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REPRINT

FOUR PAPERS CONCERNING RECENT WORK
ON GROUND MOTION MEASUREMENTS

by

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APPROVED FOR PUBLIC RELEASE

APRIL 1965

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G. J. Hansen, and D. G. Palmer

July 1965

PREFACE

The four papers contained in this Sandia Laboratory Reprint were presented at the invitation of Headquarters, Defense Atomic Support Agency at a meeting of the Working Group on Instrumentation Development and Techniques for Nuclear Weapons Effects Research in Protective Construction. The intent of these papers was to re-examine earlier earth stress observations in the light of more recent experiment and new approaches to analysis, to present results of field use of new instruments and data processing components and to examine the general concepts of data acquisition and conditioning equipment as applied to observation of stress or motion induced in the earth by large explosions.

The meeting at which the papers were presented was held at the U. S. Naval Civil Engineering Laboratory at Port Hueneme, California, on February 16 and 17, 1965. Organizations represented at the meeting, in addition to Headquarters, DASA, Naval Civil Engineering Laboratory, and Sandia Laboratory were Air Force Shock Tube Facility, Air Force Weapons Laboratory, Ballistic Research Laboratory, Illinois Institute of Technology Research Institute, Ohio River Division Laboratory (Corps of Engineers), Rensselaer Polytechnic Institute, and U. S. Army Corps of Engineers Waterways Experiment Station.

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A. GROUND MOTION MEASUREMENTS

W. R. Perret

During World War II and since that time, a great deal of experimental and theoretical work has been undertaken to learn how the earth reacts to both chemical and nuclear explosions and what effect that reaction has upon the nature of the stress pulse generated. It is the purpose of this paper to discuss briefly some types of measurements made in these studies and the types of instruments used, emphasizing not so much the detail of these subjects as the reasons and practical factors which influenced choice of instruments and methods of installation.

Studies of ground motion have been made in all response domains, earlier ones at stress levels within or near the region of linear elastic response, and, most recently, within the hydrodynamic domain. This paper will be concerned only with studies made in the intermediate and the more remote elastic regions; more specifically, in the range of peak stress levels from about one kilobar (15,000 psi) to a few bars (a few tens of psi). It will be concerned with those effects produced by relatively large explosions and will include transient stress waves of several hundred milliseconds positive phase duration and several milliseconds rise time. Instrumentation for observation of similar effects from small explosive charges must meet different criteria of size and frequency response and will not be discussed here.

Under these conditions and objectives, what do we measure, how do we go about making such measurements, and within what limitations must we learn to operate? The most logical measurements are transient stress and strain, not only because these are parameters which are useful in engineering design but because strain probably reflects best nonlinear and irreversible response of an environment and because direct comparison of stress and strain results provides estimates of energy dissipation.

Historically, free-field earth pressures were the primary measurements of underground explosion studies conducted during World War II under the direction of Dr. Curtis Lamson for the Office of Scientific Research and Development. Ground motion was also observed during these tests using buried accelerometers and geophones. An early pressure gage shown in Figure A-1 was a fluid pressure transducer sealed in a rubber bag filled with oil and placed in a boring in the earth. The boring was usually filled with fluid such as drilling mud or was backfilled with soil.

These measurements and similar ones made during later explosion tests were purely pressure measurements without directional sensitivity. Studies of "oil-bag" gage response showed that they were sensitive to reaction of the fluid column in the gage hole and to voids between the oil bag and soil backfill when subjected to air-blast loading on the earth. And it must be noted that nearly all sources of ground motion studied during this period involved explosions from which all

or an appreciable portion of the energy which produced the ground motion was derived from air blast. In addition to these problems, evidence was also found that gage borings were distorted by passage of the ground shock. Circular holes became elliptical with the minor axis in the direction of shock propagation. Consequently, indicated pressures included strong perturbations and were possibly more indicative of strains induced in the gage holes by the free-field stress than of the free-field stress wave itself.

During Operation Greenhouse and through several subsequent chemical and nuclear explosion tests, Carlson pressure cells, originally designed for static stress measurements in large concrete dams, were modified and used for earth stress measurements. These gages, one of which is shown schematically in Figure A-2, comprised two concentric rigid circular metal plates bound at the periphery by narrow annular diaphragms and separated by a thin circular space which was filled with viscous silicone oil. One plate included a concentric circular cavity in its outer face so that the inner face, in contact with the confined fluid, responded as a diaphragm to fluid pressure developed by loading normal to the parallel outer faces of the gage. A sensor, usually a Wiancko variable reluctance device, generated a signal proportional to diaphragm deflection.

Carlson-Wiancko gages are highly-directional in their response to load and are consequently classified as stress gages. They were used singly or in orthogonal groups to respond to specific stress components and in one experiment were used to define the complete stress tensor induced by incident air-blast from nuclear explosions. Data from these gages were, for the most part good; that is, wave forms from subsurface gages matched reasonably well the incident overpressure wave forms. Similar correspondence of detail in earth strain records was observed in these experiments.

Considerable skepticism concerning data from deeper gages, particularly the attenuation of peak stresses, was expressed by soil mechanics and structural design people. Briefly, the arguments were these: soil parameters such as compressibility are dependent upon both past and current loading history, and there is a variable mismatch between Carlson-Wiancko gage characteristics and those of soils. In addition, removal of appreciable quantities of material to permit gage installation and compaction of soil backfill around the gages introduced not only a questionable degree of mismatch between backfill and the undisturbed environment but may also have developed a zone of residual shear stress at the contact between compacted backfill and undisturbed material. These conditions were thought capable of causing serious deviation of the stress attenuation pattern within the backfill from that in the undisturbed environment.

It is pertinent, then, to make some comparisons of results of these early observations of vertical stress attenuation and more recent data from particle velocity attenuation in the same Frenchman Flat environment. Stress measurements were made with gages installed in relatively large diameter holes backfilled with native soil hand-tamped to approximately natural density. Particle velocity data came from gages placed in smaller diameter borings backfilled in one case with neat cement grout at gage positions and rodded dry sand between grout plugs. In the other case, backfill was a grout designed to match approximately the undisturbed environment. Figure A-3 compares attenuation of peak stresses from the earlier experiments with peak

particle velocities obtained in the later tests. Data from Upshot-Knothole Shot 10 indicate exponential attenuation of stress between depths of 1 and 15 feet at an average depth coefficient of about -0.05 ft^{-1} ($\sigma = \sigma_0 e^{-0.05D}$) over a range of incident pressures from 140 to 70 psi. Particle velocities from shallow gages, less than 100 feet deep, in both the Priscilla and Small Boy ground motion studies indicate an average depth coefficient for exponential attenuation of a little less than -0.05 ft^{-1} over a range of incident pressure from 250 to 60 psi.

The similarity of results from these markedly different sets of observations and consistency of response shown between incident overpressure and vertical earth stress measurements suggests that skepticism of dynamic earth stress measurements was excessive.

Observations of strain in the earth are subject to problems similar to those suggested for stress measurements. Strain gages such as that illustrated schematically in Figure A-4 were developed during the early 1950's at the Ohio River Division of the Corps of Engineers and at Sandia Laboratory. They comprised two thin concentric circular plastic discs connected at a prescribed separation by a rod through the axis. Changes in separation of the discs actuated a linear variable differential transformer. Compliance of the gages to axial strains was very high, but eccentric loading caused by shear strains could seriously reduce compliance. These gages were used in several series of air-blast induced ground motion measurements. They responded specifically to strains induced in the backfill between the end discs by loads transmitted through the surrounding backfill, and data from them were limited in reliability by the unknown differences in characteristics of that backfill and the undisturbed environment.

Stress and strain measurements in rock are sensitive to the same kinds of problems as those encountered in soils. But here the backfill material is usually a cement grout which, under fortuitous conditions, may bond securely to the surrounding rock and match it in pertinent mechanical properties. Strains are usually measured by bonding resistance-wire or solid-state strain gages to a rock core or by measuring rock core deformation by means of a linear variable differential transformer, Figure A-5. Gaged rock cores are secured in bore holes in the rock environment by the matching cement grout.

