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Guidelines for Selecting Seismic Detectors for High-Resolution Applications

By C. Melvin Lepper

UNITED STATES DEPARTMENT OF THE INTERIOR

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CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS--Continued

TABLES

GUIDELINES FOR SELECTING SEISMIC DETECTORS FOR HIGH-RESOLUTION APPLICATIONS

by

C. Melvin Lepper[1]

ABSTRACT

To provide the U.S. mining and energy industries with information in the selection of seismic detectors for high-resolution applications, the Bureau of Mines evaluated 35 velocity detectors (geophones) and 9 accelerometers.

It was found that velocity detectors with natural frequencies from 10 to 100 Hz were effective for seismic studies in the 5- to 600-Hz spectrum and that accelerometers were most effective in the 100- to 1,000-Hz range. Although the accelerometers described in this report performed about equally with the better velocity detectors tested, the accelerometers showed higher output voltage levels at higher frequencies, which is an advantage.

It is important that a seismic detector and its intended purpose be matched properly to achieve the intended results in high-resolution applications. There are many factors that could affect proper matching, thus careful selection of the best detector for a particular application must be exercised.

INTRODUCTION

Changing demands of the U.S. mining and energy sectors have placed some new requirements upon the seismic industry. The purpose of this report is to provide the mining and geophysical service industries with information that will aid in the selection of seismic detectors for high-resolution applications. The report describes the important parameters that should be evaluated.

Although currently available geophones provide effective signal detection for many high-resolution applications, improved dectors capable of high-frequency detection would allow expansion of ultrahigh-resolution seismic reflection studies. The use of other high-resolution geophysical measurement techniques in conjunction with ultrahigh-resolution seismic techniques could provide greater resolving potentials for investigators and could lead to an integrated geophysics approach to geophysical investigations. The mining and

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energy industries of the United States will find that an integrated geophysics approach can provide answers to many of the present and future geologic questions.

BACKGROUND

A fundamental understanding of the physics of motion will be helpful to the readers of this report. An understanding of displacement, velocity, and acceleration are vital for an appreciation of the work described. A very brief discussion in included; however, if further knowledge is desired, the topics are well-covered in most physics texts.

Displacement is the linear movement of a particle or a body from one point to another. It is measured in meters, feet, or multiples of these.

Velocity is the rate of change of displacement and is measured in meters or feet per second.

Velocity is calculated from the mathematical formula.

$$v = 2\pi f \mu, \qquad (1)$$

where π = 3.1416 (a constant),

f = frequency in hertz,

and μ = displacement in meters.

Geophones, which are actually velocity-sensitive seismic detectors, respond to particle velocity changes of the earth.

Acceration is the rate of change of velocity with time. The mathematical formula for computing acceleration is

$$\alpha = 2\pi f v, \qquad (2)$$

where π = 3.1416 (a constant),

f = frequency in hertz,

and v = velocity in meters per second.

Accelerometers are detection devices that respond to an acceleration type stimulus, thus their classification as accelerometers. Accelerometers exhibit a 6-dB/octave greater output voltage than velocity detectors when both are excited with a constant velocity signal. Figure 1 shown the output voltage of a velocity detector and that of an accelerometer versus frequency with accelerometer output voltage increasing at the 6-dB/octave rate with increasing frequency of excitation. The earth's near surface absorbs high-frequency sonic signals thus causing attenuation of the high-frequency seismic signals.

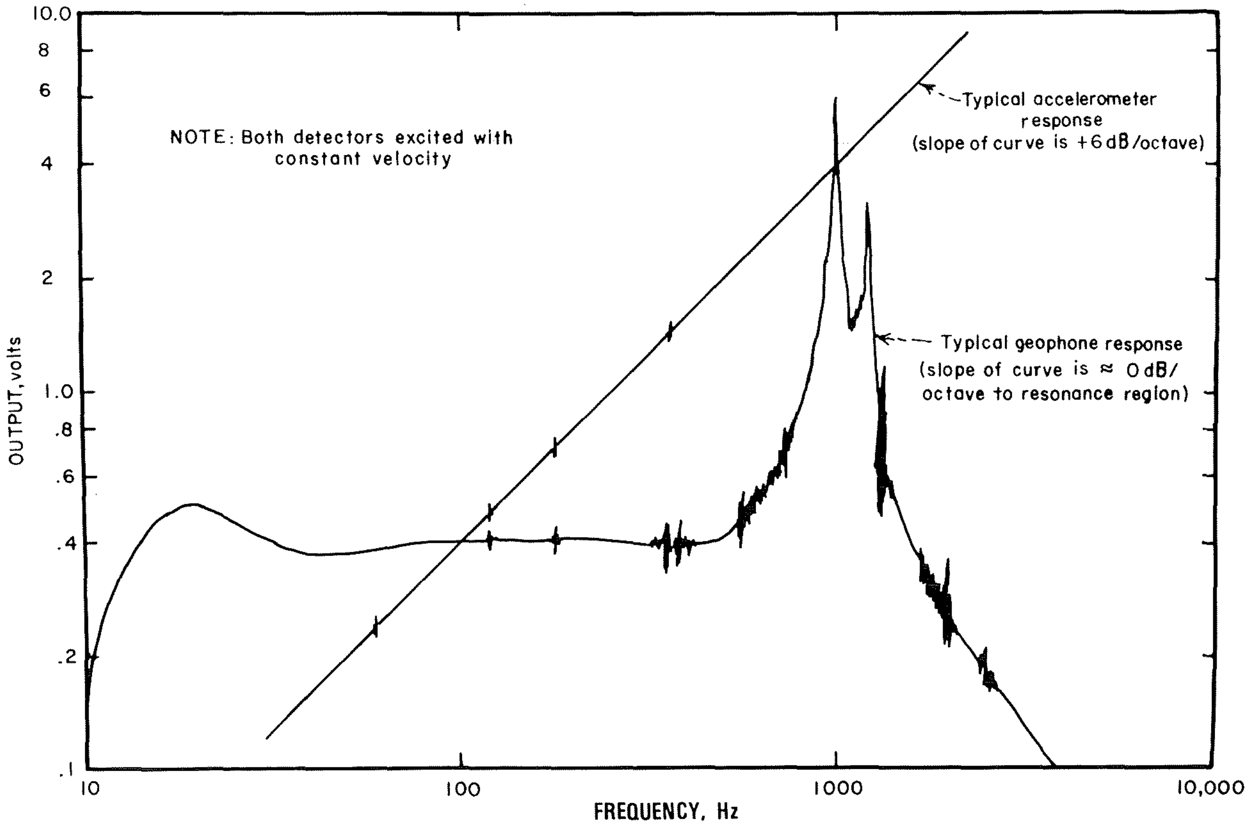


FIGURE 1. - Output voltage of a velocity detector and an accelerometer with changing frequency and constant velocity.

Accelerometers used as seismic detectors tend to compensate for the attenuation of high-frequency signals traveling in the earth; for this reason, accelerometers are more often being considered as seismic detectors.

Geophones are typically moving coils suspended in a magnetic field. The coils are free to move relative to the magnetic structure that is attached to the detector case. Variations of this arrangement are in use, such as the moving magnet versus fixed-coil arrangement. Regardless of the construction of the geophone, a movement of ground (earth) into which the geophone is "planted" causes it to produce a small output voltage that is proportional to the particle velocity of the ground. Until recently, geophones were designed to respond to the very low end of the frequency spectrum, typically between 1 and 50 Hz, because use of these very low frequencies was required for petroleum explorations. Since the earth is a very absorptive medium that filters out much of the high-frequency energy, the emphasis was on low-frequency geophones.

With the changing emphasis on energy demands in the recent past and for the foreseeable future, the use of shallow seismic investigations has increased. Shallow studies for coal, in particular, demand the use of very high-resolution seismic reflection methods for mapping deposits and anomolous geologic conditions near the earth surface. Since the typical petroleum-type geophone is not well suited for shallow high-resolution reflection applications, the use of high frequencies is essential to obtain the necessary resolution of geologic structures at the shallow depths. Geophone manufacturers have recently recognized the need and the demand for this type of detector and have responded with some improved models in their product lines. However, much work remains to be done to produce detectors specifically suited to very high-resolution seismic investigations.

GENERAL DISCUSSION

Mining Industry Needs

Traditionally, mining disciplines have used seismic investigations sparingly. But with the need for greater coal production, the increasing interest in uranium deposits, and increased environmental constraints, higher resolution seismic reflection studies are desirable. The geologic problems of the U.S. mining industry are normaly found at a depth of 300 meters or less. To obtain the necessary resolution of geologic structures at these shallower depths, high frequencies must be used. This, in turn, requires the use of high-frequency detection devices, as well as refinements in field data acquisition techniques and innovative measures in data processing.

One of the problems associated with performing shallow high-resolution seismic reflection studies is the ground roll or low-frequency interference that results from the seismic energy source. Other low-frequency interference also originates from domestic sources such as road traffic, mining operations, rotating machinery, persons walking, wind, aircraft, and 60-Hz powerlines. Often these sources generate large amplitude ground signals that interfere with the collection of usable data from the seismic field endeavors. The attenuation or elimination of these noise sources is of prime importance. Seismic detectors can help reduce these problems to a workable level.

With improved field instruments and greater processing power at permanent computer centers, high-resolution reflection is now practical for many geologic studies related to mining. The Bureau of Mines has directed a considerable portion of its efforts toward solving this problem over the last several years.

Petroleum Industry Needs

The oil industry uses seismic investigations to search for petroleum sources to great depths which require the use of very low frequencies--in the range of 1 to 50 Hz--to allow seismic signals to penetrate the earth strata, often to depths of a few thousand meters. The seismic signals reflected from a geologic structure return to the earth surface where the geophone detects the feeble resultant surface motion. Since the earth is a very absorptive medium for seismic signals above 100 Hz, the emphasis is on low frequencies for deep work. Seismic detectors for oil exploration are probably adequate for today's needs, but the same detectors are not adequate for shallow mining applications.

Fieldwork Evaluations

During recent Government and industry research in high-resolution seismic reflection, serious velocity detector deficiencies were discovered. The limitations of some standard 14-Hz geophones for high-resolution investigations was observed during field tests requiring the collection and recording of frequencies to about 1 kHz. It was discovered that for the intended new application, the recently purchased geophones in use were totally inadequate for the application. At typical low seismic frequencies, the geophones performed satisfactorily, but at frequencies above 200 Hz the geophone outputs were weak and distorted. To determine the reason for the poor performance, several of the geophone cases were opened and inspected. The elements were found to be electrically satisfactory; however, they were isolated from the case by a layer of silicone rubber on the bottom, top, and sides. Silicone rubber is soft and pliable at moderate temperatures, and with the active element cushioned in this material, contact with the case was not sufficient to transmit the high-frequency energy into the detector active element. This "potting" method apparently has been used by most manufacturers of "standard" geophones for many years. The assembly technique is a quick, inexpensive method for holding the active element in the case and produces a good environmental seal that cannot be overlooked. This technique is probably an acceptable mounting method for detectors used at low frequencies, as there is little decoupling effect at frequencies below 50 Hz; however, at higher frequencies, the silicone serves as a very efficient decoupling medium and prevents the geophone from properly responding to stimulation. For high-frequency work, intimate coupling between the active element and the case must be achieved. Therefore, improved mounting methods must be devised to be used in high-resolution seismic detectors.

To improve the performance of these detectors, all geophones were opened and the silicone removed. The active element was reinstalled using stainless steel spacers in the bottom of the case to insure that the active element was held securely to the case bottom. A remarkable improvement was noticed immediately in the high-frequency response of the units.

Since intimate coupling must be achieved between the active element and case for high-frequency work, a check of geophones should be made to determine the adequacy of the mounting. And, since silicone is too soft and pliable, it should not be used to secure the active element to the case in geophones for work above 100 Hz.

Industry Testing Procedures

Testing of geophones by manufacturers is usually done electrically, either by the "damped response" method or the "motional impedance" method. Both methods are relatively inexpensive and can determine the electrical characteristics of a geophone. Using a circuit such as the one shown in figure 2, the coil is driven by a voltage produced by an oscillator and the output response of the unit under test is plotted as a function of frequency. This gives an indication of the spurious noise and distortion in the detectors.

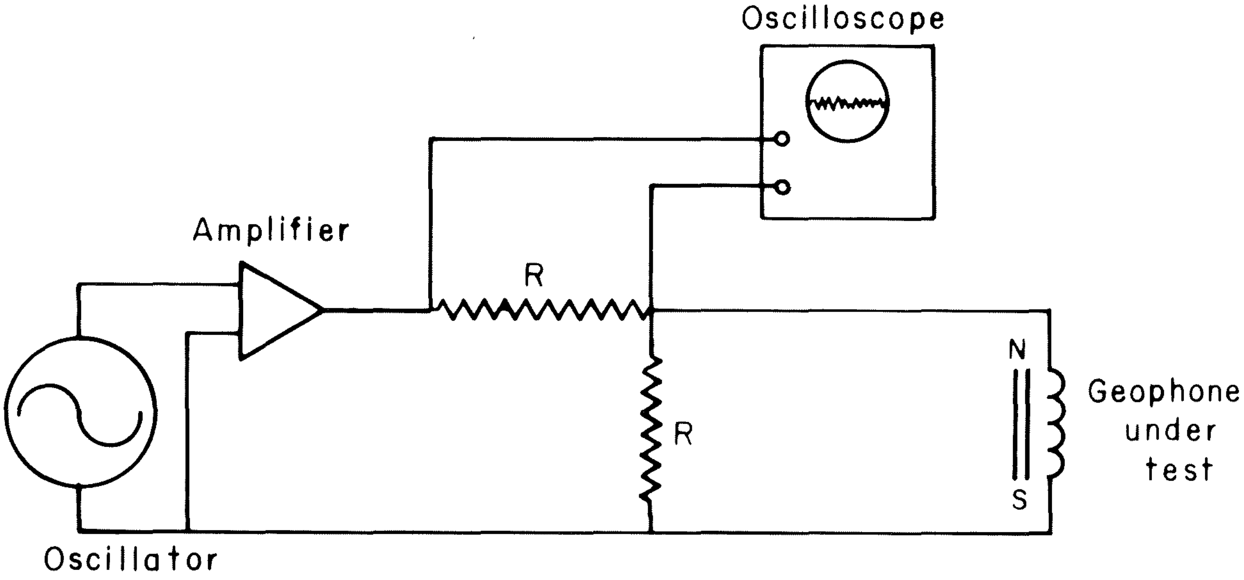


FIGURE 2. - Manufacturer's typical test technique.

The geophone sensitivity is also determined from this test setup. Although this method of testing geophones is adequate for some applications in the industry, it does not clearly define all of the electrical characteristics of geophones, especially the frequency response over a given bandwidth. Seismic detectors are expected to produce an output voltage proportional to an earth movement--most often a very minute movement. This stimulus is physical, not electrical: it is applied to the detector case and then to the internal electromechanical element by physical coupling. The output voltage is thus a function of the case motion. To realistically determine the true response of the detector to a physical stimulus at high frequencies, more useful tests can be performed by applying a vibrational stimulus to the base of the detector. Although applying a vibrational stimulus is a well-known evaluation method, it is expensive and time consuming and has been used infrequently for geophone testing.

