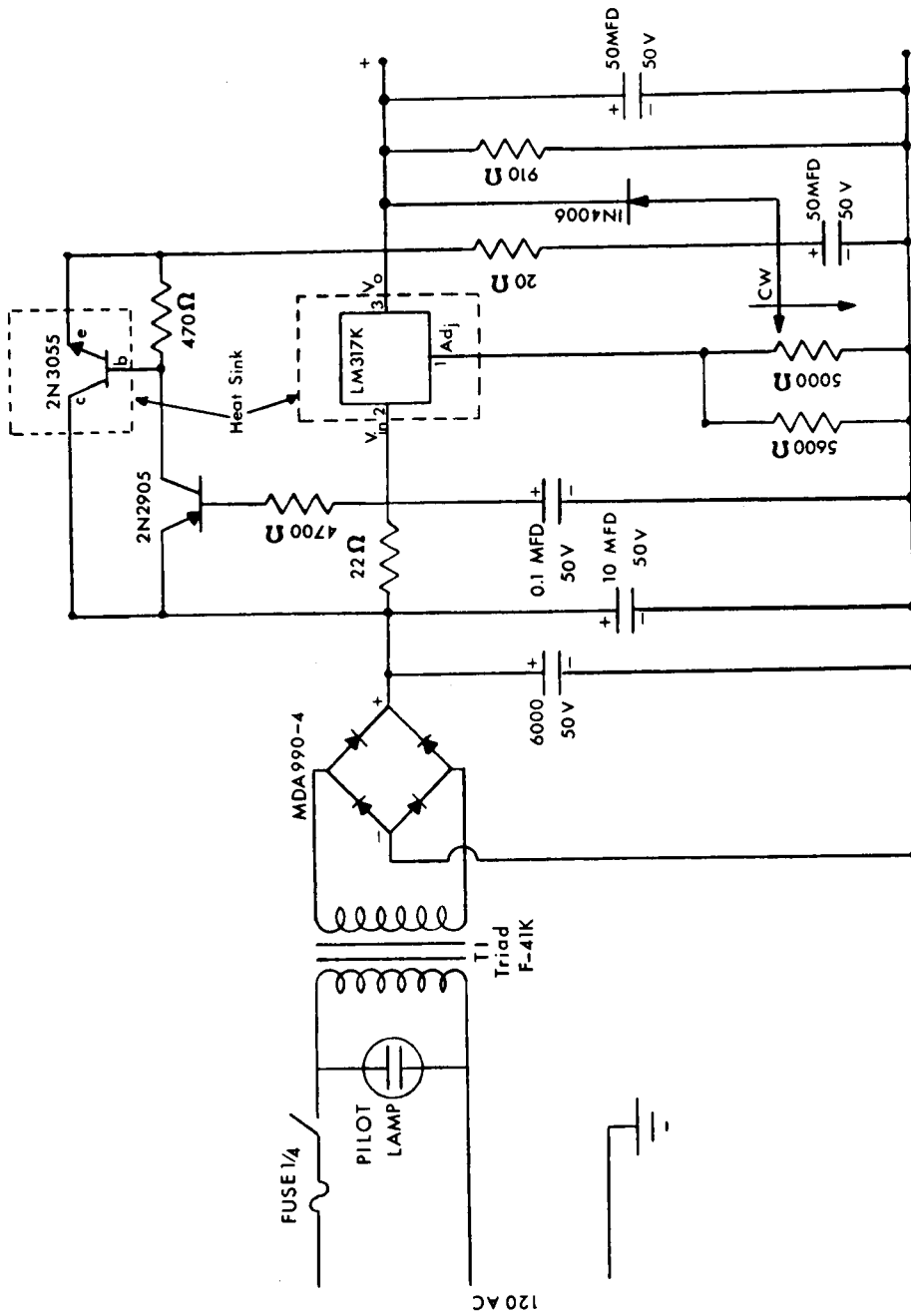


Fig. C-1. The circuit diagram of the automatic impactor power supply.

APPENDIX D

ROSENBROCK HILLCLIMB OPTIMIZATION METHOD

The program developed by Yancey and Spear of Naval Weapons Center, China Lake, California, finds the maximum or minimum of a multivariable, nonlinear function subject to nonlinear inequality constraints:

$$\text{optimize} \quad F(x_1, x_2, \dots, x_N) \quad (D.1)$$

$$\text{subject to} \quad G_k \leq x_k \leq H_k \quad k = 1, 2, \dots, M \quad (D.2)$$

The implicit variables $x_{k+1}, \dots, x_m$, if any, are dependent functions of the explicit independent variables, $x_1, x_2, \dots, x_N$. The upper and lower constraints H_k and G_k are either constants or function of the independent variables.