One highly useful and generally neglected source of information derivable from dynamic earth stress and strain observations is the measure of local energy dissipation which is indicated by hysteresis in the dynamic stress-strain plot. Records from two vertical stress gages and companion strain gages among a group installed for Project 1.4 in Frenchman Flat during Operation Upshot-Knothole are shown in Figures A-6 and A-7. They illustrate correspondence of detail between records from these types of gages and are the source of data for a stress-strain plot which will be discussed next. The records indicate that strain maxima and minima lag a few milliseconds behind corresponding phases of stress records, but all features of record pairs are analogous.

The stress-strain diagram shown in Figure A-8 is a plot of corresponding points from the records shown in Figure A-6. Minor oscillations in stress-strain curves follow oscillations in the records caused by turbulence in the incident air blast. Area within the stress-strain loop is

a measure of strain energy lost per unit volume by the ground shock as a consequence of the inelastic character of porous granular soil.

A similar stress-strain plot of data from the pair of records presented in Figure A-7 is shown in Figure A-9. Energy densities represented by areas of hysteresis loops of the two stress-strain plots are 200 and 330 microfoot-pounds per cubic foot of which about 40 microfoot-pounds per cubic foot were contributed by the 23 psi precursor. It is interesting to note that energy densities derived from the same gages loaded by a classical air shock generated by Upshot-Knothole Shot 9 were about 30 microfoot-pounds per cubic foot at a peak stress of 19.5 psi, a result which implies good internal consistency in the data.

Volume rates of energy dissipation from a stress pulse in transit through earth, combined with the more commonly derived attenuation rate of stress or particle velocity, can provide very useful tools for theoretical studies of wave propagation through the earth in the region of nonlinear response. To the best of my knowledge, no measurements other than the experimental ones reported by Project 1.4 of Operation Upshot-Knothole have been treated in this manner.

Limited usefulness, real or presumed, inherent to transient earth stress or strain data has been ascribed to difficulties of matching mechanical properties of gages, backfill, and environment, and led to increased emphasis on observation of ground motion. Requirements for matching gage and environment and problems of installation of accelerometers have generally been considered less exacting than those encountered in stress or strain measurements. Free-field ground motion data such as particle velocities and displacements are of specific interest to some phase of protective structure design and to seismic detection studies. For these reasons and because emphasis was shifted from air burst to deep underground nuclear explosions, only a few earth stress or strain measurements have been made since Operation Teapot in 1955.

The shift of emphasis to ground motion studies from stress studies which accompanied the change to underground explosions involved also a shift in depth of gage installation. Earth stress gage emplacement had been limited to depths of 50 feet or less, generally between the surface and 15 feet deep. Recent earth motion gage installations have ranged from the surface to over 1000 feet; and in one recent case, the deepest gages were 3900 feet below ground surface. It is obvious that under conditions of the latter sort, a grouting technique rather than compacted backfill is the more feasible means for bonding gages to the environment.

Ground motion may be recorded as either acceleration, particle velocity, or displacement, depending upon the type of gage used; and by integration or differentiation, the observed parameter may be converted to either of the other two forms with reasonable dependability. The primary instrumentation of all early earth motion studies and of many later ones was acceleration because suitably rugged accelerometers could be had in adequate signal and frequency ranges to fulfill the requirements for the experiments planned. More recently (after 1960) a particle velocity gage developed by Stanford Research Institute has been used in numerous gage arrays with increasing effectiveness and now frequently comprises primary instrumentation.

Installation of earth motion gages requires a remote facility for orientation or sensing orientation of several orthogonally mounted gages. Such facilities were not needed for shallow, manual installation of stress or strain gages. The problems of matching earth motion gages to the environment have customarily been met by mounting gages in canisters the bulk density of which matches bulk density of the environment within a few percent. Canisters are bonded to the environment with a grout designed to match it in seismic impedance, density times propagation velocity or, where feasible, by compacted soil backfill.

It is evident from the foregoing discussion that, in addition to the requirement that gage response range and frequency be compatible with the incoming signal, one of the pertinent factors in adequate instrumentation for observation of free-field earth stress, strain or motion is adequate mechanical matching of the instrument system to its environment. It is, of course, not always feasible to accomplish this requirement exactly, but good approximations are generally possible. Perhaps the outstanding problem here is that the term "adequacy" has not been well defined. Recent analysis suggests that the degree of mechanical matching required heretofore has probably been more rigorous than necessary.

Establishment of an approximate mechanical match between an instrument system and an environment may be expected to vary in complexity with both the type of environment and the magnitude of loading. One basic requirement follows from the fact that any load which causes plastic or visco-elastic deformation of the instrument will distort that portion of its output signal which it has generated and may cause false response to later portions of the incident mechanical signal. This condition limits the useful load range for an instrument to the linear elastic range of materials comprising its mechanical portions.

An analogous generalization for environmental materials simplifies mechanical matching problems and, in fact, serves for a few cases. Unfortunately, most earth materials in situ are characterized by low linear elastic limits, and they are most likely to respond in a visco-elastic or hysteretic manner to loads of interest in studies of explosion-produced ground motion.

These considerations suggest that gage-backfill-environment matching may be difficult. Fortunately, several factors act favorably in much of the problem areas. Among these, response of massive materials to nonlinear, irreversible effects requires finite time periods often greater than the rise time of the stress or velocity pulse.

It is of interest here to examine the significance of gage-environment mismatch in terms of stress or velocity wave interaction with a gage. We assume a single stress pulse traveling through a soil environment which contains a gage. Both environment and gage are loaded within the range of linear reversible elastic response. The gage is represented as a right circular cylinder having its axis parallel to the direction of propagation of the pulse and having dimensions which are very much less than one wave length of the stress wave.

The equation of motion, assuming for simplicity a compressive plane wave traveling in the x-direction, will be

$$\rho \frac{\partial^2 s}{\partial t^2} = (\lambda + 2\mu) \frac{\partial^2 s}{\partial x^2} ,$$

and displacement, s , is described by the solution of this equation

$$s = f(ct + x) ,$$

where ρ is density and λ and μ are Lamé's constants for the material. The propagation velocity, c , is defined by

$$c^2 = (\lambda + 2\mu)/\rho .$$

The strain, ϵ , is $\partial s / \partial x$ or $f'(ct + x)$ and particle velocity, u , is $\partial s / \partial t = cf'(ct + x)$. The prime in both cases represents the first partial derivative of the function $f(ct + x)$ with respect to either x or t , both derivatives having the same form.

Therefore, particle velocity and strain are related by the equation

$$u = c \epsilon .$$

Stress and strain in this elastic response region are related by the equation

$$\sigma = (\lambda + 2\mu)\epsilon .$$

Then it is possible to write

$$\sigma = \rho \frac{\lambda + 2\mu}{\rho} \epsilon = \rho c^2 \frac{u}{c} = \rho c u ,$$

the relationship between stress, density, and propagation and particle velocities. The derivation has been limited to one-dimensional propagation and the effect of Poisson's ratio has been ignored but a relation of the same form holds for the regions of hydrodynamic or of plastic response and for spherical wave propagation. It is evident now that in this region of linear response, the seismic or acoustic impedance, ρc , is the proportionality coefficient relating stress to particle velocity.

It remains now to define the boundary conditions which must apply at the environment-gage interfaces. These are equality of stresses and particle velocities across the interface, A, where the wave is incident at the gage and across the other interface, B, where it is first reflected within the gage.

It is now feasible to draw a stress-particle velocity graph, Figure A-10, in which both the gage and environment are represented by straight lines. The slopes of these characteristic lines are the seismic impedances, $\rho_e c_e$ and $\rho_g c_g$, of the environment and the gage. In this diagram, the gage is

2
the stiffer element having an impedance about five times that of the environment. Any stress in one material will have associated with it a particle velocity, and it is evident then, except at zero stress, conditions on the two impedance curves differ. However, it is possible to fulfill the boundary condition at an interface by reflection within the incidence material. This adjustment takes place along a reflection impedance line; that is, a curve of negative slope equal to the positive slope of the transmission characteristic and passing through the point which represents the incident stress on the environment characteristic.