BUREAU TESTS

In an attempt to determine which presently available seismic detectors best meet the needs of the seismic industry for mining applications, the Bureau undertook the testing of some representative samples of U.S.-manufactured seismic detectors. Three geophones of each type furnished were tested to establish detector performance and manufacturing uniformity. Tests were also performed on several types of accelerometers for comparison.

Test Specifications

The test specifications were established after a thorough study of field seismic work from which particle velocities were determined. Most often the velocity levels were found to be quite low, on the order of 10^{-3} to 10^{-6} cm $\cdot \text{sec}^{-1}$ producing detector output voltages between 1 μV and 1 mV. Input amplifiers raise these voltages to usable levels for recording the data in memory and/or on tape.

The data in table 1 details the desired test parameters for the detector evaluations and those actually achieved in this series of tests. Note that not all of the desired test parameters were attainable because of the stringent levels.

TABLE 1. - Test parameters

Parameter	Desired	Obtained
Waveform.............	Sinusoidal................	Sinusoidal.
Bandwidth............	10 Hz to 10 kHz...........	20 Hz to 5 kHz.
Level................	10^{-5} cm/sec................	10^{-3} cm/sec, typical.
Excitation...........	Mechanical................	Mechanical.
Axis.................	Vertical..................	Vertical.
Sweep rate...........	Slow......................	1 to 2 octaves per second.
Sweep duration........	5 min (minimum), 15 min (maximum).	5 min, typical.
Sweep type...........	Upsweep only...............	Upsweep.
Input level control...	By calibrated accelerometer	Special high output accelerometer.
Response documentation	X-Y plot-amplitude versus frequency.	X-Y plot-amplitude versus frequency.

Seven environmental test laboratories in the United States were contacted while setting up this series of tests. One laboratory concluded that the prescribed tests could be performed satisfactorily at or near the desired specifications in test facilities.

Equipment Setup

The tests were performed using the equipment arrangement shown in figure 3. The vibration exciter, control accelerometer, detector under test, and the low-noise preamplifiers were all enclosed in a quiet test chamber to reduce ambient and electronic noise. To reduce physical noises to an acceptable level, the vibration exciter was placed on a massive seismic block isolated from the earth, building, etc., by a sophisticated suspension system. The limiting background noises were thus primarily electronic in nature. The input levels of vibration excitation are as low as could be obtained practically with the given setup and are considered reasonable for these prescribed tests.

Test Procedures

The test procedure used to obtain the response of the detectors was finalized after making preliminary tests of the instrumentation and test fixtures. Initially, the electronic noise level and its spectral distribution were determined. Due to the very low test levels desired and the inherent noise in the monitoring systems, a low-noise preamplifier was necessary to raise the level of the detector output signals to give good signal-to-noise ratios and to allow reliable recordings to be made of the output signals. A Princeton Applied Research (PAR) model 113 low-noise amplifier, operating at a gain of 200:1 (46 dB), and with a bandwidth of 10 Hz to 10 kHz, was used. The

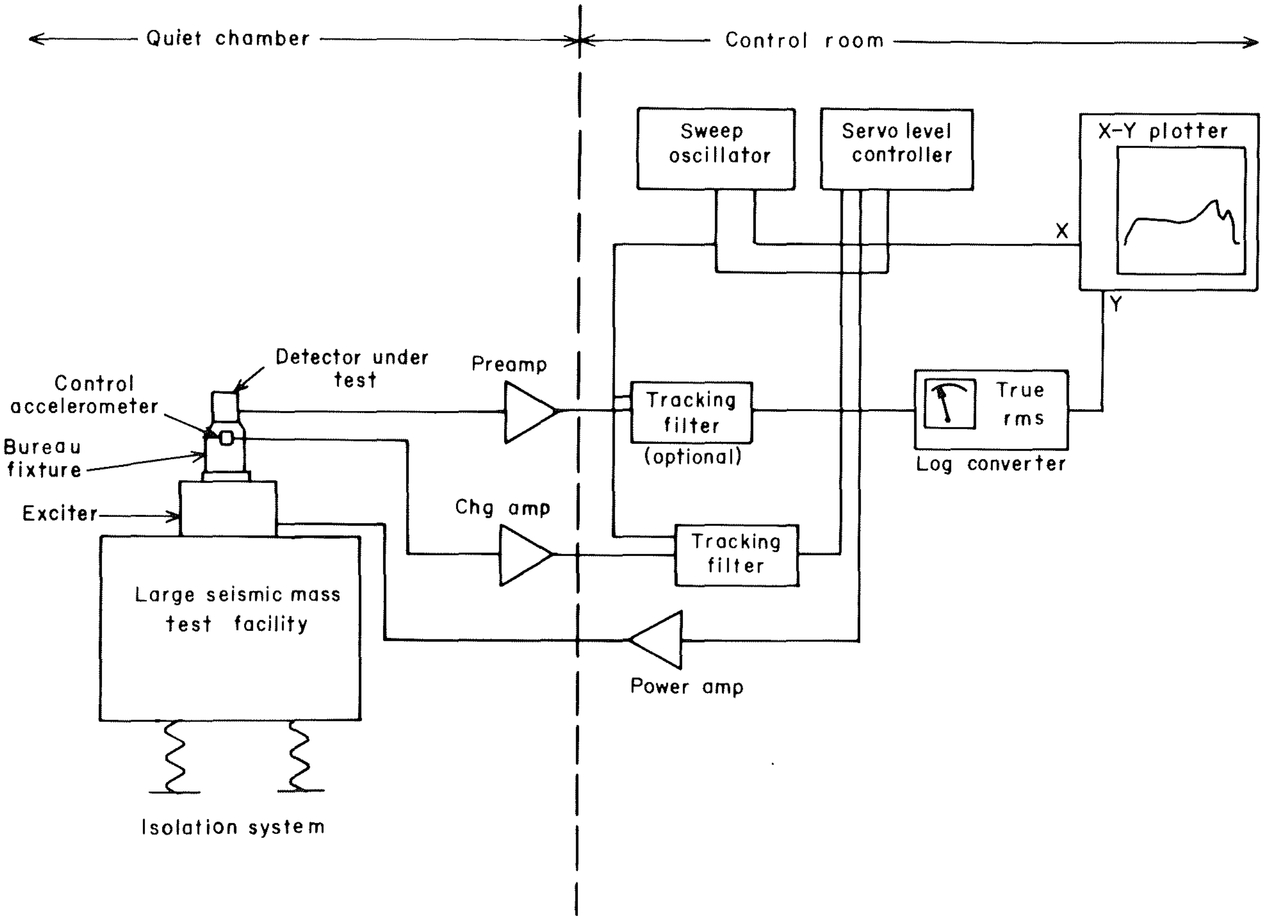


FIGURE 3. - Instrumentation setup used for testing all detectors.

low vibration levels in these tests were closely controlled by individually selected components. A high output accelerometer was chosen to monitor the test levels and to provide input signals to the servocontrol amplifier. This accelerometer (Endevco 7708-500) and its associated charge amplifier (model UD-11) have calibration curves traceable to the National Bureau of Standards references.

Since vibrational levels were to be controlled by an accelerometer and it was desired to test the geophones with a constant velocity input, the servo-level controller was set to utilize a built-in precision integrator, thus controlling the vibrator in the constant velocity mode. Note that all response curves are normalized to volts per centimeter per second even though the input levels were on the order of 10^{-3} cm•sec^{-1}. The normalization of all curves to the same scale makes it easier to compare the specimens.

Test Fixtures

The setup used for these tests is shown in figure 4, with the vibration exciter, the test fixture, a mounted geophone, and the UD amplifier in a typical arrangement. The test fixture is constructed from a piece of solid aluminum stock. The dimensions and design details of the Bureau of Mines test fixture are presented in figure 5. The fixture was designed to fit the

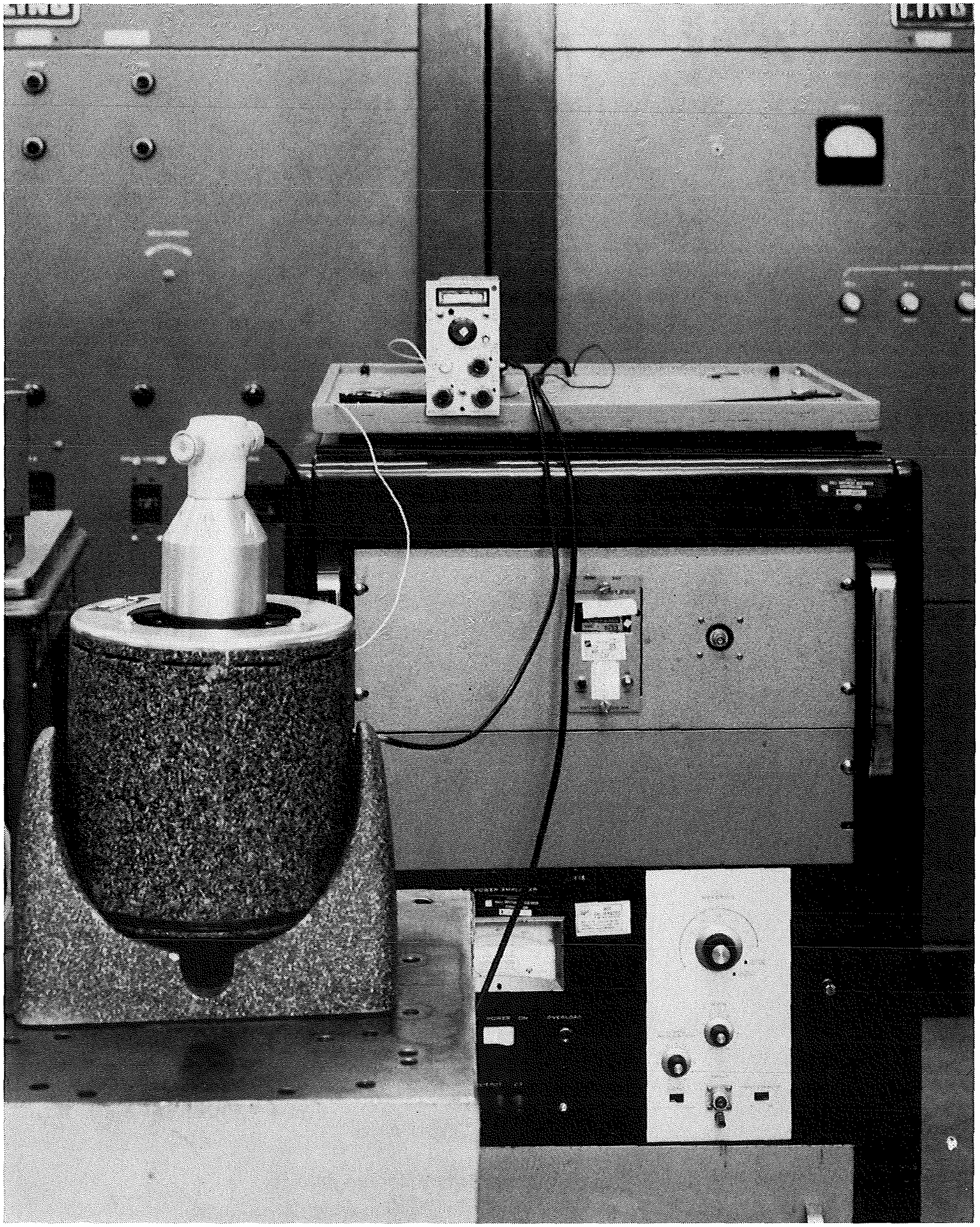
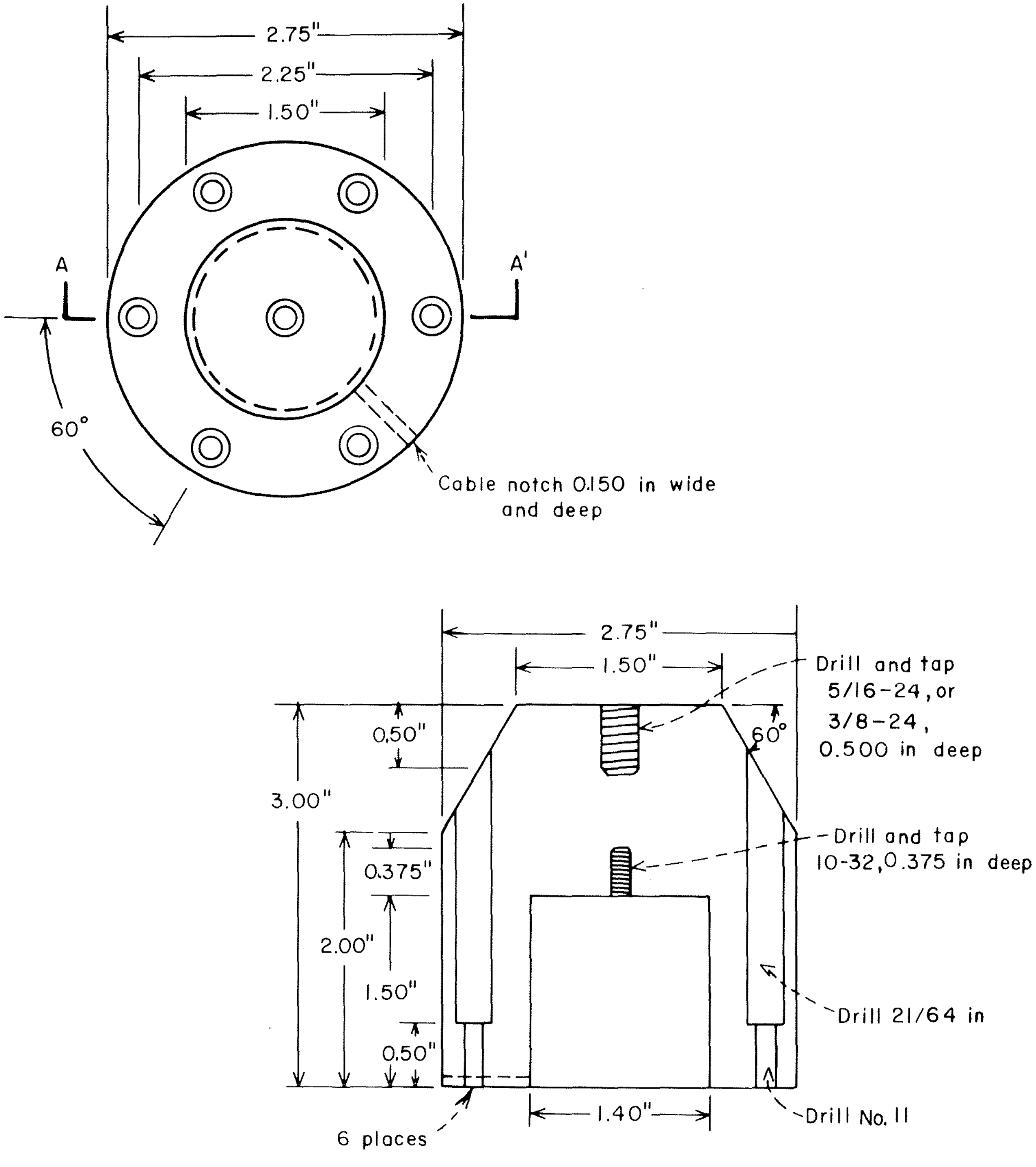


FIGURE 4. - Vibrator, test fixture, and mounted geophone.