The procedure is based on the "automatic" method proposed by H. H. Rosenbrock.^{17,18} This method is a sequential search technique which has proven effective in solving some problems where the variables are constrained. The algorithm proceeds until convergence is reached or a boundary zone in the vicinity of the constraints is entered. The boundary zones are defined as follows:

$$\text{lower zone:} \quad G_k \leq x_k \leq (G_k + (H_k - G_k) \cdot 10^{-4})$$

$$\text{upper zone:} \quad H_k \geq x_k \geq (H_k - (H_k - G_k) \cdot 10^{-4})$$

$$k = 1, 2, \dots, M \quad (D.3)$$

The procedure requires a starting point that satisfies the constraints and does not lie in the boundary zones. The algorithm proceeds as follows:

1. A starting point and initial step sizes, S_i , $i = 1, 2, \dots, N$ are picked and the objective function is evaluated.
2. Define by F° current best objective function value for a point where the constraints are satisfied, and F^* the current best objective function value for a point where the constraints are satisfied and in addition the boundary zones are not violated.
3. If the current point objective function evaluation, F , is worse than F° or if the constraints are violated, the trial is a failure and the procedure is continued.
4. If a current point lies within a boundary zone, the objective function is modified as follows:

$$F(\text{new}) = F(\text{old}) - [f(\text{old}) - F^*][3\lambda - 4\lambda^2 + 2\lambda^3] \quad (\text{D.4})$$

where

$$\begin{aligned} \lambda &= \frac{\text{distance into the boundary zone}}{\text{width of the boundary zone}} \\ &= \frac{G_k + (H_k - G_k) \cdot 10^{-4} - x_k}{(H_k - G_k) \cdot 10^{-4}} \quad (\text{lower zone}) \\ &= \frac{x_k - H_k + (H_k - G_k) \cdot 10^{-4}}{(H_k - G_k) \cdot 10^{-4}} \quad (\text{upper zone}) \end{aligned}$$

at the inner edge of the boundary zone, $\lambda = 0$, i.e., the function is unaltered ($F(\text{new}) = F(\text{old})$). At the constraint,

- $\lambda = 1$, and thus $F(\text{new}) = F^*$. Thus the function value is replaced by the best current function value in the feasible region and not in a boundary zone. For a function which improves as a constraint is approached, the modified function has an optimum in the boundary zone.
5. If an improvement in the objective function has been obtained without violating the boundary zones or constraints, F^* is set equal to F^0 and the procedure continues.
 6. The first variable X_1 is stepped a distance S_1 parallel to the axis, and the function evaluated. If the value of F increased, the move is termed success and S_1 increased by a factor α , $\alpha \geq 1.0$. If the value of F decreased the move is termed failure and S_1 is decreased by a factor β , $0 < \beta \leq 1.0$, and the direction of movement reversed.
 7. The next variable, X_i , is in turn stepped a distance S_i parallel to the axis. The same acceleration or deceleration and reversal procedure is followed for all variables in consecutive repetitive sequences until a success (increase in F) and failure (decrease in F) have been encountered in all N directions.
 8. The axes are then rotated by the following equations. Each rotation of the axes is termed a stage.

$$M_{i,j}^{(k+1)} = \frac{D_{i,j}^{(k)}}{\left[\sum_{\ell=1}^N (D_{\ell,j}^{(k)})^2 \right]^{\frac{1}{2}}} \quad (\text{D.5})$$

where

$$D_{i,1}^{(k)} = A_{i,1}^{(k)}$$

$$D_{i,j}^{(k)} = A_{i,j}^{(k)} - \sum_{\ell=1}^{j-1} \left[\sum_{n=1}^j M_{n,1}^{(k+1)} \cdot A_{n,j}^{(k)} \cdot M_{i,1}^{(k+1)} \right],$$

$j = 2, 3, \dots, N$

$$A_{i,j}^{(k)} = \sum_{\ell=j}^N d_1^{(k)} \cdot M_{i,1}^{(k)}$$

where

i = variable index, 1, 2, 3, ..., N

j = direction index, 1, 2, 3, ..., N

k = stage index

$D_{i,j}$ = sum of distances moved in the i direction since
the last rotation of axes

$M_{i,j}$ = normalized direction vector component

9. Search is made in each of the X directions using the new coordinate axes:

$$\text{new } X_i^k = \text{old } X_i^k + S_i^{(k)} M_{i,j}^{(k)}$$

10. The search procedure is terminated when the convergence criteria is satisfied.

A flow sheet showing the above process is given in Fig. D-1. The program consists of a main program and four user supplied function subprograms (Function F, Function CX, Function CG, and Function CH).