A compressive stress σ_1 incident in the environment at gage face A is represented by the point, $\sigma_1 u_1$, on the environment curve. Because of differences in impedance, the wave cannot be transmitted into the gage at the σ_1 stress level but will be altered by reflection within the environment along the reflection curve of slope $-\rho_e c_e$ through $\sigma_1 u_1$. This curve intersects the gage characteristic at the point, $\sigma_1 u_1$; a higher stress and lower particle velocity but under circumstances which satisfy the boundary conditions for stress and particle velocity across the interface since the point is common to curves representing both materials.

Stress σ_1 is now transmitted through the gage and reflected within it at surface B, decreasing along the gage reflection characteristic of slope $-\rho_g c_g$ through the point $\sigma_1 u_1$. This reflection line intersects the environment characteristic at $\sigma_2 u_2$ where boundary conditions are again met, and a stress wave of magnitude σ_2 is propagated through the gage from surface B back to surface A.

At surface A, the stress wave is again reflected within the gage, and here the stress change requisite to boundary conditions must occur along a curve of slope $\rho_g c_g$ through the point $\sigma_2 u_2$. This curve intersects the environment reflection impedance curve at $\sigma_3 u_3$, and a stress wave of amplitude σ_3 is reflected within the gage from surface A to surface B. This process of adjustment to satisfy boundary conditions is repeated at the gage-environment interfaces for each reflection as indicated in the diagram.

The most pertinent considerations involved here are (1) oscillation of the stress level with decreasing amplitude about the incident stress σ_1 and (2) the cumulative transit time of multiple reflections within the gage. The first of these two effects is evident from the diagram and might appear as a damped overshoot signal. Significance of the second factor follows if we assume a thickness for the gage and use the propagation velocity assumed for the gage to derive transit times. We choose as reasonable, a thickness of 0.1 feet and a velocity of 10^4 feet per second. Thus one transit of the stress wave through the gage between faces A and B requires 10 microseconds. According to the diagram, ten transits represent a final gage stress which differs by less than ten percent from incident stress, and will occur in 0.1 millisecond. Rise times of stress waves (or particle velocity waves) in earth at nearly elastic response stress levels range from several milliseconds to several tens of milliseconds and thus, a gage-environment mismatch of 5 cannot seriously perturb either the wave shape or stress level within the limits of elastic response. In fact, if the frequency response of the observation system does not exceed greatly that required for response to the incident stress wave, the overshoot suggested by oscillation of the stress level within the gage becomes negligible.

Evidently this diagram may be followed through essentially the same procedure of adjustment and reflection for velocity gages. The principal departure from the stress gage case results from differences in shape and dimensions of velocity gage canisters. Transit times become longer and the cylindrical shape may cause some focusing effects. However, for either type of gage it appears that mismatch of a factor of 5 to a relatively stiff soil environment may not introduce serious distortion into resulting records.

This treatment is admittedly simplified. A more precise treatment including a third material such as grout, may introduce complications resulting from relative grout and gage transit times. However, if the environment is a competent rock the gage environment mismatch factor will approach one and if a grout is used which does not deviate from the environment by a factor greater than 2, even the faster rise times of stress waves in such environment may be accommodated with little distortion.

Discussion of ground motion instrumentation has not been treated in much detail in the foregoing because it is familiar to those presently concerned with field observations of underground explosive effects and because other papers to be given here will deal with specific new instrumentation. Previous mention has been made of the early use of accelerometers and the more recent addition of a particle velocity gage to the instruments suitable for ground motion studies.

It is desirable next to discuss briefly the means for obtaining ground displacement data. Since displacement is the time integral of particle velocity and the double integral of acceleration, the most obvious means for acquiring displacement data is to integrate the time-velocity records from observed velocities or accelerations. This is precisely the means by which most displacement data are acquired. However, two basic types of displacement gages have been developed and used with varying success. The first of these, a relative displacement gage of the type used for measurement of air-blast induced ground displacements caused by Priscilla, is actually a long-base strain gage and a direct descendent of the Ballistic Research Laboratory wire displacement gage. It has been used to measure relative displacements of anchor points separated by as much as 200 feet and as little as 10 feet. Of course, if absolute motion of one anchor point is negligible, the gage response may be interpreted as absolute displacement of the other anchor.

The other type of displacement gage is an inertial type of instrument intended to respond to large, long-period displacements and hopefully to indicate residual static displacements. Inertial displacement gages are essentially either a massive, short length pendulum (SRI) or a free-riding mass on a horizontal shaft (Sandia). The mass in each gage drives through geared coupling a massive fly-wheel which serves as a motion demagnifier. This mechanism permits the gage to respond to displacements of a few feet with only a few inches of travel allowed the inertial mass. However, there is a requirement of very low friction which makes them hypersensitive to tilting along the response axis. This sensitivity may be reduced by coupling the mass to the case by means of soft springs, but such coupling requires sinusoidal correction of records if displacements continue beyond about one-half the initial period of the mass-spring system.

Recent development of electronic integrator circuits of long time constant have permitted very successful integration of velocity gage output signals. These integrators will be discussed in another paper of this series and are mentioned here to indicate the trend we consider most fruitful for acquisition of displacement data.

The questions asked at the start of this discussion have been answered in some detail. These answers may be summarized thus:

1. Measurement of stress, acceleration, or particle velocity in soils or rock is feasible and reliable.
2. Measurement of strain in soil or rock is feasible but, because in nearly all cases the measurement includes a highly disturbed portion of the environment, reliability of the results may be marginal.
3. Perturbations of the stress pattern introduced by mismatch between the seismic impedance of gages and environments are probably not nearly so serious as has generally been considered.
4. Measurement of displacement by gages devised for that purpose has been found much less fruitful than the use of electronic integrating circuits in conjunction with the more reliable particle velocity gages.
5. Combined use of stress and strain wave data, where the latter are considered reliable, provides in the form of a stress-strain hysteresis diagram a very useful tool for study of energy dissipation in the earth.

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Figure A-1. Oil Bag Gage for Measurement of Earth Pressure

Figure A-2. Carlson-Wiancko Earth Stress Gage

Figure A-3

Figure A-4. Earth Strain Gage

Figure A-5

Figure A-6

Figure A-7

Figure A-8

Figure A-9

Figure A-10

B. AN EXTENDED RANGE VELOCITY GAGE FOR MEASUREMENTS IN HIGH SHOCK ENVIRONMENTS

J. W. Wistor

Background

Over the past several years a considerable effort has been expended on the development and evaluation of a high range velocity gage for utilization in structure and free field measurements.

This device is basically a highly overdamped, low-natural-frequency accelerometer operating in the "velocity" portion of its response spectrum. Velocity gages operating on this principle have been constructed by several agencies. Two models which were first used to make structure and free field velocity measurements in conjunction with full scale nuclear and HE tests were designed by the British and by the Stanford Research Institute (SRI). The British model was a large self-recording velocity meter having limited frequency response and employing magnetic damping. It was first used during Operation Buffalo and later on Antler where good results were obtained. The SRI horizontal velocity gage developed after Hardtack-2 was a compact, electronically recorded, overdamped pendulum accelerometer having a natural frequency of about 5 cps. Its sensing element was a carrier excited variable reluctance pickup which was employed in a standard bridge circuit. Modulation of the bridge circuit was effected by an armature attached to a pendulum suspended from a shimstock hinge. When the bridge circuit was balanced at zero velocity, then bridge unbalance (i. e. pendulum displacement) was proportional to case velocity within its operating frequency spectrum. Figure B-1 shows the configuration of the original SRI horizontal velocity gage. The present Sandia velocity gage is an adaptation of this basic SRI design.

Further development effort by SRI produced a velocity gage modified for vertical operation. A relatively "soft" coil spring was used to support the pendulum in the horizontal plane. This vertical modification is illustrated by Figure B-2.

