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Development of a Magnetostrictive Borehole Seismic Source

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Robert P. Cutler, Gerard E. Sleafte, Russell G. Keefe

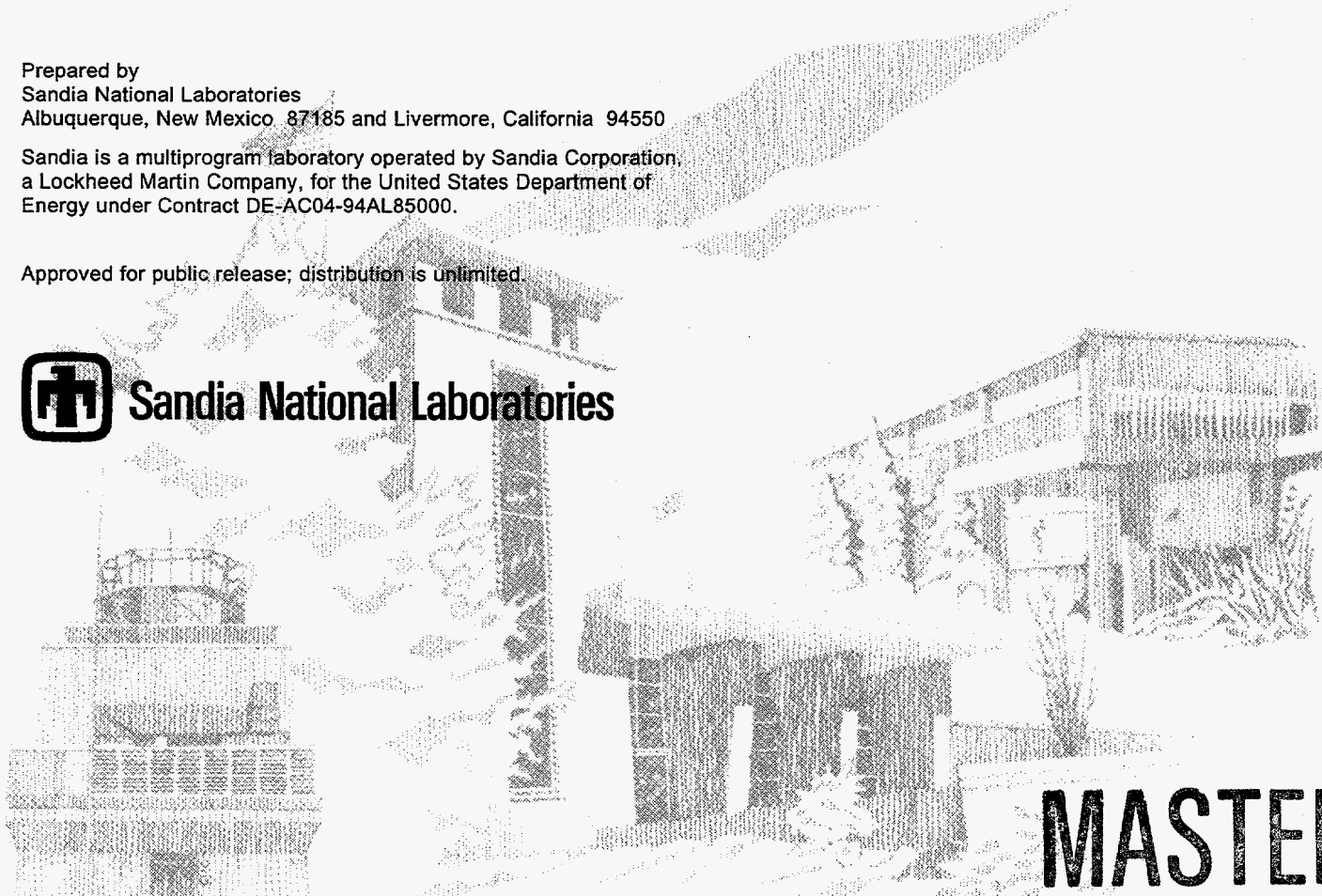
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Development of a Magnetostrictive Borehole Seismic Source

Robert P. Cutler, Gerard E. Sleaf, and Russell G. Keefe

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Abstract

A magnetostrictive borehole seismic source was developed for use in high resolution crosswell surveys in environmental applications. The source is a clamped, vertical-shear, swept frequency, reaction-mass shaker design consisting of a spring pre-loaded magnetostrictive rod with permanent magnet bias, drive coils to induce an alternating magnetic field, and an integral tungsten reaction mass. The actuator was tested extensively in the laboratory. It was then incorporated into an easily deployable clamped downhole tool capable of operating on a standard 7 conductor wireline in borehole environments to 10,000' deep and 100° C. It can be used in either PVC or steel cased wells and the wells can be dry or fluid filled. It has a usable frequency spectrum of ~ 150 to 2000 Hz. The finished tool was successfully demonstrated in a crosswell test at a shallow environmental site at Hanford, Washington. The source transmitted signals with a S/N ratio of 10-15 dB from 150-720 Hz between wells spaced 239 feet apart in unconsolidated gravel. The source was also tested successfully in rock at an oil field test site, transmitting signals with a S/N ratio of 5-15 dB over the full sweep spectrum from 150-2000 Hz between wells spaced 282 feet apart. And it was used successfully on an 11,000' wireline at a depth of 4550'. Recommendations for follow-on work include improvements to the clamp, incorporation of a higher sample rate force feedback controller, and increases in the force output of the tool.

Acknowledgments

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Introduction

This report describes work performed at Sandia National Laboratories over a two year period in designing, laboratory testing, and field testing a clamped magnetostrictive borehole seismic source for use in high resolution crosswell imaging applications at environmental sites. Many borehole seismic source concepts have been proposed or developed over the past 10-15 years. Most of these have been designed for use in deep (5,000-15,000') open hole or cased oil and gas wells. Few of these sources have been widely accepted due to the high cost of performing surveys, the loss of oil or gas production while the surveys are performed, the limited or inappropriate frequency range of the sources, the complexity of the tools, the high cost of fabricating and fielding the sources and associated surface support equipment, and the comparatively low signal output from the sources which limits their use to closely spaced wells.

The few borehole seismic sources which are commercially available have a number of limitations when applied to environmental applications. In environmental surveys, sampling wells are usually cased with PVC rather than steel, they are closely spaced, they are usually un-cemented, they are often dry, and the formation often consists of loose dirt, sand, or gravel, which are very attenuating to high frequencies. In addition, there is usually little surface support equipment available, and the surveying is often done by one or two people.

The goal of this project was to develop a new source designed specifically for environmental applications. The source needed to be small, inexpensive, and easy to deploy on a conventional wireline; have a broad output frequency range of ~100-2000 Hz; have high force output; be non-impulsive, non-volume expanding, and wall locked for good coupling to the formation and to minimize tube waves; be usable in PVC or steel cased wells; be usable in fluid filled or dry wells; and allow easy modification of the output spectrum and force levels.

A number of different actuator types were evaluated, and a magnetostrictive actuator was selected. Various borehole tool implementations were investigated, including both p-wave and s-wave generators. A vertical-shear, reaction-mass shaker design was selected for the downhole source. Small, commercially available, magnetostrictive actuators were tested in the laboratory to determine their operating characteristics and to establish requirements for a larger custom actuator for use in a fieldable tool.

A custom actuator was fabricated, consisting of a spring pre-loaded magnetostrictive rod with permanent magnet bias, drive coils to induce an alternating magnetic field, and an integral tungsten reaction mass. This actuator was tested extensively in the laboratory. It was then incorporated into a wall-locking downhole tool (see Figure 1) which could operate on a standard 7 conductor wireline in borehole environments. The finished tool was successfully demonstrated at an environmental site and at an oil company test site.

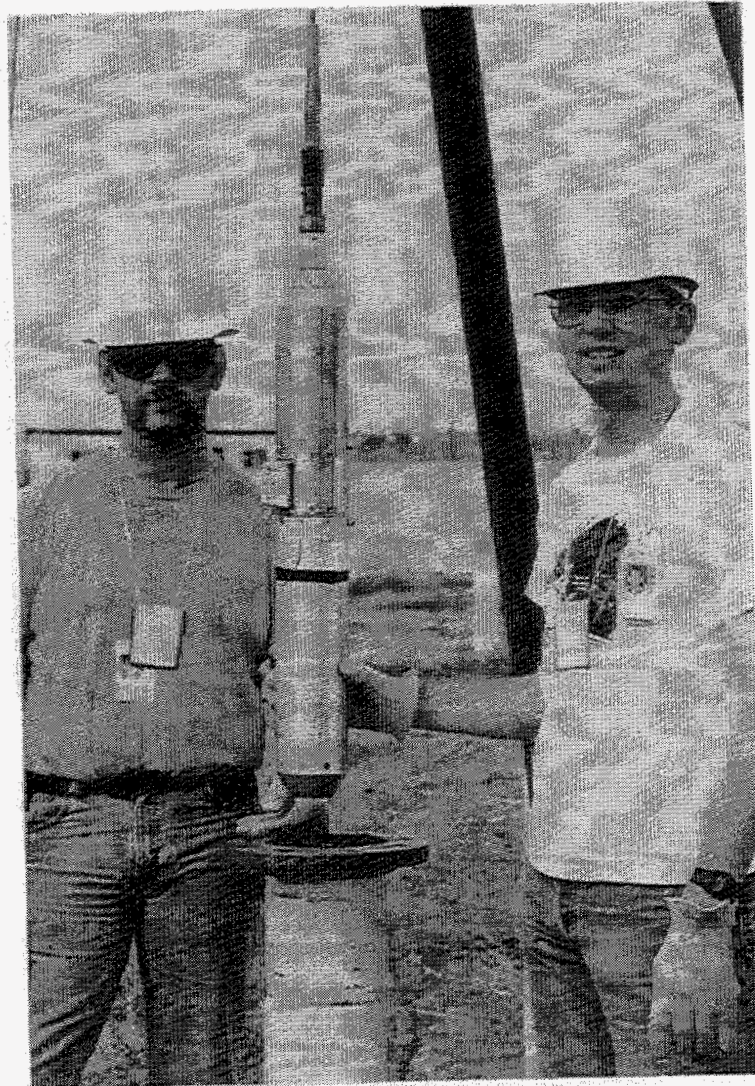


Figure 1: Magnetostriuctive Seismic Source Being Deployed in Crosswell Seismic Survey at Hanford, Washington

Background

Seismic imaging has been used for over half a century to locate oil and gas reserves hidden beneath the earth's surface. Conventional seismic imaging involves the generation of seismic waves at the earth's surface and then detecting waves which are reflected from sub-surface layers and travel back to the surface. This method has fairly coarse resolution (tens of feet) and does not allow structures other than layered strata to be resolved. In recent years, scientists have developed a technique, referred to as cross-well seismic imaging, to image complicated structures with high resolution. These crosswell seismic surveys are becoming a useful addition to other existing methods of evaluating underground formations in environmental, petroleum, and mining studies.

Crosswell seismic surveys are conducted by placing a seismic source in one well and transmitting seismic energy to a receiver in a second well (see Figure 2). By analyzing the spectral content, velocity, amplitude, polarization, and phase of the transmitted and received signals, information can be obtained about the medium through which the seismic energy has passed or from which it was reflected. By moving the source and the receiver to a large number of locations in the well, one can build up a map of the formation between the two wells. Some of the advantages of crosswell seismic imaging are that it evaluates the formation over much greater distances than conventional well logs, and it can provide much higher resolution than surface seismic due to its closer proximity to the area of interest, the higher frequencies that can be propagated, and the orientation of the tools in the formation.

There are a large number of surface and borehole seismic sources presently available for performing seismic surveys. These include air guns, sparkers, explosives, weight drop mechanisms, impact hammers, piezoelectric benders, hydraulic or pneumatic vibrators, unbalanced motors, audio speakers, and other designs. Some of these sources are commercially available through service companies, others are available only in industry, university, or laboratory research departments.

Each of these sources has advantages and disadvantages for a given application. Many of these sources were designed for use in oil and gas exploration, and have a number of limitations in shallow environmental applications. For example, impulsive and explosive sources are potentially damaging to the PVC or fiberglass well casing typically used at environmental sites. Low frequency sources cannot produce the high resolution images often required for environmental sites. Very high frequency sources are severely attenuated in loose, near-surface formations typical of environmental sites. Some of these sources have a fixed, non-uniform output. Others are difficult and expensive to field due to large tool size, the requirement for specialized trucks and extensive surface support equipment, or long pneumatic or hydraulic hoses. Some require a fluid filled borehole, which is often unacceptable in environmental monitoring wells. As a result, many of these sources are not usable for shallow environmental surveys.

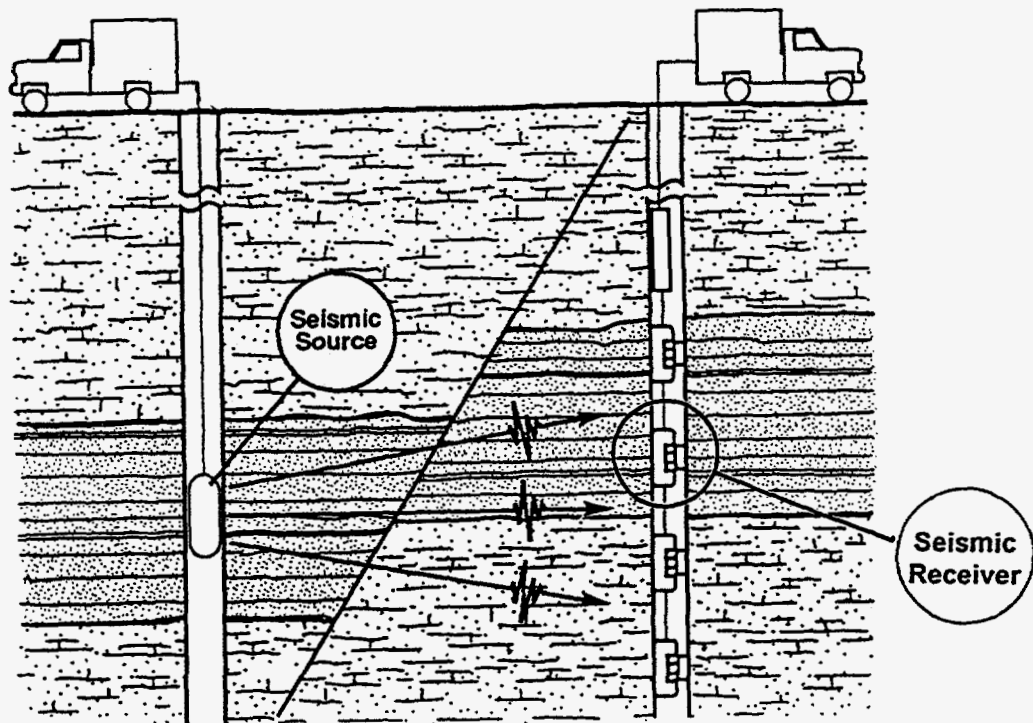


Figure 2: A Crosswell Seismic Survey Images the Formation by means of a Seismic Source in one well, and Seismic Receivers in a second well

Borehole Seismic Source

Design Criteria

A design study was conducted to determine requirements for the seismic source. The requirements were based on the need for the source to propagate energy between monitoring wells at environmental and geotechnical sites. A survey of the types of sites and wells at which Sandia has performed environmental surveys resulted in several observations:

Table 1: Environmental Survey Site Requirements

1. Maximum depth of monitoring wells is approximately 400 ft
2. Majority of Sandia monitoring wells have 4" ID PVC casing, 2" PVC is also common
3. Average spacing between monitoring wells is 40 ft, maximum separation 200 ft.
4. Zone of interest at about 50% of sites is above water table (vadose zone)
5. Source must be non-destructive to the wells
6. Source must be deployed with minimal surface equipment
7. Source must be usable in dry wells
8. The unconsolidated vadose zone above the water table is extremely attenuating, so the source must have high force output.
9. The source must produce low enough frequencies to propagate through this environment, yet it must also produce high enough frequencies to afford high resolution of the intervening formation.

A number of candidate seismic actuators were evaluated for use in these environmental applications. For a good description of the state of the art in borehole seismic sources see reference [1]. A prime consideration was that the seismic source must not cause any damage to the cased wells. Based on calculations and experimental measurements, it was determined that the 4" standard PVC casing can withstand stresses up to 1000 psi. As a result, impulsive and explosive sources were ruled out since they develop stresses well in excess of the 1000 psi limit. Thus, a frequency-swept seismic source which distributes its energy over longer time periods was selected.

The resolution of crosswell images is determined in part by the energy spectrum of the transmitted seismic signal. For high resolution images the source should output as high a frequency as the ground will allow to be transmitted. However, the ground attenuates high frequency signals much more severely than low frequency signals. This effect is site dependent and is worse near the surface where the ground is uncompacted, and unsaturated, which is the case at many environmental sites. For a swept frequency source, in addition to needing as high a center frequency as possible, it is important in the data processing step known as correlation to have as wide a frequency spectrum as possible in order to minimize the ringing of the data. This is explained in more detail, with some examples, in Appendix E. Therefore, the source needs to be capable of producing a broad, easily modified output spectrum.

It was determined for several reasons that the swept source should couple to the formation by clamping directly to the PVC casing. Direct coupling permits the source to operate in dry wells which is advantageous, since adding fluid to environmental monitoring wells is often unacceptable. Even if the well is naturally filled with fluid or if it is permissible to add water, using a non-clamped source can cause data processing difficulties. Many non-clamped sources use a volume expansion principle, which generates compressional waves in the borehole fluid, known as tube waves. These propagate along the full length of the wellbore and reradiate additional waves at numerous interfaces. These tube waves can seriously affect the data analysis process to the point that only the first compressional (P-wave) arrivals are usable. Without reflections, shear waves (S-waves), and other waves, effective site characterization cannot be performed.

Using a clamped, non-expanding source eliminates this detrimental tube-wave generation. Clamped sources do have the disadvantage of being mechanically more complicated and taking longer to deploy in a field survey than unclamped sources, which can operate while moving up the wellbore.

Calculations were performed to evaluate the required energy from a swept source in order to propagate sufficient energy between the monitoring wells (100-200 feet between wells). The propagation of seismic energy is extremely site dependent, and is also frequency dependent. Therefore, source and receiver signal data from prior field tests with other sources were also analyzed to help bracket the desired force level. It was determined that the swept source should deliver approximately 400 pounds force to the formation to overcome typical vadose-zone attenuation across these distances.

Size and operational constraints indicated that the source should be housed in a borehole tool package with a maximum length of 24" and a maximum diameter of 3.5" OD. To minimize the required surface support equipment, the source should be operated on an electric wireline. Based on these observations the requirements established for this source are as follows:

Table 2: Seismic Source Requirements

1. Small, lightweight tool for easy deployment (< 100 lbs.)
2. Deployment on conventional seven conductor wireline
3. Frequency spectrum 150 - 2000+ Hz
4. Non-impulsive, swept frequency output
5. High force output (~ 400 lbs)
6. Clamped for good coupling to formation, for use in dry wells, and to prevent tube waves
7. Usable in PVC or steel cased wells, wet or dry, at ambient temperature
8. Easy modification of output spectrum and force levels.
9. No active cooling
10. On-board accelerometers for monitoring and control

Transducer Selection

A number of transducer types were considered to meet these requirements. The transduction mechanisms considered included air guns, piezoelectric benders, hydraulic reaction mass shakers, hydraulic pulsed clamp vibrators, pneumatic reaction mass vibrators, electric motor orbital sources, electric motor torsional sources, magnetostrictive shakers, explosives, spring loaded impact hammers, and electro dynamic exciters. A comparison of the studied devices is given in Table 3.

Table 3: Typical Characteristics of Transduction Mechanisms

Mechanism	Peak Force (lb.)	Frequency Range (Hz)	Fit well size constraints ?	Stress on Casing (psi)	Cooling Needed?	Power (Watt)	Clamped	Deployment	Dry Wells
Air gun	9000	20-1000	no	2000	no	3000	no	Hoses	no
Piezo electric Bender	?	500-5000	yes	0	no	800	no	Wireline	no
Hydraulic reaction mass vibrator	6000	10-640	no	200	maybe	1000	yes	Heavy Wireline or Hoses	yes
Hydraulic pulsed clamp vibrator	400	10-640	no	200	maybe	1000	yes	Hoses	yes
Pneumatic reaction mass vibrator	200	40-300	no	100	no	1000	yes	Hoses	yes
Electric motor orbital source	100-200	50-400	yes	0	no	3000	no	Wireline	no
Electric motor torsional source	?	?	yes	?	maybe	1000	yes	Wireline	yes
Magnetostrictive	400	100-4000	yes	250	no	1000	yes	Wireline	yes
Explosives	?	50-600	yes	5000	no	?		Wireline	no
Spring loaded impact hammers	?	50-400	no	1000	no	?	yes	Wireline	yes
Pulsed electrical Clamp Motor	400	20-1500	yes	250	maybe	1000	yes	Wireline	yes
Electro-Dynamic	100	20-2000	maybe	200	no	3000	yes	Wireline	yes

Evaluation of these transducer types indicated that only the magnetostrictive actuator and clamp modulator techniques met all of the design requirements for this application. Use of these techniques could yield significant improvements over the best current technology (piezo-electric). In particular, increased force, use in dry wells, more useful frequency range, and reduced size and power requirements can be achieved.

Several prototype sources were built and tested, including a clamped, electric-motor driven torsional source, a clamped source containing 4 magnetostrictive actuators oriented horizontally in the wellbore which could be driven simultaneously or in varying combinations to produce P or horizontal shear waves, and an oscillating electric-motor clamp drive.

A magnetostrictive actuator was selected as the most appropriate for this application. Various modes of operation were investigated, including both P-wave and S-wave generators. Several methods were designed for implementing this actuator into a downhole tool. A reaction-mass shaker design was selected. Due to the size constraints of the tool, the desire for large strokes and high forces, it was decided to concentrate on a vertical vibrator.

In addition to the vertical vibrator, we designed and built a combined P-wave and horizontal shear wave vibrator source consisting of four short magnetostrictive actuators in an array. These were built into a modified clamp package, and oriented such that they expand and contract in-line with the clamp shoe. These can be driven simultaneously to produce a strong directional P-wave, or they can be driven out of phase of one another to produce directional shear waves. Although the hardware was fabricated and the four small commercial magnetostrictive actuators were purchased, this horizontal vibrator was not extensively tested in the laboratory and has not been used in the field.

The remainder of this report will cover the development of a vertical-shear magnetostrictive reaction-mass shaker.

Commercial Actuator Description

Magnetostrictives are materials which exhibit a change in length when subjected to a magnetic field. There are a number of these materials, but the material exhibiting the greatest change in length for a given magnetic field is a rare earth magnetostrictive alloy composed of terbium, dysprosium and iron. It was developed by the U. S. Navy for use in sonar transducers, active vibration isolators, and other actuators. It is marketed exclusively in the U.S. by Etrema Products Inc. under the trade name Terfenol-D. Terfenol-D exhibits strains of 1000 to 2000 ppm, compared to 100 to 300 ppm for PZT ceramics and 40 ppm for Nickel. Appendix D includes sample Etrema product literature showing the properties of Terfenol-D and Etrema commercial actuator details.

Etrema sells:

1. Bare Terfenol rods
2. Terfenol rods biased with permanent magnets
3. Complete packaged actuators
4. Enhanced stroke actuators

Initial laboratory and field tests were conducted using several small, commercially available magnetostrictive actuators from Etrema Inc. These gave very promising results.

The complete packaged actuators consist of a magnetostrictive rod which is mechanically pre-loaded in compression to the maximum rated load of the actuator by means of a spring. This improves actuator response in several ways:

- a) It insures that the magnetostrictive rod is always in compression. This is important since Terfenol has high compressive strength but almost no tensile strength.
- b) It increases the material's output strain rate.
- c) It reduces hysteresis in the rod, making the response of the actuator much more linear.

The rod is surrounded by an electromagnet drive coil. When a voltage is applied to the coil, a current flows, generating a magnetic field. The magnetic field induces a strain (increased length) in the magnetostrictive rod, pushing out on the push rod at the end of the actuator, and acting against the force of the pre-load spring. When the current stops flowing the magnetostrictive rod returns to its original, shorter, length.

Surrounding the coil is a rare earth permanent magnet circuit. The purpose of the permanent magnet bias is to allow the actuator to be driven bidirectionally. Without a magnetic bias, the rod lengthens whenever a magnetic field is present, whether induced by a positive or negative current in the drive coil. By adding the magnetic bias, the Terfenol rod is elongated through half of its total linear range when no electrical current is applied. When current is applied in one direction it adds to the permanent magnet field and the rod expands. When current is applied in the opposite direction it opposed the permanent magnet field and the rod contracts.

Etrema also makes enhanced stroke actuators. The enhanced stroke actuators incorporate a lever-arm linkage mechanism to increase the stroke, but decrease the force. This is beneficial at low frequencies, but the lever mechanism has its own resonances and does not work well at high frequencies, so it was not used for this application.

These commercial actuators were tested extensively at Sandia in the laboratory, and also in limited field tests. These tests included measurements of drive current, voltage, force output, phase, linearity, resonances, transmitted frequency spectrum, and signal-to-noise, as well as various drive and control schemes and mounting methods. These tests are discussed later in this report. Based on results of these tests, a contract was placed with Etrema Products in June, 1993 to develop a custom actuator for this borehole application.

Custom Actuator and Borehole Tool Description

Overview

During the second year of the project a large, custom magnetostrictive actuator was designed and fabricated by Etrema Products, Inc., based on the results of our earlier tests. This actuator was a scaled up version of their commercially available actuators. It contained a larger diameter, longer Terfenol rod than the commercial actuators. It also contained an integral 30 lb. tungsten reaction mass built into the body of the actuator. The custom actuator was incorporated into a modified version of a clamped downhole receiver tool which had previously been jointly developed by Sandia National Laboratories and OYO Geospace (See reference 2). This tool included a high force output electric motor driven clamp that had been optimized for high frequency performance, and was ruggedized for use on a wireline in borehole environments. The actuator was attached to an internal bulkhead in the borehole tool by means of a threaded push-rod and jam nut, which allowed nearly the entire mass of the actuator to act as a reaction mass.

Figure 3 shows the assembled borehole tool. Figure 4 shows the borehole tool with one cover removed, showing the custom magnetostrictive actuator. Figure 5 shows the borehole tool fully disassembled, showing the clamp motor and gear reducer, the right angle gearbox and clamp piston, the custom magnetostrictive actuator, and the knurled break-away clamp shoe.

The custom actuator and the complete borehole tool were tested extensively in the laboratory to determine their output characteristics and to optimize various drive and control schemes. When the tool is driven open-loop with a constant voltage or constant current input it has a very non-flat output, due to mechanical resonances, increasing accelerations with frequency, and variations in actuator electrical impedance with frequency. The device is also stroke limited due to rod length and material property limitations. This stroke limitation, combined with the limited reaction mass size that can be incorporated into an easily handled borehole tool, limits the force output of the tool at low frequencies (<150 Hz). There are also electrical current limitations of the drive coil, voltage limitations of the power supply, and a mechanical strain limitation at resonance to prevent damage to the magnetostrictive rod. All of these factors indicated that a closed loop control scheme should be used, rather than running the actuator in an open-loop mode.