SECTION A–A'

FIGURE 5. - Vibration fixture design details.

armature of a model PM 50 vibration exciter manufactured by MB Electronics. The back-to-back arrangement of the control accelerometer and the detector assures that the input signal levels are controlled from a point in close proximity to the base of the detector under test. It further insures that the detector is excited at the amplitudes measured and in an orientation that closely approximates those typical of actual field uses. The control accelerometer and the test fixture were evaluated before any detector testing was begun.

Vibration Level Control

After mounting the control accelerometer in the test fixture, G-level plots were made to check the associated circuitry and to verify the capability of this instrumentation to provide adequate vibration control. The results, shown in figure 6, demonstrate that this equipment provides acceptable control of the vibration levels used. The noise bursts are powerline interference at 60-Hz harmonics, but do not affect the linear control capabilities of the circuitry.

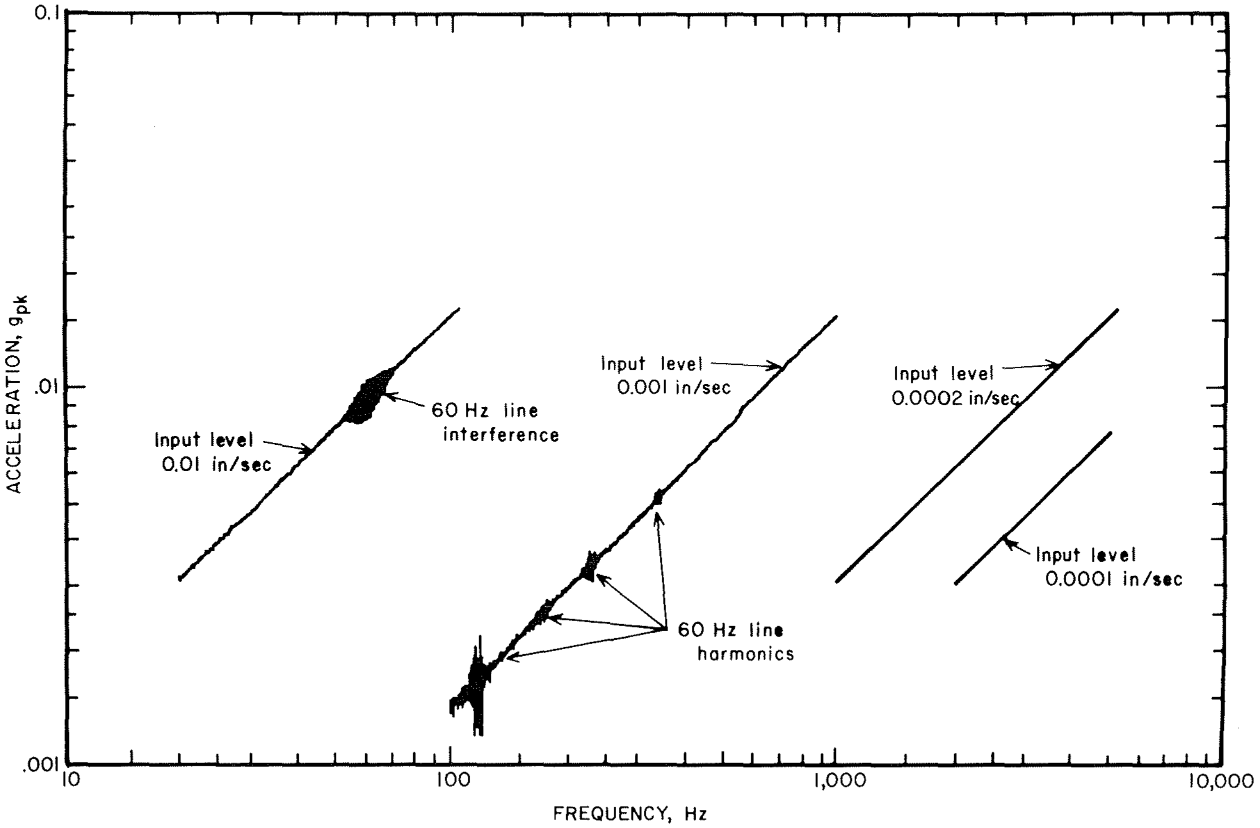


FIGURE 6. - Control accelerometer spectrum.

Fixture Integrity

To determine the integrity of the test fixture, it was attached to the vibration exciter head, and a miniature accelerometer was attached to the top of the fixture adjacent to a mounted detector to provide a typical load to the test apparatus. A transmissibility plot (fig. 7) shows the test fixture to be acceptable although not quite as good as could be hoped for in the spectrum above 2 kHz.[2] The large broad peak at approximately 3.5 kHz is a fixture resonance that may shift to a slightly lower or higher frequency with various detector weights. However, the resonance was not serious enough to prevent the use of the fixture as these peaks can be processed out of the test data with minimum effort. The presence and characteristics of these peaks must be known so that in later tests it will be recognized and the detector judged accordingly. Overall, the test setup was determined to be acceptable for the intended purpose, and it was used as shown throughout all of the detector tests.

Test Procedures

The manufacturers and model numbers for the detectors tested are listed in table 2 along with most of their specifications as given by the manufacturer's literature. The physical and electrical specifications were obtained from the manufacturer's literature supplied or, in some instances, computed. Each detector was tested using a sinewave input to the base of the detector. The frequency spectrum from 20 Hz to about 5 kHz was swept slowly at the prescribed level, while the detector output was monitored and plotted on an X-Y analog plotter. The resulting detector responses are presented as individual curves for each unit tested in figures 8 through 22. Remember that all responses are presented in output voltage versus velocity; that is, volts per centimeter per second, and that they are normalized to make comparisons easier.

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[2] The curve of transmissibility was produced from rationing A/B, where A was the accelerometer on top of the test fixture and B was the control accelerometer mounted in the fixture cavity as it would normally be found for these tests.

TABLE 2. - Specifications of detectors tested

Detector	Manufacturer	Type or model No.	Number of units tested	Natural frequency, Hz	Normalized transduction constant $(\sqrt{Rc})$, V/in·sec^{-1}	Coil impedance (Rc), ohms	Rated frequency band, Hz	Basic element dimensions, cm		Weight of electromagnetic element, g	Detector weight as tested, g	Weight moving mass (coils), g	Open circuit damping factor, pct critical	Open circuit sensitivity, mv/in·sec^{-1}	Operational orientation, vertical or horizontal
								Diameter	Height						
G-1.....	Geospace, Inc.	GS-100..	3	100± 5	0.037	600	To 650	3.20	3.40	125	375	6	60	900	Vertical.
G-2.....	...do......	GS-33...	3	40± 2	.05	420	To 250	3.43	2.54	75	-	7.5	28	1,020	Do.
G-3.....	...do......	GSC-11D.	3	14± .75	.042	380	To 500	3.18	3.36	111	145	16.1	39	810	Do.
M-1[1]	Mark Products.	L-100...	6	100± 5	.034	2,420	To 650	3.80	7.30	380	1,000	10.5	50	1,660	Vertical and horizontal.
M-2[4]....	...do......	L-30....	2	100	NA	1,570	NA	NA	NA	NA	NA	NA	NA	2,000	Vertical.
M-3.....	...do......	L-25E...	3	40± 2	.049	710	To 350	3.38	5.56	NA	185	NA	36	1,250	Do.
M-4.....	...do......	L-28E...	3	40± 2	.047	410	To 300	3.20	3.60	NA	150	NA	31	1,000	Do.
E-1[2]....	Electrotech	MD-81...	3	28± 2.8	.043	380	To 200	3.18	4.11	118	254	19.5	14	840	Do.
EN-1....	Endevco....	2219E...	3	16,000±1,600	NAp	(3)	To 3,000	2.31	2.02	72	72	NAp	NAp	[5]370	Vertical and horizontal.
H-1[4]....	Houston Products.	XC-5....	3	>1,000	NAp	(3)	To 1,000	NA	NA	NA	NA	NAp	NAp	[5]150	Do.
L-1.....	Litton.....	LRS-1000	3	10± .75	.021	630	270	2.22	2.54	41.9	NA	NAp	61	410	Vertical.
L-2[4]....	...do......	YA-1....	3	300	NAp	(3)	150	3.20	3.30	142	NA	NAp	NAp	[5]3,400	Vertical and horizontal.
D-1.....	Dymac......	M-80....	3	<20	NA	650	20-2,000	5.00	5.00	≈25	42.5	NAp	(6)	(7)	Do.

NA Not available.
NAp Not applicable.
[1] Run twice; second test performed on 3 units without shunts.
[2] Same as Geosource, Inc.
[3] Accelerometer.
[4] Prototype units. No specification sheet available.
[5] In millivolts rms per peak acceleration (mV_{rms}/G_{pk}).
[6] Eddy current critical.
[7] 100 mv/in·sec^{-1} into 10-k ohm load.

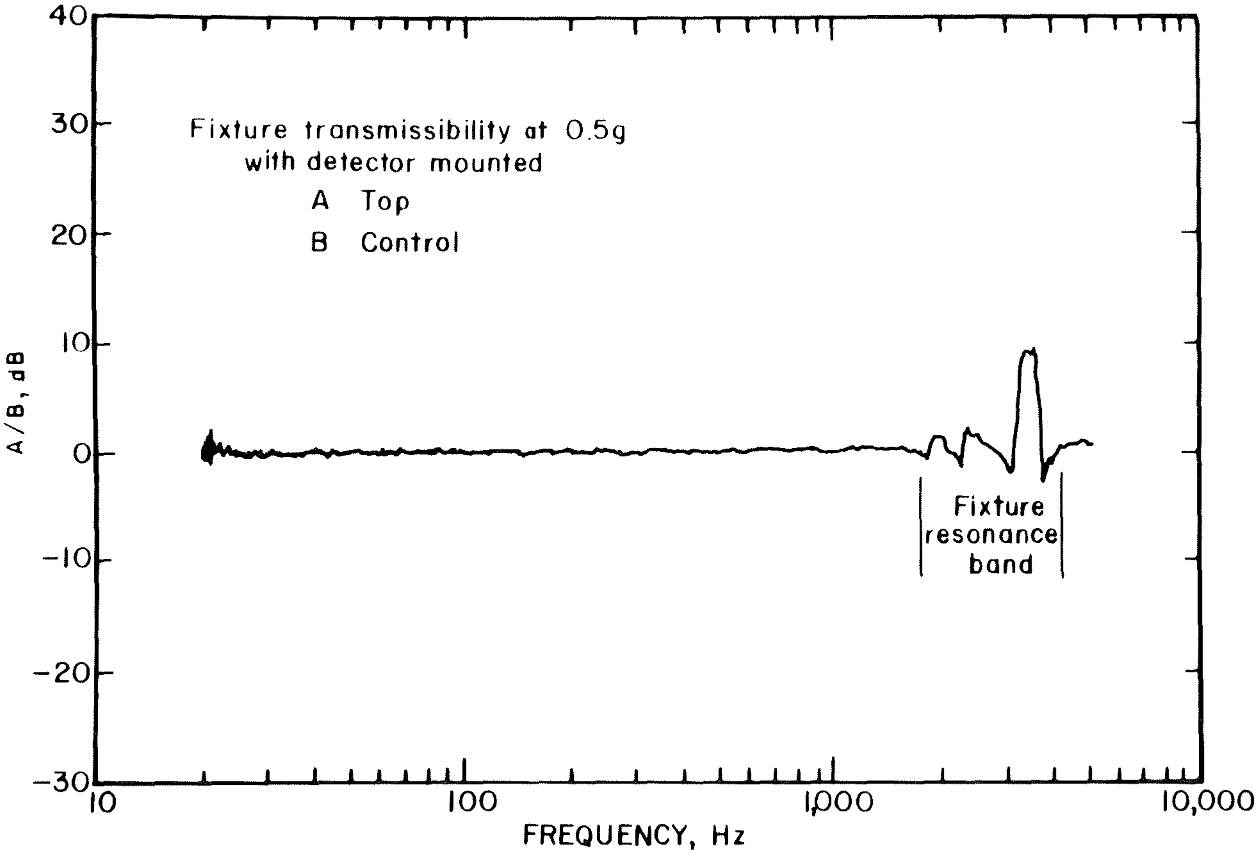


FIGURE 7. - Test fixture transmissibility plot. The curve results from the ratio A/B.

Discussion of Tests

Output voltage levels, resonant frequencies, resonant peak amplitudes, low-frequency rolloff, high-frequency response, damping, phase response, spurious noise, and tracking between like units are some of the factors that should be taken into consideration when selecting detectors for specific applications. Considering established field requirements, detector selection should be based upon the technical specifications for detectors falling into the usable category.