Response of the Overdamped Accelerometer

Figure B-3 shows the theoretical response of an overdamped seismic system to a sinusoidal velocity input. The dependence of the gage flat frequency response spectrum and the gage output (E) on the damping ratio (n) where

$$n = \frac{\text{actual gage damping factor}}{\text{critical damping factor}}$$

is clearly indicated. It can be shown* that the low frequency cutoff (down 5 percent) is determined by:

$$\frac{\omega}{\omega_0} \approx \frac{3}{2n} \quad \text{for } n \gg 1 \quad (1)$$

and that the high frequency cutoff (down 5 percent) is determined by:

$$\frac{\omega}{\omega_0} \approx \frac{2n}{3} \quad \text{for } n \gg 1 \quad (2)$$

where (ω) is the gage forcing frequency and (ω_0) is the gage undamped natural frequency. The corresponding phase shift (gage output referenced to gage input) at these end points is 18.4° leading at the low frequency cutoff and 18.4° lagging at the high frequency end. Figure B-4 shows the relative phase shift variation with driving frequency and the damping ratio (n) .

The theoretical transient response of the overdamped accelerometer to a step input of velocity is illustrated by Figure B-5. The dependence of the gage rise time, decay time, and output amplitude on the damping ratio (n) is clearly illustrated. The rise time of the gage to a step input of velocity is governed by:

$$1 - e^{-2n\omega_0 t} \quad (3)$$

The gage decay time is determined by:

$$e^{-\frac{\omega_0}{2n} t} \quad (4)$$

For an exponential of the form $X = e^{-\alpha t}$

$$\alpha = \frac{\ln \frac{X_1}{X_2}}{t_2 - t_1} \quad (5)$$

where X_1 and X_2 are the values of X at times t_1 and t_2 , respectively.

*The theoretical analysis of the response of the overdamped seismic system will not be presented in this paper, since numerous treatments of the problem have been presented by members of the SRI and Sandia staffs and by others. The final report on the Sandia High Range Velocity Gage (to be published about July 1965) will include a complete analysis of this system.

With a properly assembled, balanced gage, a step of velocity can be simulated by moving the pendulum (which is partially constructed of magnetic material) to one side with either an internal electromagnet (SRI gage) or an external magnet (Sandia gage) and then releasing it. By recording the exponential return to the null position, measurements of X_1 , X_2 , t_1 and t_2 can be made in the linear range and (α) calculated. Then setting

$$\alpha = \frac{\omega_0}{2n} \quad (6)$$

the value of (n) can be calculated, using the measured value of (ω_0) .

Design Objectives

As background information on the performance and limitations of state-of-the-art velocity gages was acquired, several problem areas became apparent. In addition, much interest was expressed by hardened-structures people and other military agencies in extending the range of velocity measurements to close-in regions where background accelerations were beyond the capabilities of existing gages ($A > 500$ g). The design objectives for the new Sandia velocity gage were:

1. To extend the gage frequency response to cover the range from 0.01 cps to 600 cps.
2. To extend the dynamic range of the gage to measure velocities from 0.1 ft/sec to 600 ft/sec.
3. Design the gage to withstand shock loads of at least 3000 g.
4. Investigate techniques of obtaining large effective values of the damping ratio (n) without the necessity of using high viscosity damping fluids with possible thixotropic behavior. (Thixotropic fluids are shear rate dependent, i. e., their apparent viscosity decreases with increasing shear rate.)
5. Extend the pendulum-reluctance pickoff linear operating range from $\pm 1.2^\circ$ to at least $\pm 4^\circ$. (This objective is highly desirable because in deep well instrumentation it is generally difficult to level instrument packages to better than $\pm 2^\circ$ without the aid of complex leveling mechanisms.)
6. Design the velocity gage with a sealed expansion bellows to accommodate temperature expansion of the damping fluid and to allow vacuum filling of the gages in order to prevent anomalous gage behavior because of the "bubble effect." (With respect to this objective, tests on numerous velocity gages subjected to impulses from a spring driven displacement test sled showed that the presence of air bubbles in the damping fluid could, under certain circumstances, cause a large decrease in the effective viscosity of the damping fluid. This is particularly noticeable when the bubbles lodge in the gap between the armature and the pole pieces of the "E" core. This "bubble effect" can cause errors in both amplitude and frequency response since the damping ratio (n) is directly proportional to the damping oil viscosity. Gage amplitude errors as large as 200 percent of the actual sled velocity were noted during the early sled tests. An examination of the early velocity gage records from full scale nuclear and HE tests reveals some cases where large errors,

not attributable to calibration or operational procedures, are evident between the primary velocity gage data and velocity data derived by integration of acceleration records. The writer believes that these errors are due to the "bubble effect." Since the inception of the vacuum filling technique in the Sandia gage, the correlation of primary velocity data to the integrated acceleration data has been excellent.)

Objectives (1), (2), and (3) define the velocity gage capabilities necessary to make ground motion measurements, in the regions of maximum interest, near subsurface nuclear and chemical explosions.

Sandia Model DS Velocity Gage

The first Sandia prototype was the Model DS velocity gage built and tested during the fall and winter of 1962. This model was subsequently used successfully on the Shoal (Fallon, Nevada - 1963) and Dribble (Hattiesburg, Mississippi - 1964) operations. Figure B-6 shows an exploded view of the DS velocity gage. The following major changes were incorporated into the design of this gage:

The pendulum suspension system, the pendulum-armature-E coil assembly and the gage body were completely redesigned and strengthened sufficiently to meet the 3000 g shock requirement.

A miniature ballbearing and pivot assembly was substituted for the shimstock hinge which was found to be incompatible with high "g" operation. The ballbearing-pivot-type pendulum suspension has slightly greater friction than the shimstock hinge assembly but this has not proved to be a response problem.

The variable reluctance sensor as used in the SRI gage was retained, but the linear operating range of the gage was doubled by increasing the armature gap.

To avoid possible problems associated with air entrapment in the damping fluid, a system for filling these gages with DC 210 silicone damping fluid under a moderate vacuum and for subsequent sealing was devised.

Temperature expansion of the damping fluid was accommodated by a flexible bellows decoupled from the pendulum working chamber by an orifice plate containing a small diameter bleed hole.

These changes increased the gage diameter by 1/4 inch but decreased the overall length by 1/2 inch. The undamped natural frequency of the gage was 3 cps.

The standard DS gage was provided with a brass pendulum and was used to measure velocities in the range of 0.1 ft/sec to 25 ft/sec. A higher "g" version of this gage had an aluminum pendulum and measured velocities between 5 ft/sec and 300 ft/sec.

During the proof testing period these gages were used to measure ground motions in the vicinity of buried 1000-lb. HE spheres. Particle velocities in the range 0.1 ft/sec to 230 ft/sec were successfully measured. Peak accelerations corresponding to these velocities were 0.5 g to greater than 1500 g. Electronically integrated accelerometers were used as a comparison standard over the range 0.5 g to 500 g. Typical records obtained from the Shoal and Dribble Events are illustrated by Figure B-7.

Sandia Model DX Velocity Gage

Further experimentation and redesign produced the Sandia Model DX velocity gage which is presently in use and which has replaced the DS Model. Prototype testing was completed in sufficient time to allow 15 of the first 300 production units to be used in the Dribble Operation. Figure B-8 shows an exploded view of the DX velocity gage. Major improvements incorporated into this design were:

An improved pivot and bearing assembly which decreased the friction in the pendulum suspension system and extended the gage operating limit into the 3000 g region.

The armature gap was increased to provide linear operation over $\pm 4^\circ$ of pendulum rotation. Maximum pendulum rotation was $\pm 6.5^\circ$. This gap change extended the velocity measuring capability of the gage to about 600 ft/sec. Figure B-9 shows the DX gage output characteristic as a function of pendulum displacement.

Other changes provided an improved sensor clamping arrangement and simplified the machining of the various component parts.

DX gages with brass pendulums cover the velocity range 0.1 ft/sec to 50 ft/sec; those with aluminum pendulums operate in the range 5 ft/sec to 600 ft/sec.

Typical results from displacement sled tests on DS and DX velocity gages are shown in Figure B-10.