To accommodate the non-linear output of the source, a closed loop force feedback system was implemented, using an accelerometer mounted on the actuator as an input to the control loop. This worked very well at low sweep rates (<20 Hz/sec sweep rate) and produced flat outputs from the shaker. However, the sample rate of the force feedback system which we used was too slow to give a flat output at higher sweep rates needed in the field (200 - 400 Hz/sec), and instead gave a stepwise output. Therefore, in the field tests the tool was clamped in place, a low power open-loop test sweep was run, and then the required drive signal was calculated, based on our earlier laboratory testing, to meet all of the above constraints while obtaining a flat output. The tool was then driven with this programmed, amplitude-varying sinusoidal sweep signal through a large audio amplifier. This allowed adjustment of the sweep rate, dwell, frequency spectrum, and

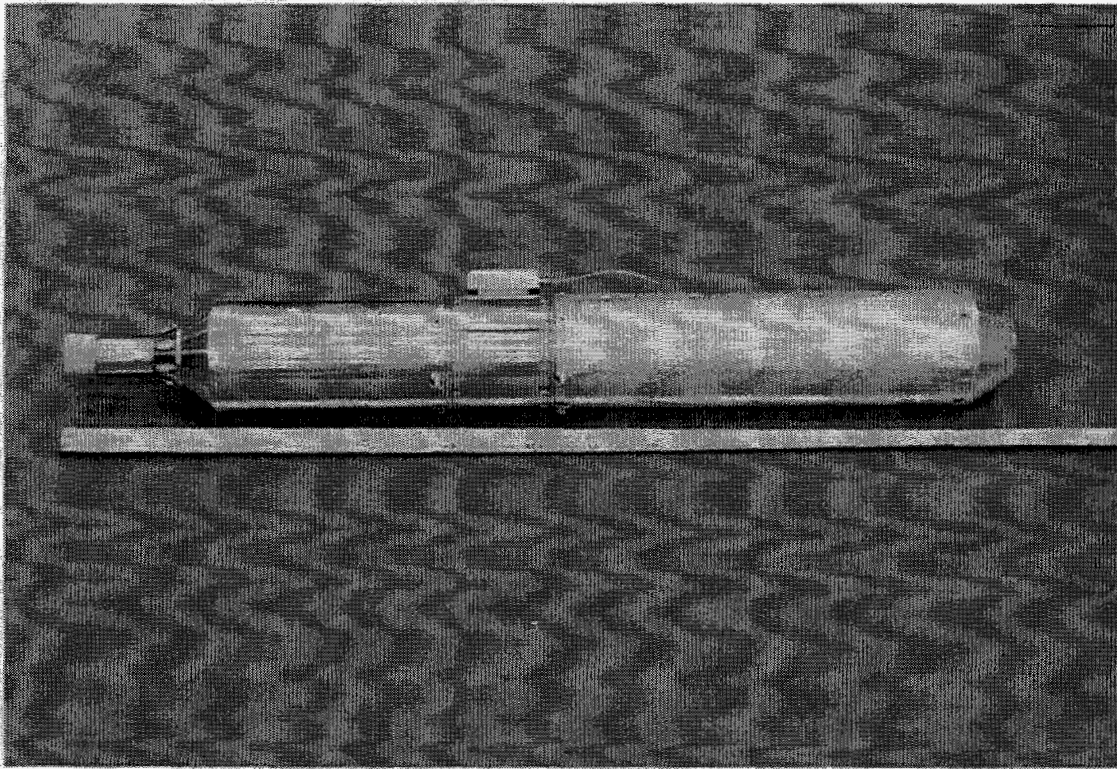


Figure 3: Custom Magnetostrictive Actuator incorporated into Borehole Tool

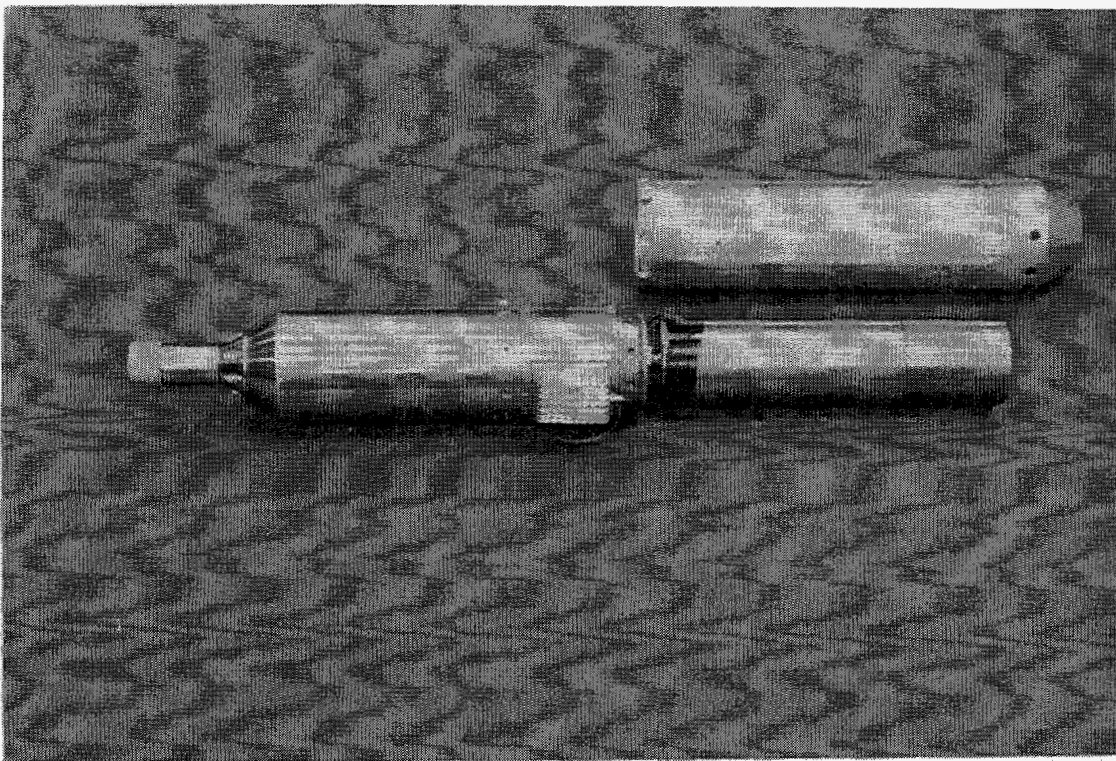


Figure 4: Borehole Tool with cover removed, showing Custom Magnetostrictive Actuator



Figure 5: Borehole Tool disassembled showing Motor, Clamp, and Custom Magnetostrictive Actuator

amplitude throughout the sweep in order to obtain a flat output from the tool. While this was time consuming it worked well and gave a flat tool output even with very fast sweeps (~2000 Hz/sec).

The magnetostrictive actuator can be driven over a very broad frequency spectrum, and the tool was tested from 100 Hz to 10 kHz, but since ground attenuation increases with frequency, and because of mechanical resonances inherent in both the actuator and in the borehole tool, most of the testing for this environmental application was conducted from 150 Hz to 2000 Hz.

Tests of the tool showed that the force output and resonances of the custom actuator were dramatically affected by the structural stiffness of the overall tool, including the clamp mechanism, and how well the tool is coupled to the formation. Variations in clamping to the well bore from one location to another can be minimized by using a very stiff clamp and tool, and to some extent can be accommodated by variations in drive signal.

Actuator

A contract was placed with Etrema to develop and test a custom actuator for this borehole application. The goal was to provide higher force output capabilities and flatter response at low frequencies than was attainable with their commercial actuators. The design requirements for the actuator were:

Table 4: Custom Actuator Characteristics

<u>Actuator Characteristics</u>	<u>Specification</u>
Minimum Reaction Force	400 pounds force
Frequency Range (+/- 6 dB)	140 Hz to 2000 Hz
Resonant Frequency	Above 400 Hz
Total Harmonic Distortion	Less than 5%
Maximum Length	12 in.
Maximum Diameter	3 in.
Operating Temperatures	15 °C to 70 °C
Maximum Weight of Reaction Mass	40 lbs.
Preferred Reaction Mass Material	Tungsten Alloy
Monitoring Accelerometer	Adhesive mount unit
Power Requirements	Audio amplifier not exceeding 3 kVA
Actuator Mounting	Stud mount, 0.75" diameter

Sandia reviewed and approved Etrema's design and the actuator was fabricated. The actuator contains a large tungsten reaction mass built into the actuator body. The actuator is mounted to the borehole tool by means of a threaded push rod rather than by the actuator base so that

essentially the entire mass of the actuator behaves as a reaction mass, with only the push rod not moving.

The Terfenol rod is 0.975" in diameter and 6" long. The large diameter rod allows higher mechanical preload and hence higher rated load. In addition, the spring rate of the Terfenol determines the mechanical resonance of the system. Since the spring rate is proportional to the rod cross sectional area, a larger diameter makes the actuator stiffer, which in turn leads to a higher natural frequency. (Since the time this actuator was fabricated, Etrema has increased their maximum rod diameter to 2", which would be much more desirable for this application than the 0.975" rod). The long rod provides increased stroke, since the stroke is fixed by material properties to ~ 0.001 inch per inch of rod. The longer stroke improves the low frequency output of the device.

The resulting actuator is 3" in diameter, 12" in length, and mounts directly to the borehole clamp bulkhead. The actuator can generate a peak force of 900 lbs., but is operated at about 300 lbs. from ~150-2000 Hz in order to obtain a flat response. The actuator has a closed loop magnetic field, so putting it against a steel well casing does not adversely affect it. The actuator was potted using thermally conductive potting to minimize internal heating.

The actuator was tested by Etrema and shipped to Sandia in October, 1993, along with a final development report (see Appendix B). The actuator was tested extensively at Sandia in the laboratory, first mounted to a plate, then in a modified borehole tool clamped into a cored hole in a granite block. The completed tool was then successfully demonstrated in the field at three sites.

Borehole Tool

The actuator was mounted to a modified OYO/Sandia wall locking seismic receiver tool. This tool had been optimized for high frequency seismic transmission to 2000 Hz. It was ruggedized for borehole environments up to 10,000 psi external pressure and 200 °C. It can be deployed on a standard 7 conductor wireline. For these shallow applications, the pressure and temperature capabilities of the borehole tool were not needed. However, it provided a very nice, readily-available platform for testing and deploying the source. While this borehole tool worked well in the laboratory and field tests, it was not designed for this application. The clamp was only designed for holding passive accelerometers in place, not a large vibratory source. In order to achieve adequate clamping force the clamp was run at nearly its mechanical strength limits. However, developing a completely new borehole tool with a stiffer, fail safe clamp was outside the scope of this project.

In order to use this borehole tool with the magnetostrictive actuator, we made several modifications, including:

- a) Designing a thicker, stiffer middle bulkhead
- b) Increasing the motor gear reducer ratio to increase clamping force
- c) Removing the accelerometer mount to make room for the actuator
- d) Increasing the bell housing length to make room for the actuator
- e) Installing new clamp bushings, gears, shafts, gear box plates, and splines made of PH 17-4 and 15-5 PH (Sy ~ 160 ksi) rather than 304 (Sy ~ 40-60 ksi) stainless steel.
- f) Pressing bronze bushings into shaft holes to eliminate galling
- g) Adding rails and/or pointed nubs to give 3 point contact with the wellbore

The following table gives the characteristics of the magnetostrictive seismic source in the borehole tool:

Table 5: Overall Borehole Source Characteristics:

Tool Diameter	4"
Tool Length	30"
Tool Weight	50 lbs.
Hydrostatic Pressure limit	10,000 psi
Maximum Temperature	70 °C
Deployment	Standard 7 conductor wireline
Clamp	Electric motor driven wall-lock clamp
Clamp force	~ 600 lbs.
Drive Signal type	Swept frequency sine wave
Radiation pattern	Vertical Shear source
Drive Signal Amplitude	Variable, Programmable
Useful frequency spectrum	~180 - 2000 + Hz
Drive current	1 to 8 amps
Peak force	900 pounds peak force, 250 lbs flat from 180 - 2000 Hz
Sweep length	0.2 sec to continuous

Laboratory Tests

This section discusses laboratory testing conducted on the commercial and custom magnetostrictive actuators, both as bare actuators and also incorporated into borehole tools. The commercial models tested were: Models # 50/6-MP, 75/12-MP, 100/6-MP, 110/12-MP (see actuator details in Appendix D). The actuators were operated under a number of conditions to determine their response and limitations. These tests included the following:

Table 6: Laboratory Tests of Commercial Actuators, Custom Actuator, and Borehole Tool

1. Constant voltage frequency sweeps at various voltages (1, 2, 5, 10, 20 volts rms)
2. Constant current frequency sweeps at various currents (1, 2, 3, 6, 8 amps)
3. Constant force output vs. frequency using programmed drive signal (1, 2, 3, 4, 5, 6, 8, 10 g's)
4. Constant force output vs. frequency using closed loop force control (1, 2, 5, 8, 10 g's)
5. Maximum force output vs. frequency
6. Fast sweeps (300 to 1000 Hz/sec) vs. slow sweeps (5 to 15 Hz/sec)
7. Sweeps with different reaction masses (11, 15, 30 lbs.)
8. Single frequency tests at increasing voltages for linearity and distortion
9. Temperature rise during extended operation
10. Voltage, current, electrical impedance, and force vs. frequency from 100 Hz to 10,000 Hz
11. Relative phases of current, voltage, and force from 100 Hz to 2000 Hz
12. Actuator upright vs. inverted
13. Bare Actuator vs. Actuator in Borehole Tool
14. Borehole Tool unclamped vs. clamped with various clamp gear reducer ratios (47:1, 68:1, 99:1, 144:1) vs. clamped with pneumatic clamp at various pressures (20, 30, 40 psi)
15. Borehole tool with back rails vs. pointed nubs vs. bare tool
16. Electrical circuit tuning by adding varying capacitance (0.2 to 20 μ f)
17. Borehole tool on short leads vs. 500' wireline

In initial tests the actuators were mounted to a 12" x 12" x 1.5" aluminum plate, which in turn was bolted to a 3' x 3' x 4.5' granite block weighing 6700 lbs. For the commercial actuators, the base of the actuator was attached to the plate, and the push rod was attached to a brass or tungsten reaction mass. For the custom actuator the reaction mass is incorporated into the actuator, and the actuator was attached to the plate by means of a threaded push rod, and was secured with a jam nut. In later tests the actuators were bolted to the bulkhead of the borehole tool, which in turn was clamped into a cored out hole in the granite block by means of the built in electric motor driven clamp. Figure 6 shows the laboratory set-up for testing the actuator by itself and for testing the actuator in the borehole tool. The actuator was driven by a B&K fully programmable low distortion signal generator connected to a large Elgar audio amplifier power

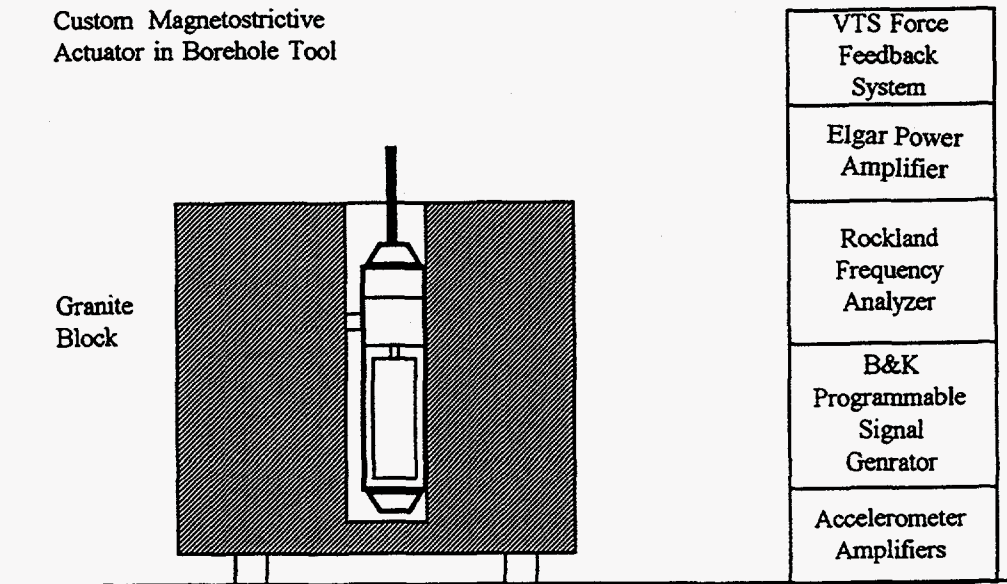
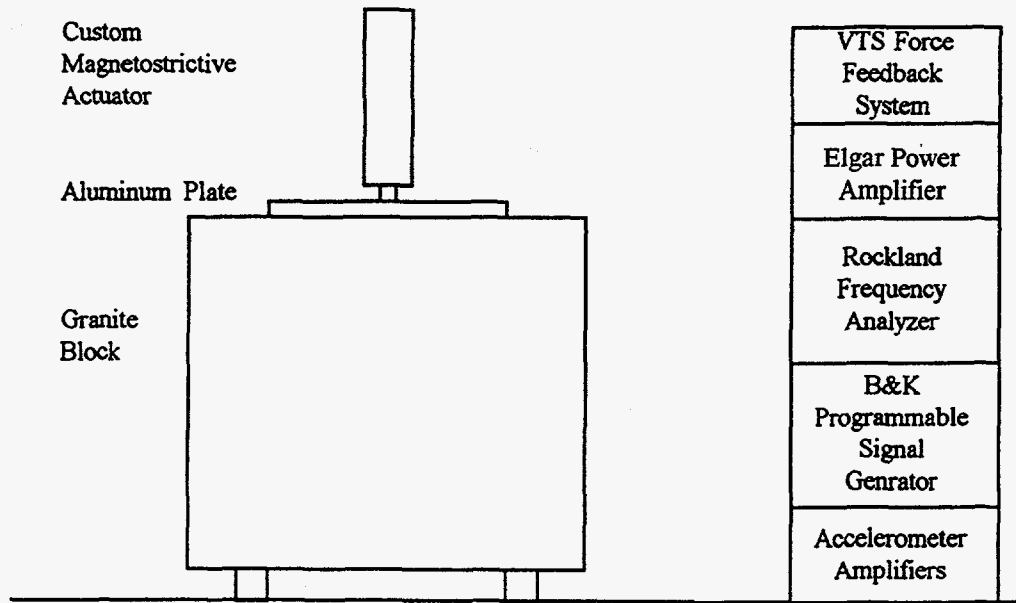


Figure 6: Laboratory Set-Up for Testing Bare Actuator (upper) and Actuator in Borehole Tool (lower)

supply. The drive current and drive voltage waveforms were recorded on a Rockland Signal Analyzer. The accelerations of the reaction mass, the aluminum plate, the outside of the source tool housing, and the granite block were measured using Wilcoxon accelerometers. These signals were amplified and sent to the Rockland Signal Analyzer. These files were then transferred to a PC computer for further analysis.

Table 7: List of Laboratory Equipment

1. Signal Generator, Bruel & Kjaer low noise, low distortion, Model 1051
2. Power Supply, Elgar Model 1751
3. Digital Sine Vibration controller, VTS DSC-1 modified for sweeps to 1000 Hz/sec
4. Current Monitor, Pearson Electronics model #411
5. Accelerometers on top of the block, back of the block on the actuator top, on the actuator bottom, and on the tool bulkhead, were Wilcoxon Models 731
6. Clamp DC power supply and control box
7. Accelerometer amplifiers, battery powered and optically isolated
8. Rockland Signal Analyzer
9. Granite block $40.8 \text{ ft}^3 \times 165 \text{ lb./ft}^3 = 6700 \text{ lbs.}$

Test Set-up Issues

Initially, many of the tests of the commercial and custom actuators were not repeatable. This was eventually determined to be due to very slight modifications in how firmly the actuators were mounted to the test plate, borehole tool, or granite test block. Because of the short stroke length (a few thousandths of an inch maximum) and the high frequencies involved, the actuator force output is extremely sensitive to changes in system stiffness, including changes in tool clamping, actuator mounting, and reaction mass attachment. Several methods were tried to achieve more repeatable results. We eventually achieved a very repeatable test set-up by insuring that all mating surfaces were very clean, the mounting bolt holes in the plate were counter-bored to minimize bolt stretch, the mounting bolts were torqued to the same value each time, and the actuator jam nut was torqued to the same value each time. Figure 7 shows three 20 volt constant voltage sweeps of the custom actuator mounted in this manner to a test plate. The actuator was removed, replaced, and used for other testing between each of these three tests. The high force output, strong central peak at the mechanical resonance, and very repeatable data are typical of the data acquired from this type of mounting.

Figure 8 shows eight tests of the custom actuator at the same 20 volt drive level shown in Figure 7, but this time with the actuator mounted in the borehole tool. The peak force is reduced by a factor of two, and there is much more variability between the eight tests than in the three tests of Figure 7. There are also additional tool resonances around 1000 Hz. This is due to reduced overall system stiffness with the borehole clamp compared to the bolted down test plate, to the additional moving mass of the borehole tool rather than just the actuator, and to non-repeatable

Actuator Mounted to Test Plate
Constant 20 Volt Sweep

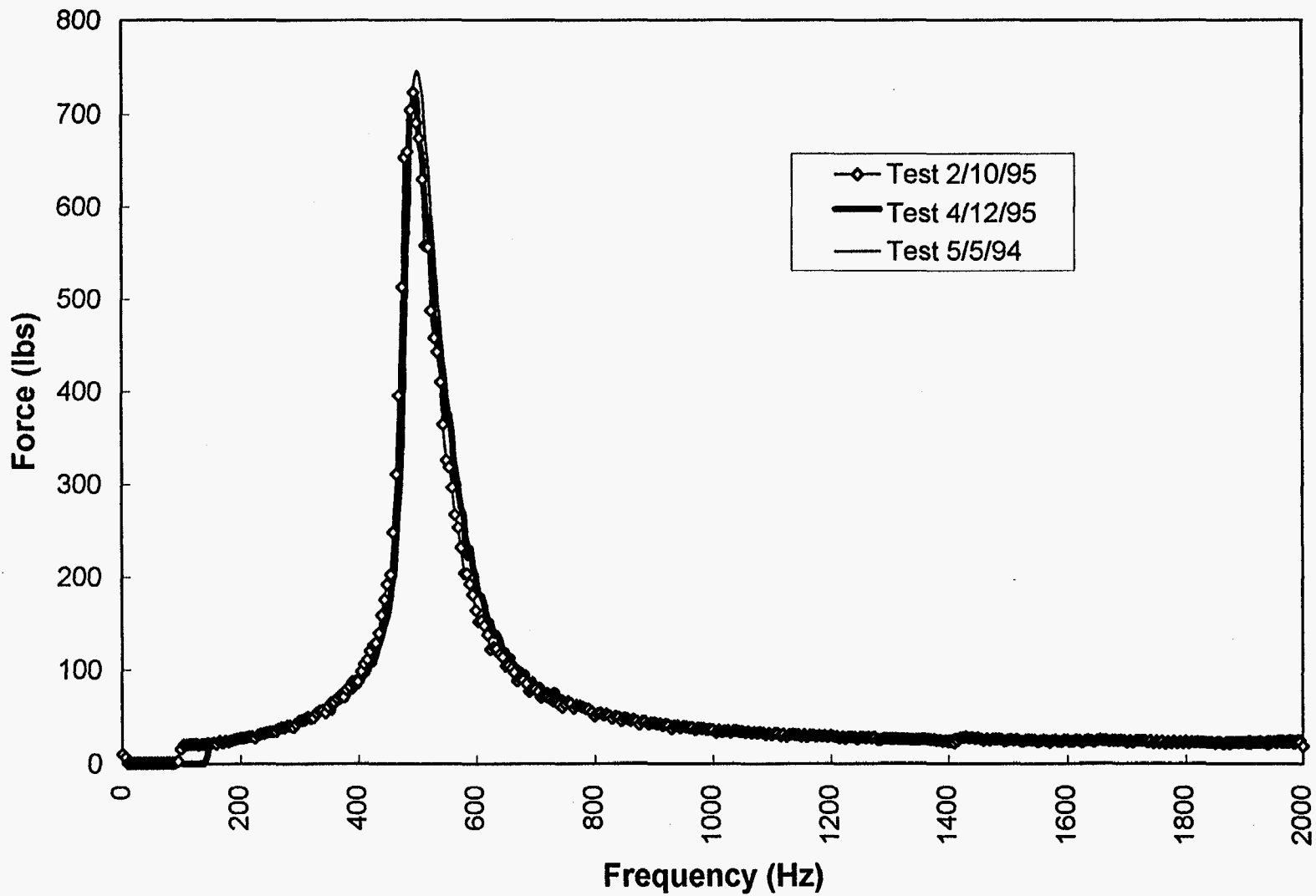


Figure 7: Force Output from 20 Volt Sweep with Source Mounted on Plate

Actuator Mounted in Borehole Tool Constant 20 Volt Sweep

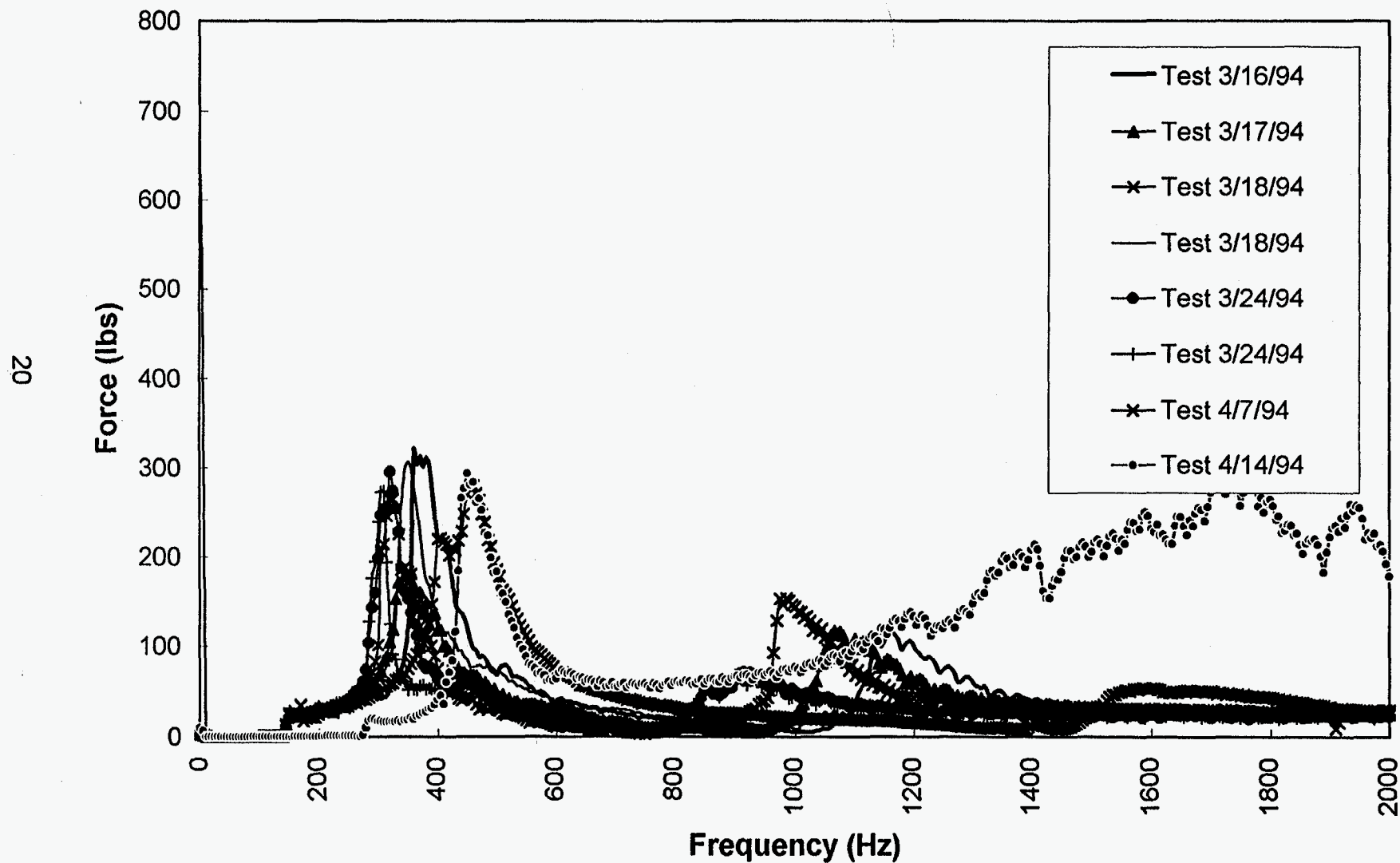


Figure 8: Force Output from 20 Volt Sweep with Source Mounted in Borehole Tool

clamping of the borehole tool in the hole in the granite block. Even though the resonant peak changes, the peak output force level is fairly repeatable in these tests.

Figure 9 shows seven tests with the identical test conditions as Figure 8. Investigation showed that during each of these tests, the jam nut holding the threaded push rod from the actuator into the plate has loosened slightly. In many cases, this loosening was almost imperceptible, but when it was re-tightened the output returned to that shown in Figure 8. These figures illustrate very graphically the dramatic effect that changes in overall system stiffness can have on the force output, the need for a better method of attaching the actuator to the borehole tool, and also the advantages in force output and repeatability that could be achieved with a stiffer borehole clamp tool.

While the test results became more repeatable in the lab, this pointed out the difficulties anticipated in obtaining consistent output from the source under actual field conditions when the borehole tool is repeatedly clamped and reclamped in different parts of the well bore. In the tests conducted in the field, the clamp functioned very well in PVC casing, and quite well in steel casing, but a stiffer, higher force clamp and a better connection between the actuator and the borehole tool would help to give more repeatable results in the field.