Keeping these factors in mind, a study of the following curves should be enlightening. The first spectrum analysis (fig. 8), is for three G-1 geophones. The output voltage of specimens A and B averaged about 0.4 $V \cdot cm^{-1} \cdot sec^{-1}$, but specimen C produced about one-half of this amount. The difference in output is most likely due to coil and suspension construction. This nonuniformity is common in geophones; however, most do not differ by a 2:1 ratio. The resonant peaks between 1,050 and 1,200 Hz are mechanical resonances of the coil and the suspension system used to center the coil in the magnetic field. Resonant peaks in the spectrum of a geophone output are often 10:1 higher than the average output level in the flat portion of the usable range. This detector is typical of many competitive units and is not considered abnormal. For

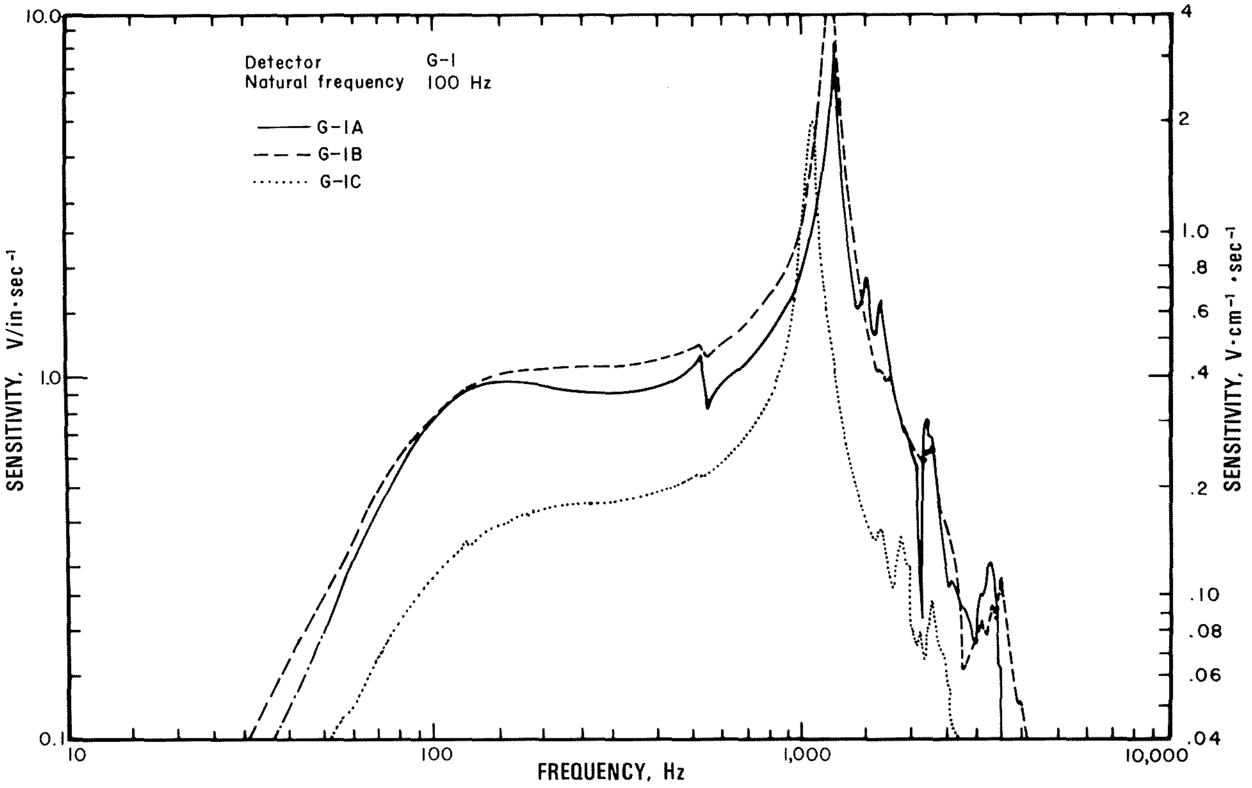


FIGURE 8. - Spectrum of three G-1 detectors.

very-high-frequency seismic work these peaks could cause serious saturation of the input circuits of the amplifiers. A low-pass filter would probably reduce the amplitude to a tolerable level without adversely affecting the rest of the spectrum. The most useful spectrum for this detector is from 100 to 500 Hz. All three specimens exhibit about 10-dB/octave rolloff of the frequencies below 100 Hz, which is very useful and desirable to eliminate low-frequency ground roll caused by the seismic source.

In figure 9, three G-2 geophone spectrums are shown to have exceptionally uniform output levels between units averaging about 0.3 $V \cdot cm^{-1} \cdot sec^{-1}$ in the midspectrum. The slight rise at 50 Hz is due to the natural frequency of the coil suspension elements. The damping network (1,500 Ω) tends to flatten this peak, which would be much higher if undamped. This geophone would be usable from 40 to 1,000 Hz. The resonant peaks due to coil and suspension design at 1,100 to 1,200 Hz are reasonable and show no intolerable spurious noises. The geophone should be suitable for high-resolution work provided that the low-frequency ground roll and domestic noises are not a problem at the survey site. If these factors are a problem, either a high-pass filter, set for about 70 Hz, should be used, or a geophone with a higher frequency rolloff would have to be used to reduce the noise factor in the geophone output. The uniformity of the three output voltages shows good quality control in these units.

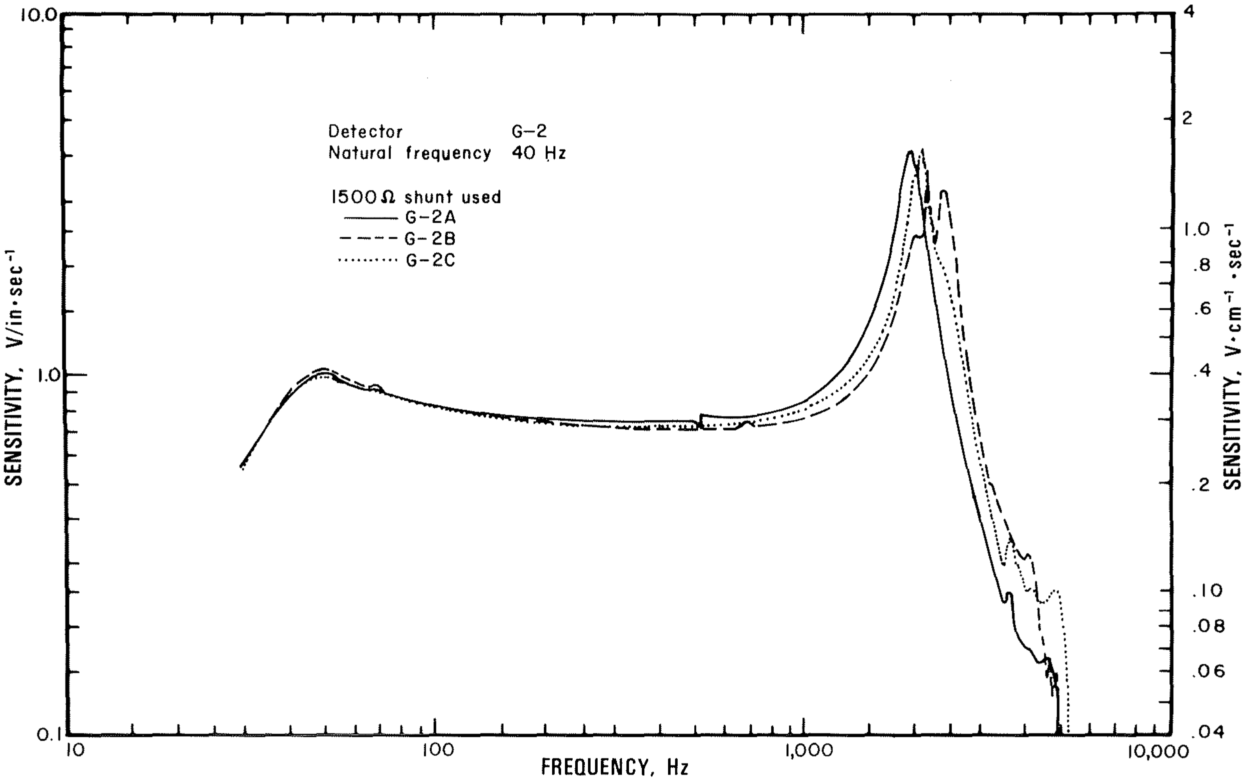


FIGURE 9. - Responses of three G-2 detectors.

The relatively flat spectrum from 100 to 1,000 Hz for three G-3 detectors was unexpected as these are ordinary geophones, figure 10. No damping resistors were installed in the output of these units during testing. A 2- to 2.5-$V\cdot cm^{-1}\cdot sec^{-1}$ resonant peak at 14 to 15 Hz (the natural frequency of the geophone) totally dominated the output signals at the test frequencies. These high-level, low-frequency peaks were troublesome because they could not be eliminated from the output even with special isolation of the test apparatus. After much experimentation, a 10-Hz bandwidth tracking filter was inserted between the PAR model 113 preamplifier and the monitoring instrumentation. This removed the low-frequency resonant peaks from the output signal and allowed the test frequencies to be recorded, but actually the low-frequency peaks were still present and in a field situation could cause serious problems for the input circuitry of the recording system due to amplifier saturation. Normally, 1.6-kΩ damping resistors would be installed to reduce these low-frequency peaks, which would reduce the output signals from about 0.4 to about 0.2 $V\cdot cm^{-1}\cdot sec^{-1}$. If this reduction of output were intolerable, an alternative solution might be to use high-pass filters after the geophones. The filters should have an attenuation rate of 20 dB/octave with rolloff beginning at around 80 Hz. The first high-frequency peaks are near 2.5 kHz, which would not be troublesome for normal high-resolution work.

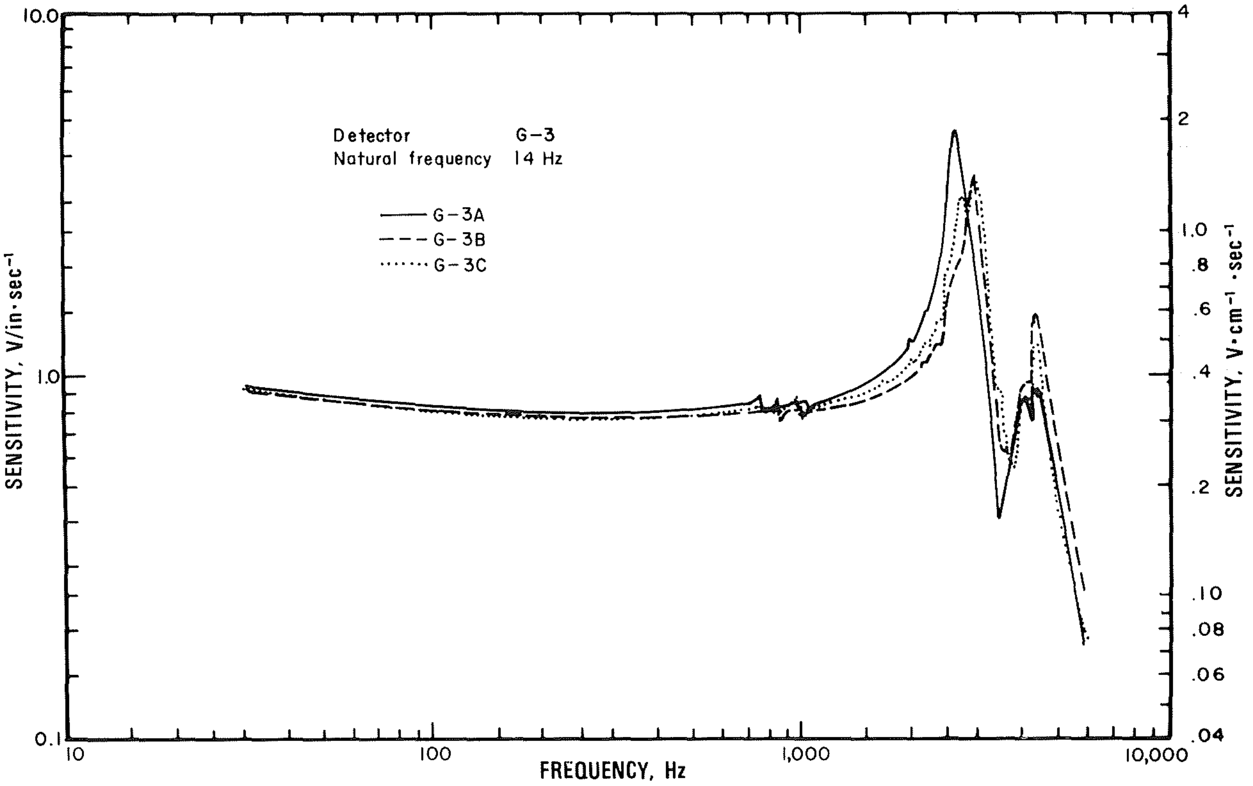


FIGURE 10. - Results of three G-3 detectors.

The spectrums of six M-1 geophones with 970-Ω damping resistors showed slight deviation in output voltages between units, figure 11. These detectors are designed to eliminate most low-frequency output voltages resulting from ground roll and other domestic noises. They are very effective for this purpose and thus eliminate many problems resulting from these phenomena. The attenuation rate for the detectors is about 5.5 dB/octave below 100 Hz, and the useful bandwidth is between 100 and 600 Hz, which is adequate for much of the present-day high-resolution work. The output voltage levels averaged about 0.2 V•cm^{-1}•sec^{-1}, which is a bit low compared with competitive units. If the recording instrument has adequate gain in the input amplifiers, say 100 dB, or has a programed gain feature, the output voltage of 0.2 V•cm^{-1}•sec^{-1} should not be a problem. M-1 geophones appear to be very rugged devices that are well-designed for protection from severe weather and rough handling. The M-1 geophones have another salient feature not found in all high-frequency geophones; the coil suspension mechanism allows the geophones to be used in the horizontal position for detecting horizontal p or s waves. This feaature can eliminate the need for two different sets of geophones when doing both vertical and horizontal studies. A major high-frequency peak for specimen E, located at about 674 Hz is not satisfactory, but the detector can still be useful since most of the data will be below this frequency in high-resolution efforts. The scattering of the high-frequency resonant peaks is probably due to differences in individual internal construction. The manufacturer might be able to insure that these peaks always occur above 1 kHz with better assembly techniques and closer quality control, making this a good detector for most shallow reflection applications.

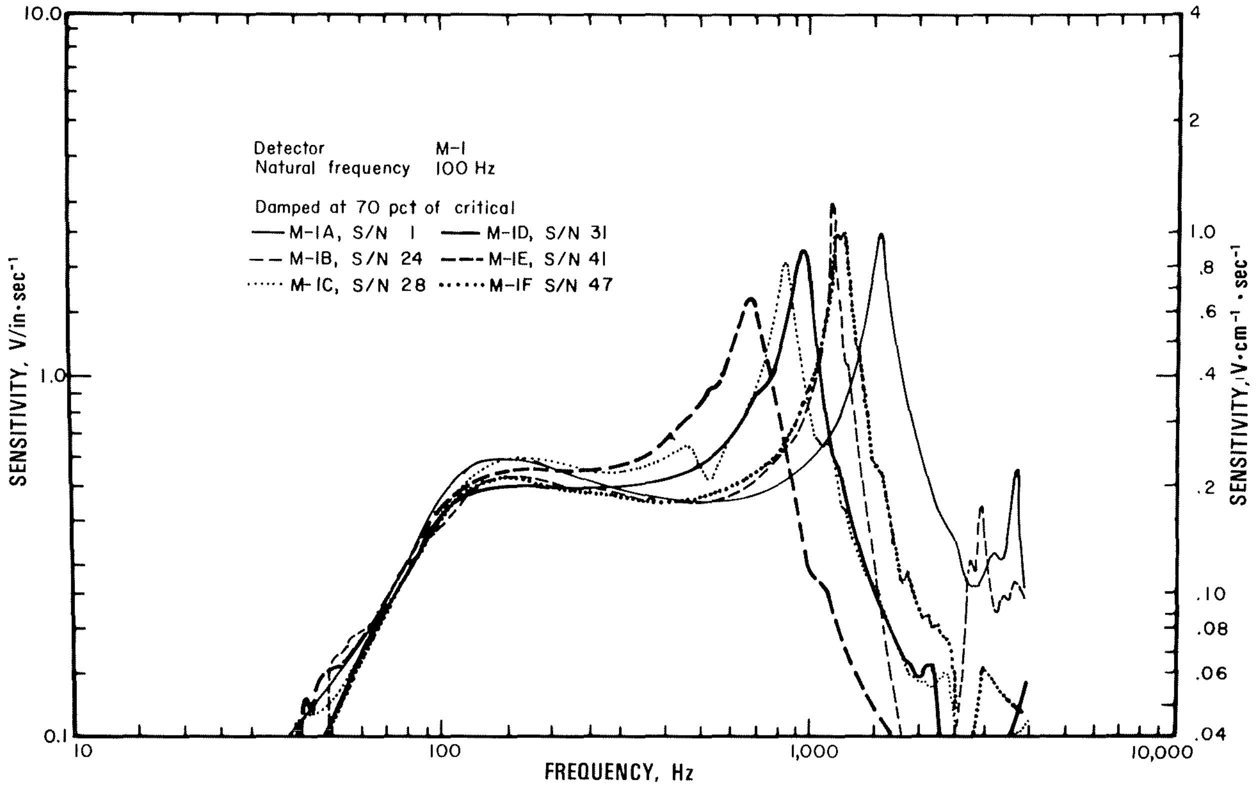


FIGURE 11. - Scattered frequency peaks of six M-1 detectors.