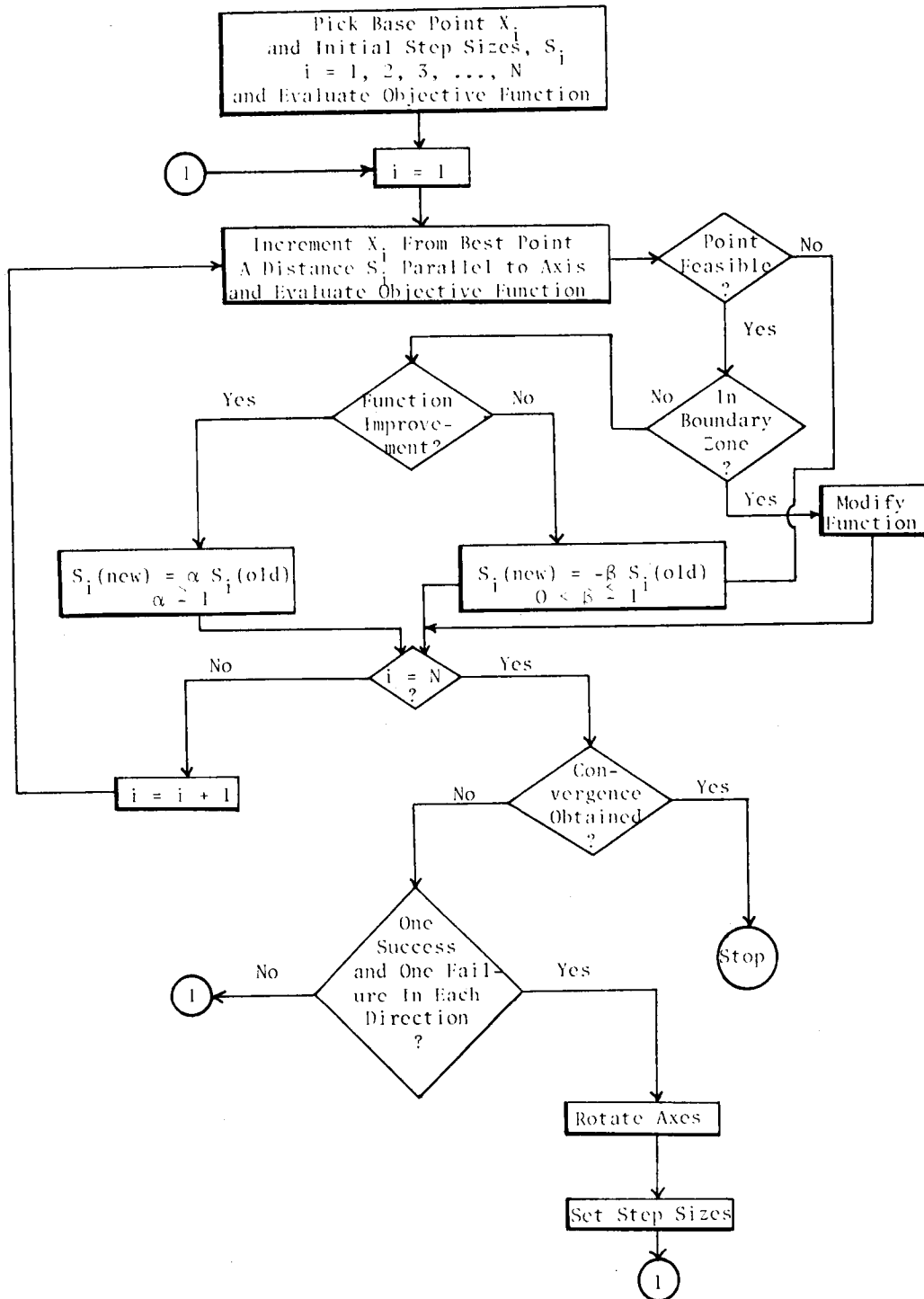


Fig. D-1. Flow chart of the Rosenbrock Impact Location technique.