Analytical modeling and laboratory testing confirmed that the granite block has approximately 14 resonant modes which lie below 2000 Hz. The lowest one that would affect our data is at 1140 Hz. Therefore, laboratory data above 1100 Hz must be evaluated carefully. They are included in most of the plots that follow, because they do show comparative signals at higher frequencies. However, absolute values measured by accelerometers on the granite block may be amplified or reduced at the higher frequencies due to these block modes. In all of the tests we measured the acceleration of the test block, the acceleration of the borehole tool, and the acceleration of the reaction mass on the actuator. When these accelerations were multiplied by the corresponding masses the force data matched fairly well below 1000 Hz.

Figure 10 compares the force calculated by multiplying the output from the accelerometer mounted on the actuator reaction mass by 30 lbs. (the weight of the moving portion of the actuator), with the force calculated by multiplying the output from the accelerometer mounted on the granite test block by 6700 lbs. (the weight of the test block).

The granite block rests on two pieces of 2" square tubing, which rest on the floor. Tests were conducted to insure that the granite block was vibration isolated from the ground and that ground contact was not affecting the data. Comparative tests, conducted with the block sitting on the square tubing compared to the granite block floating on air bags showed no measurable difference in block acceleration, actuator acceleration, resonances, or actuator drive current. Therefore, all further tests were conducted with the granite block resting on the square tubing.

We compared the output of accelerometers located on the top center of the reaction mass and on the bottom of the actuator near the threaded stud, to make sure that the entire actuator was moving together as a unit. There was no discernible difference in the two signals.

Actuator Mounted in Borehole Tool Loose Jam Nut, Constant 20 Volt Sweep

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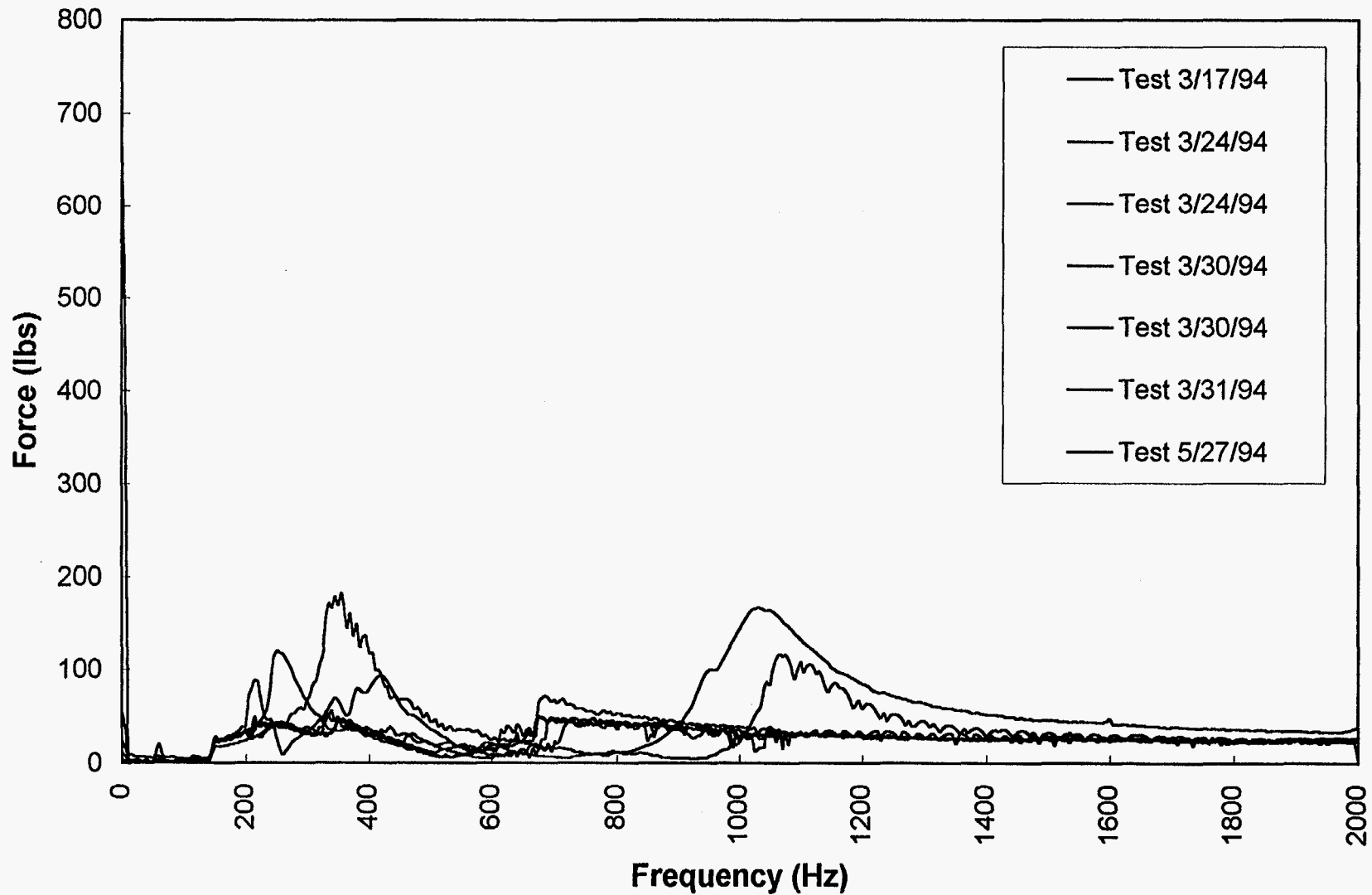


Figure 9: Force Output from 20 Volt Sweep, Source with Loose Jam Nut

Force Coupled From Actuator Into Block for 20 Volt Sweep Source in Borehole Tool

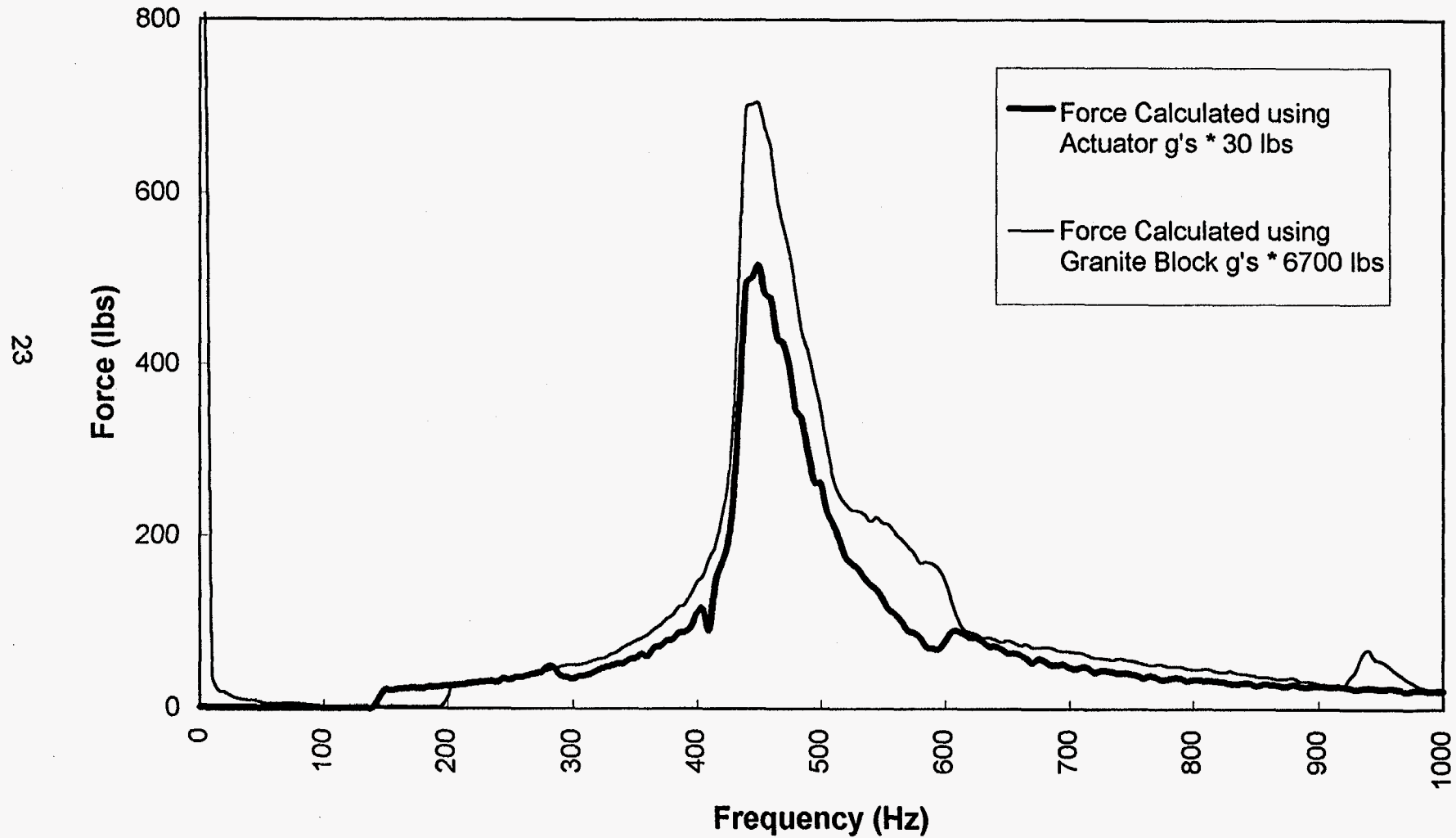


Figure 10: Force Coupled From Borehole Tool into Test Block for 20 Volt Sweep

Results of most of the tests conducted on the commercial actuators have not been included in this report because of the non-repeatability of the test setup, mentioned earlier. However, the tests of these commercial actuators did give valuable insight into the design requirements for the custom actuator.

Following initial testing of the commercial actuators attached to the aluminum plate, the 75/12-MP commercial actuator and a 15 lb. brass reaction mass were bolted to a modified OYO/Sandia borehole receiver tool, which in turn was clamped into a cored out hole in the granite block. The tests were then repeated to determine what effects the borehole tool would have on the actuator output. The tool was also driven over a short length of wireline to simulate field conditions.

Figure 11 shows this commercial actuator with the attached brass reaction mass and an early version of the clamp package. Figure 12 shows the force vs. frequency output from this device. As noted above, it was later determined that data above 1100 Hz is suspect due to test set-up limitations.

The small commercial actuators were, in many cases, tested far beyond their rated limits in order to determine their maximum operating conditions and failure modes. While these tests demonstrated very impressive source output, a number of the actuators were damaged or destroyed during testing. With the large custom actuator, we tried to keep all of the tests within the rated limits. In addition, as shown by the clamp tests, there is a significant reduction in force output when the actuators are mounted in the borehole tool rather than being bolted to the test plate. As a result, the output from the large custom actuator in the borehole tool, when operated within its rated limits, is not a lot higher than that of the smaller commercial actuators when they are bolted to a plate and are driven beyond their rated limits.

Etrema Testing of Custom Actuator

Etrema performed final performance testing of the custom actuator before shipping it to Sandia. See Appendix B "Etrema Reaction Mass Actuator Final Report". There were several differences between their test set up and the one that we used. In their tests the actuator was mounted to a 1" thick steel plate, which in turn was bolted to a 500 pound steel mass. All of the tests were performed without unbolting the actuator. Their tests were conducted at discrete frequencies rather than sweeping the drive signal. In Figure 4 of their report the small peak and valley are mounting plate resonances and anti-resonances. They measured the current using a current viewing resistor which may have shifted the impedance. When the actuator arrived at Sandia we repeated Etrema's testing, using our set-up on the aluminum plate bolted to the granite block. The results were similar, but the resonant peak was at a lower frequency, indicating a lower system stiffness.

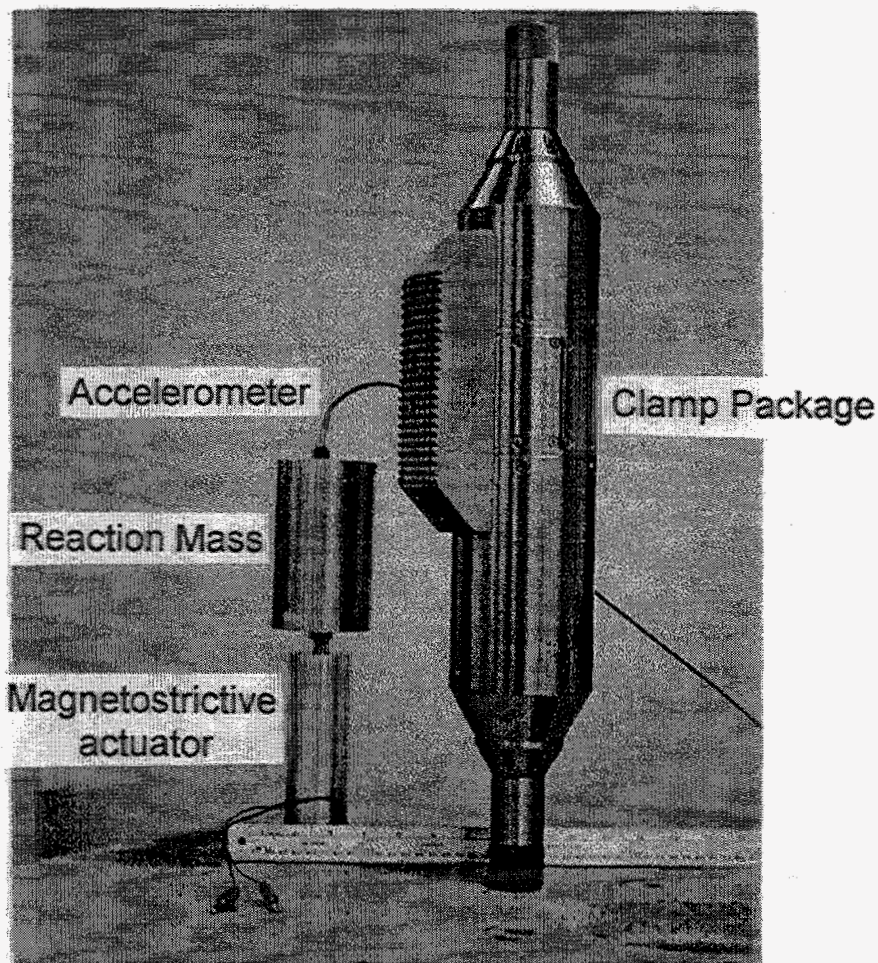


Figure 11: Photograph of Commercial Magnetostrictive Actuator, Reaction Mass, and Clamp Package

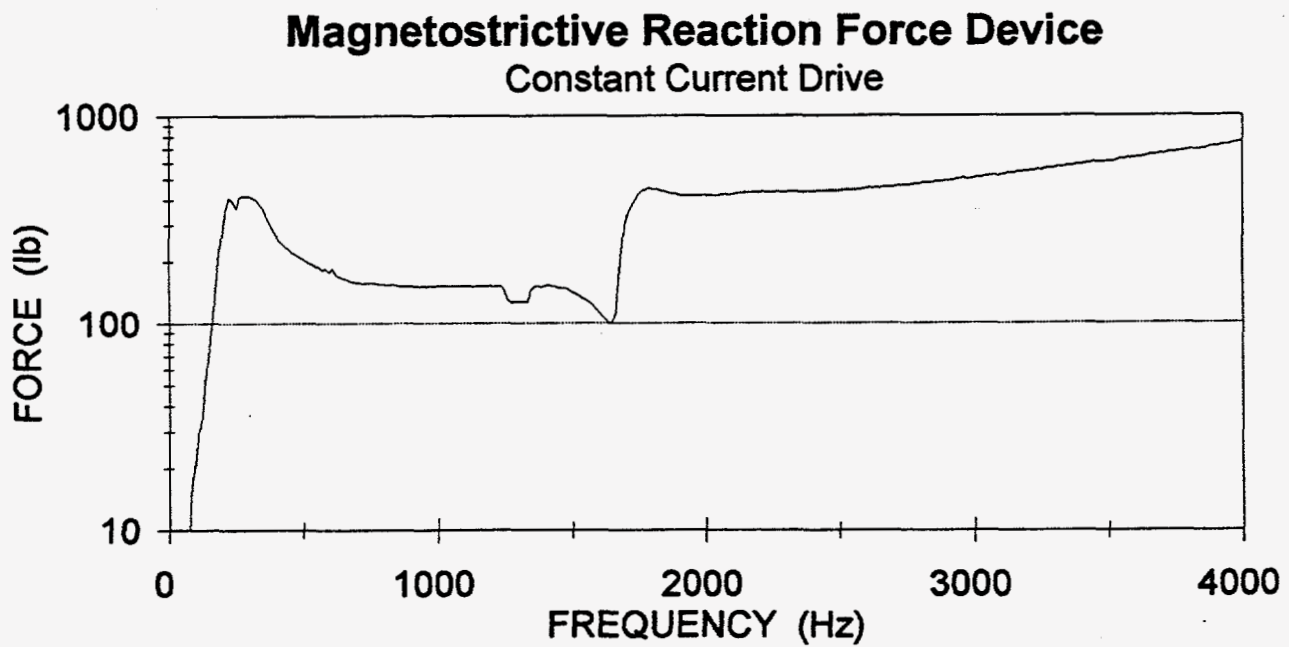


Figure 12: Force vs. Frequency from Commercial Actuator

Operating Limits

When the actuator is driven open loop with a constant voltage or constant current input it has a very non-uniform output, due to mechanical resonances, increasing accelerations with frequency, and variations in actuator electrical impedance with frequency. The device is also stroke limited due to rod length and material properties. This stroke limit, combined with the finite reaction mass size that can be incorporated into an easily handled borehole tool, limits the force output of the tool at low frequencies (<150 Hz). There are also electrical current limits of the drive coil, voltage limits of the power supply, and a mechanical strain limit which must not be exceeded to prevent damage to the magnetostrictive rod. This section discusses some of these limits.

Voltage Limits:

The Elgar Power Supply used, Model 1751 SL-12, produces a linear frequency response from 45-5000 Hz. Its output is limited to 10 amps, 260 volts, and a combined 1700 watts. The 260 volt limit, in conjunction with the low impedance of the magnetostrictive actuator and the relatively high impedance of long wirelines limits operation at low frequencies, where the current drain is the highest, to about a 500' wireline. For example, $10 \Omega/1000' \times 500' \times 8 \text{ amps} = \text{a } 40 \text{ volt drop}$ in the wireline. The performance of the device without any wireline loss was already limited by the 260 volt maximum power supply voltage. To operate on a long wireline (for example $10\Omega/1000' \times 5000' \times 8 \text{ amps} = \text{a } 400 \text{ volt drop}$ in the wireline) a higher power supply starting voltage is needed. Other ways to alleviate this problem are to use a higher impedance coil in the actuator, so that more of the voltage drop is in the actuator rather than in the wireline, or to use a wireline with lower resistance, which can be achieved by using larger conductors or by connecting multiple conductors in parallel.

Elgar builds larger power supplies (3 kW, 6 kW, and larger). Several of these power supplies could be operated in series, or an external transformer could be used with these power supplies to obtain a higher starting voltage.

Current Limits:

The length increase of the actuator rod is directly proportional to the magnetic field, which in turn is directly proportional to current level, so it is desirable to operate at as high a current level as possible for maximum output. The coil in the actuator is limited by the wire size to handling a current of 8 amps momentarily without damaging the device. At low frequencies (since the accelerations are low), the current required by the actuator to produce a given force level is fairly high, but still has to be limited below 8 amps to keep from damaging the coil. Since the actuator impedance changes with frequency, and since the actuator is operated in a swept frequency mode, we needed to be sure that the coil current did not peak above 8 amps.

Our control scheme used the output from the reaction mass accelerometer with a comparator to determine the required drive current to maintain a flat force output. However, since the force output is very non-linear with current, it was likely that, at various portions of the sweep, the controller would call for a higher current than the actuator coil could handle. In order to avoid exceeding the maximum allowable current on the actuator, we looked into fast acting current monitoring electronics that would react quickly enough to prevent the drive current from exceeding a fixed limit regardless of what the controller tried to drive it with. It turned out that incorporating fast current sensing and limiting on a sinusoidal drive signal which is continuously varying in both amplitude and frequency is a fairly difficult thing to do. We talked with Etrema, who said that they felt that very brief current spikes would not damage the device, and that the damage would be more of a thermal effect which has longer time constants.

Thermal Limits:

The permanent magnets used in the actuator can be permanently damaged at elevated temperature. The actuator was potted with heat-sink epoxy to help transfer the heat out of the device and to minimize localized heating. The specifications require that actuator skin temperature be kept below 70 °C. In the laboratory testing and in shallow applications this was not a problem, but in deep well applications this would have to be evaluated carefully.

Force Limits:

The Terfenol-D rod is fairly brittle, and although it has high compressive strength, it has almost no strength in tension. To prevent the rod from going into tension, it is put under an initial pre-load by use of Belleville washers. The preload is selected to optimize device performance. For this particular actuator, the preload is 900 lbs. Therefore, the reaction mass acceleration cannot exceed 30 g's (30 g's x 30 lbs = 900 lbs) or the rod will go into tension and fail. This is especially important at the resonance frequency of the actuator. During testing we looked at the output spectrum from the device and found that at some frequencies the harmonics exceeded the fundamental. We talked with George Toby at Etrema, who said to keep the average acceleration spectrum to less than 30 g's, but not to worry about the peak g's on a specific harmonic. He also said that it would be possible to build a larger actuator with higher mass loading, which would increase the low frequency output but drop the resonant frequency.

Frequency Limits:

Etrema said that there is no upper frequency limit in terms of damaging the Terfenol-D material, but to be wary of mechanical and electrical resonances and not to exceed the pre-load. At low frequencies the actuator requires higher and higher current levels to produce a given force level. In order to stay within the current limit of the actuator we did not operate it below 100 Hz. We initially tested the actuator from 100 Hz to 10 kHz, but the data above 1100 Hz was distorted due

to test block vibration modes. In addition, the borehole tool has resonances that limit its use to less than 2000 Hz. Therefore, most of the testing was done between 150 and 2000 Hz.

Constant Voltage Tests

Figure 7 showed the custom actuator force output using a 20 volt constant voltage sweep. As can be seen, the output when operated in a constant voltage mode is very non-linear. Figure 13 shows the current flow to the custom actuator when driven with a 20 volt constant voltage sweep. The current is highest at low frequencies. When driving the actuator harder (approaching the 260 volt limit of the power supply or the 30 g limit of the magnetostrictive rod), or when operating at low frequencies, or when commanding a flat output, it is important to monitor the current flow to the actuator to stay within the 8 amp limit of the coil.

Maximum Output Force and Flat Output Force Tests

The initial laboratory tests of the tool were run open loop on short leads. The original goal for this actuator was to achieve 400 lbs. force +/- 6 dB output from 140 Hz to 2000 Hz. Etrema's tests (see Appendix B figure 6) show a flat maximum force output of 300 lbs. from 200 Hz to 2000 Hz. In our testing the seismic source was driven at increasingly higher levels to determine its maximum output force. During one test it was inadvertently over driven, briefly reaching a peak output at resonance of 1600 lb. (even though it was only rated to 900 lbs.) and exhibiting an average output from 200 to 2000 Hz of 400 lbs. During this test the actuator began to chatter. After the test, the actuator was inspected and no damage was found.

These tests showed that the tool force output was very non-linear with frequency, and also that the output level varied a great deal depending on how well the tool was clamped. To accommodate the non-linear output of the source, and in an effort to minimize the expected variability in tool output caused by differences clamping from place to place in the wellbore, a closed loop force feedback system was implemented, using an accelerometer mounted on the actuator as an input to the control loop. This control loop adjusted the amplitude of the drive signal as needed to maintain a constant force output at varying frequencies. A commercial PC based force feedback card from VTS was used. We tried running the VTS control software under the Windows 3.1 operating system, but the update rate was slow and the drive voltage changed in large discreet steps, rather than smoothly. It worked much better under DOS, but still changed force levels in small discreet steps.

The laboratory testing used a Rockland System 90 Frequency Analyzer to record and analyze the accelerations. The Rockland 90 is limited to a sweep rate of ~ 15 Hz/sec. Above that sweep speed the analyzer begins to distort the data. We did not have a fast recording system in the laboratory like those used in the field for seismic recording, so no fast sweeps were recorded

Current vs. Frequency for Constant 20 Volt Sweep

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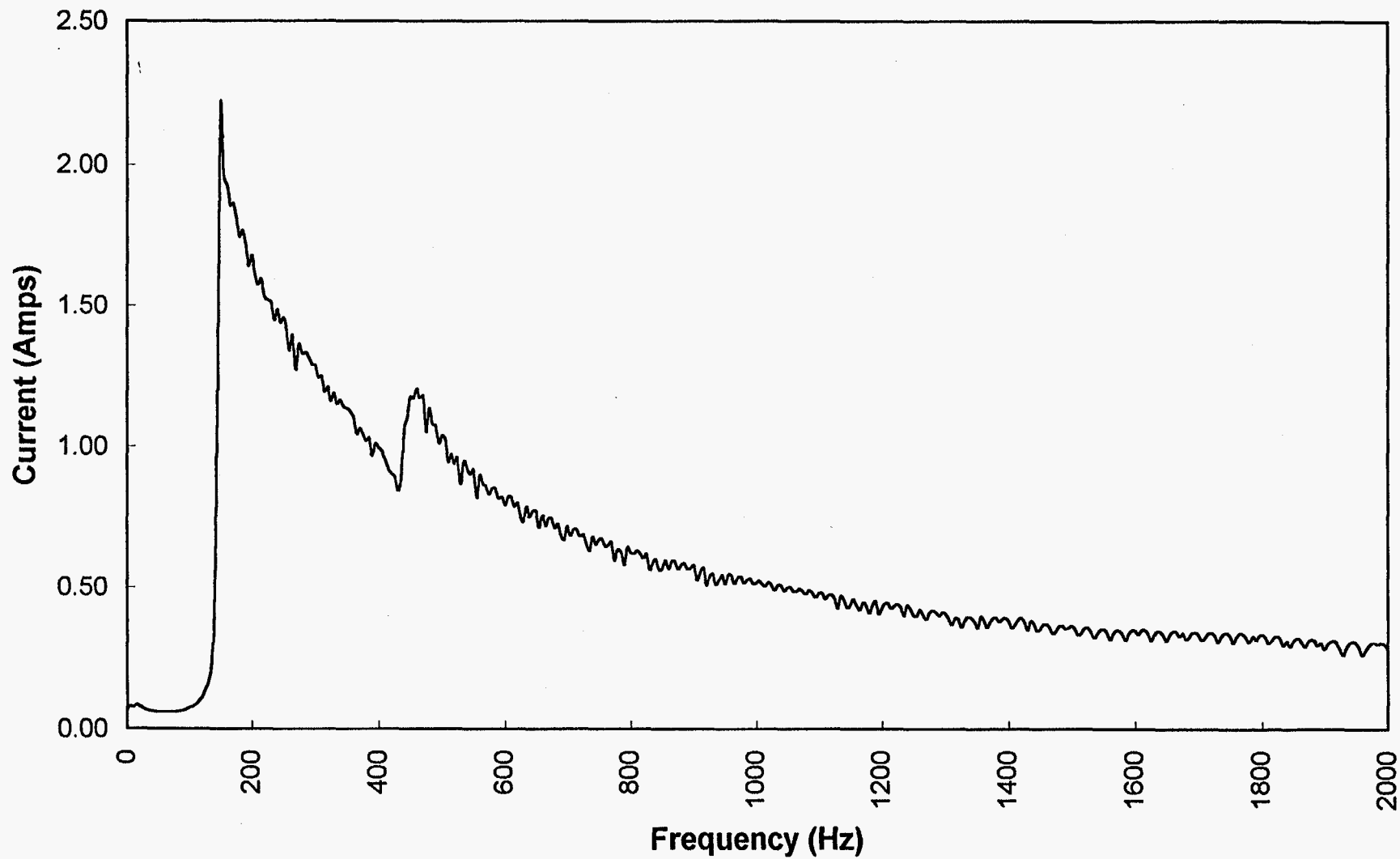


Figure 13: Current vs. Frequency for 20 Volt Sweep

except at field sites. At these very slow sweep rates the force feedback system worked well and produced flat force outputs from the shaker. With the actuator mounted on the plate, and at these slow sweep rates, the control system produced very flat force outputs for sweeps from 600-2000 Hz at commanded force levels of 1g, 2g, 5g, and 8g. When a 10 g level was commanded the force started to fall off significantly at the higher frequencies.