Figure 12 shows the results of testing three M-1 detectors with the damping resistors removed. Output signal levels came up from 0.2 $V \cdot cm^{-1} . sec^{-1}$ (damped units) (fig. 11) to about 0.6 $V \cdot cm^{-1} . sec^{-1}$ average (undamped). Specimen B produced a very distorted response curve for no explainable reason. This may be the result of a coil and suspension system antiresonance since the coil appears motionless at 375 Hz. Specimens A and E produced curves shaped much like they did when first tested with the damping resistors installed. These detectors apparently need damping resistors across their coil terminals. The use of 4-kΩ damping resistors would produce an output of approximately 0.4 $V \cdot^{-1} \cdot sec^{-1}$ and should allow responses similar to those shown in figure 11.

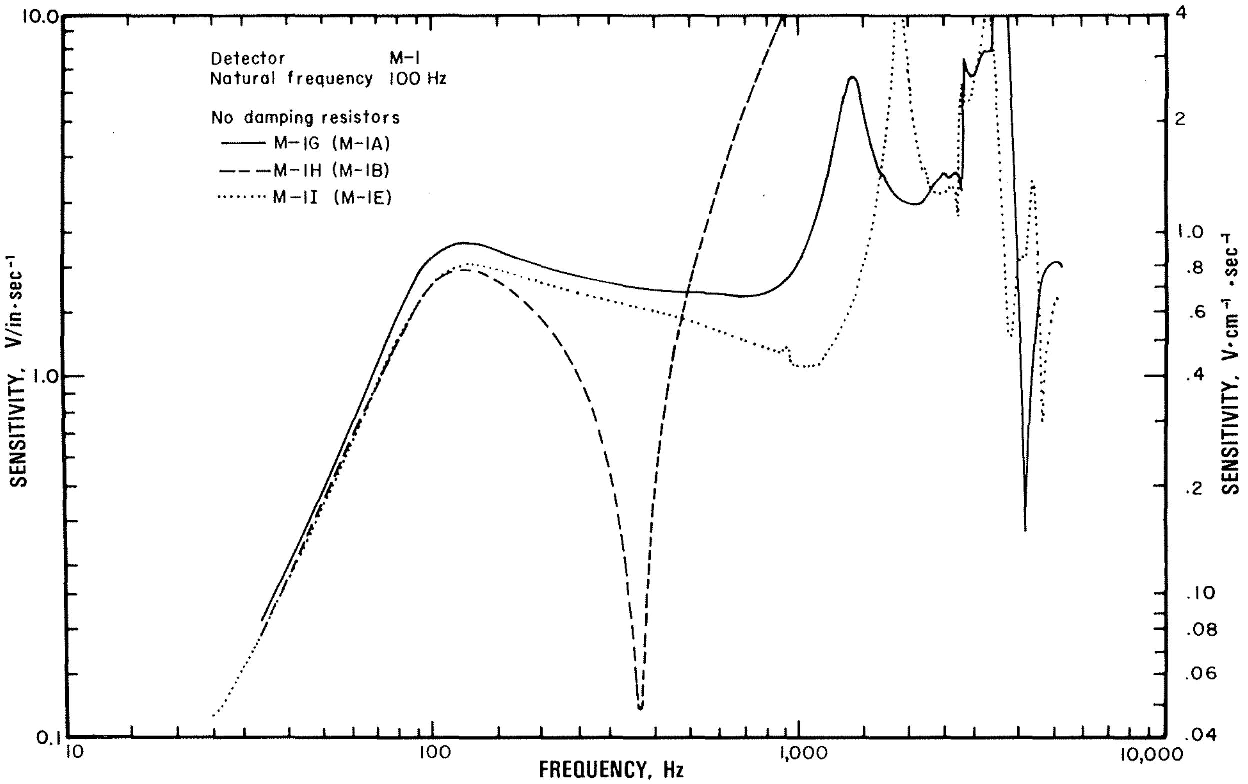


FIGURE 12. - Three M-1 detectors with damping resistors removed.

Two prototype M-2 detectors with natural frequency of 100 Hz exhibit excellent attenuation of all frequencies below 100 Hz at a rolloff rate of 11.5 dB/octave (fig. 13). The first high-frequency resonant peak for these detectors appear at 600 to 750 Hz and may be too near the upper working frequency of present-day high-resolution work rendering them usable from 100 Hz to only about 400 Hz. This bandwidth is narrow for high-quality detectors, but they are certainly usable for some higher resolution work. The outstanding feature of these detectors is the relatively high output voltage of about 0.75 $V \cdot cm^{-1} \cdot sec^{-1}$ in midspectrum. No damping resistors were necessary in these units, a decided advantage in terms of sensitivity figures. These detectors might be well-suited for application in special, low-level, narrow bandwidth high-resolution work.

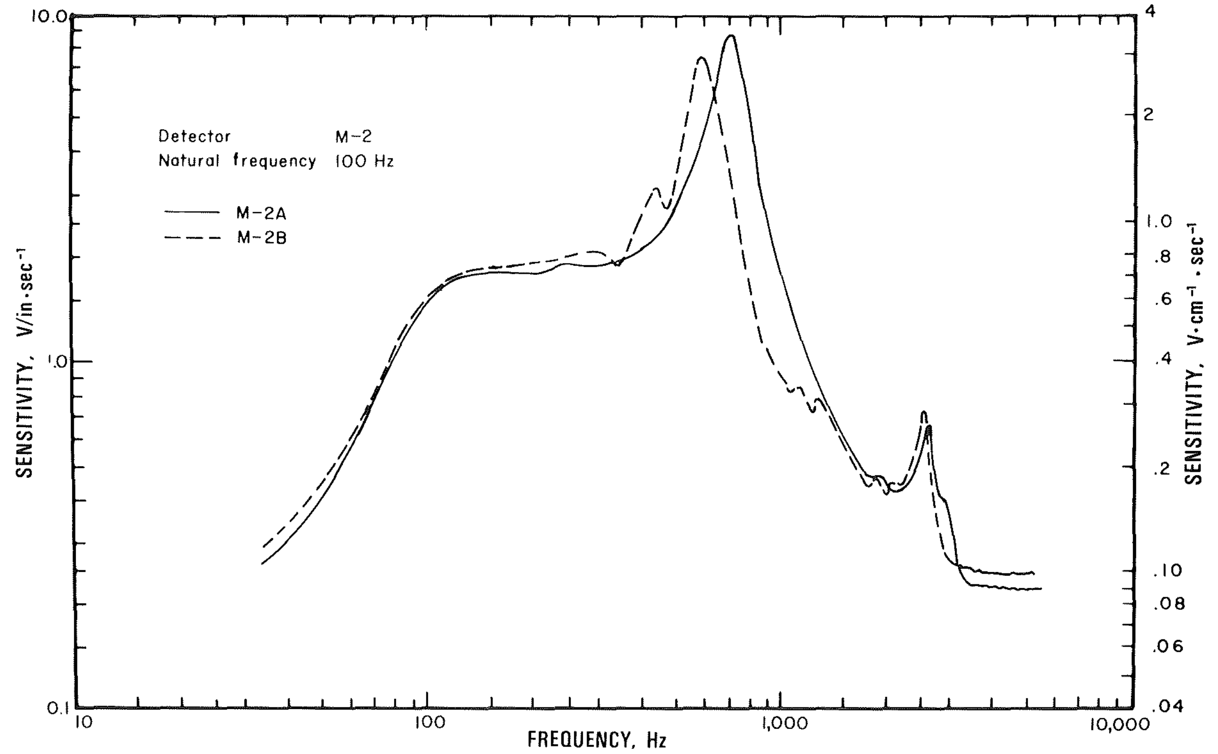


FIGURE 13. - Two M-2 prototype geophones with high outputs and good low-frequency attenuation.

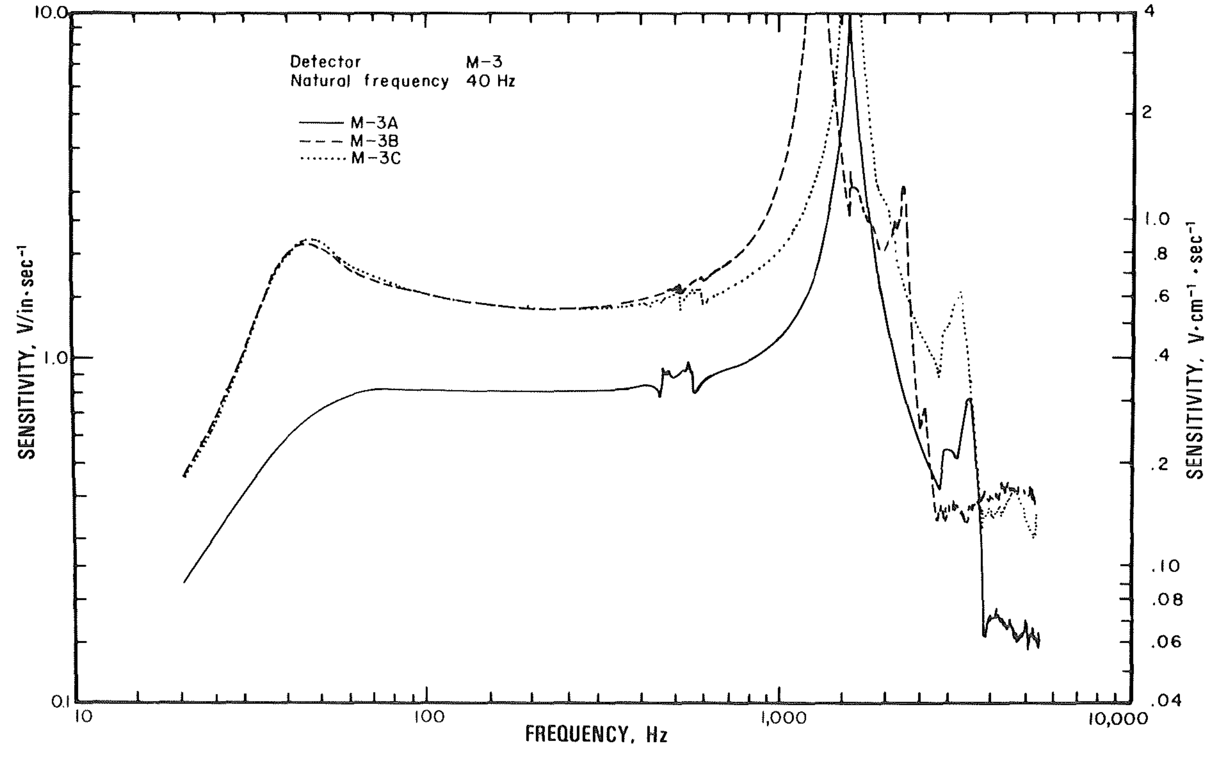


FIGURE 14. - Three M-3 detectors with different output levels.

Figure 14 presents the response curves for three M-3 detectors that did not all have the same damping resistors, as witnessed by the lower output voltage of one unit. The high-frequency peaks are well beyond 1 kHz, with the low-frequency cutoff starting just below 40 Hz. If the low-frequency performance is tolerable, these detectors have a usable bandwidth of about 70 to 700 Hz, a quite respectable performance. The small perturbations centered at 500 Hz in the response curves are most likely coil noises that could probably be eliminated during manufacturing. These small striations would not seriously affect the overall performance of the units. If properly damped to produce about 0.5 $V \cdot cm^{-1} \cdot sec^{-1}$, these detectors might be a good choice for high-resolution work, providing the low-frequency response characteristics could be tolerated.

Three M-4 detectors produced almost identical response curves (fig. 15), attesting to consistency in manufacturing and quality control. The detectors have natural frequencies of 40 Hz, which accounts for the location and shape of the low-frequency end of the responses. The usable upper frequency limit before resonance is possibly 600 Hz since the output rapidly rises above this frequency. The output level averaged about 0.4 $V \cdot cm^{-1} \cdot sec^{-1}$ in midspectram making these detectors satisfactory within a bandwidth of about 70 t0 500 Hz. The low-end peak could be troublesome where heavy ground roll persists, but the spectrum might be improved somewhat (flattened) by heavier damping of the output.

The curves of the three E-1 detectors shown in figure 16 have exceptionally high output voltages, approaching 1.0 $V \cdot cm^{-1} \cdot sec^{-1}$ throughout the usable spectrum. This is a desirable feature in many instances where adequate amplifier gain is absent. The detectors have some disadvantages for high-resolution work, however. The first and most serious, is the lack of attenuation at frequencies below 100 Hz that could limit their usefulness in high noise environments. The second disadvantage is the maximum voltages at the upper resonant peaks since most amplifiers would be saturated by these 8.0- to 12.5-$V \cdot cm^{-1} \cdot sec^{-1}$ resonant peak outputs. Heavy filtering might reduce the peaks to a workable level but at some degredation of response in the 400-Hz region. These detectors are probably most useful for deep high-resolution studies in petroleum searches.