FUNCTION F(X, DA, N, NPAR) specifies the objective function.

FUNCTION CX(X, DA, N, NPAR, K) specifies function to be constrained.

FUNCTION CG(X, DA, N, NPAR, K) specifies lower bound of constraints.

FUNCTION CH(X, DA, N, NPAR, K) specifies upper bound of constraints.

The following is a description of the parameters used:

M	Problem controller; +1 for maximization, -1 for minimization.
P	Number of variables.
K	Point index.
L	Number of variables plus implicit constraints.
LoopY	Maximum number of stages to be calculated.
PR	Print controller (number of stages between output).
ND	Storage controller; 1 for storage in DA, 0 for no storage.
DA	General storage vector.
NDATA	Number of data points to be read in DA.
NPAR	Dimension limit in subroutines.
E	Vector of initial step sizes.
X	Vector of initial guesses for independent variables.
N	Dimension limit in subroutines.
NSTEP	Control on step sizes for each rotation; 0 for original step sizes, 1 for step sizes from previous rotation.
DELY	Convergence criteria, error in objective function (difference between current value and previous stage value).
NI	Input logical unit number.

NO Output logical unit number.

V Direction vector.

The DIMENSION statement in the main program should be modified according to the requirements of each particular problem. The parameters included in the following DIMENSION statement conforms to the input parameter definitions above:

```
DIMENSION X(P), E(P), V(P,P), SA(P), D(P), G(L), H(L), AL(L),
           PH(L), A(L,L), B(L,L), BX(L), DA(NDATA), VV(L,L), EINT(P), VM(L)
```

The main program furnishes all printouts of STAGE, PROGRESS, LATERAL progress, function value and variable values. PROGRESS represents the total progress in the direction of maximum change in the objective function. LATERAL PROGRESS denotes the change in the second most sensitive direction. When the problem has converged or the maximum number of iterations has been reached, the final values of the independent variables and objective function are printed out, plus the final step sizes, direction vector components, number of function evaluations and a graphic representation of convergence process after each stage of iteration.

The following test problem was chosen for illustration of this optimization process. The calculation and graphics were performed on a PDP 11/34 computer.

Function:

Minimize $F(x_0, y_0, z_0)$ of Eq. (4.18)

Detectors coordinates:

$$x_1(0.0, 0.0, -120.0)^{-1}$$

$$x_2(-50.675, 87.7725, -64.2493)^{-1}$$

$$x_3(-50.675, -87.7725, -64.2493)^{-1}$$

$$x_4(101.351, 0.0, -64.2493)^{-1}$$

Implicit variable:

$$P = x_0^2 + y_0^2 + z_0^2$$

Constraints:

$$-120.0 \leq x_0 \leq +120.0$$

$$-120.0 \leq y_0 \leq +120.0$$

$$-120.0 \leq z_0 \leq +120.0$$

$$|P - 14400.0| \leq 288$$

Starting point:

Not a factor, it can be started from any point on the
reactor vessel

Parameters used:

$$E(I) = 0.9, I = 1, 3 \quad PR = 1$$

$$M = -1 \quad ND = 0$$

$$P = 3 \quad NDATA = 0$$

$$L = 4 \quad NSTEP = 1$$

$$LooPY = 1000$$

RMS response of each detector:

$$A_1 = 0.417, A_2 = 2.0, A_3 = 1.7, A_4 = 0.21$$

Impact at:

$$S_0(-101.351, 0.0, -64.2493)^{-1}$$

Algorithm results:

$$S'_0(-96.000, 9.139, -71.450)^{-1}$$

Error:

$$E = 12.81 \text{ inches}$$

The graphical representation of the convergence process after each stage is shown in Fig. D-2, followed by the fortran listing of the algorithm.