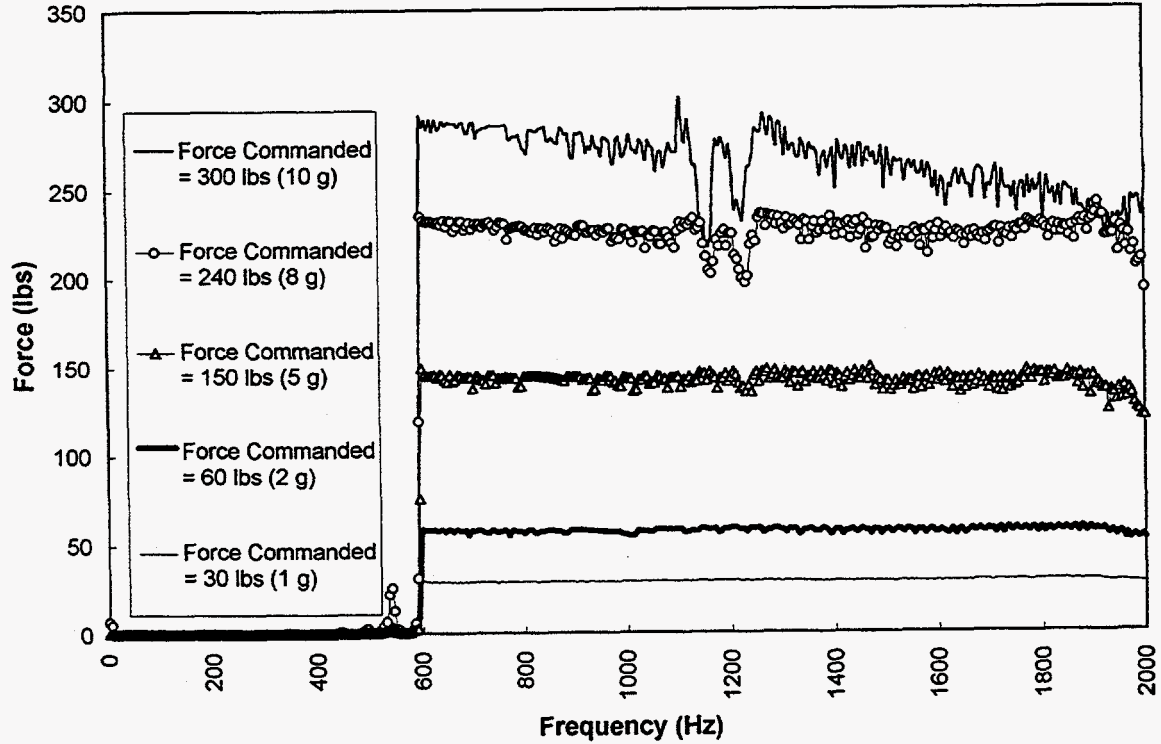
Figure 14 shows the flat force output achieved from 600 to 2000 Hz with the custom actuator mounted on a test plate, using the feedback controller, and also the drive current required. As can be seen, the force levels are very flat and accurate up to a force level of 240 lbs. over this frequency range, and the current levels are relatively low. At lower drive frequencies (below 600 Hz) we could not command a flat, high g force output without violating the voltage, current, or force levels at resonance.

Figure 15 shows the flat force tests from 150 to 2000 Hz with the custom actuator mounted in the borehole tool. Since the peak force achievable from the actuator in the borehole tool is about half that achievable on the test plate for a given drive voltage, and since the actuator mounted in the borehole tool has more than one resonance, these curves look very different than those in Figure 14. Note that the current levels are much higher, and that even for a 120 lb. force command the current is approaching the current limit of the coil at 150 Hz and at 800 Hz. These tests were run at a higher sweep rate than those in Figure 14. The Rockland Analyzer had difficulty with the high sweep rates, accounting for the ringing of the output signal.

These slow sweep speeds are not usable in actual field situations due to limitations on receiver recording length. When the tests were repeated at the fast sweep rates planned for use in the field (~ 250 Hz / second to 2000 Hz per second) using a programmable sweep generator, we found that the force feedback control loops were not fast enough. Rather than a smooth output they gave a stepwise controlled output which was not usable.

Therefore, in the field tests the tool was clamped in place, a low power test sweep was run using a constant voltage drive level, and then the required drive signal was calculated which would meet the voltage, current, and force constraints of the actuator, while obtaining a flat output. This was done by plotting on a single graph the force limit of the actuator, the maximum current that could be induced in the actuator at each discrete frequency without violating the 260 Volt limit of the power supply, plotting the 8 amp limit of the coil, plotting the g's per amp of current derived from the constant voltage test, and then multiplying that curve by a different factor at each of a number of discrete frequencies throughout the sweep range that would maximize the force output without exceeding the envelope of the force, voltage or current limits. This drive signal was then programmed into a B&K fully programmable sine wave generator. This signal generator had much lower distortion and much greater flexibility in designing sweeps than other signal generators we tried. The tool was then driven using this programmed, amplitude-varying sinusoidal sweep signal through a large audio amplifier. This allowed adjustment of the sweep rate, dwell, frequency spectrum, and amplitude throughout the sweep in order to obtain a flat force output from the tool. While this was time consuming it worked well and gave a flat tool output even with very fast sweeps (~2000 Hz/sec). In the future it would be very useful to

**Constant Force Tests-- Force Produced
Source Mounted on Plate**



**Constant Force Tests-- Current Required
Source Mounted on Plate**

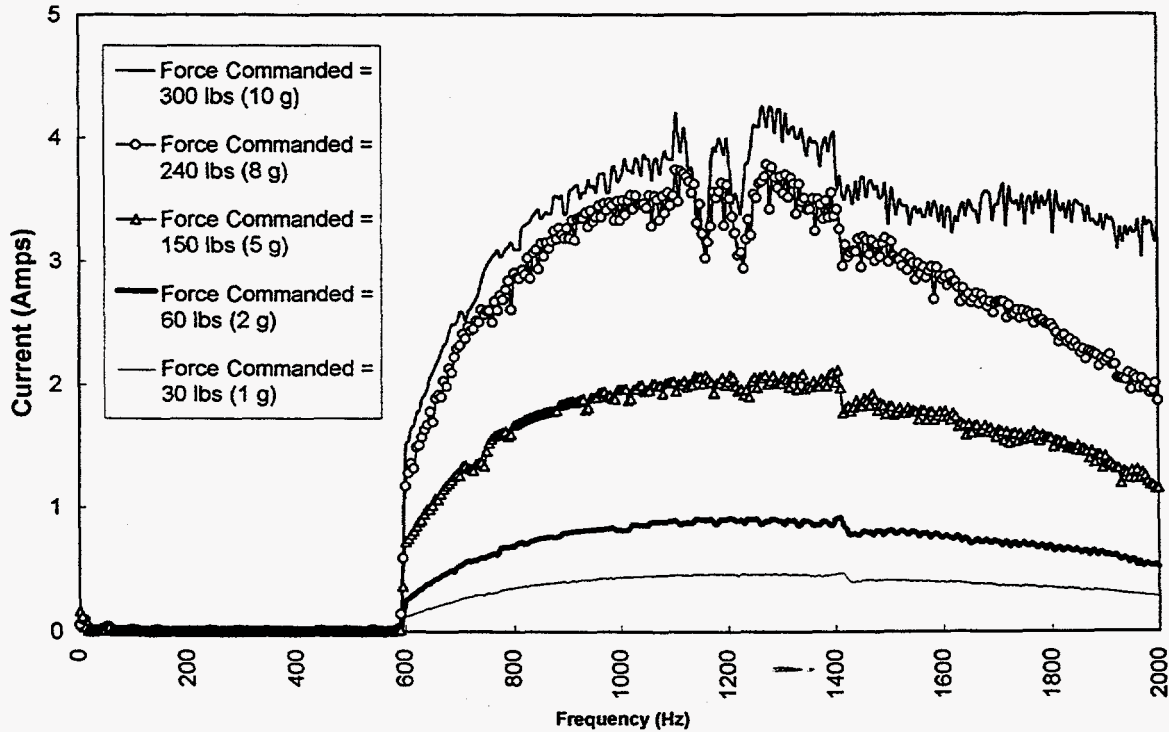
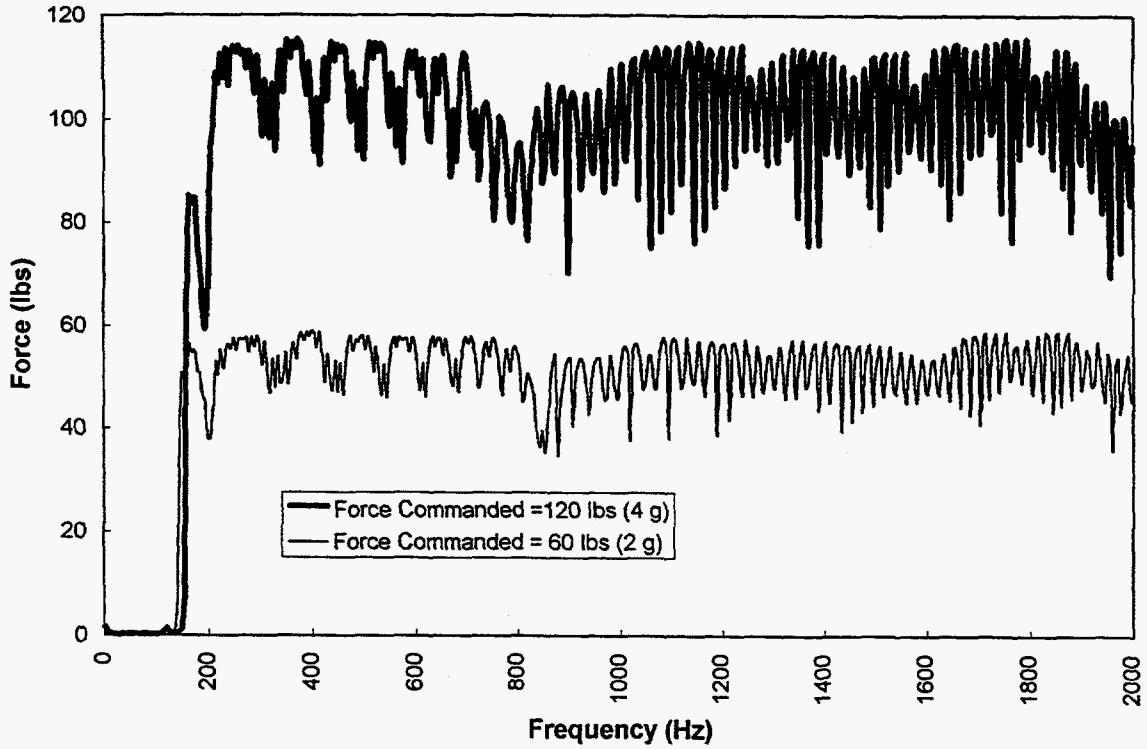


Figure 14: Flat Force Output with Actuator on Plate, using Feedback Controller-- Force (upper), Current (lower)

Constant Force Tests-- Force Produced
Source in Borehole Tool



Constant Force Tests-- Current Required
Source in Borehole Tool

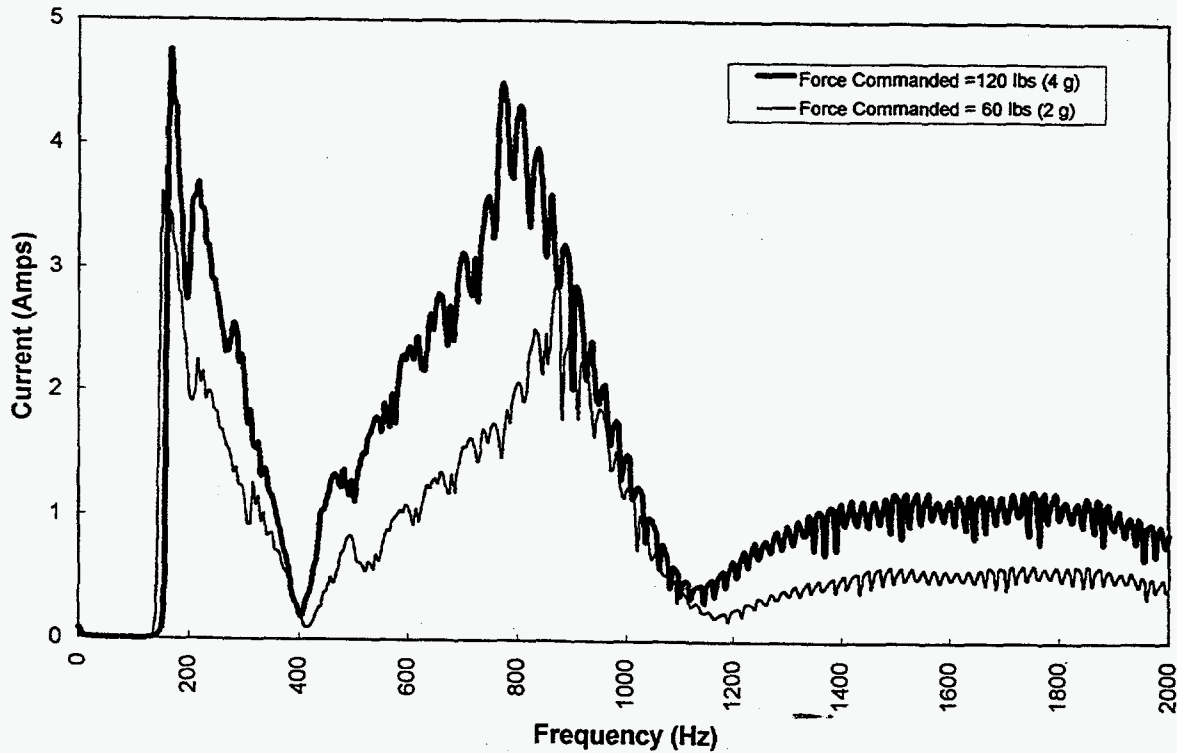


Figure 15: Flat Force Output with Actuator in Borehole Tool, using Feedback Controller-- Force (upper), Current (lower)

incorporate a very fast active feedback system that has current, voltage, and force loops, rather than just a force loop and the voltage limit of the power supply.

We talked with several seismologists about whether it is better to generate the maximum force output from the tool at every frequency, or to generate a reduced signal output but one that is fairly flat at all frequencies. They said that it is better to get the maximum signal out at every frequency, and not to put too much effort into getting a flat output. As long as the output is flat to within about 10 dB across the full sweep, good cross correlated wavelets can be calculated.

Clamp Tests

Based on the variability in resonances and force output that we saw while testing the commercial actuators mounted on the test plate, and having traced these to minor changes in the mounting method, we realized that it was important to use a very stiff clamp in the borehole tool. Therefore, a number of tests were conducted of various clamping methods, to determine the effect of clamping on the actuator output, as measured both by the acceleration of the granite block and by the accelerometer mounted to the actuator body.

a) Clamp Force

Comparison tests were conducted of the actuator output under the following conditions:

- a) Actuator bolted to plate
- b) Actuator in borehole tool, unclamped hanging free in the air
- c) Actuator in borehole tool, unclamped hanging free in water in the block
- d) Actuator in borehole tool, clamped with various gear reducers (47:1, 68:1, 99:1, 144:1)
- e) Actuator in borehole tool, with various motor clamp currents (0.75 amps, 0.9 amps)
- f) Actuator in borehole tool, with inflatable clamp at 20, 30, and 40 psi
- g) Actuator in borehole tool, with back rails, pointed nubs, or nothing
- h) Actuator upright vs. inverted

The borehole tool clamp consists of an electric motor, gear reducer to reduce the motor speed and increase the torque, a right angle gear box to change drive direction, and a threaded piston shoe. We tried several different gear reduction ratios. We measured the clamping force using a piezoelectric force gauge between the clamp shoe and the wall of the cored out hole in the granite block. This is the force normal to the borehole wall. Since the shaker output force is perpendicular to this clamp force, the clamp force must be multiplied by an appropriate coefficient of friction to determine if it is high enough to resist movement of the tool caused by the shaker force.

<u>Gear Ratio</u>	<u>Measured clamp force</u>	<u>Comment</u>
47:1	350 lbs.	Normally used with seismic receiver
68:1	550 lbs.	Used for most of our field tests
99:1	750 lbs.	
144:1	1250 lbs.	Shaft broke, gear box lid bowed

It was speculated that a large, compliant clamp might provide more secure clamping than one that contacted the borehole at only a few points. Therefore tests were conducted with an air inflated clamp. This consisted of a large diameter flexible air hose inserted between the borehole tool and the wall of the cored hole in the test block. This hose was slightly shorter than the borehole tool and was constrained at both ends, giving a large surface area contact and hence a high resultant clamping force even at low pressures. It was inflated to various pressures, pressing the mounting surface on the back of the tool body against the wall of the cored hole in the test block.

Representative clamp test results are shown in Figure 16. In general, the lower the clamp force or the more compliant the mounting, the lower the peak output and the higher the other resonances. There was a factor of 2 reduction in peak output when the actuator was clamped with the 68:1 or 144:1 gear reducer, compared to being bolted to the granite block (refer to figures 7 and 8). Also, the resonant frequency is lower in the borehole tool than on the plate due to lower system stiffness.

The peak force was higher and the high frequency resonances lower with the 144:1 gear reducer and back rails than with the 68:1 gear reducer and back rails. However, both of these had lower output than the 68:1 gear reducer without back rails. That suggests that the back rails and/or their attachment to the borehole tool are somewhat springy. Back rails or nubs are needed in order to give more than line contact on the back of the tool, in order to minimize cross-axis motion.

There is better energy coupling with the higher ratio gear reducers. When the actuator is hanging free in water, the energy coupled to the block drops by an order of magnitude compared to when it is clamped, and the frequency spectrum changes significantly.

There was little difference between the output with the inflated clamp at 20, 30, and 40 psi. It is possible that this type of clamp would work well at much higher pressures, but we could not test that with the equipment we had.

There was no measurable difference in output with the actuator upright vs. inverted.

b) Contact Points on Back of Borehole Tool

With the clamp of the borehole tool extended, the clamp shoe makes 1-point contact with the formation, and the back of the tool makes line contact with the formation. We discussed the issue of tool contact with several borehole tool designers who stated that there is much less off-axis side-to-side rocking of the tool if there is wide separation of contact points on the back side of the

Actuator Output for Various Clamping Conditions Constant 20 Volt Sweep

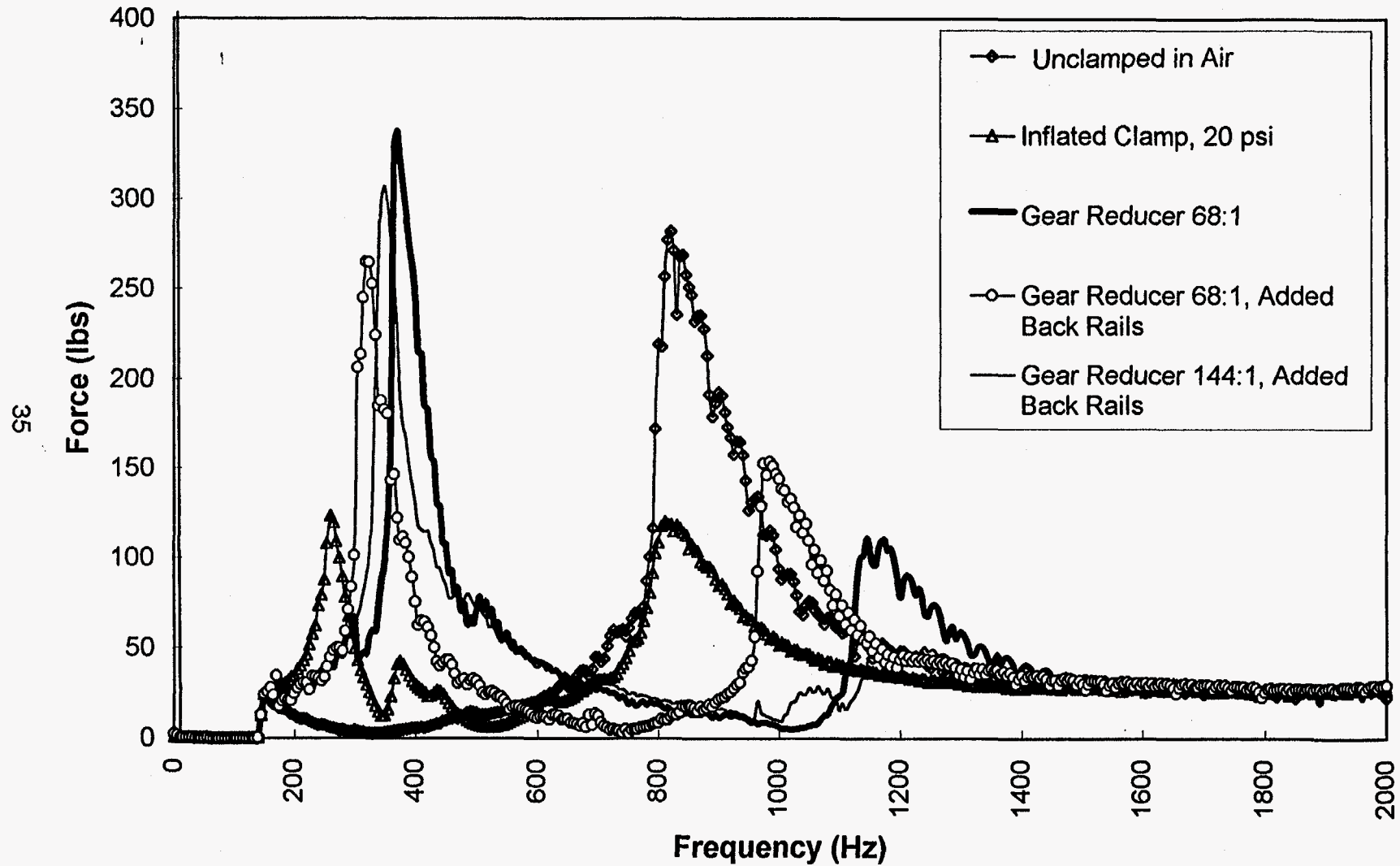


Figure 16: Actuator Output for Various Clamping Conditions

tool rather than line contact. Some designers suggest creating 3-point contact (like a three legged stool) on the back of the tool by adding three raised nubs. Others recommend adding two linear rails. Some suggest using soft shoes or rounded shoes to conform to the well radius and provide broader surface contact, and some suggest using hardened points to bite into the well casing. We conducted a number of tests with rails, pointed nubs, and with the bare tool. This tool is much shorter than most borehole sources or receivers. Long tools naturally align themselves along the axis of the borehole, but this short tool can turn a significant amount. This proved to be the case when we tried 3 point mounting with pointed studs. The tool tended to clamp on one stud and the clamp shoe, leaving it free to rock. The pointed studs did work well in the field in PVC casing, because they could bite into the casing, but they did not work well in steel casing or in our granite test block. Two long vertical rails, widely spaced, on the back side of the tool did work well in the test block and in steel casing, and minimized side to side rocking.

c) Clamp Reliability

As mentioned earlier, this clamp was designed to hold passive accelerometers in place, not a large vibratory shaker, so it is understandable that the clamp would be damaged when we used the largest gearheads. We calculated the stress in the clamp drive shaft and found that, even with the 68:1 gearhead, the 304 stainless material strength was marginal. We ordered new clamp parts made of PH 17-4 stainless steel, which has a yield strength of $\sim 140,000$ psi, compared to $\sim 30,000$ psi for 304. After replacing the damaged clamp parts with these new stronger parts, we did not have any additional problems with the clamp.

Tuned Circuit Tests

A proposal was made to tune the actuator circuit, which is inductive and resistive, by adding an appropriate capacitor, so that more of the power would be real power useful to the device rather than reactive power. We also hoped by adjusting the capacitance to decrease the force output at the mechanical resonance of the actuator and increase the force output at other frequencies in order to give a flatter overall response when using a fixed voltage level drive sweep.

Figure 17 shows the changes in actuator output force for a fixed 20 volt sweep as a function of the capacitance added to the circuit. The heavy line shows the output with no capacitor added. As can be seen, adding a capacitor reduces the peak force output at resonance and increases the force output over some range of frequencies, but also reduces the force output over other ranges of frequencies.

Figure 18 shows the changes in current flow through the actuator as a function of the capacitance added to the circuit. The heavy line shows the current flow with no capacitor added. Adding a capacitor increases the current flow over some range of frequencies, and reduces it over other ranges of frequencies, which explains the shift in force output seen in Figure 17.