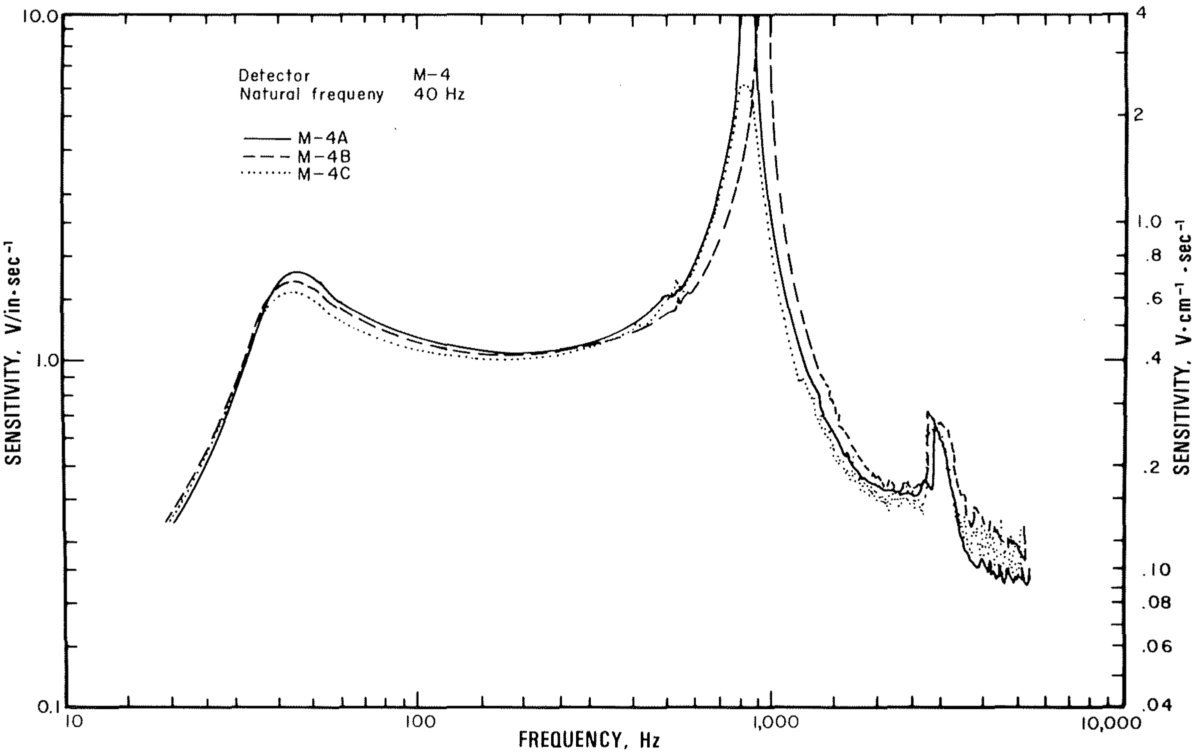


FIGURE 15. - Responses of three M-4 detectors.

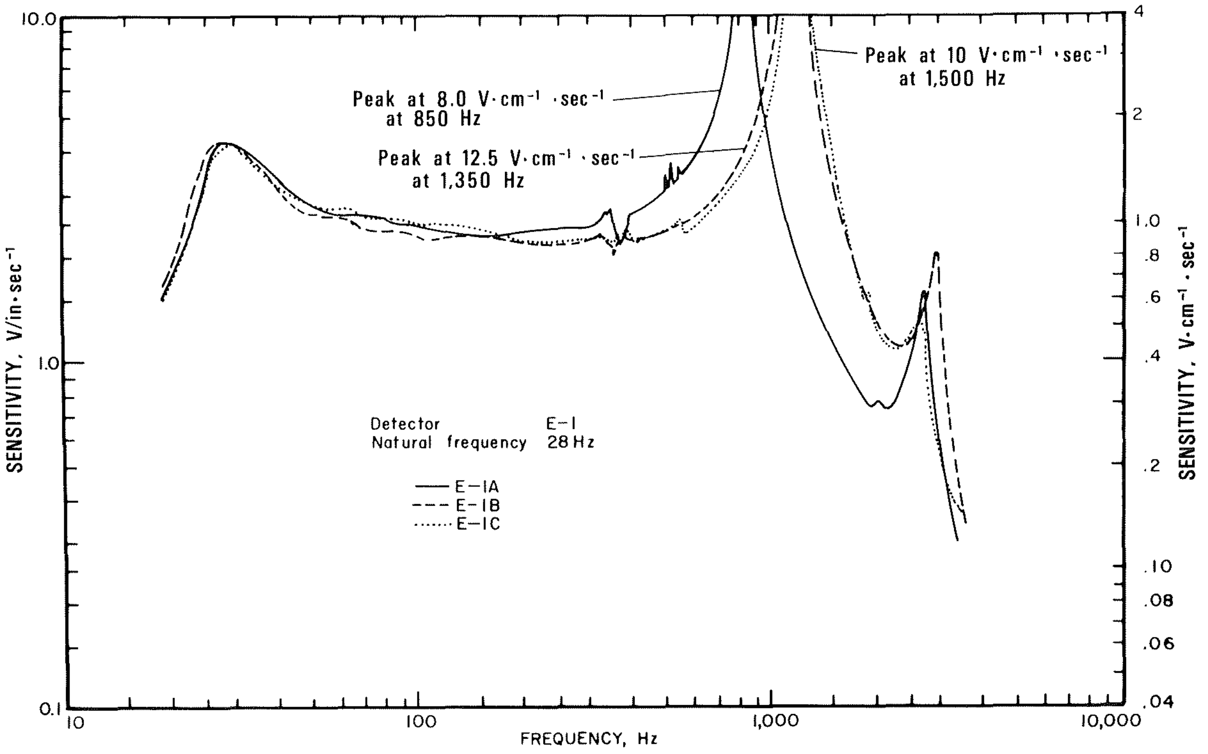


FIGURE 16. - Output of three E-1 low-frequency detectors.

Three EN-1 accelerometers normally used in vibration testing laboratories to evaluate aircraft and aerospace hardware were not packaged for seismic field use. They were tested for two reasons; first to demonstrate how accelerometer response compares with velocity detectors (geophones), and second to allow comparisons with the seismic accelerometers that were tested. The response curves, as in figure 17, demonstrate the smoothness of the accelerometers' performance to beyond 5 kHz. The perturbations in the curves between 3 kHz and 5 kHz are due to minor test fixture resonances and must not be allowed to discredit the performance of these detectors. There is considerable difference in the response of the accelerometers with velocity input compared with the response of the geophones. As expected, the accelerometer response climbs at a rate of 6 dB/octave compared with the velocity devices. These response curves show that accelerometers emphasize the higher frequency portion of velocity spectra, which is desirable for very high-resolution work. The rising response can be useful if clean high-frequency performance is demanded from detectors for frequencies in the 1-kHz region. Accelerometers will gain greater acceptance as seismic detectors with the use of higher frequencies.

The H-1 detector is an accelerometer designed for seismic applications. The response curves for three prototype H-1 accelerometers, obtained for testing only, are presented in figure 18, and demonstrate a rise of approximately 6 dB/octave as discussed previously. These accelerometers have a resonant peak at approximately 2 kHz which should allow their use for seismic work over a bandwidth of 70 Hz to about 1 kHz with relatively flat response. Precautions would have to be taken to prevent amplifier saturation from voltages beyond 1 kHz, but with attenuators and/or filters this could be tolerated. One unit was tested for comparison with a constant acceleration input of 0.25 g.

The H-1A accelerometer in figure 19 shows a 20- to 1,000-Hz clean, flat, constant output. This detector when used with a sharp high-pass filter set at 100 Hz would provide good performance of many high-resolution seismic applications, especially where the upper frequencies were of interest.

The response curves of the L-1 velocity detectors shown in figure 20 are typical of detectors with natural frequencies of 10 Hz. The first high-frequency resonant peak is just beyond 1 kHz and should cause no problems for normal seismic studies. The low-frequency response has a large peak at around 10 Hz, but it was removed by filtering to allow the output to be plotted for comparison with similar geophones. The sweep was started at 20 Hz to eliminate the trouble these peaks caused during testing. As previously stated for similar geophones, these low-frequency peaks usually cause problems with ground roll and domestic noises. The interferences at 160 to 230 Hz are of unknown origin, but are probably suspension spring noises that are not severe enough to warrant undue concern but are undesirable. The detectors are usable from 20 Hz to possible 300 Hz if precautions are taken to handle the very low frequencies. The output from these devices was lower than most of the other competitive detectors, possibly due to heavy damping, and may be cause for concern if low signal levels are a problem for recording instruments. The detectors are best suited for petroleum exploration and would not be a good choice for high-resolution mining applications.

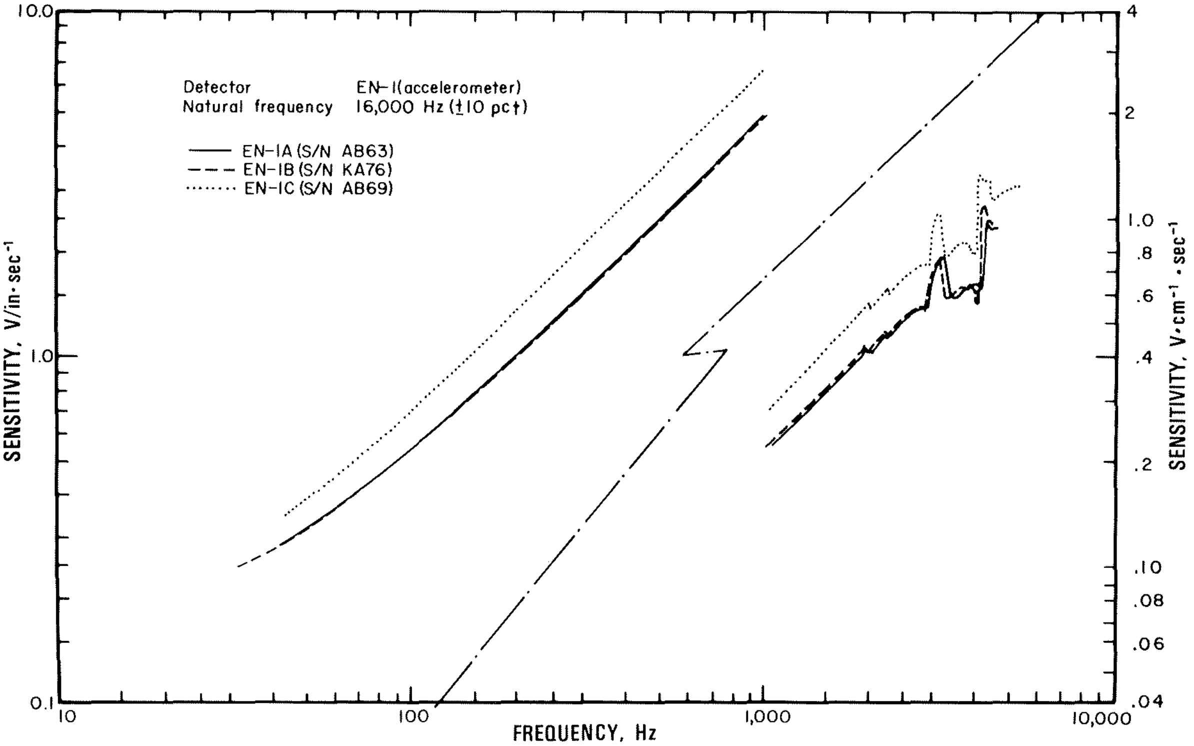


FIGURE 17. - Three EN-1 high-quality accelerometers with constant velocity input. Output climbs at 6.0 dB/octave.

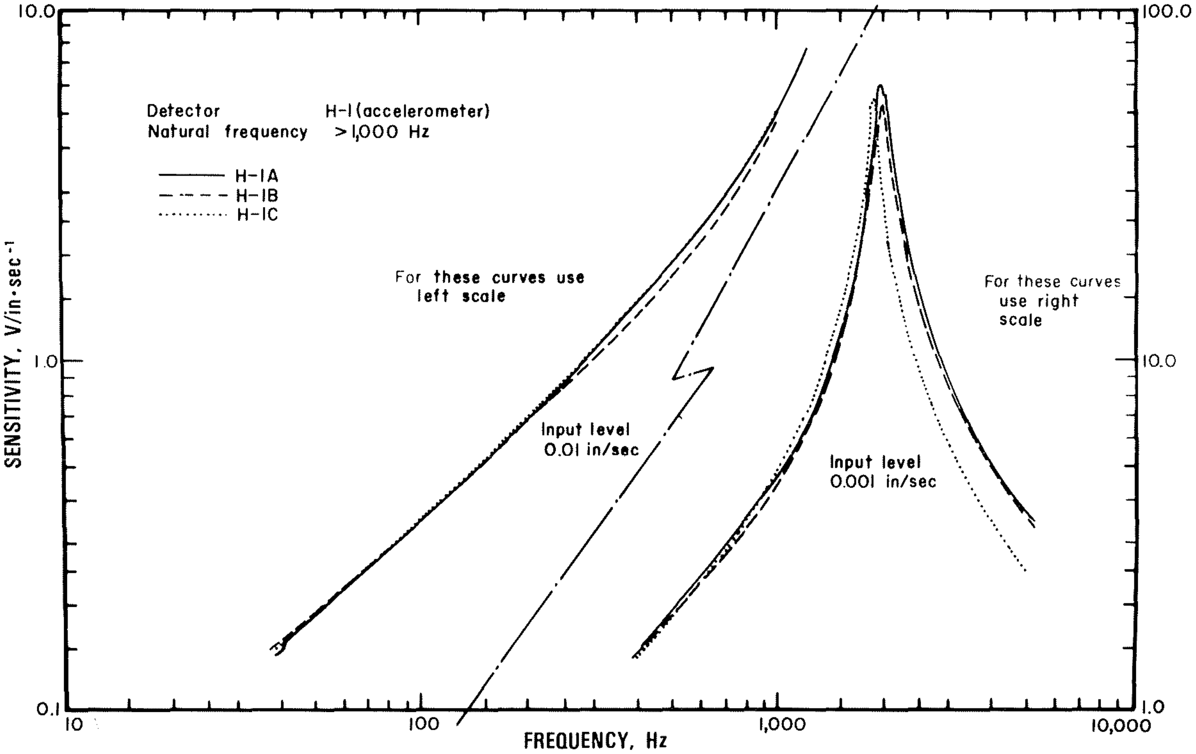


FIGURE 18. - Responses of three H-1 accelerometers designed and packaged for seismic uses.

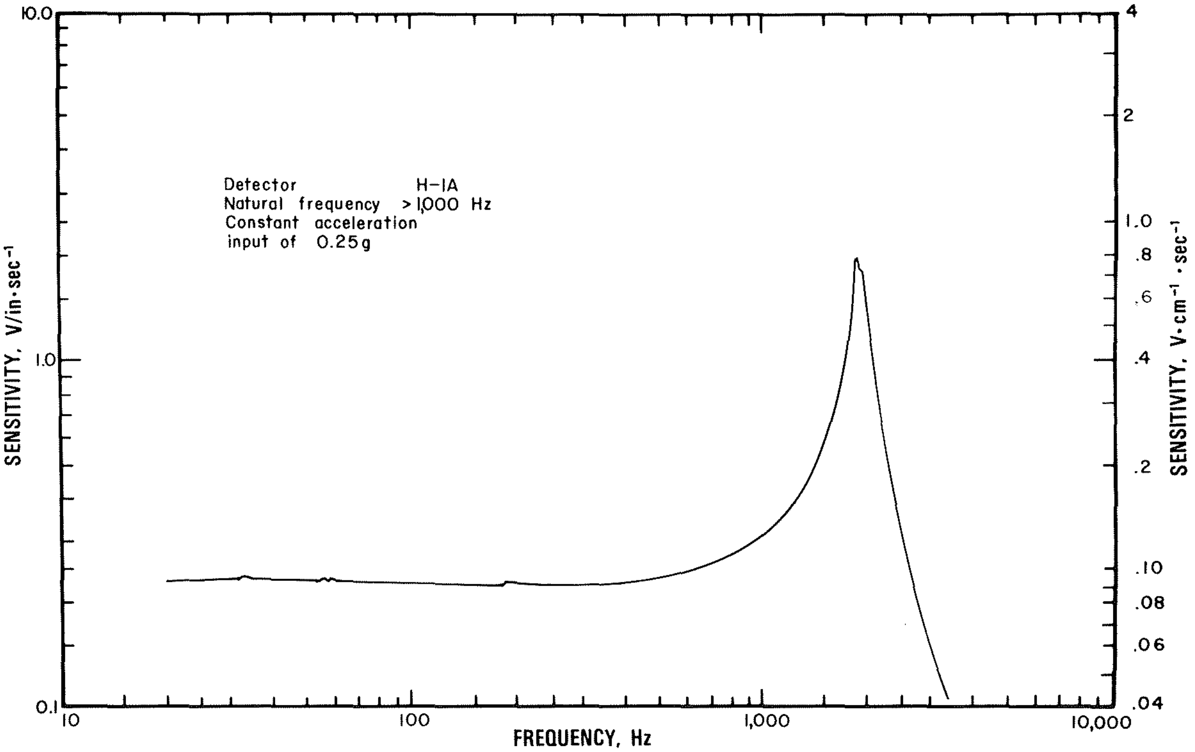


FIGURE 19. - Response of a H-1A detector with a constant acceleration input of 0.25 g.