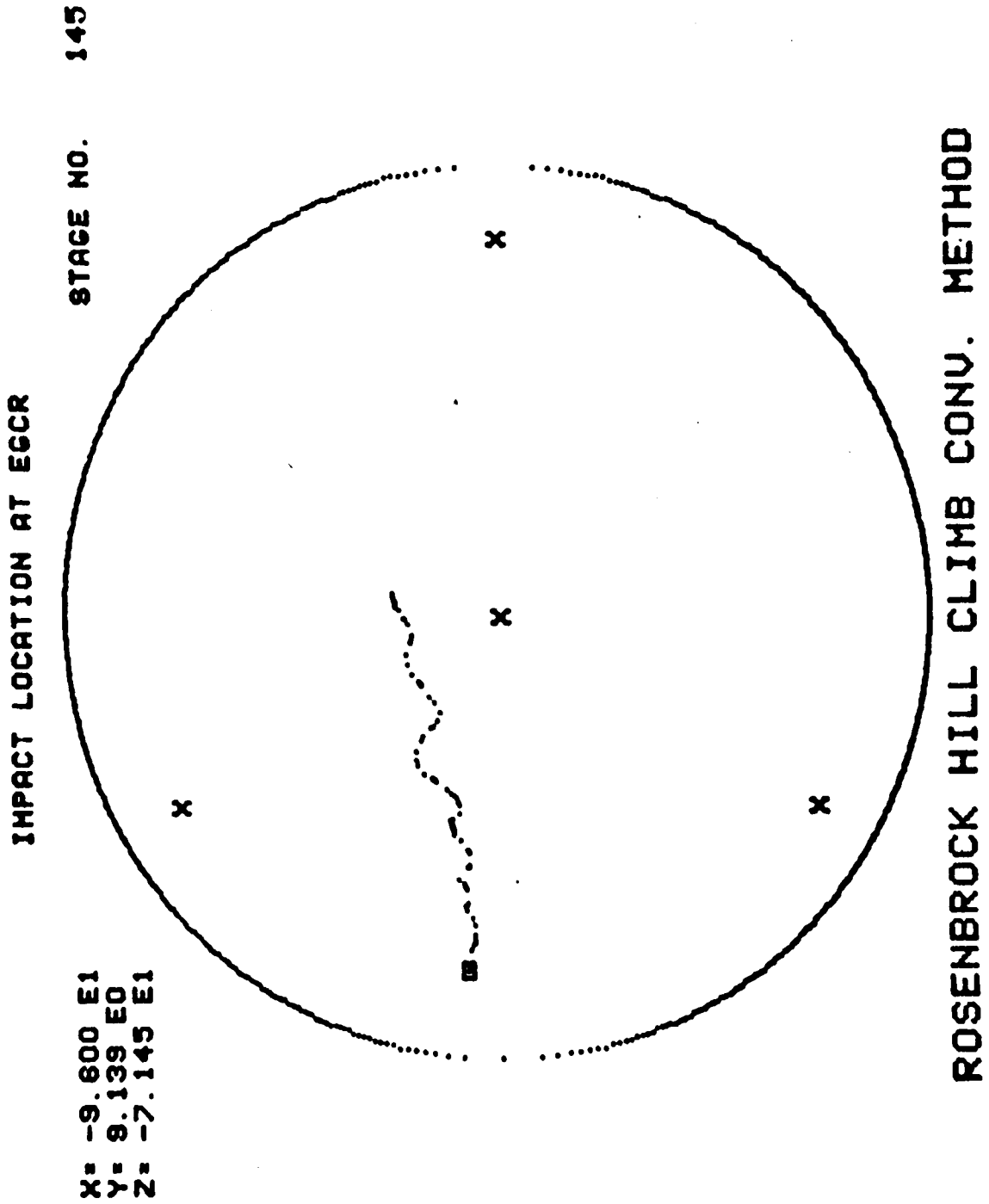


Fig. D-2. Results of impact location sample problem.

SOURCE LOCATION PROGRAM USING ROSENBROCK HILLCLIMB

INPUT REQUIREMENT:

INITIAL GUESS IN R, THETA, Z

MAIN LINE PROGRAM FOR ROSENBROCK HILLCLIMB

F. SHAHROKHI AUG-3-1979

```

IMPLICIT REAL*8(A-H, O-Z)
DIMENSION X(3), E(3), V(3,3), SA(3), D(3), G(4), H(4), AL(4),
&PH(4), A(4,4), B(4,4), BX(4), DA(1), VV(4,4), EINT(3), VM(4)
COMMON KOUNT
COMMON /DATA/XX(4), YY(4), ZZ(4), AA(4), JJJ, RRR
INTEGER*2 P, PR, R, C
REAL*8 LC

```

```

DEFINE FILE 1(200,34,U,IREC)
CALL ASSIGN(1, 'DKO:ROSHIL.DAT', 14, 'NEW')
IREC=1
NI=7
NO=7

```

```

JJJ=2
RRR=120.00
XX(1)=0.0
XX(2)=-50.675
XX(3)=-50.675
XX(4)=101.351
YY(1)=0.0
YY(2)=87.7725
YY(3)=-87.7725
YY(4)=0.0
ZZ(1)=-120.0
ZZ(2)=-64.2493
ZZ(3)=-64.2493
ZZ(4)=-64.2493
WRITE(NI,900)