Tuning Circuit by Adding Capacitors 20 Volt Sweep Source Mounted on Plate

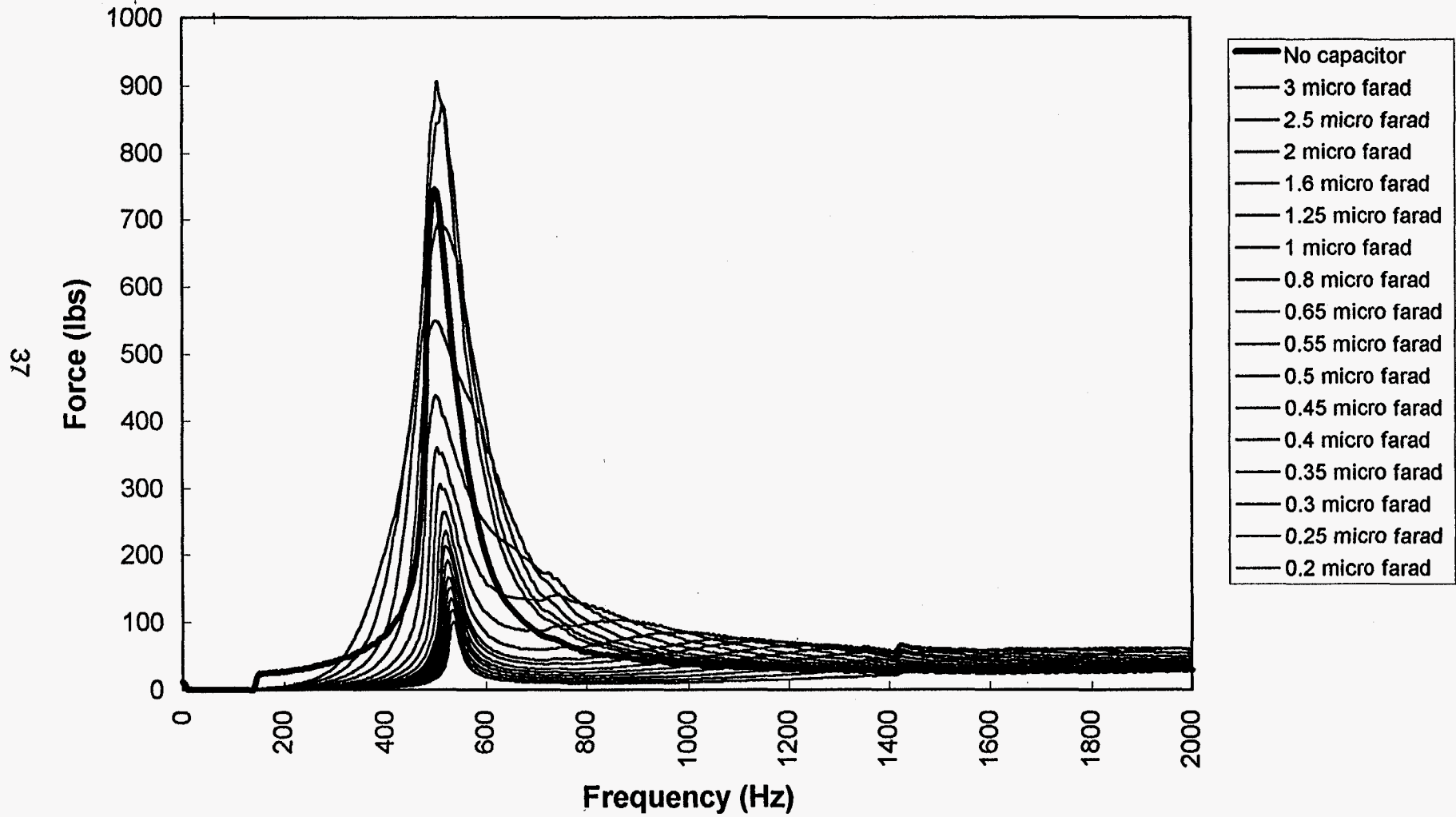


Figure 17: Force Output from Actuator as a Function of Capacitance

Tuning Circuit by Adding Capacitors 20 Volt Sweep Source Mounted on Plate

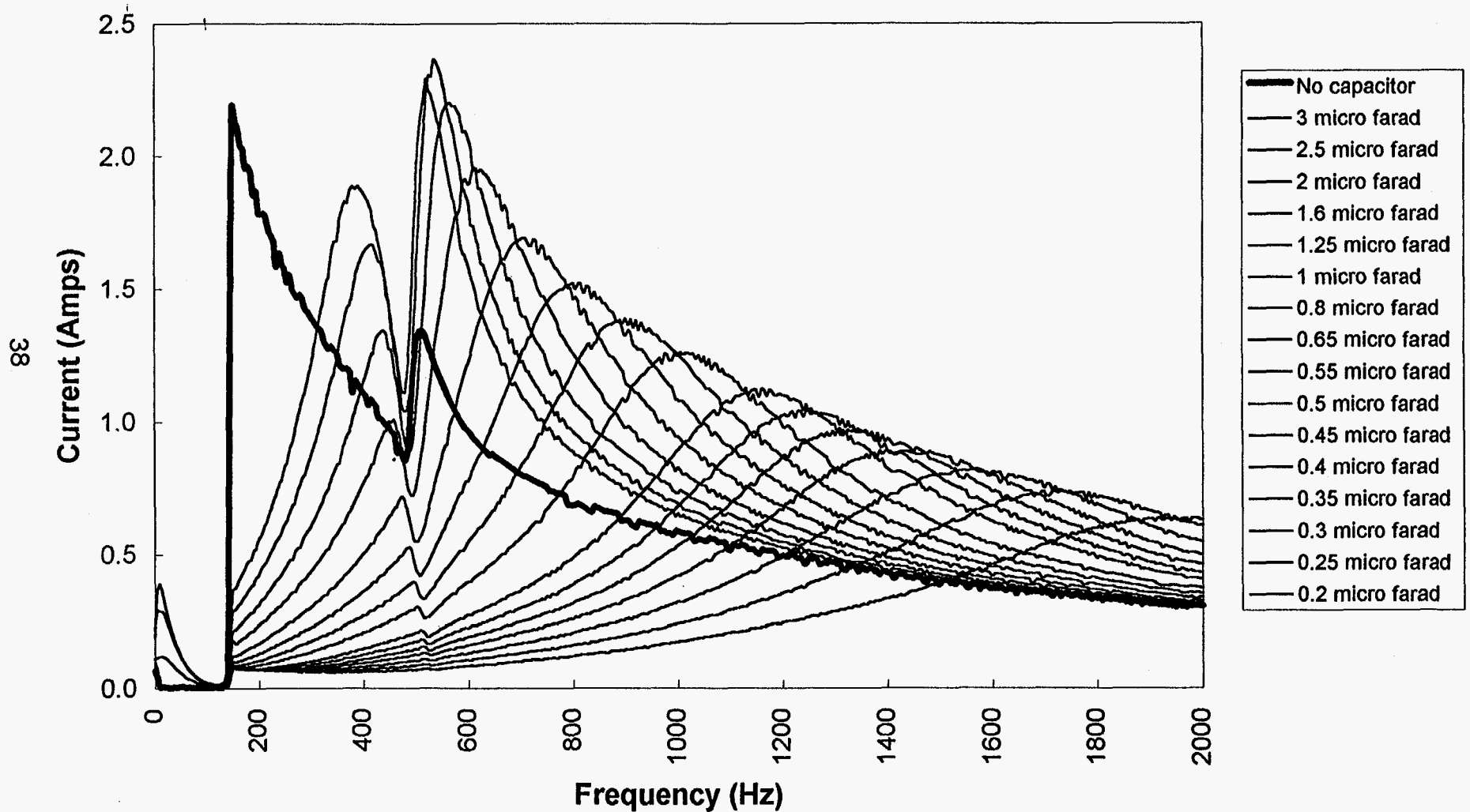


Figure 18: Current Draw of Actuator as a Function of Capacitance

Adding capacitance trades off drive voltage for drive current by reducing the voltage required to push a given current through the device. It was felt that actively changing the capacitance of the circuit would allow us to avoid the current or voltage limitations of the device at a particular frequency. This helps in the portions of the curve where the output is voltage limited by the power supply, but not in the rest of the curve where the output is current limited or force limited. In addition, we can only increase the output with the capacitors up to the current limit of the device. This allows about a 50% increase from about 800-2000 Hz.

Modeling and testing showed that the circuit could be optimized with a given capacitor at a particular frequency, but that same capacitor would not optimize the circuit over the full frequency spectrum of interest. The shift in the curve for a given capacitor is broad enough that 3 or 4 capacitors should cover all of the curve from the resonance to 2000 Hz. Plans were made for a switching circuit which would monitor the frequency of operation, and at discreet frequencies during zero voltage crossing to switch in different capacitors, so that the circuit would be continuously tuned throughout the sweep. However, in most of our tests we found that we could accomplish the same result by simply driving the actuator harder. This scheme is not needed if the power supply has high enough voltage capability or if the device is operated on a short wireline to minimize the voltage drop in the wireline.

Distortion and Harmonic Tests

Tests were conducted to determine the level of harmonic distortion and to examine various tool resonances. The tool was swept from 150 to 1500 Hz, and the output signal from the accelerometer mounted on the actuator reaction mass was sent to the Rockland Analyzer. Figure 19 shows a typical plot for one of the commercial actuators. This plot shows the relative strength of the fundamental frequency and of its harmonics. Above 200 Hz where the fundamental frequency output is strong, the total harmonic distortion was less than 10%. Below 200 Hz, where the fundamental frequency output is lower, and particularly at sub-multiples of the resonant frequency, the distortion is substantial when driven at full rated current. The distortion decreases significantly when driven below the rated current.

We also visually evaluated the distortion in output wave form. The tool was operated at increasing voltages at a fixed frequency and the output force waveform was recorded. This was done for a number of discrete frequencies from 150 to 2000 Hz. The waveforms were then compared for distortion. The drive current did not include any harmonics, so the distortion was not due to drive signal problems. Some of the distortion is due to overdriving the actuator itself and moving off of the linear portion of the operating curve. Some of it is caused by the type of mounting. The distortion is worse at low frequencies and at increasing drive levels.

Figure 20 shows the force output from the custom actuator at 200 Hz for four different voltages. With no distortion the output would be a sinusoid. As can be seen, there is substantial distortion at this frequency, which increases with increasing drive voltage.

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 TITLE: Sweep from 150Hz to 1500 Hz

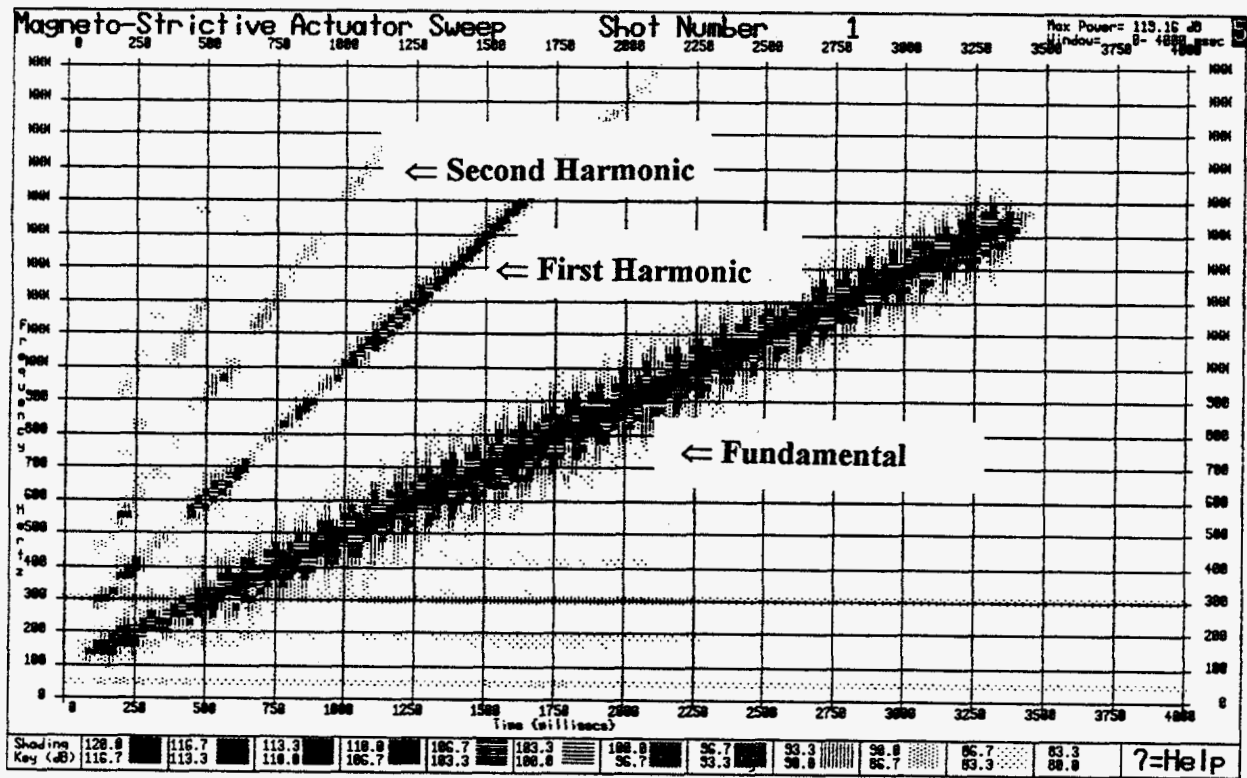


Figure 19: Harmonic Distortion of Commercial Actuator

Distortion in Output as a Function of Voltage, at 200 Hz Source Mounted on Plate

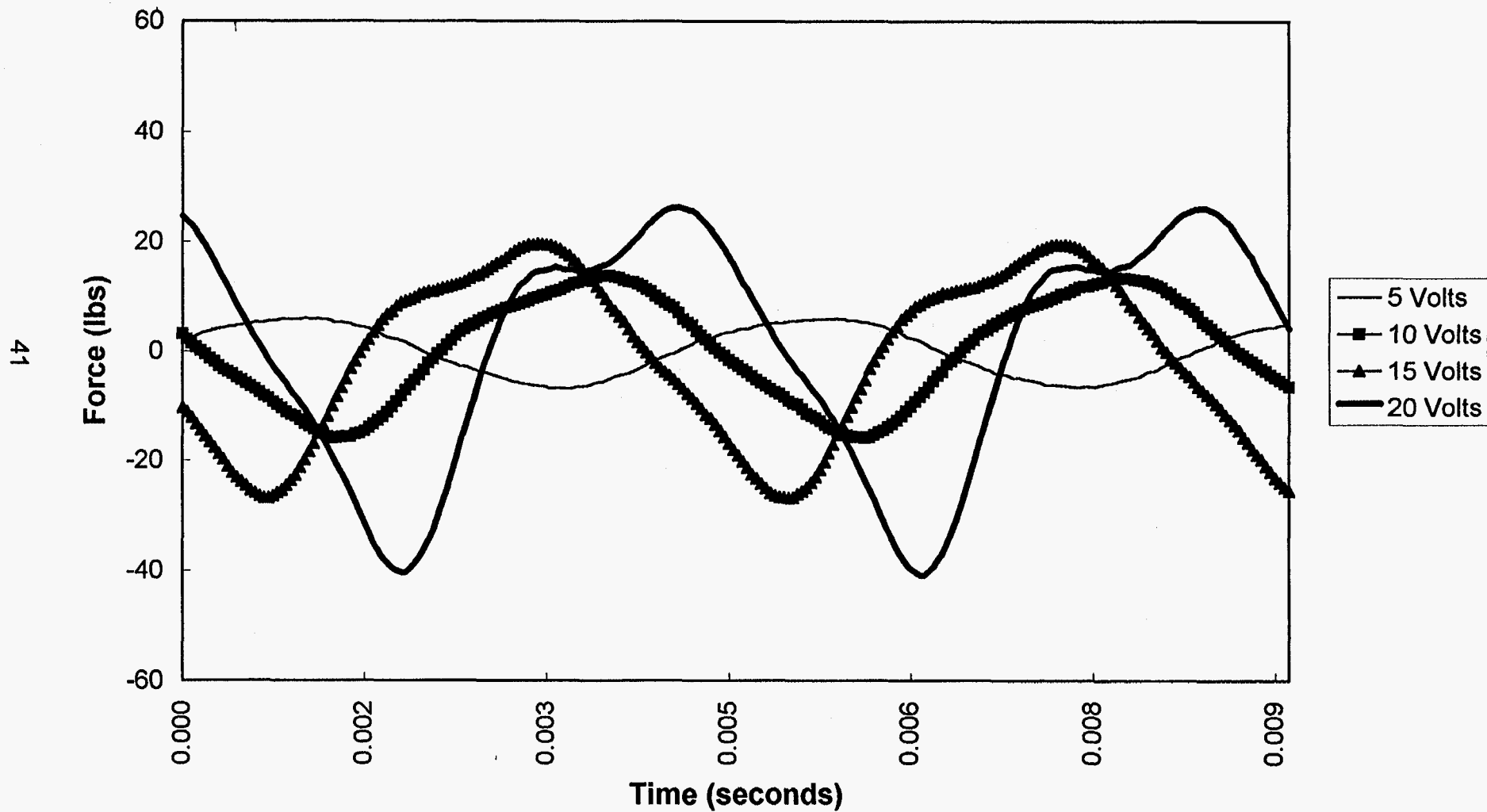


Figure 20: Distortion at 200 Hz as a Function of Drive Voltage

**Distortion in Output as a Function of Voltage, at 300 Hz
Source Mounted on Plate**

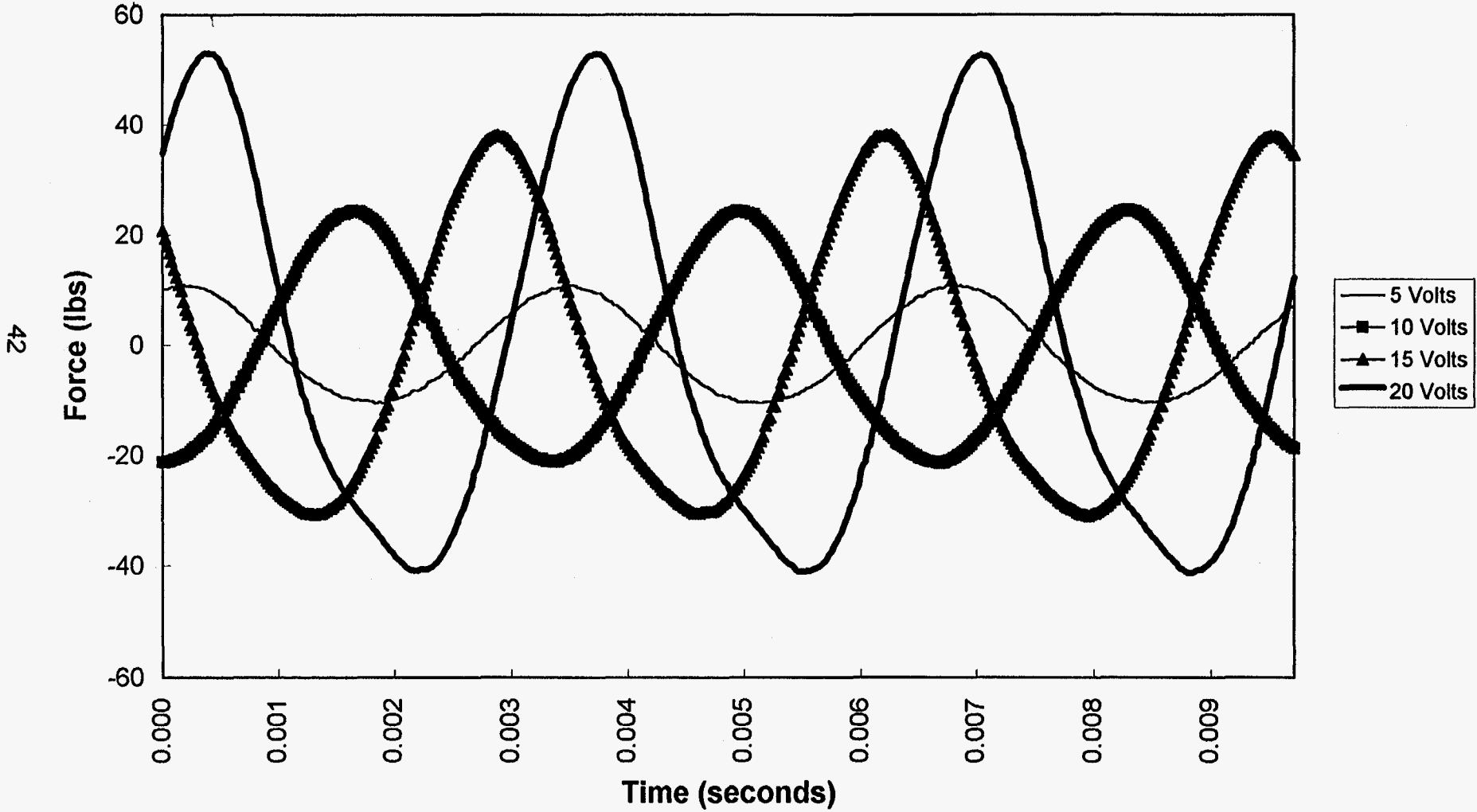


Figure 21: Distortion at 300 Hz as a Function of Drive Voltage

Figure 21 shows the same information at 300 Hz. Note that there is very little visible distortion in the output except for a slight amount for the 20 volt drive level. At higher frequencies there is little or no distortion in the output, even up to drive voltages of 150 volts.

We also recorded the instantaneous spectrum for a number of fundamental frequencies. The tool produces harmonics of the fundamental frequency. Some of these harmonics have a fairly high amplitude, and when the harmonics approach the tool resonant frequency the amplitude of the harmonic can exceed the amplitude of the fundamental. These are mainly a problem for fundamental frequencies from 150-300 Hz. These harmonics represent wasted energy that could have gone into the fundamental, so we tried to minimize them. However, Dale Cox at Conoco said that the harmonics will not adversely affect the correlated seismic data, since they go through both positive and negative cycles, while the fundamental is going through just a positive cycle, so when the signal is correlated with the pilot signal the positive and negative harmonic contributions will essentially cancel out.

It was found that any chattering of parts, such as the rails, housing, gears, etc. caused increased distortion in the output waveform. To minimize this we used removable Loctite on all screws and torqued them as tight as possible.

Driving over wireline

Standard 7-conductor wireline has a relatively high resistance (#20 wire, 10 Ω /1000' resistance) compared to the very low impedance of the custom actuator's drive coil (1-2 Ω). This can result in large voltage drops in the cable. Laboratory testing was conducted using short power leads. Initial field tests at shallow sites were conducted using 500' of 7 conductor wire line, using 4 wires in parallel for the positive actuator lead, the shield for the negative actuator lead and negative clamp motor lead, two wires for the accelerometer, and one wire for the clamp motor positive supply. In this configuration the wireline had a measured resistance of 5 Ω and the drop in actuator output was barely perceptible. However, for deep applications the wireline resistance needs to be considered. For example, the Rifle, Colorado field test was conducted using an 11,000' wireline. In these applications one should use multiple conductors to drive the actuator or use larger conductors.

We discussed this issue with Etrema, who said they could modify the actuator design to increase the impedance of the actuator, allowing us to operate at a higher voltage and lower drive current in order to obtain the same force output while minimizing losses in the wireline. However, this might result in actuator heating problems.

In addition to wireline loss problems, when the source was operated on the 11,000' wireline, there was considerable crosstalk between the power lines driving the source and the signal lines from the accelerometers. This could be overcome by amplifying or digitizing the accelerometer signals, or by using shielded twisted pair for the signal lines.

Field Tests

Following the laboratory testing of the commercial actuators, two field tests were conducted using the commercial actuators. The results of these test were used to guide the requirements for a larger custom actuator with a large built in reaction mass, a larger diameter and longer length magnetostrictive rod, and a custom permanent magnet bias. After laboratory testing of the large custom actuator was completed, it was tested in three field tests. This section of the report describes these tests. Table 8 summarizes the results of all of the field tests.

Table 8: Summary of Field Tests

Site	Actuator	Mounting	Test	Depth	Well	Formation	Results
Sandia FACT site	Commercial	Bolted on plate	VSP	12'	Dry	Sand, gravel	Good signals over 40', 100'
Sandia FACT site	Commercial	Borehole tool	Crosswell	60'	Dry	Sand, gravel	Good signals over 20', 40'
Hanford, Washington	Custom	Borehole tool	Crosswell	80'	Dry	Gravel	Good signals over 239'
Newkirk, Oklahoma	Custom	Borehole tool	Crosswell	120'	Wet	Sandstone	Good signals over 282'
Rifle, Colorado	Custom	Borehole	Crosswell	4500'	Wet	Sandstone	Good signals over 350'

Commercial Actuator in VSP Test at Sandia FACT Site

The Sandia Facility for Accepting, Calibration, and Testing (Sandia FACT site) has a number of closely spaced shallow boreholes and bunkers for calibrating and testing earth motion sensors. On March 31, 1993, a test was conducted at the FACT site to determine if a magnetostrictive reaction-force shaker could propagate seismic energy through unconsolidated soils. A prototype magnetostrictive reaction mass shaker was used as a seismic generator (refer to Figure 11). This device consisted of the Etrema Products Inc. Model 75/12-MP actuator with an 11 lb. brass reaction mass attached to the drive shaft. Earth coupling was achieved by securing the actuator to a vertical wall of an underground bunker. The bunker wall consists of 6" thick concrete. The exterior wall of the bunker is in direct contact with the soil. The interior wall of the bunker contained a 2" thick steel plate, epoxied and bolted to the concrete wall. The steel plate was drilled and tapped for direct mounting of the actuator. A 1/4-20 stud attached the base of the actuator to the plate. The placement of the actuator was 12 ft. below the earth's surface, and its direction of reaction motion was parallel to the earth's surface.

Two reference accelerometer measurements were mounted near the seismic source. The first reference accelerometer was bolted directly to the reaction mass on the actuator, and provided an indication of the reaction force applied to the bunker wall. Peak observed accelerations of the reaction mass were 27 g, which implies a peak reaction force of 300 lbs. The second reference accelerometer was epoxied onto the external surface of the bunker roof. The external surface of the roof was buried approximately 1 ft. below the soil surface, and the accelerometer was emplaced by digging a small hole down to the roof, epoxying the accelerometer, and back-filling the hole. The sensitive direction of the accelerometer was in the vertical plane (i.e. perpendicular to the reaction motions).

Two vertical ground sensors were deployed, one 40' from the bunker and the other 100' from the bunker, to determine the propagation of the seismic energy through the soil. The sensors utilized were Wilcoxon accelerometer model 731-40, equivalent to those used in the Advanced Borehole Receiver. Each sensor was emplaced by digging a hole 12" deep, pushing the 2" coupling stud / accelerometer assembly into the soil, and then back-filling the hole. Burial of the sensors in this manner significantly reduced wind-borne noise. The observed soil was a composite of gravel ranging in size from 1/8" to 1" in a matrix of unconsolidated sandy loam. The top 6" of soil was partially saturated due to recent rains, but was quite dry below that point.

The signals from the four accelerometers were recorded and analyzed using a Rockland System 90 Frequency Analyzer. The source was excited with a sine wave at a number of discrete frequencies. The drive signal was amplified by a Techron 500 Watt power amplifier. The amplifier was operated in constant current mode to deliver a nominal output of 7.0 amps p-p as the frequency was varied.

Figure 22 depicts a received signal obtained from the ground sensors for a single source tone. In this figure, the source excitation frequency was 600 Hz. The measured response is from the

STATUS Ch A	
10.0 dBV FS	
AC Coupling	
Cal: 10.0	
mV/g (M)	
Intg: OFF	
Diff: OFF	
A-Wt: OFF	
SYS STATUS	
2 KHz FS	
Hanning Wtg	
Avg: SF 32	
Avg: N= 32	
Zoom: x1	
Trg: Free Run	
Internal A ↑	
Lev: +30%FS	
Autorange OFF	
Filter In	
Overlap: 0%	
STATUS Ch B	
-20.0 dBV FS	
AC Coupling	
Cal:	
dBV	
Intg: OFF	
Diff: OFF	
A-Wt: OFF	

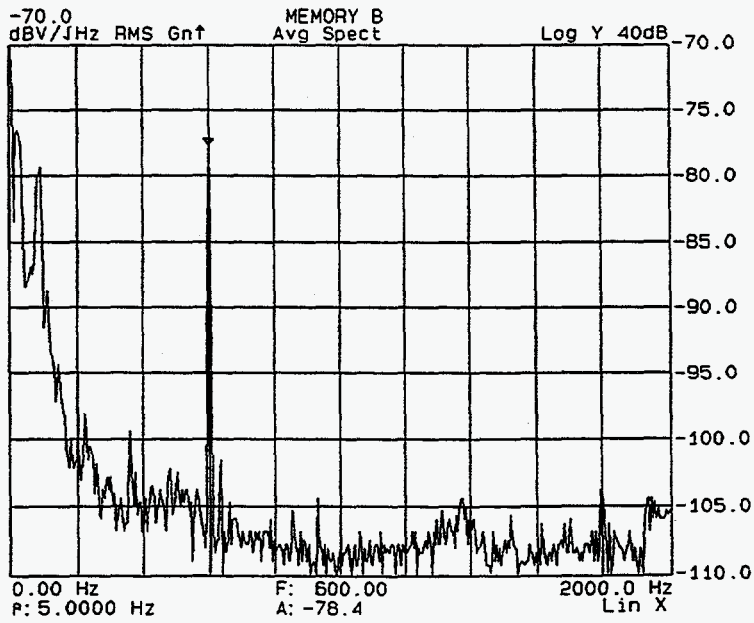


Figure 22: Commercial Actuator at FACT Site—Single Tone Response

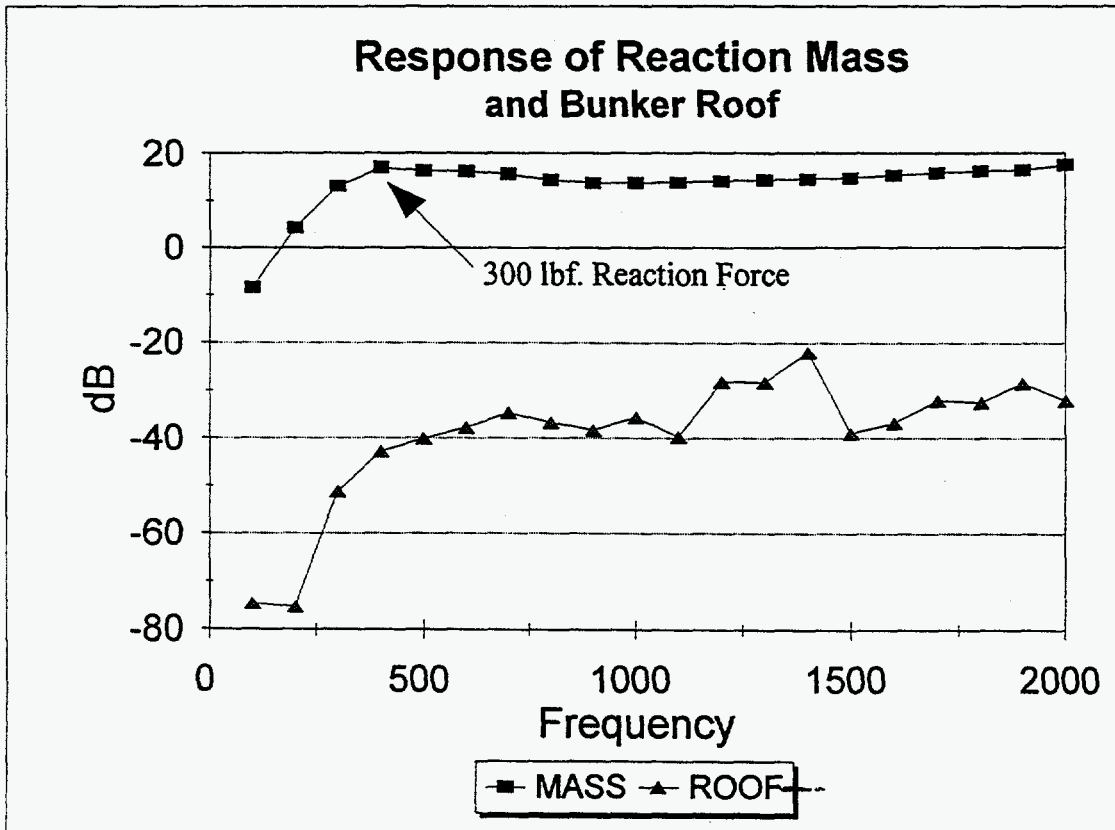


Figure 23: Commercial Actuator at FACT Site—Acceleration of Reaction Mass and Roof

buried accelerometer offset 40 ft. from the source. It is clear from this plot that the received energy is well above the background noise. At almost all frequencies, an observable signal above background noise was obtained. Note that the measured background noise for this test was approximately 10 dB higher than that observed in shallow boreholes.