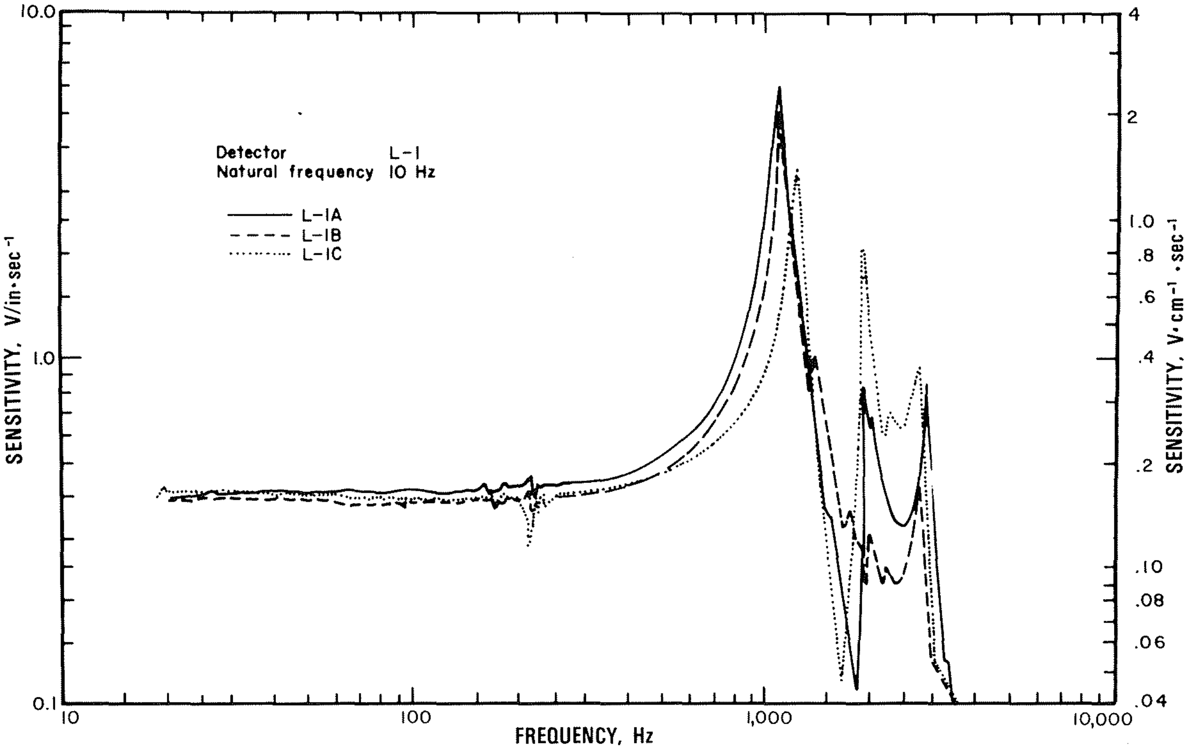


FIGURE 20. - Three L-1 velocity detectors with similar curves and a relatively low-level output.

Three L-2 seismic accelerometers were excited at a constant velocity of 0.0025 $cm \cdot sec^{-1}$ with one unit showing an erratic output, however the response could not be explained (fig. 21). The spectrum from 20 to 100 Hz exhibits the normal 6-dB/octave curve slope, but the first resonant peak is near 180 Hz, causing the response curves to climb faster than 6 dB/octave above 100 Hz. The projected peak voltages shown in the plots were calculated from the data obtained during testing, and were not actually attained due to physical limitations in the devices themselves, but they are presented to show the potential output voltages at the peaks. These accelerometers would not be useful for high-resolution work due to their erratic behavior, but they might produce acceptable results for some low-frequency petroleum studies.

A very special velocity detector has been available for some time. Three of these D-1 detectors produced relatively flat response curves, and good tracking between units. In figure 22, we find the first major high-frequency peaks well beyond 3 kHz, which is quite commendable for a velocity detector. D-1 detectors produce considerably less output than most seismic geophones. They are calibrated by the factory for 100 $mV \cdot in^{-1} \cdot sec^{-1}$, ±3 percent, which is 39.37 $mV \cdot cm^{-1} \cdot sec^{-1}$, ±3 percent. Bureau tests show the calibration to be very close to that value. The curves are actually composites since different input excitation levels were required to produce usable voltages for the recording equipment. These low-level output sensitivities would be troublesome for some seismic recording systems due to lack of gain or to poor signal-to-noise ratios at the input to the recording instruments. A good-quality, low-noise, line-driver preamplifier with a gain of 20 dB would raise the detector output levels to those comparable to other geophones, thus making these detectors excellent wide-band, ultrahigh-resolution, high-frequency detectors.

Comments and Results

Based upon the results of these tests, the accelerometers and high-frequency geophones tested would probably not provide satisfactory performance in the 5- to 40-Hz bandwidth for deep petroleum exploration. The geophones with lower natural frequencies and proper damping would provide good performance down to 10 Hz or less for this type of application.

At the other end of the spectrum, for high-resolution shallow reflection purposes in mining investigations, the accelerometers, the 100-Hz geophones, and some 40-Hz geophones could perform well in a bandwidth from 75 to 500 Hz. This spectrum would be adequate for much of the mining investigations because it provides resolution adequate for typical mining depths in the United States. Most of the detectors with resonant frequencies above 60 Hz performed well in attenuating the unwanted low-frequency end of the spectrum; i.e., 1 to 70 Hz, which is the ground roll, domestic noise menace, and 60-Hz powerline often encountered and not easily overcome if it is recorded with the data.

For very shallow applications requiring extremely high resolution, as with acoustic investigations, none of the velocity detectors tested are extremely well-suited for this purpose. The one possible exception is the D-1 detector which had relatively clean, flat response from 100 Hz to about 3 kHz. The one disadvantage of this unit is its low output voltage of about

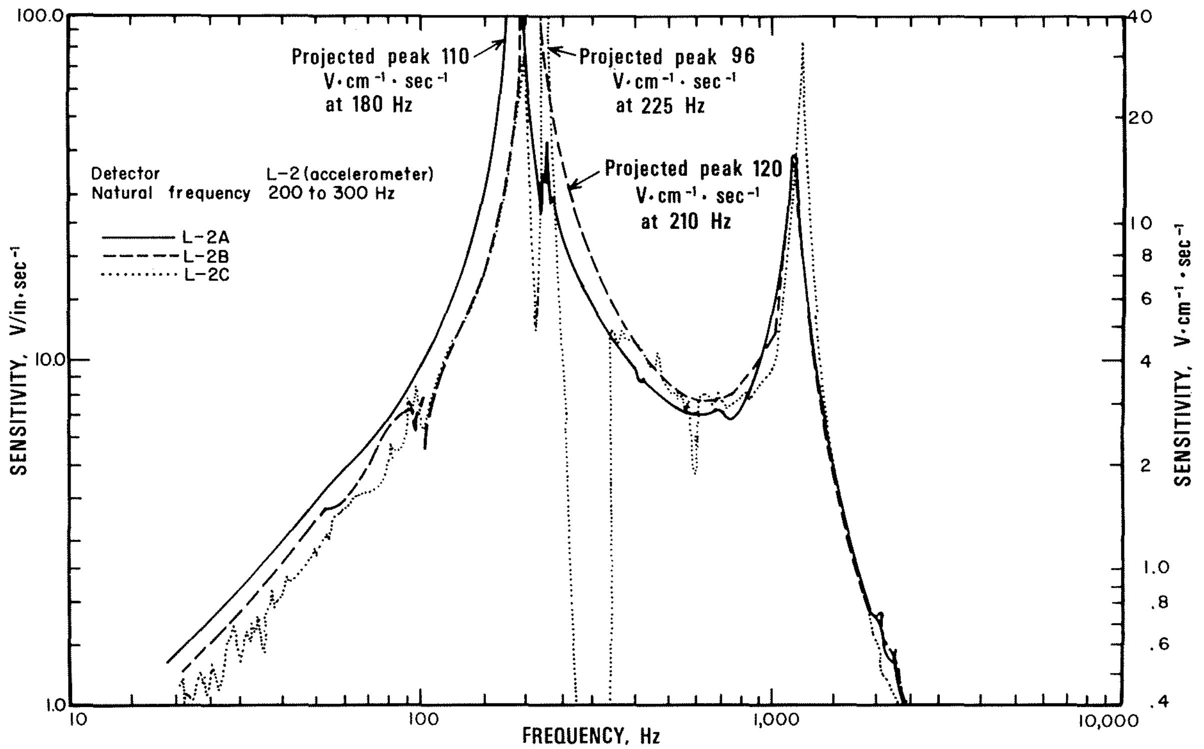


FIGURE 21. - Responses of three L-2 seismic accelerometers at 0.0025 cm/sec constant velocity.

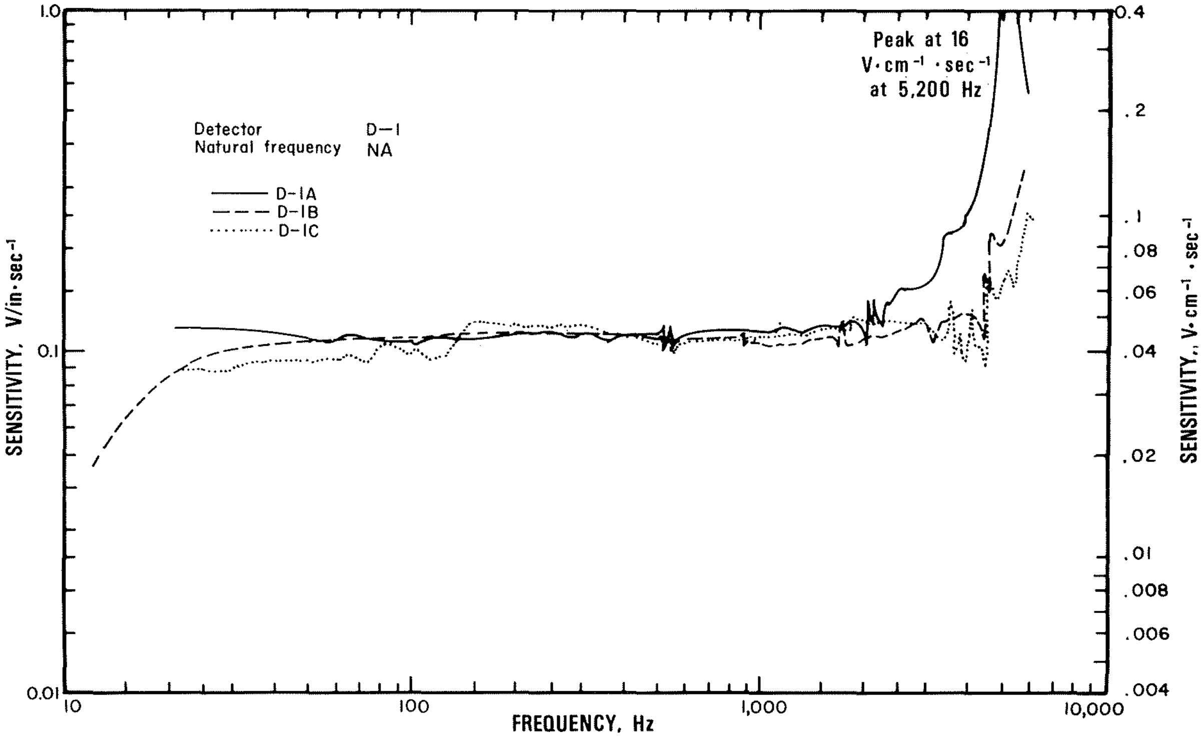


FIGURE 22. - Three D-1 special purpose velocity detectors with flat, broadband response curves good to about 3 kHz.

40 mV$\cdot$cm$^{-1}\cdot$sec^{-1}. The use of this detector would require an additional 20 dB of gain in a preamplifier or in the input amplifier to bring the signals to a level comparable to that of other detectors. Since this added gain requirement may not be present in some instrument systems, line amplifiers would be required. The Endevco accelerometers tested and some similar units would provide adequate performance up to 5 kHz. These devices were not packaged for field use, however, and would have to be protected from the elements to be useful for field work. Thus, for very high-frequency use, much improved detectors are needed which could be velocity-type devices (geophones) but will most likely be accelerometers as time and use prove their utility. Accelerometers typically require line-driving amplifiers to properly match the high-impedance crystal in the accelerometer to the lower impedance recording system. Charge amplifiers can provide good performance in this application, but rugged, field-worthy units of this description are not readily available as seismic field units.

DETECTOR SELECTION CONSIDERATIONS

There are several factors that should be considered when selecting seismic detectors for any particular application. The two types of detectors commonly used are geophones and accelerometers. Accelerometers are in use in far fewer numbers for seismic work. Accelerometers do have some advantages over geophones for special applications, but they also have some disadvantages. These factors were discussed previously in the "Background" section.

Output Voltage

The output voltage level of a detector is an important consideration when selecting geophones for a specific type of application. Several construction features affect the output voltage level, commonly referred to as the sensitivity, of a detector. Output voltages of about 0.5 mV$\cdot$cm$^{-1}\cdot$sec^{-1} are desirable for most work.

Coil Construction

The design of the geophone coil(s) is one of the controlling factors in output level. Most geophones are designed with dual coils to provide "hum bucking," a 60-Hz reduction in noise output. The dual coils are very helpful when working close to high-voltage transmission lines or where heavy electrical machinery is being used close to the test area. Manufacturers can be helpful by providing specific models of geophones that provide 60-Hz rejection.

Accelerometers are not normally responsive to 60 Hz powerline interference, therefore, this is usually not a serious problem for users.