Damping System Details and Temperature Correction

The damping system used on the old Model DS gage had certain drawbacks. Damping fluid viscosities of 6000 centistokes and 2000 centistokes, respectively, were required to provide a damping ratio of $n = 100$ (at room temperature) for the brass and aluminum pendulum gages. Dow Corning 210 fluids having viscosities greater than a few thousand centistokes behave increasingly as thixotropic fluids rather than simple Newtonian fluids. This implies that at certain critical shear rates and therefore critical pendulum velocities, anomalous gage response can be expected, since the apparent viscosity of the DC 210 fluid decreases with increasing shear rate. Calculations for DS gages operated within their design limits indicate that even for extremely high viscosity damping fluids (20,000 centistokes) the maximum shear rate is below the critical value of

200 reciprocal seconds. However, it was desired to increase the effective damping available from any given viscosity fluid, since not only do lower viscosity fluids have a higher critical shear rate, but they simplify gage filling procedures. The damping system designed for the Model DX gage increased the effective damping ratio (for any given fluid viscosity) by a factor of about four. This was accomplished by designing a close tolerance gap of about 0.060 inch between the pendulum and pendulum housing. This detail is illustrated by Figure B-11. By forcing the pendulum to move in this restricted space, we take advantage of the "mass effect" of the damping fluid to increase its apparent viscosity. Damping ratio as a function of damping fluid viscosity for various brass and aluminum velocity gages is shown in Figure B-12. Dow Corning 210 fluid is specified for use in these velocity gages since it is specifically designed for high shear rate applications. However, in controlled tests using velocity gages no differences could be detected between the DC 200 and DC 210 fluids. Both have similar temperature-viscosity characteristics.

For large values of the damping ratio (n), the gage velocity range (U) and the damping ratio (n) are directly proportional to the damping fluid viscosity (h), while the gage output (E) is inversely proportional to the fluid viscosity (h), i. e.,

$$U \propto n \propto \frac{1}{E} \propto h . \quad (7)$$

The variation of these gage parameters with temperature and the appropriate correction factor (F) is indicated by Figure B-13. The solid line is the published Dow Corning temperature-viscosity data. The circled datum points indicate the measured gage response as a function of temperature. The difference between the two sets of data for any particular temperature (T) and the normalizing temperature (T_N) appears to be proportional to the absolute temperature ratio $\left(\frac{T}{T_N}\right)$. This deviation is still being investigated.

Vertical Operation

Both the Model DS and the Model DX velocity gages have been converted to vertical operation by supporting the pendulum in the horizontal plane by means of a "soft" coil spring which just counteracts the earth's gravitational field. The early DS gage employed a high carbon steel coil spring. The temperature versus gage zero drift characteristic of this system was quite severe and was only slightly improved by heat treating the spring as illustrated by Figure B-14. Since the Dribble deep hole instruments would encounter predicted ambient temperatures as high as 140°F, it was necessary to balance the Model DS vertical velocity gages at the expected operating temperature prior to installations.

Intensive investigation of this temperature drift problem produced a vastly improved pendulum suspension system for the DX vertical gage. This improvement is indicated in Figure B-14; the DX gage relative temperature drift is seen to be decreased by a large factor. This improvement was effected in two ways. First, the high carbon steel coil spring was replaced by a specially

5 mil wire loop was designed. The coil spring anchors were designed to provide a linear spring restoring force over the full $\pm 6.5^\circ$ of pendulum rotation. The flexible wire loops on the spring anchors prevent a hysteresis effect sometimes noticed in the DS gages and caused by the spring end or hook shifting position in the anchor holes as a result of spring displacement or rotation. Figure B-15 shows details of the DX vertical gage assembly. With this system the gage can be balanced at room temperature and then operated over the range 0°F to 200°F without further adjustment.

Typical velocity records from horizontal and vertical DX gages operated on the Salmon Event of Operation Dribble are shown in Figure B-16. This gage station was located 500 feet below the shot horizon and at a slant range of 740 feet. The peak radial acceleration at this station was 400 g. The most recent full-scale tests involving the use of Model DX velocity gages were the Handcar/Painted Pony and Mudpack Events of Operation Whetstone. Handcar was fired in dolomite at a depth of about 1300 feet, and Mudpack was fired above the dolomite at a depth of 500 feet. Five deep wells were instrumented at various depths between the surface and the 1400 foot depth. The DX velocity gages were given two calibration steps (differing by as much as 20 to 1) and were operated on both events. Good velocity records were obtained from both shots, the measured peak velocities were between 0.09 ft/sec and 50 ft/sec.

Shock Loaded Vehicle Tests

Recently high range DX velocity gages have been placed in test vehicles subjected to blast waves from HE driven shock tubes and sheet explosives tests. The vehicles undergo complex motions in which the various vibratory modes of the vehicle are superimposed on the rigid body motion of the gross structure. Attempts to measure vehicle acceleration with commercially available accelerometers have generally been unsuccessful. The tremendously sharp acceleration pulse imparted to the vehicle appears to excite the accelerometers to resonance, with resultant spurious response. The overdamped velocity gage does not suffer from this shortcoming. The DX gage with proper damping has sufficient frequency response to define the rigid body motion of the test vehicle and the lower frequency modes of vehicle vibration. Figure B-17 shows typical DX velocity gage results obtained from two such tests. The upper trace, obtained from an HE shock tube test, has considerable high-amplitude, low-frequency (about 1100 cps) vibration, superimposed on the rigid body motion. Cable breakage occurred about 5.5 msec after shock arrival. Five accelerometers mounted in the vehicle indicated various peak accelerations lying between 4000 g and 10,000 g. The lower velocity gage trace is from a test vehicle loaded by a sheet explosive charge. A foamed plastic interlayer effectively damped out most of the high amplitude vehicle vibration. Four accelerometers located in the test vehicle and having working ranges of 7500 g were over-ranged and badly damaged. The DX velocity gages from both tests were recovered and found to be in working condition with calibration factors remaining essentially unchanged (± 2 percent). In most vehicle tests to date the peak velocities obtained from the DX gages agree well with the measured vehicle displacements.

Summary and Future Development

In the "Design Objectives" section it was shown that the Model DX velocity gage was *designed* specifically to meet current requirements for measuring ground motions in the vicinity of subsurface face detonations. All of the listed objectives have been successfully met. In order to achieve the desired low-frequency response (0.01 cps), a gage with a low natural frequency was required. The consequences of such a design are (1) tilt sensitivity and (2) modification for vertical operation.

It has further been shown that by extending the frequency response (by increasing the damping ratio "n") of the present DX gage it can be usefully employed to make velocity measurements in the frequency range 0.01 cps to 2000 cps, on shock loaded structures. This high frequency response limit is sufficient to define the rigid body motion of small structures, but not their higher frequency vibratory modes. A second limitation of the present velocity gage is its size, which is somewhat larger than desirable for small test structures.

With these considerations in mind, some preliminary effort has been directed toward the design of a miniature velocity gage for use in extreme shock environments. This gage design would not be tilt sensitive and, therefore, could be operated in any orientation. The dynamic range of the gage would be 1 ft/sec to 600 ft/sec and the frequency range would be 1 cps to 30,000 cps. The gage would be capable of operation in shock environments in excess of 20,000 g.

Such a velocity gage would be useful not only for structural response studies but also for very close-in measurements on underground tests. The extent of future development in this area has not been established.

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Figure B-1

Figure B-2

Figure B-3

Figure B-4

Figure B-5

Figure B-6

STA: PM-6 (shot depth)
500 Ft. Radial Range

Peak Radial Acceleration = 285 G

OPERATION SHOAL

Figure B-7

Figure B-8

Figure B-9

Typical Instrumentation Results from Displacement Sled Tests

Figure B-10

Model DX-DS Velocity Gage
Damping System Detail

Figure B-11

Damping Ratio as a Function of Damping
Oil Viscosity for Various Velocity Gages

Figure B-12

Figure B-13

Comparative Temperature Response of Type DS and Type DX Vertical Velocity Gages

Figure B-14

DX Vertical Velocity
Gage Detail

Figure B-15

Figure B-16

Typical DX Velocity Gage Records from Shock Loaded Vehicles

Figure B-17

C. ELECTRONIC INTEGRATORS FOR INSTRUMENTATION APPLICATIONS

G. J. Hansen

Background

Problems of design, calibration, and installation of velocity and displacement transducers for ground motion measurement have indicated the desirability of integrating the output signals of accelerometers and velocity gages to obtain time-histories of particle velocity, displacement, and displacement potential. Accelerometers have proven, from long experience, to be the least troublesome transducer for deep hole installation and the most tolerant of improper alignment. An accelerometer experiencing a few degrees of tilt will seldom be a problem, while under the same conditions, a pendulum type horizontal velocity gage might have a serious unbalance and an inertial displacement transducer could be rendered useless.