Figure 23 depicts the response of the reference accelerometers as the excitation frequency was varied from 100 Hz to 2000 Hz in 100 Hz increments. The response of the reaction mass was fairly flat across the entire frequency band, but fell off rapidly below 300 Hz as expected, due to the stroke limitations of the magnetostrictive actuator. The roof accelerometer shows a similar response, but some amplification is observed in the 1100-1500 Hz range. Also, it should be noted that the roof accelerometer indicated large harmonic distortion below 300 Hz. This is consistent with laboratory testing, in which it was found that the harmonic distortion of the actuator was worse at low frequencies.

Figure 24 depicts the response of the buried accelerometers 40' and 100' from the source as the excitation frequency was varied from 100 Hz to 2000 Hz. Also plotted in Figure 24 is the typical borehole noise floor for these sensors. Clearly, the signal level was in excess of the noise floor for all frequencies throughout the measurement band. However, the measured results between 1100 Hz and 1500 Hz lacked repeatability and raised some question about performance at the higher frequencies. However, the bunker structure shows amplification in this frequency band, which indicates that the bunker is effecting the high frequency energy driven into the ground. Furthermore, no significant harmonic distortion was observed at any frequency in the ground measurements. The observed distortion in the bunker roof measurements is likely due to the fact that the reference accelerometer was orthogonal to the direction of excitation.

Broad-band seismic energy was successfully propagated through unconsolidated soils. At an offset of 40 ft. the signal-to-noise ratio exceeded 20 dB from 100 Hz to 1000 Hz. This implies that the 300 lb. force imparted is adequate for high resolution imaging from 40 ft offset wells. With an offset of 100 ft, the signal-to-noise ratio exceeded 20 dB from 100 Hz to 700 Hz. This implies that the energy level is also reasonably adequate for 100 ft. well spacing. Note that the soil conditions encountered at the site are extremely attenuating. It is unlikely that any environmental site would offer worse soil conditions. Soil attenuation will also decrease dramatically when the depth is increased and fluid saturation of the soil is increased. In particular, it is anticipated that when deployed below the water table, the 300 pounds force shaker would easily propagate energy in excess of 2000 Hz over these distances with very high signal-to-noise ratios. Further note that long sweeps and / or signal stacking can be applied, if needed, to further enhance the signal-to-noise.

Based on the measurements obtained at the FACT site, two suggestions for improvement were made: 1) increasing the energy below 100 Hz, and 2) ramp up the force at frequencies above 600 Hz to compensate for attenuation. The custom magnetostrictive actuator was designed to provide these features. In particular, a 10:1 increase was expected at frequencies below 100 Hz and a 4:1 increase was expected at frequencies between 600 Hz and 1200 Hz.

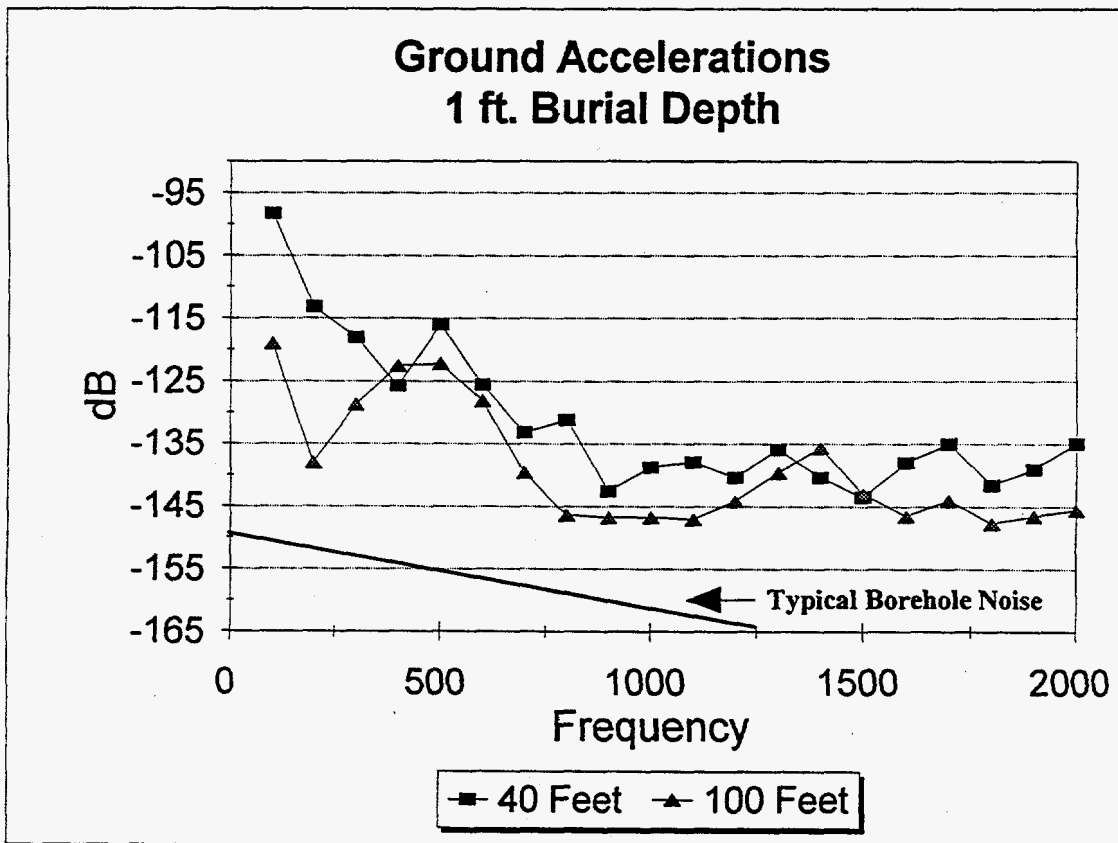


Figure 24: Commercial Actuator at FACT Site—Signal Levels at Ground Acceleration Sensors spaced 40' and 100' from Source

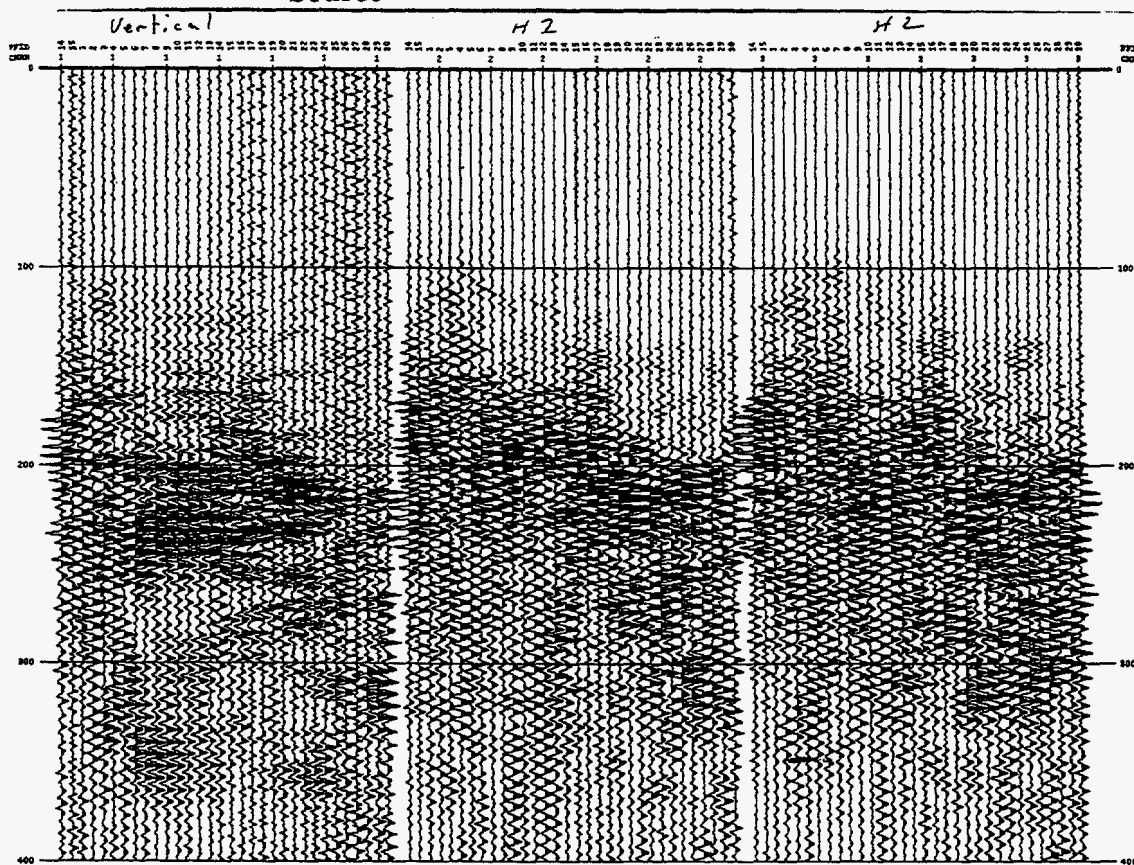


Figure 25: Commercial Actuator at FACT Site—Common Source Gather raw data

It was observed that the acceleration of the reaction mass at this test was very uniform as the frequency was varied from 300 Hz to 2000 Hz. The laboratory tests with this commercial actuator showed more variability in the frequency response. The difference was associated with the mounting of the actuator to "earth". The laboratory results (not flat) were obtained with the actuator attached to the granite block, whereas the field results (flat response) were obtained with the actuator attached to a steel plate and concrete wall configuration. The granite block is known to have modal resonances above 600 Hz, and the mounting technique used in the early laboratory tests was not consistent from test to test. It was felt that the flat-frequency results obtained from the FACT site test were more representative of what could be with a source that was well coupled to the earth, and that if the actuator was well coupled to a clamp package, and the clamp package was well coupled to the borehole, that a very flat force response could be obtained at frequencies up to 2000 Hz.

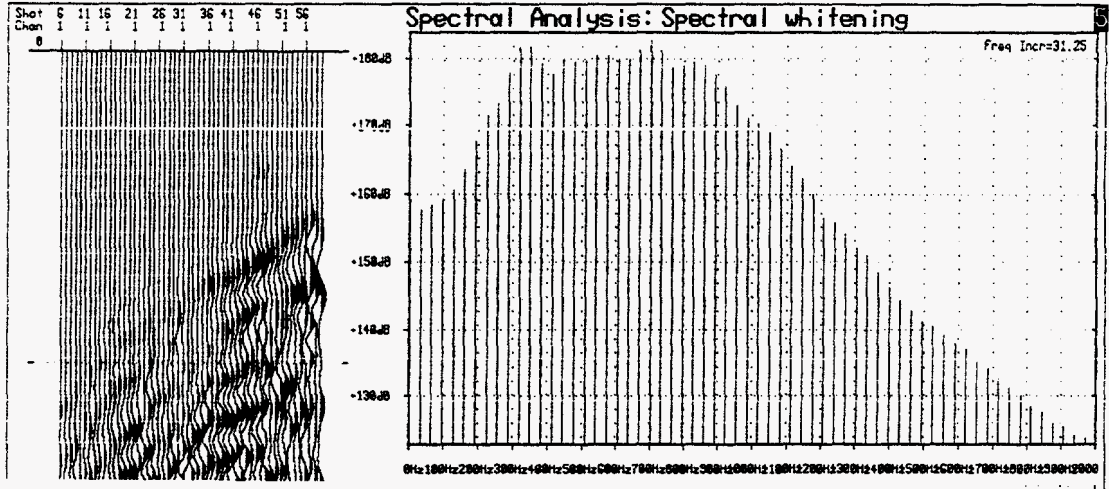
Commercial Actuator Crosswell Test at FACT Site

The first crosswell field test of the commercial actuator in the borehole tool was conducted between two closely spaced wells at the Sandia FACT site on 8/03/93. The wells were steel cased and grouted in place. The well separation between the source and receiver wells was 39' (12 meters). The soil is sand and gravel. The source tool was clamped in place at a depth of 20 meters. The receiver, a Sandia/OYO single level 3-axis accelerometer sonde, was moved from a depth of 70 meters to 2 meters in ½ meter steps. The source was swept for 3.5 seconds from 125 Hz to 1500 Hz, with a single sweep at each level. This source is capable of a peak force of 400 lbs., but to flatten the output it was run at about 150 lbs. force. Figure 25 shows a common source gather. Figure 26 shows the horizontal 1, horizontal 2, and vertical component spectral analysis. Figures 27 and 28 show one of the horizontal components and one of the vertical components correlated with the seismic source drive current, and the corresponding noise levels with the actuator off. As can be seen by comparing the spectral analysis of the noise shot and of the horizontal and vertical components, the received signal showed a signal to noise ratio of 40-50 dB S/N across this frequency range. This test verified the deployment procedures in shallow wells, use of the tool on a wireline, and the ability of the source to transmit energy from a clamped borehole tool in one well through loose soil to a clamped receiver in another well.

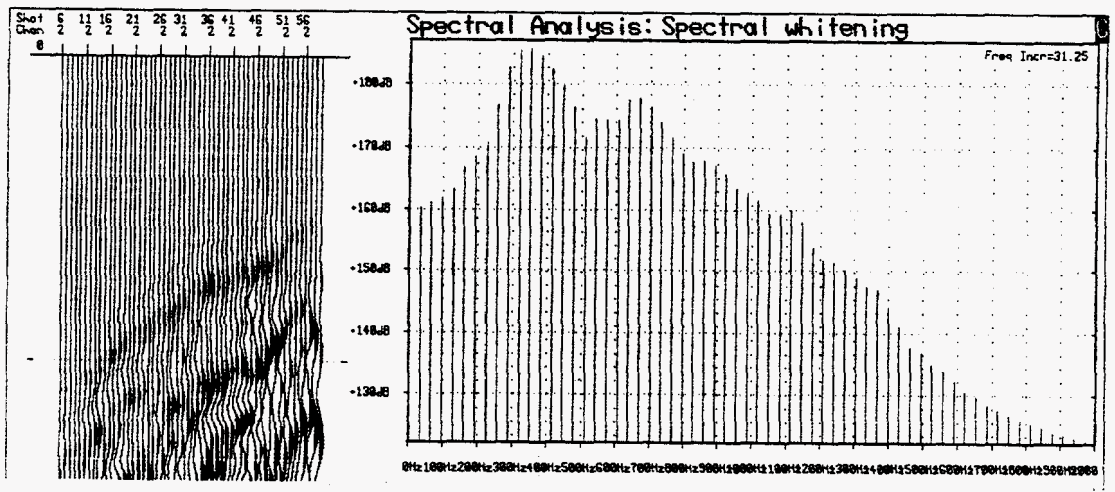
Custom Actuator Crosswell Test at Hanford, Washington

The custom actuator in the clamped borehole tool was successfully demonstrated in a combined crosswell and Reverse Vertical Seismic Profiling (RVSP) test at an environmental site at Hanford, Washington on June 6-8, 1994. The purpose of this test was to compare the results from several different seismic sources used in the same set of wells, in order to determine which sources were best suited to this shallow environmental application. The sources used were Sandia's custom magnetostrictive source, the Bolt airgun, the OYO-Conoco orbital vibrator, and the Sandia

Time and Date: 9:07:30 8/09/93
 TITLE: H1 spectrum



Time and Date: 9:09:15 8/09/93
 TITLE: H2 Spectrum



Time and Date: 9:10:51 8/09/93
 TITLE: Vertical Spectrum

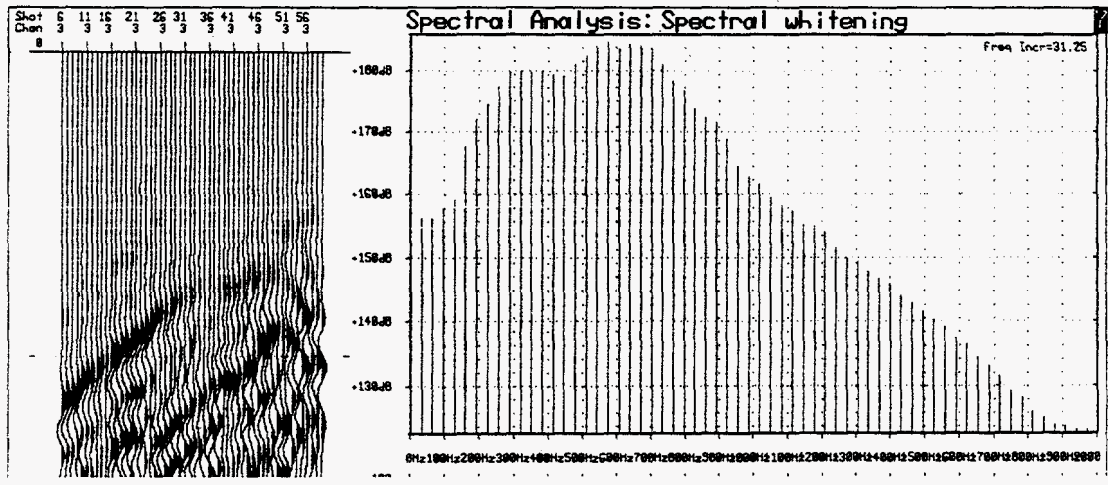
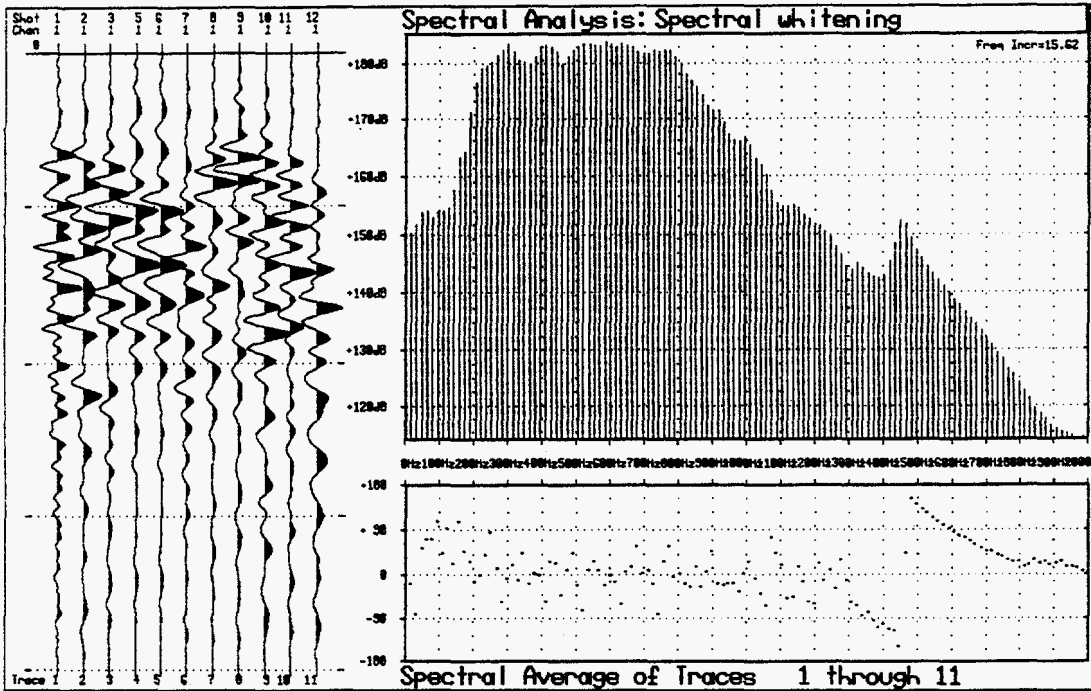


Figure 26: Commercial Actuator at FACT Site—Horizontal 1, Horizontal 2, and Vertical Component Spectrum

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TITLE: H1



Time and Date: 8:49:44 8/03/93
TITLE: h1 noise

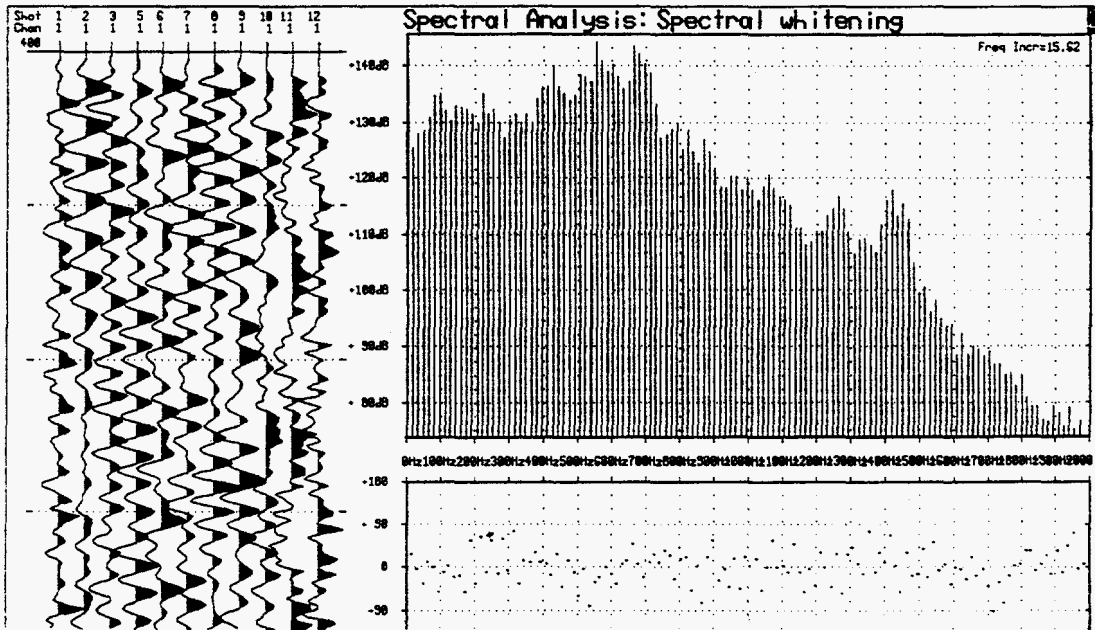
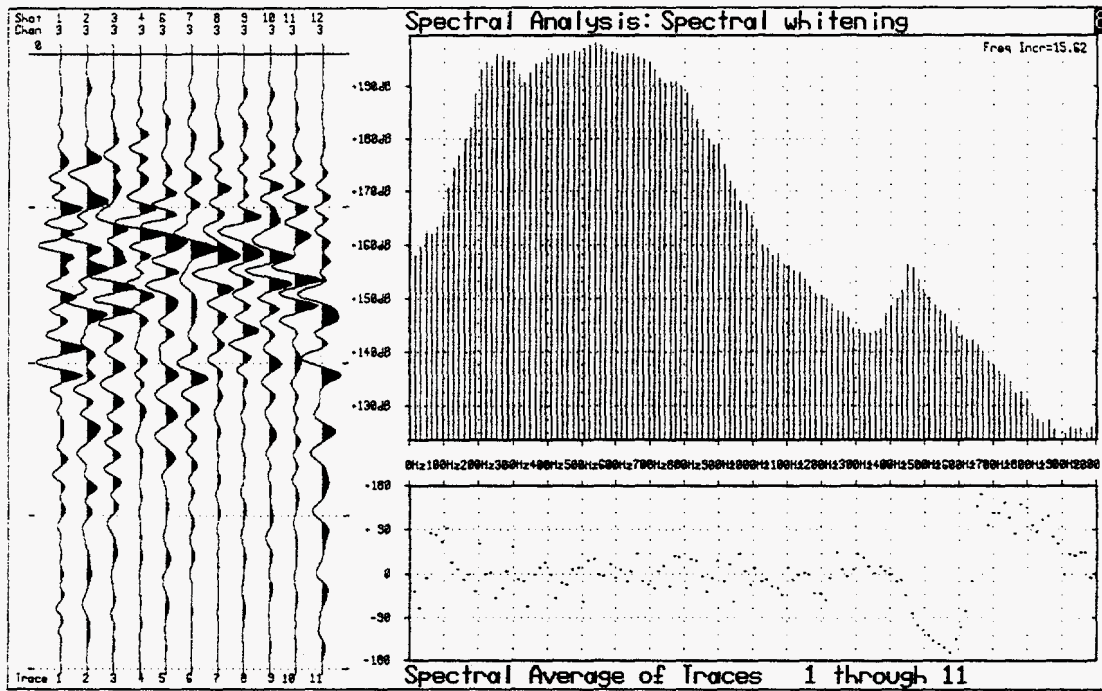


Figure 27: Commercial Actuator at FACT Site—Horizontal Component Correlated with drive current, and Horizontal Noise

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 TITLE: Vertical with current pilot



Time and Date: 12:31:38 8/03/95
 TITLE: Vertical noise with current pilot

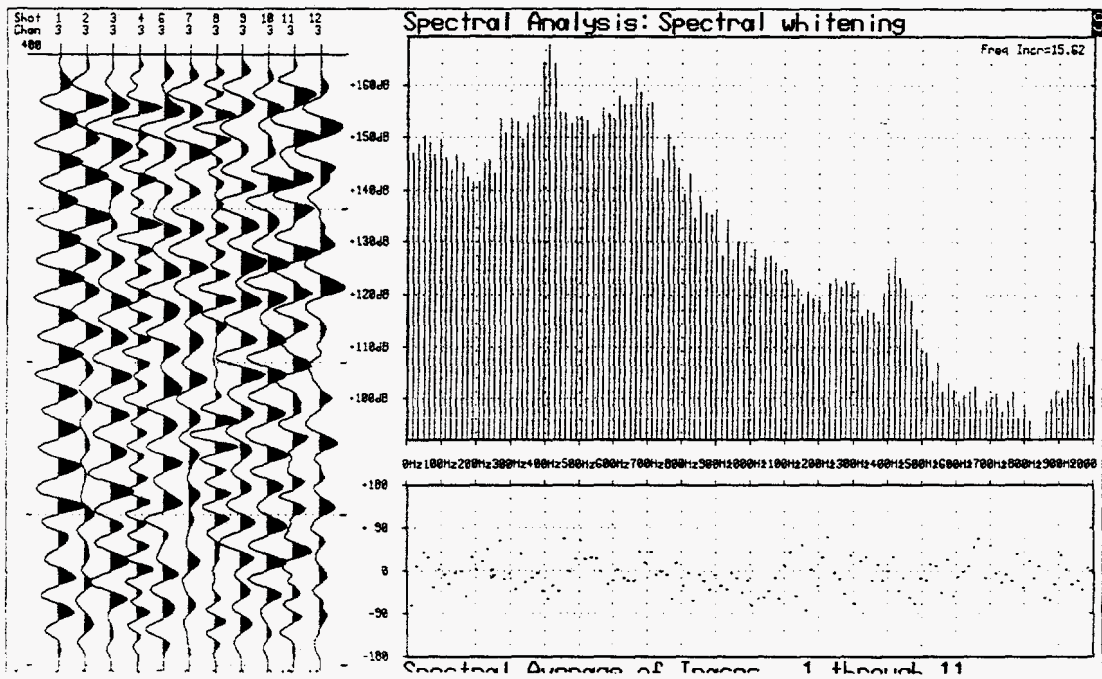


Figure 28: Commercial Actuator at FACT Site—Vertical Component Correlated with drive current, and Vertical Noise

pneumatic vibrator. The receiver in all cases was the Sandia/OYO clamped 3-axis accelerometer receiver. This portion of the report will describe the test of the magnetostrictive source. Appendix C and reference [3] contain the results and comparison for all four sources used.

The test area is referred to as Hanford 200 West. The receiver well, W18-82, was 146' deep, with 6" diameter steel casing. The source well, W18-94, was 80' deep, with 6" diameter steel casing. The two wells were 239' apart. Both wells were dry, uncemented, and above the water table.