Coil Impedance

Typically, a coil element with high output voltage also has a high impedance; the coil has many more turns of wire than a lower impedance unit. If a high output voltage is required, the instrument into which the geophone is connected must have an impedance acceptable for that particular geophone. In some instances, high output voltages are required from the geophones because there is limited gain in the input amplifiers of the recording system, or the signal levels from the detectors are so low that the input amplifiers cannot raise the signal voltages to a level that can be recorded by the data system. Whatever the case, impedance matching of the geophones to the recording system can be very important. Failure to consider this aspect of the instrumentation can cause poor overall performance in terms of signal amplitudes, distortion, spurious noise factors, ringing, and oscillation.

Magnetic Elements

The strength of the magnetic field produced by the permanent magnets in a geophone affect the output voltage of a unit. Most geophones use only one magnet per unit, but some of the high-frequency geophones use two or three magnets in the "magnetic element" to achieve special performance. Again, manufacturers can be helpful by providing literature describing the construction of the geophones and specific features of particular models best suited to an application.

Coil Damping

Another factor affecting output level is the electrical damping network that flattens the response curves of geophones and reduces large amplitude signals at or near the resonant frequency of the units, but damping reduces the output of the geophones. A heavy damping network can reduce the output of a geophone by as much as 4:1, which allows an output of only 25 percent of the signal level available if the geophone were undamped. When comparing the results of these tests, it should be noted whether the geophone was tested damped or undamped since it does affect output singal levels considerably.

Frequency Response

The type of seismic study determines the band of frequencies in which the detectors must work. This subject was discussed earlier in this report in the "Test Procedures" section. If frequencies above 100 Hz are to be used in the seismic work, the detectors should be designed for such work.

Coil Construction

One of the important determinants of the response of a geophone to high frequencies is the manner in which the coil is designed. The mass and the physical dimensions of the coil assembly also determine to some extent the amount of spurious noise and distortion produced by a geophone. Careful study of these specifications will yield some superior performance capabilities from some units.

Coil Suspension

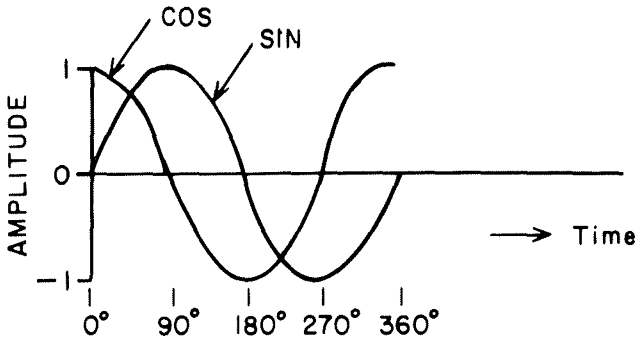
Probably one of the most critical aspects of the physical layout and construction of the geophones is in the suspension of the velocity coil within the unit. The suspension springs keep the velocity coil centered in the magnetic field while allowing movement of the coil in that field. The frequency response of the geophone as well as its natural frequency is determined primarily by this mechanical arrangement. Many different configurations are in use today, and each has its advantages, disadvantages, and expressed purpose. Manufacturers are usually eager to discuss their approach to this problem and to address the advantages of their suspension technique. The user should be familiar with the different suspension systems and what each type has to offer for a particular application. Desirable characteristics for high-resolution seismic work are flat-frequency response in the bandwidth of interest and the absence of spurious noises often caused by the suspension springs.

Stimulation from Various Angles

The output voltage from a detector is proportional to the amplitude of the stimulus. The actual response to the stimulus is determined by the orientation of the detector relative to the origin of the stimulus. If a detector is stimulated by a signal that is perfectly alined with its designed primary axis of response, the output voltage will be 1 unit of output (in volts) per unit of input (velocity or acceleration). If the detector is not alined perfectly with the axis of the stimulus, the output voltage from the detector will be less than for a perfect alinement. Equation 3 in figure 23 and the geometric respresentation describe this situation. Assume that a detector is held securely and in perfect alinement with axis Y in the drawing. A stimulus of 1 unit in the Y axis will cause 1 unit of output, 1.000 E, to be produced by the detector. If the stimulus is applied at an angle of 10° to the Y axis as shown in the Y' direction, the detector output will be about 0.985 E, and for a stimulus at 45° to the Y axis, in axis Y", the output from the detector will be about 0.707 E. This demonstrates the problem with misalinement of the primary axis of the detector to the intended axis of response or to signals coming from undesirable directions. With poor alinement, the detector not only responds less to the intended signal, but also begins to respond to the cross (transverse) axis signals. The detector responds equally well to the incoming signals of both the Y and X axis at a 45° angle. Orientation of the detector to coincide with the primary signal axis is thus an important consideration in field investigations.

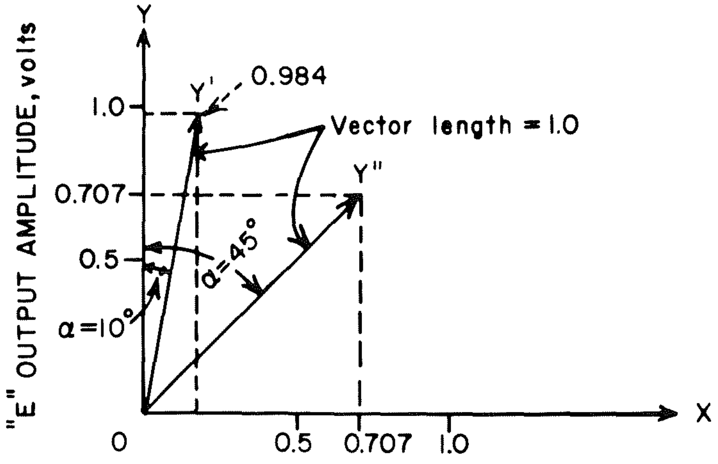
Transverse Axis Response

Another very important but often overlooked factor that should be considered when selecting geophones for high-resolution shallow work is rejection of transverse incoming energy to the geophone. Since the intent of a geophone (or any other such device) is to measure motion in a primary axis, response to cross-axis energy is undesirable. Transverse energies tend to distort or modulate the signals coming from the primary axis; this must then be unscrambled during the data reduction and processing. Removing the distortion can often be almost impossible and is expensive in terms of computer processing time.



TRIGONOMETRIC FUNCTIONS OF SIN AND COS

ANGLE	SIN	COS
0°	0.0	1.0
90°	1.0	0.0
180°	0.0	−1.0
270°	-1.0	0.0
360°	0.0	1.0
45°	0.707	0.707



By definition: $E = Y \cos \alpha$ (3)

If $\alpha = 0°$, $E = 1.0$ volts

$\alpha = 90°$, $E = 0.0$ volts

$\alpha = 45°$, $E = 0.707$ volts

$\alpha = 10°$, $E = 0.984$ volts

FIGURE 23. - Detector response for signals arriving at less than 0° with the primary axis of the detector.

Checks for transverse axis response were considered while conducting the tests described in this report. Some of the problems encountered while checking for transverse axis response follow. There is no simple way to hold a detector for these tests; i.e., special fixtures would be required for each type of detector. (2) There are no well-defined methods for actually performing the tests; i.e., how is the transverse axis excited, at what level of input should it be excited, and how can the excitation level be controlled. (3) There are no established specifications for analyzing the transverse axis interference and modulation of the primary axis signal, which should be present during the tests. (4) Other unexpected complications could arise while checking for transverse axis response. Surely, both electrical and mechanical problems will be encountered. No attempt will be made here to describe every conceivable problem as it would be a futile effort. Due to the complexity of setting up and performing these evaluations, no tests for transverse axis response were conducted during this series of tests; primary axis responses only were measured.

It is not easy to build a detector that totally rejects transverse signals throughout a working spectrum, but too little attention is being given to this problem in the high-quality geophones presently being manufactured. It would be very desirable to have a 40-dB rejection of transverse axis signals referenced to the primary axis sensitivity. Some manufacturers now include an indication of the rejection to transverse axis energies and are aware of the necessity for an acceptable level of control. Selection of detectors that exhibit good rejection to transverse axis signals will help eliminate a potentially troublesome degradation of signal quality in high-resolution seismic work. It is important to the expansion of the high-resolution seismic industry that geophone manufacturers assume the responsibility to establish realistic attenuation criteria for transverse axis attenuation and for the creation of acceptable testing techniques for this parameter.

Phase Response

Accurate response of seismic detectors to various waveform stimuli is important for high-resolution work, and even more important for acoustic work. The phase shift induced by a velocity detector may cause distortion or coloring of the true incoming signals, resulting in poor stacking of the data. Consider two detectors stimulated by the same signal. In a worst case situation, if the output of each detector was 180° out of phase but with output levels of equal voltage, the two output waveforms when single stacked (added algebraically) would result in a signal amplitude of zero volts. For smaller phase response differences between the two detectors, the results would be less dramatic, but would cause degradation of the resultant stack. Referring to figure 24, the results of mixing two waveforms of different frequency, or different phase relationships, can be seen. In this example, f_1 is the fundamental frequency and f_2 is its first harmonic at twice the frequency and half the amplitude of f_1. The resultant waveform from the stacking (algebraic addition) of these two signals is f_3; a new waveform with different amplitude and fundamental frequency has been created. It can thus be seen that phase response is a critical factor when stacking is used to raise signals out of high noise backgrounds. This also confirms the importance of phase matching between individual detectors for string applications since much data can be lost from improper detector matching.

The above discussion is based upon sinusoidal waveforms and velocity detectors. With more typical seismic waveforms, where noise and distortion are present, a detector may generate its own distortion or coloring of output signal and complicate the situation further. If the transient response, i.e., a fast risetime narrow pulse stimulation of a velocity detector was considered, other problems caused by the inability of the detector to respond instantaneously to the stimulation could surface.

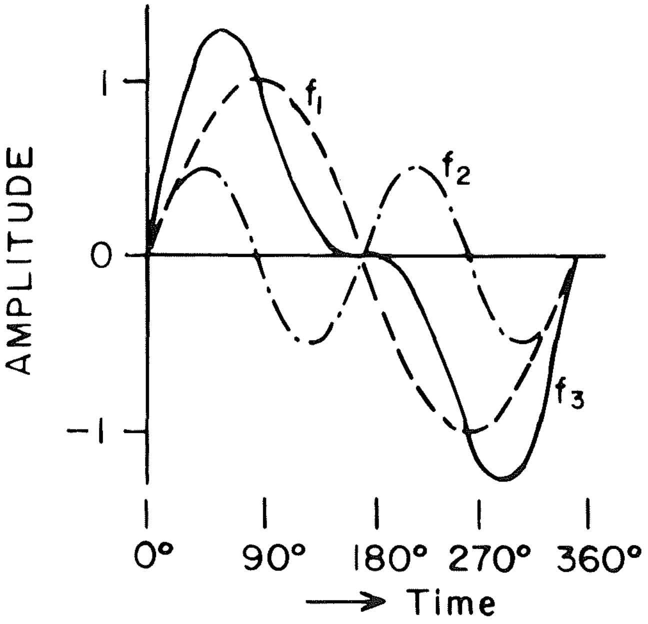


FIGURE 24. - Resultant signal from adding two waveforms of different frequency and amplitude.

One way to eliminate some of these problems is to use acceleration sensitive devices. Accelerometers normally have better response to complex waveforms and to transients than do velocity detectors. This is partly true because there is no moving mass in an accelerometer and normally no resonant peaks below 10 kHz in well-designed units.

In this series of tests, phase measurements were not attempted, not because they are difficult to make, but due to the number of detectors tested and the time necessary to conduct those tests that were performed. At a later time, phase tests should be conducted to better define detector characteristics and to identify problems in data processing caused by phase-related pertubations.

Many manufacturers of seismic detectors do not mention phase response in the litereture, but users should be aware of this parameter and should ask for information about phase response before purchasing high-resolution seismic detectors.

Costs of Detectors

The cost of seismic detectors is a very important consideration, but cost alone should not dictate which detector is selected for each type of work. Low-cost detectors certainly represent a monetary savings initially, but an error in the selection process may be very expensive in the long run. Therefore, other factors should be considered before the purchase is finalized. Detectors costing from $15 to $400 each were tested in this study. The highest priced units gave better performance for high-resolution applications than the least expensive. The intended purposes for each unit are different, however, thus it is important that the selection be made after weighing desired performance against costs. Sometimes the more expensive device is worth the added costs if performance and reliability are important criteria.

CHALLENGE TO INDUSTRY

The mining industry is accepting the fact that seismic surveys can reduce the cost of exploration and development programs by reducing the number of drill holes while providing considerably more information about the geology, stratigraphy, anomolies, and, of course, the resources. High-resolution, shallow-reflection seismic studies can be diagonostic when properly applied. For the mining and service industries, higher quality seismic detectors are required, and better selection of other equipment must be emphasized to optimize results.

As a result of requests from users, some manufacturers have designed new seismic detectors that show flatter response curves at higher frequencies. Some of the improved models will probably be satisfactory into the 200-Hz region; however, this is only the first step. Greatly improved velocity detectors are required for ultra-high-resolution, shallow-reflection seismic applications.

The Bureau of Mines is pursuing the application of high-resolution, shallow-reflection seismics and other high-resolution geophysical methods, and improved equipment is developing from this effort. New seismic sources and improved field recording systems are needed, and improved field procedures and better data processing are required. Additionally, the Bureau is pursuing the development and application of acoustic reflection seismic techniques. These techniques have applications for shallow mining and resource studies where extremely high resolution is required for delineation of deposits.

Some of these research areas are revolutionary, and some segments of the equipment industry have already responded to the more stringent demands in the seismic field. There is a sincere need for still other segments to make innovative improvements to equipment to meet the new demands. It is anticipated that the industry in the United States will respond favorably to these important and changing needs and support a new realm of seismology.

CONCLUSIONS

The results of the low-level vibration testing of 13 models, 35 velocity-detectors (geophones), and 9 accelerometers reveal some extremely useful information for seismologists and geophysicists.

Velocity detectors with natural frequencies from 10 to 100 Hz were evaluated and were found to be usable for seismic studies in a frequency spectrum from 5 to about 600 Hz when the detector is properly matched to the intended job. Many factors affect matching detectors and purpose; therefore, seismologists and field engineers must be involved in the selection process.

Accelerometers, generally usable in a frequency spectrum from 100 to 1,000 Hz, exhibit performance characteristics that are different from those of the velocity detectors. The two seismic accelerometers described in this report performed about equally with the better velocity detectors tested. One advantage of an accelerometer over a geophone is the higher output levels at higher frequencies. Accelerometer outputs increase at a rate of 6 dB/octave with increasing frequency, which may be useful in high-frequency work.

Selection of a seismic detector should be made with as much technical information as possible since available detectors vary considerably from one manufacturer to another and from one model to another within a product line. The results of the low-level vibration tests described in this report should help seismologists make educated selections of detectors for specific applications.

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APPENDIX.--ABBREVIATIONS

G	Acceleration constant at 980 cm/sec^2
Gpk	Acceleration peak amplitude
rms	Root mean square, 0.707 × peak voltage value
dB	Decible--voltage ratio = 20 log $\frac{E1}{E2}$, power ratio = 10 log $\frac{P1}{P2}$
dB/Octave	Rolloff characteristic expression
Octave	Octave--a change of 2:1 frequency ratio