For these reasons integrations have previously been performed by computer during data reduction. However, computer zero shift, tape noise, digitizing inaccuracies, and other problems cause cumulative integration errors. These errors make it necessary to recompute the integrals several times with proper compensating constants and slopes added to make the data fit the known conditions (velocities returning to zero at late times, etc.). This procedure often entails weeks or even months before reasonably accurate velocity and displacement integrals are available for analysis.

Several attempts to perform real-time integrations in the field using operational amplifiers with capacitive feedback have been made in the past. However, long-term carrier system drift and operational amplifier zero shift have caused the results to be unsatisfactory. The compensated electronic integrators described in this paper were designed to eliminate these difficulties and to allow integrated velocities and displacements to be immediately available after an event. Compensated integrators have been tested on Sandia acceleration sled runs and on various high explosive tests. They were used successfully on Projects Shoal and Air Vent in 1963 and Project Dribble in 1964.

Single Integrators

The basic circuit for integration with operational amplifiers is shown in Figure C-1(a). The current through R is $i = (e_i - e_s)/R$. Since an ideal amplifier draws no input current, this current is also the charging current for the capacitor, C. The voltage across C is, then,

$$V_c = e_s - e_o = e_o \left(\frac{1}{A} - 1 \right)$$

$$V_c = -e_o = \frac{1}{C} \int i dt = \frac{1}{RC} \int (e_i - e_s) dt.$$

Since $e_s = -e_o/A$ and A is very large, the equation becomes

$$e_o = -\frac{1}{RC} \int e_i dt,$$

which shows that the output voltage is directly proportional to the integral of the input voltage. In general an operational amplifier circuit can be shown as in Figure C-1(b). If A is very large (10^4 to 10^8), then $e_s \approx 0$. Therefore, $E_o/E_i \approx -Z_f/Z_i$.

Using Laplace transform methods to analyze the circuit shown in Figure C-1(a), we obtain

$$L\{Z_f\} = Z_f(s) = \frac{1}{Cs} \text{ and } Z_i(s) = R$$

$$\frac{E_o(s)}{E_i(s)} = -\frac{Z_f(s)}{Z_i(s)} = -\frac{1}{RCs} \text{ or } E_o(s) = -\frac{E_i(s)}{RCs}$$

Taking the inverse transform we obtain

$$e_o = -\frac{1}{RC} \int e_i dt,$$

which is the same answer obtained previously. Therefore complex impedance ratio will be used throughout this paper to determine circuit performance.

The circuit in Figure C-1(a) has characteristics which make practical application difficult. A typical instrumentation system consists of a velocity or acceleration gage whose response is amplified by a carrier amplifier; the demodulated output of the carrier amplifier is then fed into the integration circuit. Because the output voltage of the carrier amplifier drifts slowly around zero (approximately ± 50 mv) with time, when this voltage is applied to the circuit of Figure C-1(a), it causes e_o to vary several volts which is sufficient to saturate the signal recorder.

A second problem lies in the nature of the amplifiers used. All operational amplifiers require a small DC current flowing from output to summing point to stabilize them. This current varies from amplifier to amplifier; for the amplifiers in this circuit (the Astrodata TOA-110), the current ranges from 25 to 50 micromicroamperes. This current continuously charges the capacitor C , and unless a leakage path is provided, e_o will again rise to saturation level.

The circuit shown in Figure C-1(c) was developed as a possible solution to these problems. With this circuit

$$\frac{E_o(s)}{E_i(s)} = - \frac{Z_f(s)}{Z_i(s)} = - \frac{s}{R_1 C_2 (s + 1/R_1 C_1)(s + 1/R_2 C_2)}$$

Let $T_c = R_1 C_1 = R_2 C_2 =$ stabilization time constant.

Then

$$\frac{E_o(s)}{E_i(s)} = - \frac{s}{R_1 C_2 (s + 1/T_c)^2}$$

and for a unit step function input

$$e_o = - \frac{t}{R_1 C_2} e^{-t/T_c}$$

Thus for values of t less than $0.1 T_c$, this circuit will integrate a step function with less than 10 percent error. In practice it is possible to obtain values of $T_c = 50$ seconds or more with good long-term stability, allowing accurate worst-case integrations over about 5 seconds. However as the period components of the input waveform become small in respect to the stabilization time constant, accuracies improve.

Figure C-2 is a schematic of the actual single integrator used for the field experiments. This circuit allows a calibration step, derived at the transducer, to pass through the entire electronic system and be recorded. This not only provides channel calibration but also allows integration gain and stabilization time constant to be read from the final record.

Double Integrators

The most common method of performing double integration is to use two single integrators in series. This yields the following form for a step input:

$$e_o = \frac{t^2}{(R_1 C_2)^2} e^{-2t/T_c}$$

A system of this type will work; however, it includes several major problems. First, the form of the exponential requires that T_c for the two integrators in series be twice as large as T_c for a single integrator to yield the same accuracy. Then, too, the output drift of the first integrator is in the pass band of the second and is therefore integrated.

Experimentation with stabilized double integrator circuits using a single operational amplifier circuit of Figure C-1(d). Assuming that $C_b \gg C_1$ and $R_3 \gg R_2$,

$$Z_i(s) = \frac{R_1^2 C_1}{s} (s + 2/R_1 C_1)(s + 1/2R_1 C_b)$$

$$Z_f(s) = \frac{2}{C_3} \frac{(s + 1/2R_2 C_3)(s + 2/R_3 C_2)}{(s + 1/R_3 C_3)^2 (s + 1/R_2 C_2)}$$

Let $R_1 C_1 = 4R_2 C_3$ and $R_3 C_2 = 4R_1 C_b$ and $R_2 C_2 = R_3 C_3 = T_c$.

Then

$$\frac{E_o(s)}{E_i(s)} = \frac{Z_f(s)}{Z_i(s)} = \frac{2}{R_1^2 C_1 C_3} \frac{s}{(s + 1/R_3 C_3)^3} = \frac{2C_b}{T_c^2 C_3} \frac{s}{(s + 1/T_c)^3}$$

Taking the inverse transform for a step input,

$$e_o = -\frac{C_b}{T_c^2 C_3} t^2 \exp(-t/T_c)$$

which is the form desired.

This circuit has been constructed and operated with many values of T_c and gain. With values of $R_3 \leq 2 \times 10^9$, it will hold zero to ± 100 mv for long periods of time. When constructed with components of reasonable value, accurate double integrations over several seconds have been obtained.

Experimental Results

Figure C-3 is a plot of typical instrumentation results from displacement sled tests. The sled consists of a carriage approximately one foot high which rides on two Thompson ball bushings guided by a pair of parallel steel rods. The carriage is driven by a quick-release coil spring and rebounds from a second coil spring at the far end of the track. Carriage displacement is adjustable from zero to about fifty inches. Accelerations of over 100 g can be imparted to the carriage and gage assembly at full spring compression. The instrumentation used on this particular test consisted of a variable reluctance accelerometer and an over-damped pendulum-type velocity gage. Spring tension was adjusted for approximately 80 g acceleration and displacement adjusted for 37.5 inches. As can be seen in Figure C-3 single and double integrated peaks are all within a few percent of those measured directly.

Figure C-4 is a combined plot of electronic and computer integrated displacement obtained from a horizontal velocity transducer located at shot depth, 130 feet from ground zero on Project Air Vent. Air Vent was a 40,000-lb. high explosive shot at a depth of 17 feet. Comparison of the plots shows the quality of data that can be obtained from electronic integrations done in unmanned stations in field environments.

Figures C-5 and C-6 compare electronic and computer integrations of Project Dribble data. The Salmon event of Project Dribble was a 5 KT nuclear device shot in salt at a depth of 2700 feet. Instrumentation canisters were installed in wells at depths from 0 to 3900 feet. Figure C-5 is a time history of displacement at station E-11-27 which was located at shot depth and 2016 feet range. Figure C-6 shows displacement at station E-6-27; shot depth and 1063 feet range. Both figures show the close correlation between methods; the major difference being that electronic integrations were available the first day of data reductions and computer integrations took six weeks.