The formation consisted of unconsolidated sand and gravel, including cobbles up to 2.5" diameter, over the full depth of the wells. The formation velocity, based on earlier tests with a pneumatic source, was approximately 1430 feet/second. The common source gather was created with the source clamped in one well at a depth of 15 meters for all sweeps. The borehole receiver was placed in the second well starting at a depth of 40 meters, and was moved up in 2 meter steps until it reached 20 meters, and then in 1 meter increments to the surface. A string of 21 surface geophones was also placed on the ground, on 5' spacing, extending from the source well towards the receiver well.

The source is capable of generating signals from 150 Hz to over 2000 Hz, but due to recorder limitations and in order to make direct comparisons with the other three sources, the source was only swept from 150 to 720 Hz. A single 8 second source sweep used at each receiver position. The receiver signal was recorded on an EGG seismic recorder using 1/2 msec sampling. We recorded the V, H1, H2 signals from the receiver triaxial accelerometers, and also the signals from the 21 surface geophones. We also recorded the constant 5 volt source drive signal, the amplitude modulated source drive voltage, the source drive current, and the output from the accelerometer mounted to the actuator reaction mass, so that we could try all of these as pilot signals for correlation.

We began the test using the VTS force feedback controller. However, as explained earlier, the controller did not work smoothly during fast sweeps, and was not consistent from sweep to sweep. It also had a non-repeatable trigger delay. While using this system, we could hear several tones and discreet steps in frequency during fast sweeps of the source and the tool sounded like it was changing frequency in steps or jumps, rather than linearly. The correlated signals were poor, but did show that we were getting signals between the two wells. We filtered the data to 150 - 750 Hz and it looked somewhat better, but had lots of spikes and large humps in amplitude. Following these initial tests we decided that the force feedback system couldn't keep up with the 300 Hz/sec sweep rate. We reduced the sweep rate to 100 Hz/sec, and then to 50 Hz/sec, and the tool sounded much better and the data from the actuator accelerometer looked better.

We decided not to continue using the force feedback system, and instead changed to a fully programmable B&K Sine Generator. The output from it was much more linear and it had a repeatable trigger. After switching controllers, the seismic source tool sounded much better. We also changed the contact points on the back of the tool from long rails to 4 pointy nubs. We tried 3 nubs, as some people had suggested, but the tool would not clamp with 3 points-- instead it would hang up on 1 point and the clamp shoe. With the 4 nubs we had to wiggle the wireline to get the tool to clamp solidly, but the data looked much better. We began by driving the seismic

source with a 20 Vrms constant voltage sweep. We correlated the receiver signals with the output from the actuator accelerometer. The data was much better, with no spikes after zero time on correlated channels. The seismic source signals were clearly present in the correlated data from the 21 surface geophones and on the clamped receiver.

We ran constant voltage sweeps at 20, 40, 60, and 80 volts, between 150 and 720 Hz, and had good signal in the raw data from most of the geophones, in the correlated data from all of the surface geophones, some signal at all of these levels in the correlated traces from the OYO receiver, using the actuator accelerometer as the pilot trace. We then decided to use a 60 volt constant voltage drive for the common source fan. This produced a relatively flat output from the source (0.9 to 2.25 g over the range 150 - 720 Hz). We had good correlated data at all depths from 40 meters to 3 meters, and poor data at 1, 2, 3 meters depth. We did a received power spectrum, and found that most of the signal is in the 150 - 450 Hz range.

Figure 29 shows the time traces for the vertical and two horizontal components of the fan correlated with the constant amplitude 5 volt pilot sweep signal, and also the average received power spectrum for the top, middle, and bottom receiver positions of the fan.

The results of the Hanford test were better than we had hoped. The earlier field tests at the FACT site were between wells spaced only 39' apart, and we were not certain that we would be able to propagate any signals over so much greater well separation. The loose gravel and fill dirt at this site is very attenuating at high frequencies, but signals with 10-15 dB signal-to-noise ratio were received over the full sweep range and over the full depth of the well.

It should be noted that the source was not operating optimally during the Hanford Test or in the Newkirk test described in the next section. Figure 30 shows the actuator output for a 20 volt sweep of the actuator on a test plate in the laboratory compared to a 20 volt sweep with the actuator in the borehole tool at Hanford and at Newkirk. In the lab we had produced flat output at over 9 g, although in this test the source only generated 0.9 to 2.25 g's during this test, so the data from this test, though impressive, could have been much better and the source operated over much wider well spacing.

As mentioned earlier, this test included a side-by-side comparison with three other seismic sources in the same wells. The magnetostrictive tool showed excellent performance compared to the other sources. See the comparison contained in Appendix C.

Time and Date: 10:49:18 8/10/93

TITLE: Common Source Gather. Source=20m, Receiver=50m to 2 m, H1, H2, V

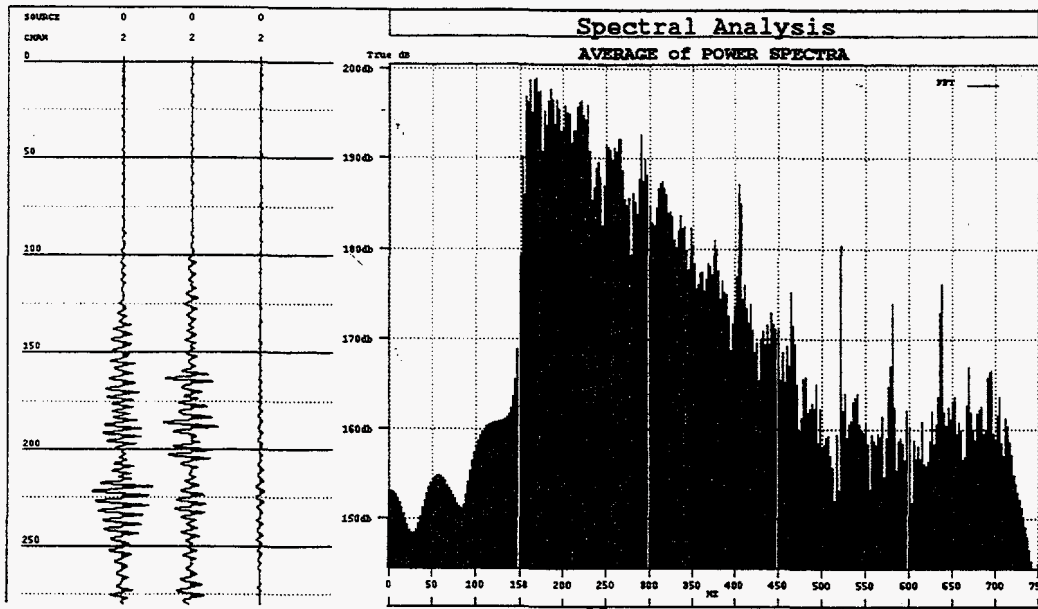
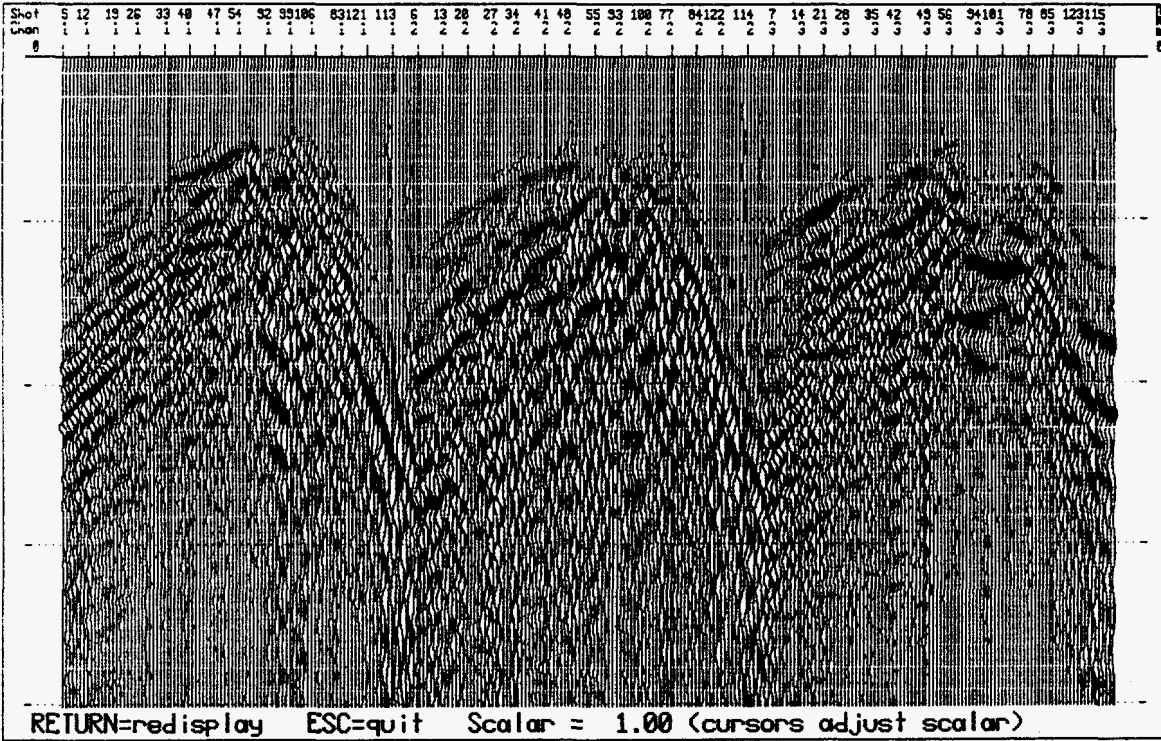


Figure 29: Crosswell Test at Hanford—Common Source Fan (upper) and Average Received Power Spectrum (lower)

Actuator Output for 20 Volt Sweep in Laboratory, at Hanford, and at Newkirk

56

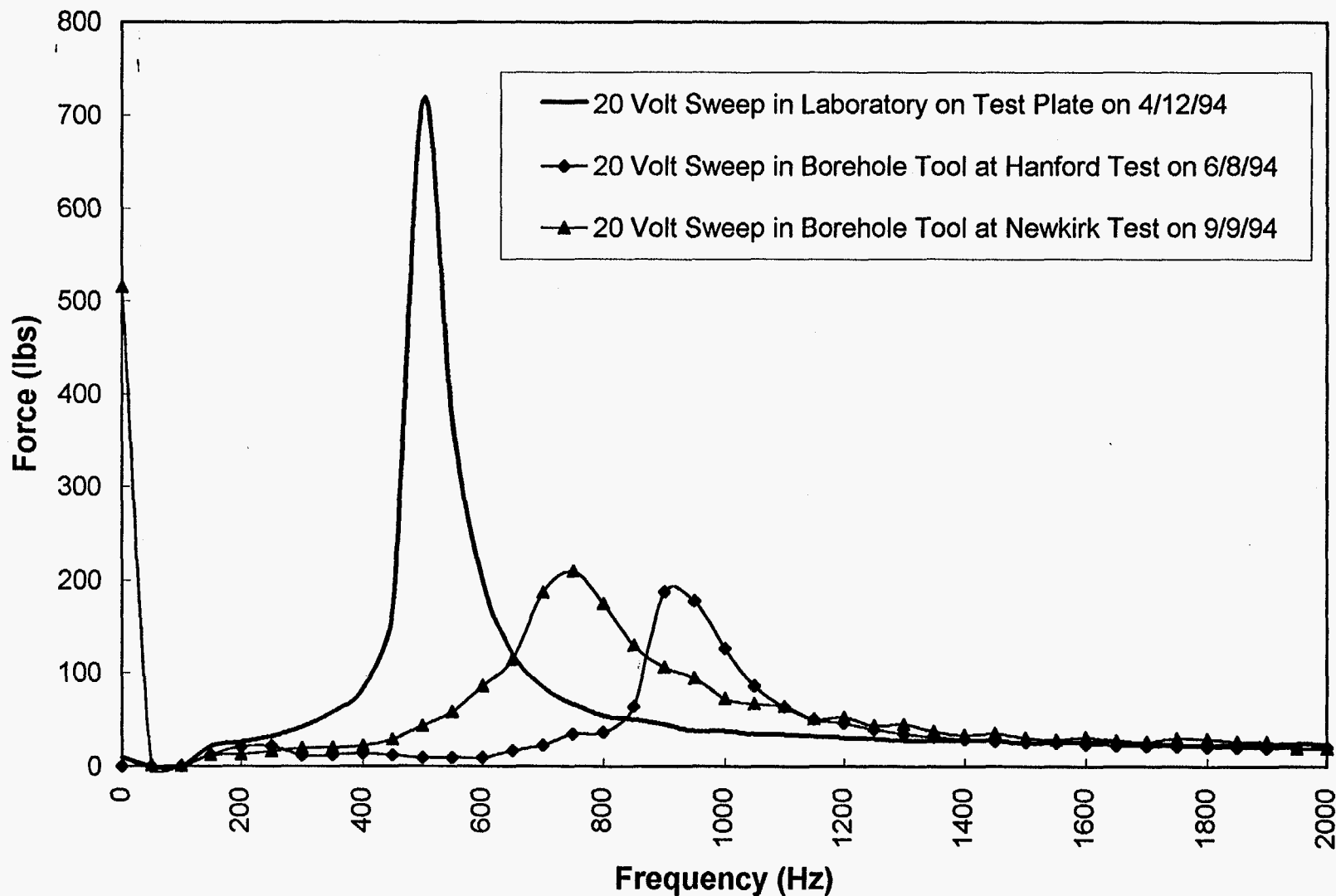


Figure 30: Actuator Output for 20 Volt Sweep in Laboratory, at Hanford, and at Newkirk

Custom Actuator Crosswell Test at Newkirk, Oklahoma

Following the Hanford test, which was conducted in loose gravel, the custom magnetostrictive actuator source was successfully tested in rock at the Conoco oil well test site in Newkirk, Oklahoma on 9/7/94. Conoco provided the test site, all of the field support, and did the data recording and processing. Figure 31 shows the source and receiver wells.

The source was deployed in well GW-4. This well was cased with 6" schedule 80 PVC. The well was 150' deep and the water level in the well was at 31'. The top 50' of the well was cemented into dirt, where the formation velocity was approximately 600 ft/sec. The next 50' of the well was slotted PVC casing which was sand packed rather than cemented, and the formation was sandstone, with a velocity of approximately 6,000 ft/sec. The bottom 50' of the well was unperforated PVC, cemented in sandstone, with a slightly lower p-wave velocity.

The source was housed in the borehole clamp tool, using the 144:1 gear reducer, 4 spiked nubs on the back side of the tool, and a knurled clamp shoe, and the source was deployed on a 500' length of standard 7 conductor wireline.

The receiver was a Sandia/OYO single-level three axis clamped accelerometer receiver. It was first placed in well GW-3, which was 135' from the source well. This well was cased with 8" schedule 80 PVC, and the water level in this well was at 35'. Later the receiver was moved to well GW-1, which was 282' from the source well. The water level in this well was at 30'. This sandstone formation is highly fractured at regular intervals, with the fractures running nearly perpendicular to the line between the source and receiver wells, as evidenced by a nearby outcropping of the sandstone.

To insure that the source tool clamp would not damage the casing, the clamp motor was operated to stall in a sample piece of 6" PVC Schedule 80 casing with both the 68:1 and 144:1 gear reducers. This was done with the bare tool, with the pointed nubs, and with the rails. The source clamped very securely in PVC with the nubs or the rails. With the bare tool, the source could still be wiggled back and forth with the clamp motor at stall. There was no damage to the sample casing in any of these tests. We found during this test that operationally, the tool produced much better output when it was clamped into PVC than it had in the steel cased wells at Hanford or in the granite block in our laboratory. This could be because the clamp and back nubs can bite into the PVC and hence do not slip at all and couple energy much more efficiently into the formation.

A functional test sweep of the source was run using a constant voltage 20 V rms sweep, with the source at 20' deep and the receiver 10' deep (both in the highly attenuating surface soil). We looked at the received instantaneous spectrum and could see the source signal above the noise in the raw data from \approx 400 to 700 Hz.

Following this test sweep we programmed in a drive signal that would follow the 6 amp curve up to 475 Hz, and then give a flat 10 g force level up to 2 kHz. We ran 1 sweep, but only measured 4 g's rather than 10 g's. We ran a 2nd identical sweep, when the source developed a complete

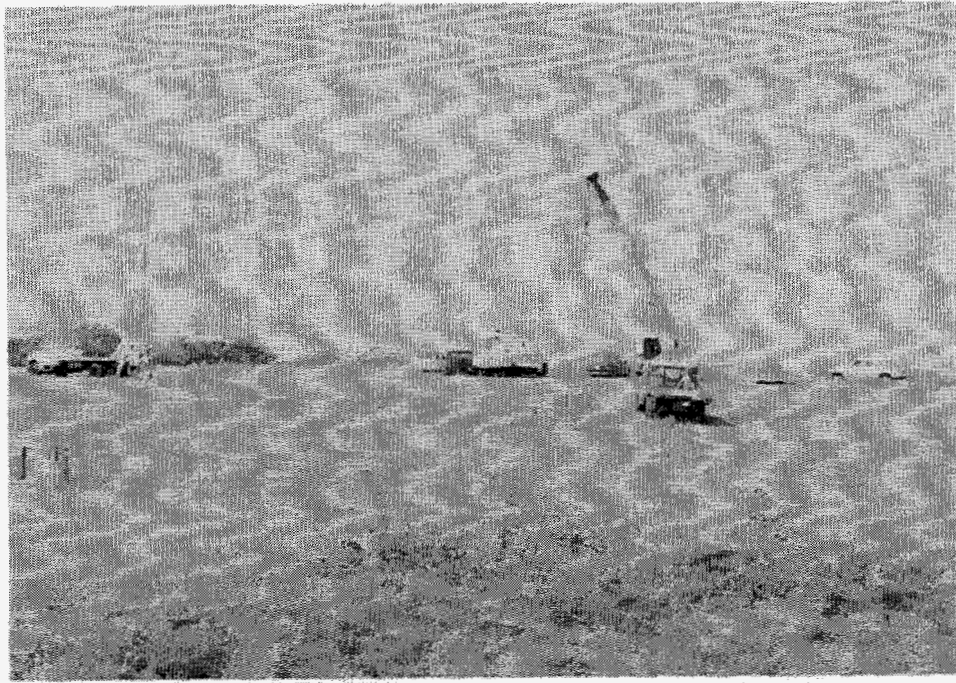


Figure 31: Crosswell Survey at Newkirk, Oklahoma

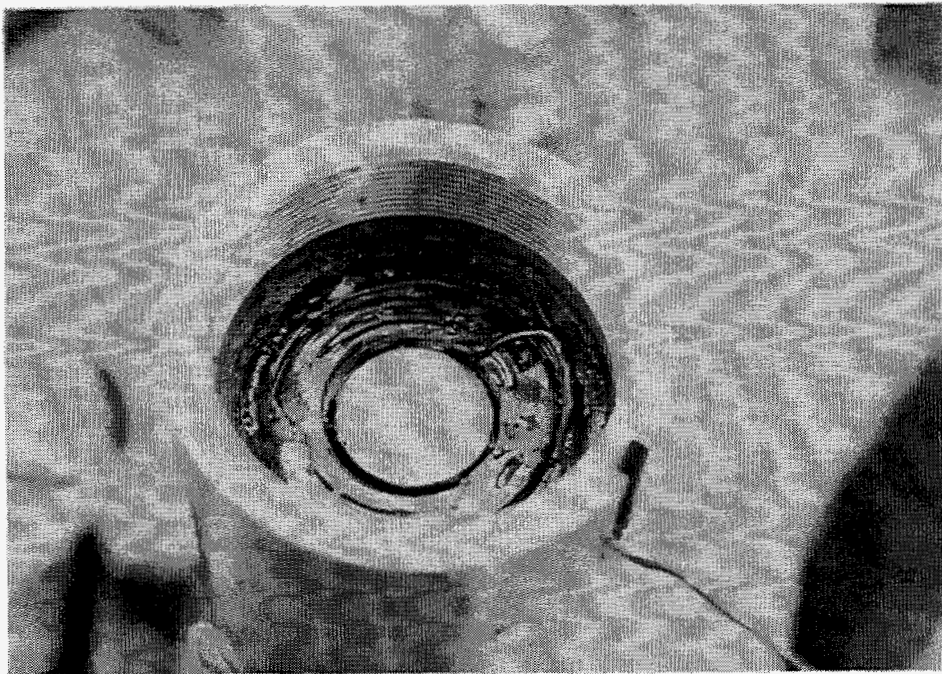


Figure 32: Actuator Disassembled for Repairs

short to case and the power supply pegged at 11 amps. We disassembled the actuator and found that the coil winding had shorted near the top of the Terfenol rod at a sharp corner where it exited the case. There were a few chips out of the end of the Terfenol rod. We unwound two wraps of the coil and put heat shrink on. There was significant grit between the coil and the Terfenol, which were rubbing on each other. We reassembled the source and completed the test. Figure 32 shows the actuator disassembled for repairs.

In this test, because of recorder record length limitations, 4 sweeps per receiver position, each 1 second long, were stacked, rather than using one longer sweep. The data was recorded on a Bison seismograph and then processed immediately on a workstation in the recording trailer. We did a sample test at individual frequencies every 100 Hz to determine the voltage required in order to produce a nominally flat 8 g's output, while also staying below the 6 amp limit on the coil, the 220 V limit of the power supply, and below the 30 g preload limit at resonance. We also tapered the drive signal between 1900 and 2000 Hz from 220 volts down to 0 volts drive to avoid the very large current spike that occurs if the drive signal stops abruptly. We programmed the resulting drive profile into the B&K signal generator, using a sweep from 150 to 2000 Hz.

We ran a common source fan with the source in well GW-4 at a depth of 70' and the receiver in well GW-3, with the receiver moving from 120' to 28' deep in 4' levels. The sweeps were 1 second long, with 4 sweeps per level. Once we were set up we programmed the B&K and the Bison seismograph to automatically do 4 each 1 second sweeps with 6 seconds between each to store the files. The total time for 24 receiver positions and 1 source position was 26 minutes (1 minute per level). We then moved the source to 120' deep and repeated the fan. It took 10 minutes to relocate the source and receiver, to run system checkouts, and to start the new fan, and then it took 26 minutes to do this fan at 1 minute per level.

Following this second fan the receiver was moved to well GW-1. One common source fan was run with the source at 120', and another with the source at 70'. The data had looked so good for both of these receiver wells, that we decided to try another fan with source at 120' depth in GW-1 and the receiver in well 33-1, which was 560' from the source well. This well was too large a diameter for the Sandia/OYO receiver to clamp into, so we used a Conoco wall locker receiver with Wilcoxon accelerometers. For this greater distance we programmed the drive signal for maximum output, rather than flat output as in the earlier fans, driving the source at 6 amps from 150 - 750 Hz, and then 220 V from 750 to 2000 Hz. This gave a peak output 32 g's at 515 Hz, and 10-18 g's over most of the sweep. When we looked at the received signal there was a great deal of noise. Later processing showed no received signal, but it was not clear if this was due to the greater well separation, using a receiver not optimized for high frequency response, or due to crosstalk.

Dale Cox and John Stock of Conoco processed the data from all of the fans. F-T plots showed good fundamental signal all the way from 150 to 2000 Hz. There were fairly low harmonics, and no 60 Hz noise. The data was filtered from 148 Hz to 2000 Hz. There was quite a bit of noise between 150 and 250 Hz but we could not tell if it was natural or source or receiver related.

They tried three different pilot signals (actuator voltage, actuator current, and reaction mass acceleration) and three different kinds of correlation (correlation, phase match filter, designature). It turned out that all three of these pilot signals were flat across the full frequency spectrum to within 10 dB, so it did not make much difference which pilot signal was used. Also, since there was such high signal to noise ratio, it did not make much difference which of the correlation methods were used. Figures 33 through 36 show the common source fans for source depths of 70' and 120' and well separations of 135' and 282'.

Figures 37 through 40 show the signal-to-noise ratio for the four common source fans. The signal-to-noise with the source at the 120' deep position was 20-30 dB for near well spacing, and 15 dB for the far well spacing. In the 70' deep position it was 15-25 dB for near well spacing and 5-15 dB for far well spacing over the full sweep spectrum of 150-2000 Hz. The data with the source at 120' deep looks better than with the source at 70' even though the formation velocity at the deeper location is slightly lower. This is probably because the top 50 ft. and bottom 50' of both wells are cemented, but the middle 50' is sand packed.

Custom Actuator Crosswell Test at Rifle, Colorado

This test was conducted at the Multi-well Site near Rifle, Colorado on 3/8/95. This site had been used extensively to test fracture mapping techniques. As part of that effort, an array of Wilcoxon accelerometers was grouted into a monitor well, covering a depth range of 4000' to 4900'. At this depth the formation is sandstone, with a P-wave velocity of 15,000'/second. The magnetostrictive source was deployed in a second well, MWX2, located 350' away from the monitor well, at a depth of 4550'. The source was deployed on an 11,000' wireline. One of the goals of this test was to determine if frequencies greater than 2000 Hz could be propagated over this inter-well distance at this site. A function generator was used to drive the magnetostrictive seismic source, and the frequency was gradually increased until it matched the mechanical resonances of the accelerometers (at approximately 2230 Hz) which greatly increased the accelerometer signal output. Then the source and the receivers were combined in a phase-lock loop to further boost the signals. The source was operated at this depth for several hours with no difficulties. The objectives of the test were met. This test showed that not only can this magnetostrictive source be used in shallow environmental applications, but it can also be operated over long wirelines at depths and over inter-well distances of interest to oil and gas applications, and is powerful enough to propagate high frequency signals over long distances.