```

```

900 FORMAT(' ENTER A1, A2, A3, A4 ... ', $)

```

```

901 READ(NO,901)(AA(JM), JM=1,4)

```

```

901 FORMAT(4F10.0)

```

```

C
WRITE(1,IREC)(AA(JM), JM=1,4)
M=-1
P=3
L=4

```

```

      LOOPY=1000
      PR=1
      ND=0
      NDATA=0
      NSTEP=1

C
10      WRITE(N1,001)
001     FORMAT(1H , 'ENTER INITIAL GUESS (R, THETA)  ', $)
      READ(N1,002)RR, THETA
002     FORMAT(2F10.0)
      THETA=(THETA*3.14157)/180.0
      X(1)=RR*DCOS(THETA)
      X(2)=RR*DSIN(THETA)
      X(3)=-DSQRT(RRR*RRR-X(1)*X(1)-X(2)*X(2))

      E(1)=0.9
      E(2)=0.9
      E(3)=0.9
      WRITE(N0,013)
013     FORMAT(1H1,10X,30HROSENBRCK HILLCLIMB PROCEDURE)
C
      IF(ND-1)30,20,30
20      DO 300 KA=1, NDATA
      READ(N1,002)DA(KA)
300     CONTINUE
30      LAP=PR-1
      LOOP=0
      ISW=0
      INLT=0
      KOUNT=0
      TERM=0.0
      DELY=1.0E-6
      F1=0.0
      NPAR=NDATA
      N=L
      DO 40 K=1, L
40      AL(K)=(CH(X, DA, N, NPAR, K)-CG(X, DA, N, NPAR, K))*0.0001
      DO 60 I=1, P
      DO 60 J=1, P
      V(I, J)=0.0
      IF(I-J)60, 61, 60
61      V(I, J)=1.0
60      CONTINUE
      DO 65 KK=1, P
      EINT(KK)=E(KK)
65      CONTINUE
C
C
1000     DO 70 J=1, P
      IF(NSTEP .EQ. 0) E(J)=EINT(J)

```

```

      SA(J)=2.0
70      D(J)=0.0
      FBEST=F1
80      I=1
      IF(1NIT .EQ. 0)GO TO 120
90      DO 110 K=1,P
110     X(K)=X(K)+E(1)*V(1,K)
      DO 50 K=1,L
50      H(K)=F0
      C
      C
120     F1=F(X,DA,N,NPAR)
      F1=M*F1
      IF(1SW .EQ. 0) F0=F1
      1SW=1
      IF(1DABS(FBEST-F1)-DELY) 122,122,125
122     1FLAGE=1FLAGE+1
      IF(1FLAGE .LT. 10) GO TO 129
      1TERM=1.0
      GO TO 450
125     1FLAGE=0
      C
      C
129     J=1
      C
130     XC=CX(X,DA,N,NPAR,J)
      LC=CG(X,DA,N,NPAR,J)
      UC=CH(X,DA,N,NPAR,J)
      IF(XC .LE. LC)GO TO 420
      IF(XC .GE. UC)GO TO 420
      IF(F1 .LT. F0)GO TO 420
      IF(XC .LT. LC+AL(J))GO TO 140
      IF(XC .GT. UC-AL(J))GO TO 140
      H(J)=F0
      GO TO 210
      C
      C
140     CONTINUE
      C
      BW=AL(J)
      C
      IF(XC .LE. LC .OR. UC .LE. XC)GO TO 150
      IF(LC .LT. XC .AND. XC .LT. LC+BW)GO TO 160
      IF(UC-BW .LT. XC .AND. XC .LT. UC)GO TO 170
      PH(J)=1.0
      GO TO 210
      C
      C
150     PH(J)=0.0
      GO TO 190