Figure C-1. Integrator Circuits

$$e_o (\text{CAL.}) = -e_i \left[1 - e^{-\frac{t}{R_1 C_2}} \right] e^{-\frac{t}{R_2 C_2}}$$

Figure C-2. Schematic-Single Integrator

Figure C-3. Typical Instrumentation Results from Displacement Sled Tests

Figure C-4: Project Air Vent

Figure C-5. Project Dribble Event Salmon

Figure C-6. Project Dribble Event Salmon

D. INSTRUMENTING NUCLEAR EXPLOSIONS

D. G. Palmer

Environmental Problems

Nuclear explosions generate pressures greater than 10^7 psi and temperatures greater than 10^7 degrees. These and other effects decrease rapidly with distance, but even so a one megaton explosion generates pressure greater than 1000 psi to distances of 1000 feet in air and to ranges like 20,000 feet in water; pressures sufficient to fracture the earth at distances like 1000 feet; gamma dose of 3,000 roentgens at 6,000 feet in air; and thermal radiations of 50 cal/cm^2 at four miles in air (this is well above the ignition threshold for materials such as wood, paper, and cotton). Many explosion effects scale as the cube root of the yield, therefore a one kiloton explosion would produce most of these effects at one-tenth the distances listed above. These and many other explosion effects are described in detail in "The Effects of Nuclear Weapons".

Of particular interest to instrumentation engineers are two electro-magnetic effects described in general terms in Reference 1. One effect is the distortion of radio and radar signals occasioned by attenuation or refraction of transmission paths. Another electro-magnetic effect is the generation of strong induction fields oscillating in the low kilocycle range. The latter phenomena is observed near the explosion and has characteristics similar to the fields generated by lightning.

From Newton's law of motion, $F = ma$, we can estimate the accelerations that instrumentation packages would experience near nuclear explosions. If an instrument package had a sectional density of one slug per square inch of frontal area, then the acceleration (in G's) would equal the shock pressure (in lbs/in^2). (This assumes that the instrument package is a rigid body that does not match the surrounding medium; i.e., surrounded by air or in a void in the earth.)

In addition to the effects described above, instrumentation for nuclear explosions must be designed to survive the environment generated by meteorological changes and the environment native to the geology of each test site. Annual temperature changes of 100°F and daily temperature changes of 30 to 40°F are common at the Nevada test site. Winds to 50 knots carry tons of alkaline dust across the test site and rain, snow and ice storms are frequent visitors to this desert location. Thunder storms may generate lightning currents greater than 10^5 amperes in the air and in the earth.

Instruments buried deep in the earth must withstand overburden pressures of several thousand lbs/in^2 and, in salt domes in Mississippi, geo-therm temperatures may be as high as 150 to 200°F . Caustic, salty or acid solutions are often present in the earth or they may be introduced by practices common to the drilling and cementing of deep wells.

Another environmental problem facing the instrumentation engineer is variation of the impedance of the field. The characteristics of earth materials are radically different at each instrument location, and instruments for measuring free field effects must either match the characteristics of the surrounding medium or the mismatch must be known. This requirement becomes more critical as the observations enter regions of very high stress where high frequency components dominate the signals.

Description of a General Instrumentation System

Figure D-1 illustrates the elements found in many instrumentation systems. Any one specific system may not contain all of the elements shown here, but in general, most systems do.

Sensors are of many types; some generate an electrical charge, some generate voltages and others modulate electrical impedances. (There are systems that are completely mechanical or optical, but most modern systems use electrical or electro-magnetic transduction.)

A calibration auxiliary is desirable in all systems because; installation is accomplished in stages, delays occur in test schedules after instrumentation is partially installed and aging and environmental effects may change instrumentation characteristics; and sensors are often installed in such a manner that calibration stimulus cannot be applied after the system is complete. An auxiliary circuit that generates a known signal (charge or voltage or impedance change) at the sensor terminals allows measurement of the sensitivity of the remainder of the system and adds significantly to the confidence in measurements.

An impedance matching network is necessary because sensors may not match the loads attached to them and because transmission lines are more efficient and generate less noise when properly terminated.

Translators change the language or the format of electrical signals as they move through the system. They may translate varying charges or impedances to a varying voltage; they may change analogue voltages to amplitude or frequency modulated carrier signals; and they may demodulate carrier signals and/or generate pulse code modulation patterns.

Translators are necessary because most sensors do not generate signals of sufficient power or with proper character for transmission through severe noise fields.

Recorders are of many types—photographic film, magnetic tape, magnetic cores, and many types of bi-stable devices. Each type has its advantages and disadvantages and selection is weighing cost, dynamic performance and sensitivity to environmental forces.

There are two recorders shown in Figure D-1 because transcription is or provide a format suitable for input to computers or for manual data inter-

Telemetry links may be installed at any point along the sequence of elements that comprise an instrumentation system. A long cable may connect the sensor to a translator, and a radio telemetry link may connect the translator to a recorder. Systems have been used with telemetry cables or radio at every interface described in Figure D-1. In some instances, the first recorder is buried near the sensor and never recovered. The information stored in such a recorder is transcribed over long cables to a second recorder after the test event is concluded.

Effects of Environment on Instrumentation

Thermal fields change the dimensions and the mechanical and electrical characteristics of materials and may cause oxidation or vaporization of materials.

Pressures and accelerations deform structures and the resulting strains modify capacitors, inductors, resistors, moments of inertia, spring constants and damping constants.

Ionizing radiation generates charges in electrical systems and modifies the molecular and/or atomic structure of materials.

The electromagnetic pulses generated by explosions or by lightning will induce currents in electrical conductors and voltages that stress dielectrics.

In general, instrumentation elements can be designed to be insensitive to environmental effects or shielding can be employed to attenuate the environment. In most cases the sensor must survive the environment because shielding modifies the field being measured. The remaining elements of an instrumentation system can be shielded or displaced from the source.

Insulating and reflecting materials will attenuate thermal fields; strong structures and shock mounts can reduce pressures and accelerations; masses of material will attenuate ionizing radiations and low reluctance or low resistance materials can be used to reduce electromagnetic fields.

Examination of the sensitivities of instrumentation components to a changing environment leads to the following general conclusions:

- A. The threshold of damage is high at the sensor and falls lower and lower as we move through the signal conditioning elements toward the recorder.
- B. The quality of measurements improves as the telemetry link moves toward the recorder.

The latter conclusion results from the following:

1. It is impractical to completely shield a long telemetry link.
2. The signal to noise characteristics of a telemetry link improves as the available power increases or as the signal format increases its band width.
3. Translators can be shielded and they can multiply the power and change the signal format that is available at the sensor.

It follows that the ultimate system would use a shielded recorder in close proximity to the sensor and data recovery would require physical recovery or transcription by telemetry after the test event is completed.

Economic Factors Affecting Instrumentation Design

Examination of the costs of the elements of an instrumentation system for an underground nuclear explosion reveals the following:

ITEM	COST	SHIELDING COST
1. Sensors	\$200 to \$1000	\$50 to \$200
2. Calibration auxiliary	\$50 to \$200	\$50
3. Impedance matching network	\$20 to \$500	\$50
4. Telemetry cables	\$200/mile	Not practical
5. Translator No. 1	\$800	\$200
6. Translator No. 2	\$500	\$200
7. Recorder No. 1	\$1500	\$2000

Notes:

1. Costs are for a single channel.
2. The shielding costs are not required for elements that follow the telemetry link.
3. Elements in front of the telemetry link are expended; elements behind the telemetry link are recoverable.

For an atmospheric test, the shielding costs would increase because of the additional requirement for protection from ionizing radiation. Test schedules are often as short as sixty to ninety days and emergency procurement and premium transportation charges may increase the costs shown here.

From this example, we see the following:

- A. Costs increase as the telemetry link moves toward the recorder.
- B. Costs decrease when existing plant equipment is available.