```

```

160    PW=(LC+BW-XC)/BW
      GO TO 180
170    PW=(XC-UC+BW)/BW
180    PH(J)=1.0-3.0*PW+4.0*PW*PW-2.0*PW*PW*PW

190    F1=H(J)+(F1-H(J))*PH(J)
C
210    CONTINUE
      IF(J .EQ. L) GO TO 220
      J=J+1
      GO TO 130
C
220    INIT=1
      IF(F1 .LT. F0) GO TO 420
      D(1)=D(1)+E(1)
      E(1)=3.0*E(1)
      F0=F1
      IF(SA(1) .GE. 1.5) SA(1)=1.0
C
230    DO 240 JJ=1,P
      IF(SA(JJ) .GE. 0.5) GO TO 440
240    CONTINUE
C
C      AXES ROTATION
C
      DO 250 R=1,P
      DO 250 C=1,P
250    VV(C,R)=0.0
      DO 260 R=1,P
      KR=R
      DO 260 C=1,P
      DO 265 K=KR,P
265    VV(R,C)=D(K)*V(K,C)+VV(R,C)
260    B(R,C)=VV(R,C)
      BMAG=0.0
      DO 280 C=1,P
      BMAG=BMAG+B(1,C)*B(1,C)
280    CONTINUE
      BMAG=DSQRT(BMAG)
      BX(1)=BMAG
      DO 310 C=1,P
310    V(1,C)=B(1,C)/BMAG
C
      DO 390 R=2,P
C
      IR=R-1
      DO 390 C=1,P
      SUMVM=0.0
      DO 320 KK=1,IR
      SUMAV=0.0

```

```

DO 330 KJ=1,P
330 SUMAV=SUMAV+VV(R,KJ)*V(KK,KJ)
320 SUMVM=SUMAV*V(KK,C)+SUMVM
390 B(R,C)=VV(R,C)-SUMVM
DO 340 R=2,P
BBMAG=0.0
DO 350 K=1,P
350 BBMAG=BBMAG+B(R,K)*B(R,K)
BBMAG=DSQRT(BBMAG)
DO 340 C=1,P
340 V(R,C)=B(R,C)/BBMAG
LOOP=LOOP+1
LAP=LAP+1
IF(LAP.EQ. PR) GO TO 450
GO TO 1000

C
420 IF(INIT.EQ. 0) GO TO 450
C
DO 430 IX=1,P
430 X(IX)=X(IX)-E(1)*V(1,IX)
E(1)=-0.5*E(1)
IF(SA(1).LT. 1.5)SA(1)=0.0
GO TO 230

C
440 CONTINUE
C
IF(1.EQ. P) GO TO 80
I=I+1
GO TO 90

C
450 CONTINUE
C
WRITE(NO,003)
003 FORMAT(//,2X,5HSTAGE,8X,8HFUNCTION,12X,8HPROGRESS,9X,
&16HLATERAL PROGRESS )
C
WRITE(NO,004)LOOP,F0,BMAG,BBMAG
004 FORMAT(1H,15,3E20.8)
C
WRITE(NO,014)KOUNT
014 FORMAT(/,2X,33HNUMBER OF FUNCTION EVALUATIONS = ,18)
C
WRITE(NO,005)
005 FORMAT(/,2X,25HVALUES OF X AT THIS STAGE )
C
PRINT CURRENT VALUES OF X
C
WRITE(NO,006)(JM,X(JM), JM=1,P)
WRITE(171REC)(LOOP,X(JM),JM=1,P)
006 FORMAT(/,2X,3(2HX(,12,4H) = ,1PE14.6,3X))
LAP=0
IF(INIT.EQ. 0) GO TO 470
IF(TERM.EQ. 1.0)GO TO 480
IF(LOOP.GE. LOOPY) GO TO 480
GO TO 1000

C

```

```

470 WRITE(NO,007)
007 FORMAT(///,2X,81HTHE STARTING POINTS MUST NOT VIOLATE THE
&CONSTRAINTS. 11 APPEARS TO HAVE DONE SO.)
480 CONTINUE
490 WRITE(NO,008)
008 FORMAT(///,2X,29HFINAL DIRECTION VECTOR MATRIX)
DO 500 J=1,P
500 WRITE(NO,009)(J,1,V(J,1),1=1,P)
009 FORMAT(/,2X,3(2HV(,12,1H,12,4H) = ,F11.8,3X))
WRITE(NO,011)
011 FORMAT(/,2X,16HFINAL STEP SIZES )
WRITE(NO,012)(J,E(J),J=1,P)
012 FORMAT(/,2X,3(2HS(,12,4H) = ,1PE14.6,3X))
C
STOP
END
FUNCTION F(X,DA,N,NPAR)
C
IMPLICIT REAL*8(A-H,O-Z)
DIMENSION X(N),DA(NPAR)
COMMON KOUNT
COMMON /DATA/XX(4),YY(4),ZZ(4),AA(4),JJJ,RRR
F1=0.0
F2=0.0
F3=0.0
C
T2=(X(1)*XX(2)+X(2)*YY(2)+X(3)*ZZ(2))/(RRR*RRR)
IF(DABS(T2) .GT. 1.0) GO TO 1
IF(DABS(T2) .LT. 0.01)ARC2=3.14157/2.0
IF(DABS(T2) .GE. 0.01)ARC2=DATAN(DSQRT(-T2**2+1)/T2)
IF(DABS(T2) .GE. 0.01 .AND. T2 .LT. 0.0)ARC2=3.14157+ARC2
T1=(X(1)*XX(1)+X(2)*YY(1)+X(3)*ZZ(1))/(RRR*RRR)
IF(DABS(T1) .GT. 1.0) GO TO 1
IF(DABS(T1) .LT. 0.01)ARC1=3.14157/2.0
IF(DABS(T1) .GE. 0.01)ARC1=DATAN(DSQRT(-T1**2+1)/T1)
IF(DABS(T1) .GE. 0.01 .AND. T1 .LT. 0.0)ARC1=3.14157+ARC1
T3=(X(1)*XX(3)+X(2)*YY(3)+X(3)*ZZ(3))/(RRR*RRR)
IF(DABS(T3) .GT. 1.0) GO TO 1
IF(DABS(T3) .LT. 0.01)ARC3=3.14157/2.0
IF(DABS(T3) .GE. 0.01)ARC3=DATAN(DSQRT(-T3**2+1)/T3)
IF(DABS(T3) .GE. 0.01 .AND. T3 .LT. 0.0)ARC3=3.14157+ARC3
T4=(X(1)*XX(4)+X(2)*YY(4)+X(3)*ZZ(4))/(RRR*RRR)
IF(DABS(T4) .GT. 1.0) GO TO 1
IF(DABS(T4) .LT. 0.01)ARC4=3.14157/2.0
IF(DABS(T4) .GE. 0.01)ARC4=DATAN(DSQRT(-T4**2+1)/T4)
IF(DABS(T4) .GE. 0.01 .AND. T4 .LT. 0.0)ARC4=3.14157+ARC4
ARC1=ARC1*180.0/3.14157
ARC2=ARC2*180.0/3.14157
ARC3=ARC3*180.0/3.14157
ARC4=ARC4*180.0/3.14157

```

```

F1=ARC1*ARC1-ARC2*ARC2*AA(2)/AA(1)
F2=ARC1*ARC1-ARC3*ARC3*AA(3)/AA(1)
F3=ARC1*ARC1-ARC4*ARC4*AA(4)/AA(1)
F=F1*F1+F2*F2+F3*F3
F=DLG10(F)
KOUNT=KOUNT+1
RETURN
KOUNT=KOUNT
1 F=1.0E20
RETURN
END
FUNCTION CX(X,DA,N,NPAR,K)
C
IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION X(N),DA(NPAR)
IF(K.EQ. 4) GO TO 1
CX=X(K)
C
RETURN
1 CX=X(K-3)**2+X(K-2)**2+X(K-1)**2
RETURN
END
FUNCTION CG(X,DA,N,NPAR,K)
IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION X(N),DA(NPAR)
C
IF(K.EQ. 4) GO TO 1
CG=-120.0
C
RETURN
1 CG=14256.0
RETURN
END
FUNCTION CH(X,DA,N,NPAR,K)
C
IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION X(N),DA(NPAR)
C
IF(K.EQ. 4) GO TO 1
CH=120.0
RETURN
1 CH=14544.0
RETURN
C
END

```

VITA

Farshid Shahrokhi was born on March 20, 1950, in Tehran, Iran. He received his primary and secondary education in Tehran and graduated with honors from Alborz High School in June of 1968 specializing in mathematics. In the fall of 1968 he began his college education at The University of Tennessee, Knoxville. He received his Bachelor of Science degree in nuclear engineering in June of 1972. He then received an adjunct research assistantship position from the Instrumentation and Controls Division of the Oak Ridge National Laboratory concurrent with his graduate studies at The University of Tennessee, Knoxville. He received his M.S. in nuclear engineering in the summer of 1974. He immediately began work toward a Ph.D. degree in nuclear engineering which he received in June of 1980.

He was married to former Sandra K. Collins from 1970 to 1978, and has two children, Siminne, 10, and Shahram, 5. He is currently happily divorced.