Description of a Compromise Instrumentation System

Figure D-2 illustrates the elements of a system that uses a long telemetry cable between the impedance matching network at the sensor and the translation equipment located at a remote recording station. This is not the highest quality system nor is it the most costly. The translators and the recording equipment are recoverable and re-useable and the sensors and telemetry cables are expended in each experiment. A thorough analysis of this system is reported by Mr. R. L. Rutter in SC-RR-64-960 "Project Dribble, Salmon Event - Preoperational Report."

A brief summary of this report follows.

The sensors are variable impedance devices connected in a bridge circuit. As the sensor varies the impedance of the bridge elements, a carrier signal is amplitude modulated.

The calibration auxiliary is located at the sensor bridge and consists of a resistor and a relay switch that can be operated by remote control cables. The switch connects the resistor in parallel with one leg of the sensor bridge and thus generates a known modulation of the bridge impedance.

The impedance matching network is a pair of transformers that couple the sensor bridge to two balanced transmission lines and the turns ratio of the transformer is selected to match the bridge impedance to the characteristic impedance of the transmission lines. For convenience, the transformers are center tapped to allow the phantom circuit associated with the two transmission lines to be used with the calibration relay.

Telemetry link No. 1 is a four conductor shielded cable that provides two balanced transmission lines with characteristic impedances of $300/45^\circ$ ohms and with a transmission attenuation less than 2 db/mile.

Translator No. 1 converts the variable impedance of the sensor into an analogue voltage. It consists of a 3 kc power supply for driving the sensor bridge and a phase sensitive demodulator for recovering the information signal from the amplitude modulated carrier generated by the sensor bridge.

Translator No. 2 is a voltage controlled oscillator that transforms the analogue voltage from translator No. 1 into a frequency modulated format. This format is necessary to overcome the amplitude noises generated in magnetic tape recorders.

Recorder No. 1 is a magnetic tape recorder located from 1 to 5 miles away from the sensor. Tape recorders are preferred to film recorders because the records are not damaged by ionizing radiation.

Telemetry link No. 2 is a healthy young instrumentation engineer who hand carries the magnetic tape record to the data reduction laboratory.

Recorder No. 2 transcribes the original record into a digital format suitable for input to a computer and generates oscillographs suitable for reporting.

Sensor Characteristics

Figures D-3, D-4, D-5, and D-6 are taken from SC-RR-64-960, and they describe the characteristics of a damped sensor such as an accelerometer, pressure gage, stress gage or strain gage. Figure D-3 is a schematic diagram of such a sensor and shows the arrangement of a sensor mass spring system with variable reluctance read-out impedances. Figure D-4 shows the response of such a system to a step input. Figures D-5 and D-6 show the phase and frequency response of such a system to sinusoidal steady state signals.

From these nomographs, we can see that systems with a damping factor of 0.7 have a fast response, a small overshoot, and rapid damping of transient induced oscillations; have a phase shift characteristic that is a constant function of frequency through the pass band from zero to the natural frequency of the sensor and have a frequency response that is essentially flat through this pass band. These conditions are optimum for applications where sensors are subject to shocks or step input signals while measuring transients whose periods are long in comparison with the natural period of the sensor.

Undamped sensors will oscillate and when excited by repeated transients, they may sum the input signals until the resulting oscillations extend into the non-linear region of the sensor. A damping ratio of 0.7 is the only condition other than zero, that will produce a phase shift that is a constant function of frequency through the pass band from zero to natural frequency. This characteristic is essential to minimize distortion, i.e., to keep all harmonic components of a complex long period transient in proper phase with each other and with the fundamental period of the wave.

Remote Calibration System

When long telemetry cables are connected to a resistive or reactive bridge circuit, the impedance of each bridge component is modified by stray capacitance in the cables. When such a bridge is calibrated on short cables and subsequently operated with long cables, the sensitivity and phase characteristics of the system are radically changed.

It is often impractical to generate calibration stimuli for sensors after the systems are installed in the field, and for this reason a method of isolating sensors from cable effects is very desirable.

A general solution to this problem is complex and lengthy to derive. An examination of the response of a typical circuit is relatively easy and demonstrates the nature of the problem and suggests a useful solution.

Figure D-7 illustrates the response of a potentiometer with and without capacitance loading. Without loading, the output is proportional to the resistance change and no phase shift occurs in the network. With capacitance loading, the response is not linear and the sensitivity approaches zero at the center of the potentiometer. Capacitance loading, in this case, causes phase shifts ranging from plus 80° to minus 16° .

Figure D-8 illustrates the response of an inductive divider with and without capacitance loading. The extreme distortion shown here is occasioned by resonance at two positions of the variable inductor. Phase shifts are not shown, but variations of 180° are to be expected when tuning through resonance.

Figure D-9 illustrates a bridge circuit modified by cable capacitance. Here we see a fixed resistive potentiometer and a variable inductive divider very similar to those shown in Figures D-7 and D-8. The output from this circuit can be inferred by subtracting the curve of Figure D-7 from that of

Figure D-8. If the capacitors are proportional to cable length, it follows that the response of the bridge will change radically as cables are lengthened.

Figure D-10 shows a bridge circuit isolated from cable capacitances. Isolation is accomplished by a Faraday shield and line matching transformers. Properly terminated lines have a characteristic impedance that is constant for all line lengths.

For small changes in the calibration impedance Z_c , this circuit will generate signals proportional to ΔZ_c and phase shifts will be small. If the sensor impedances, Z_s , are balanced and operate out of phase, the signals they generate will be proportional to the change in sensor impedance and phase shift will be zero.

Figure D-11 illustrates the relation between signals generated by the calibration impedance Z_c and the signals generated by a sensor. This relation holds for all lengths of cable, for all amplifier gain settings, and for all values of bridge excitation voltage. In practice, therefore, calibration records show only the relation of Z_c to sensor stimulus.

Figure D-12 is taken from Reference 2, and it describes the accuracy of a remote calibration system. In this analysis, measurements are assumed to be equal to good laboratory practice, but the values of the hardware and circuit elements are assumed to meet manufacturers' tolerances.

Telemetry Cables

Complete shielding of long cables is impractical, therefore cables should be designed to be insensitive to environmental effects. The effects of stresses and strains can be attenuated by constructing cables with elastic materials and by coiling them in a spiral pattern around a void. Additional protection can be provided by surrounding the cables with a crushable material and by shallow burial in the earth. Protection from electro-magnetic fields is best accomplished by using well balanced electrostatically shielded cables with symmetrical terminating circuits. The shield adjacent to the balanced line should be well insulated from earth and should be grounded at one point only. Noise induced by explosions has been observed to be 60 db lower in balanced lines than in coaxial cables.

BIBLIOGRAPHY

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2. R. L. Rutter and F. K. Millsap, "Project Dribble, Salmon Event, Pre-operational Report Characteristics of Instrumentation for Project 12.10," Issued by Sandia Corporation, August 1964, SC-RR-64-960.

Figure D-1. A General Instrumentation System

Figure D-2. A Compromise Instrumentation System

Figure D-3.: Variable Reluctance Sensor

Figure D-4. Response of a Seismographic System to a Unit Step Function of Acceleration

Figure D-5. Phase Angle ϕ as a Function of Frequency Ratio for a Seismographic System

Figure D-6. Frequency Response of a Seismographic System to a Sinusoidal Acceleration

Figure D-7. Response of Potentiometer With Capacity Load

Figure D-8. Response of Inductive Divider With Capacitive Load

Figure D-9. Bridge Circuit Modified by Cable Capacitance

Figure D-10. Bridge Circuit Isolated From Cable Capacitance

Figure D-11. Calibration Impedance Versus Sensor Stimulus

$$g_a = g_c \left[1 \pm (\epsilon_1 + \epsilon_2 + \epsilon_3 + 2\epsilon_4 + 2\epsilon_5 + \epsilon_6 + \epsilon_7 + \epsilon_8 + \epsilon_9) \right]$$

$$g_a = g_c \pm 7.8\%$$

$$g_a = g_c \pm 2.8\%$$

ADDITIVE

$$\sqrt{\sum_{i=1}^{i=9} \epsilon_i^2}$$

Figure D-12. Calibration Accuracy