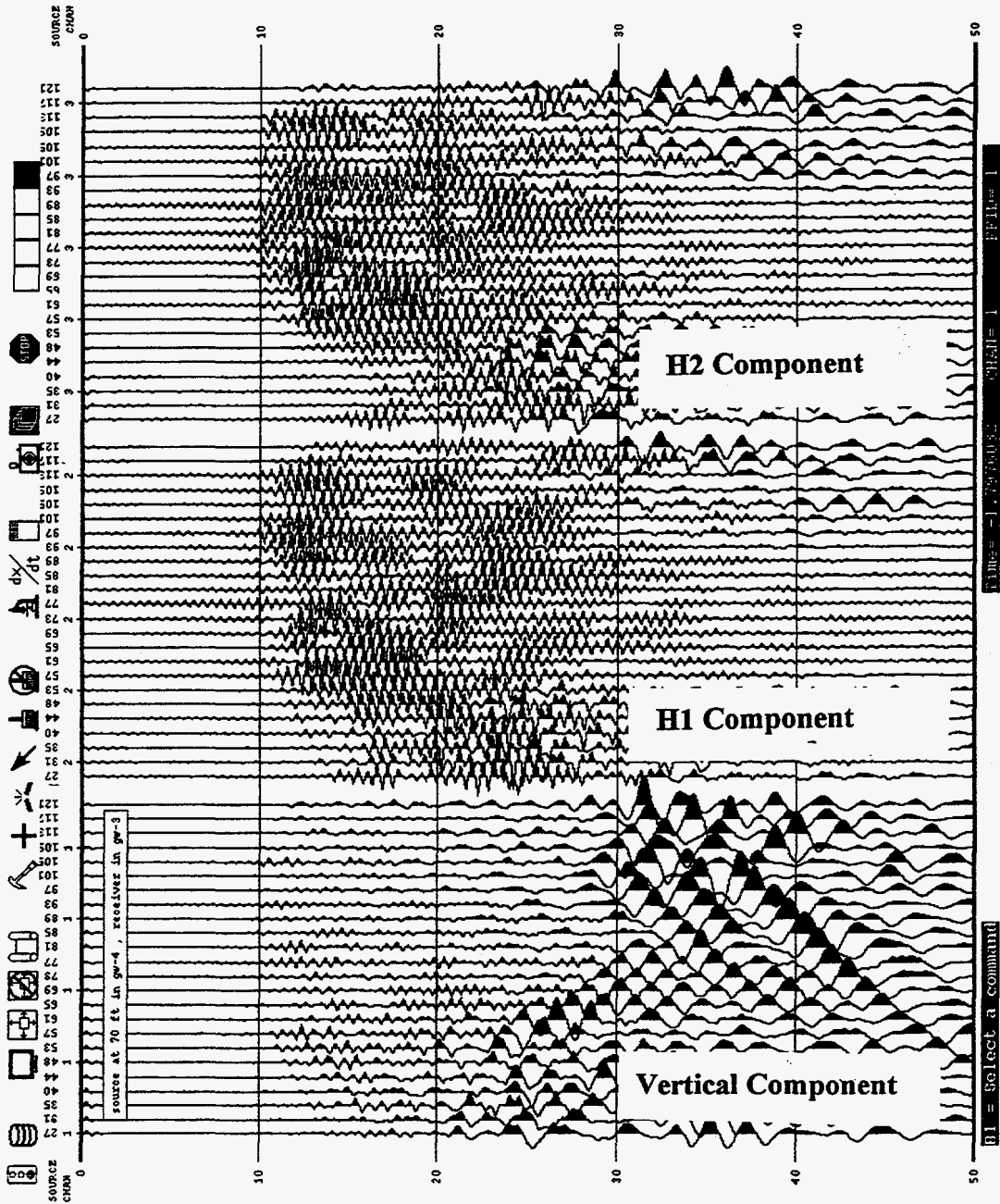


Figure 33: Source in GW-4 at 70' deep, Receiver in GW-3, Well Separation 135'

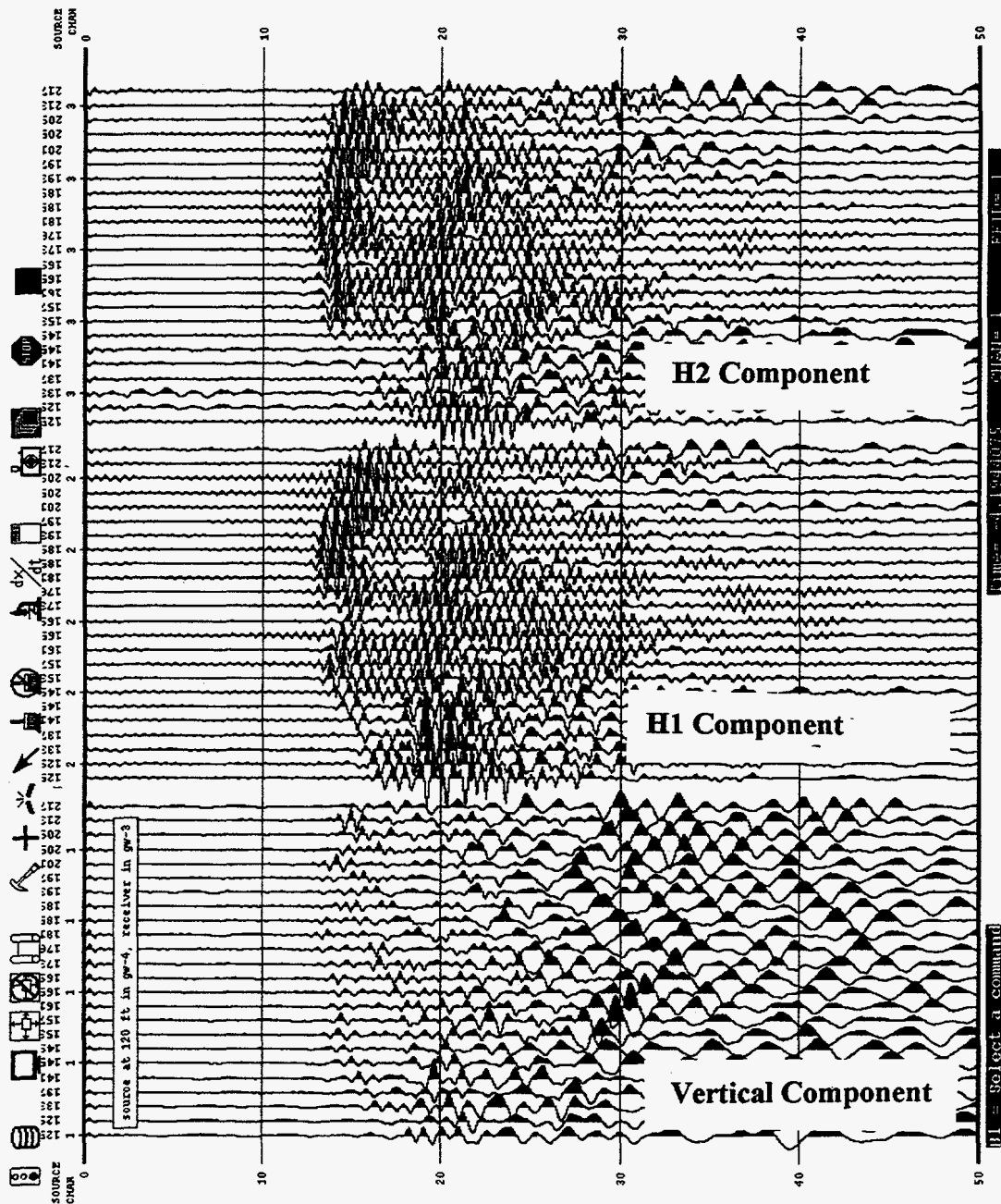


Figure 34: Source in GW-4 at 120' deep, Receiver in GW-3, Well Separation 135'

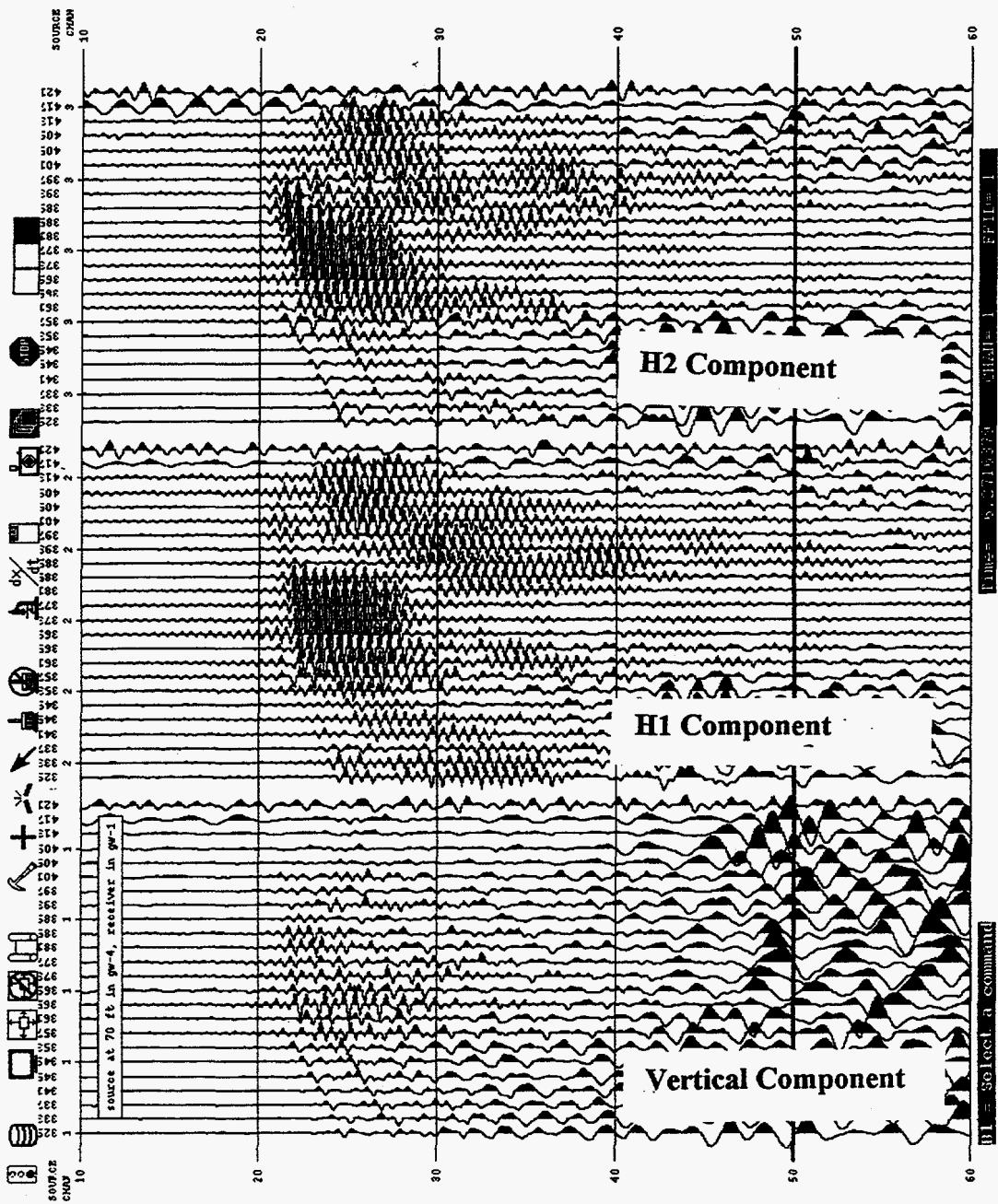


Figure 35: Source in GW-4 at 70' deep, Receiver in GW-1, Well Separation 282'

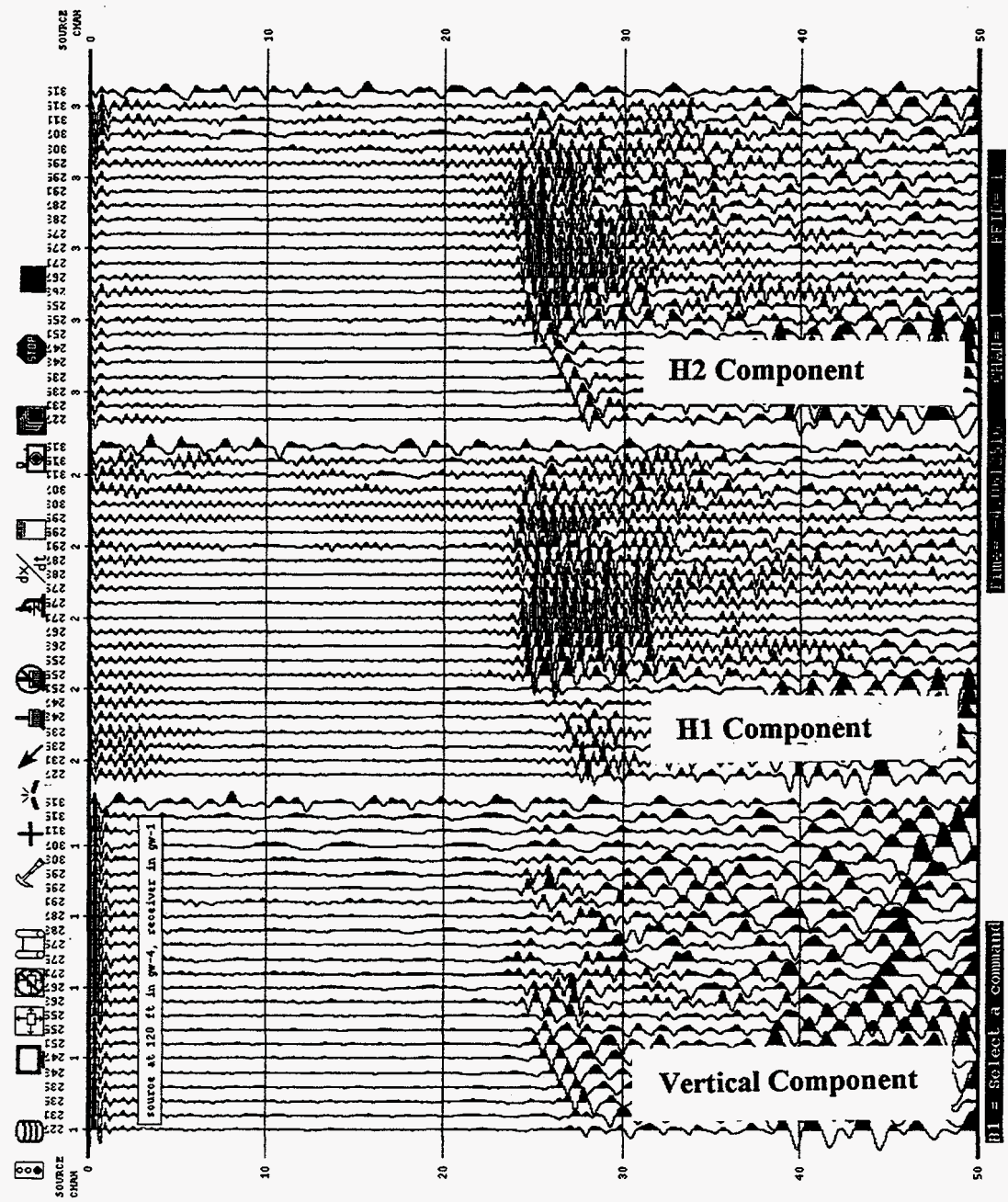


Figure 36: Source in GW-4 at 120' deep, Receiver in GW-1, Well Separation 282'

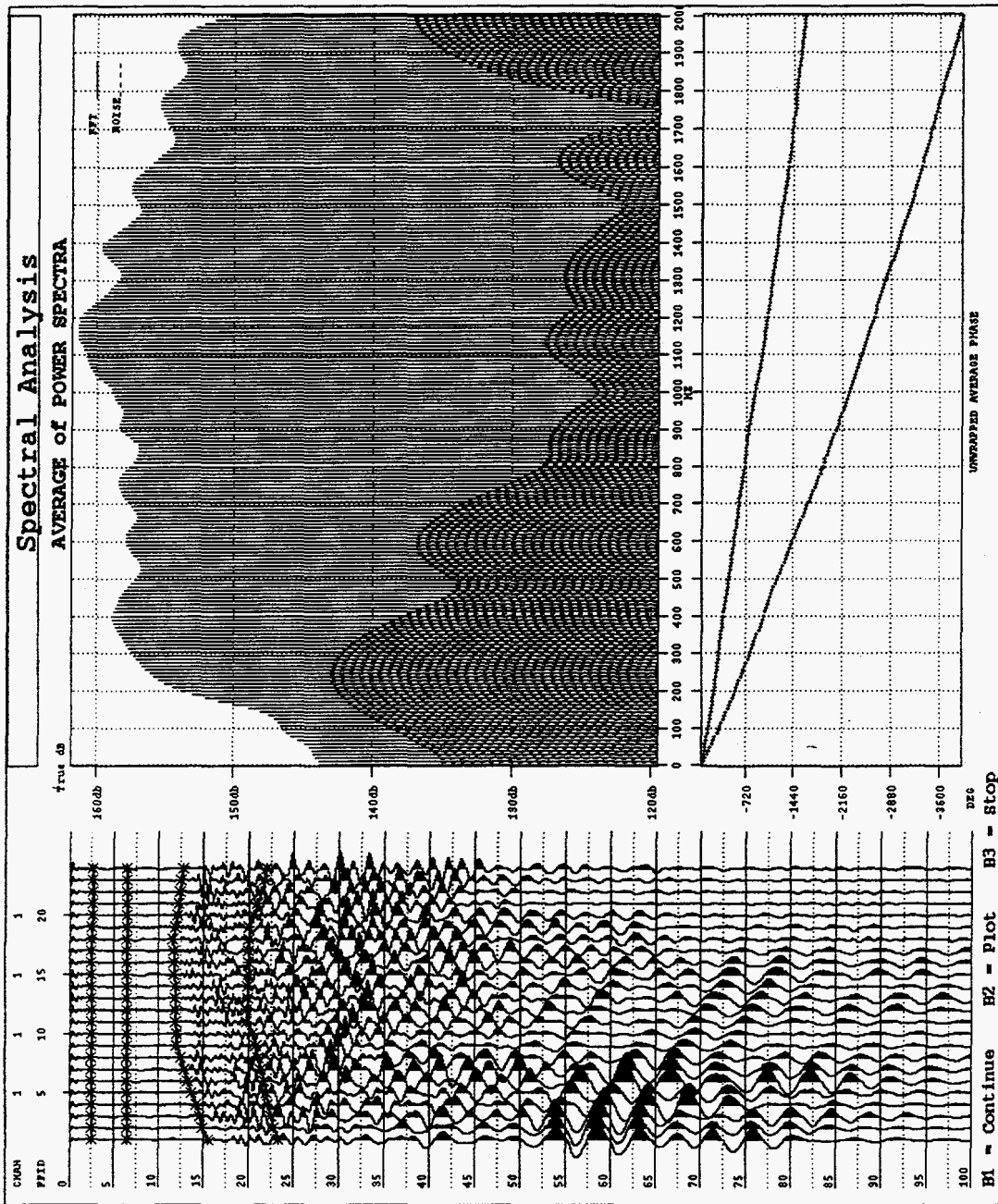


Figure 37: Signal-to-Noise Ratio, Source in GW-4 at 120' deep, Receiver in GW-3, Well Separation 135'

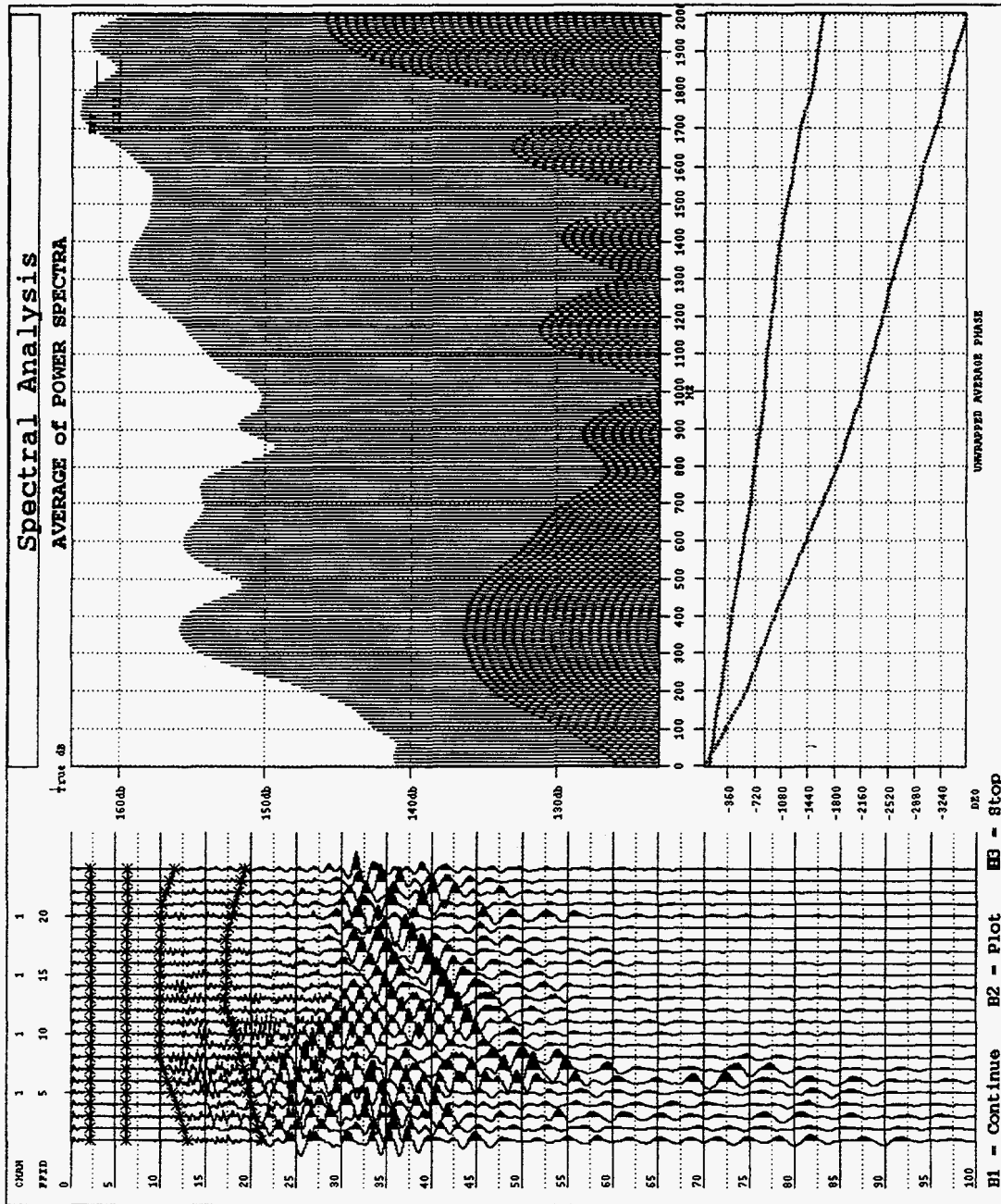


Figure 38: Signal-to-Noise Ratio, Source in GW-4 at 70' deep, Receiver in GW-3, Well Separation 135'

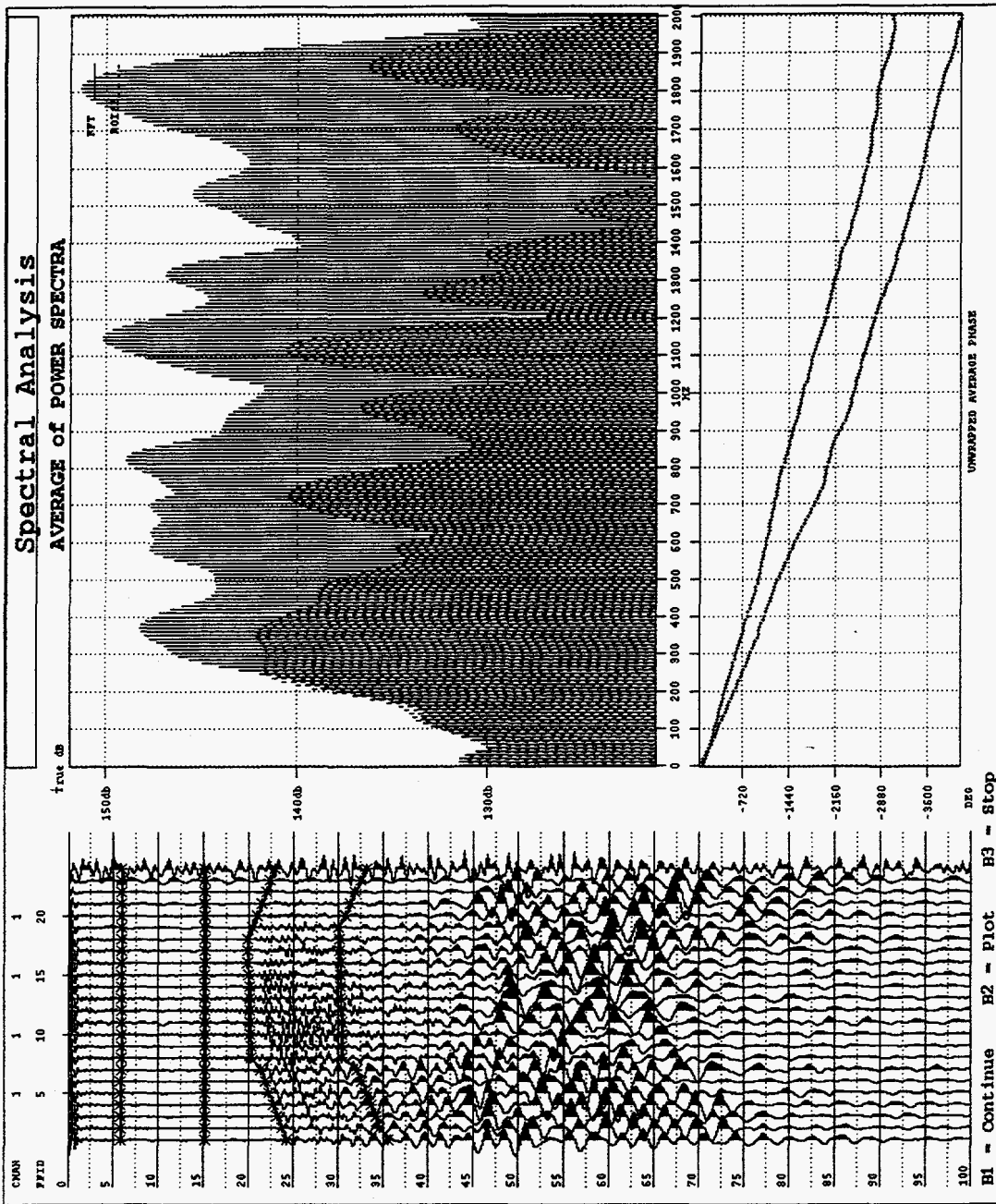


Figure 39: Signal-to-Noise Ratio, Source in GW-4 at 70' deep, Receiver in GW-1, Well Separation 282'

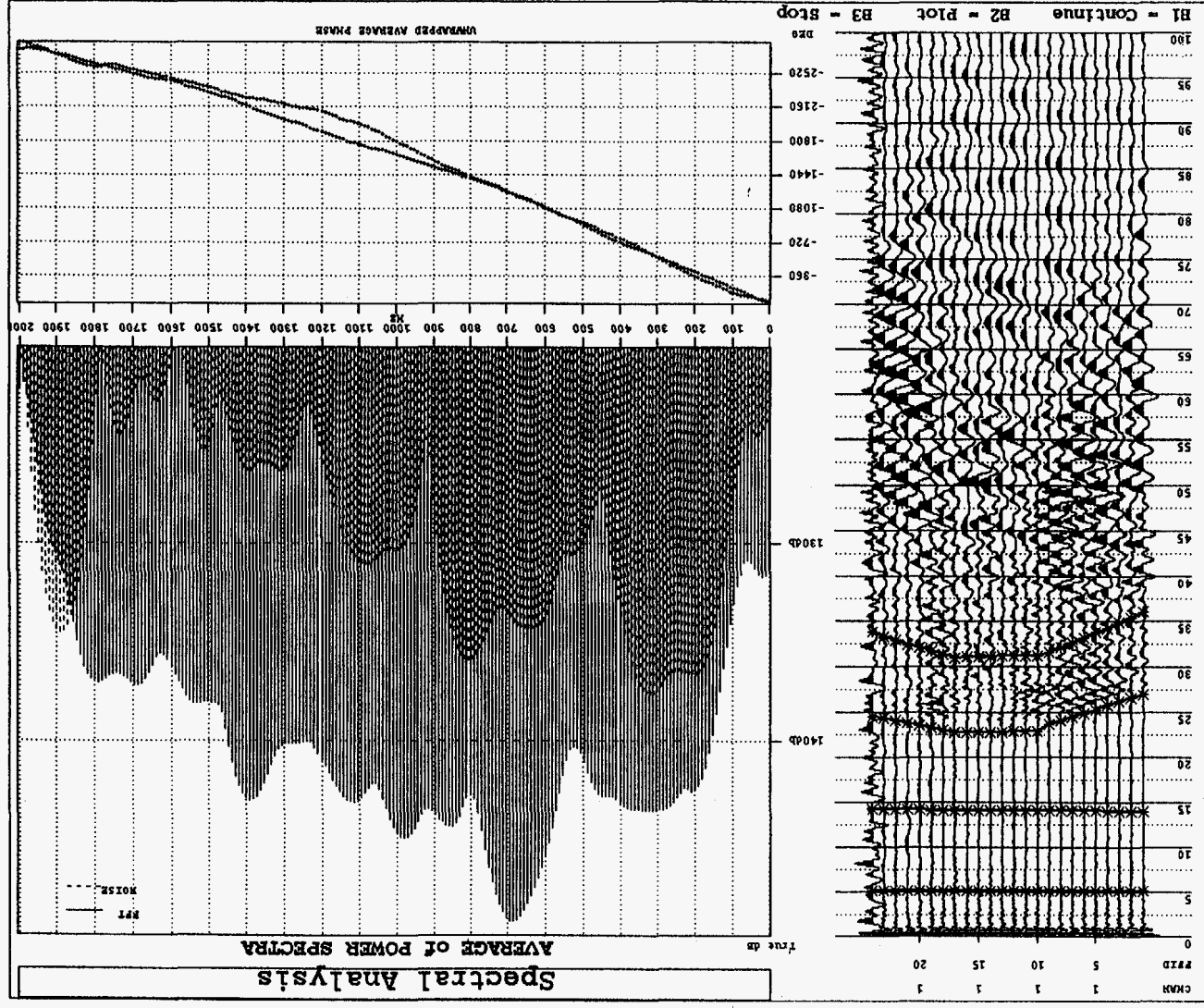


Figure 40: Signal-to-Noise Ratio, Source in GW-4 at 120' deep, Receiver in GW-1, Well Separation 282'

Recommendations

This source has excellent potential for use in environmental, oil, gas, and mining applications. Inquiries concerning the source were received from several oil companies, and also from several companies interested in commercializing the device. Sandia personnel met with Etrema Products, Inc., regarding a proposal for a next generation higher force, higher reliability version of the actuator. While the tool is usable in its present state, it would be easier to deploy, more reliable, and find a wider market if the following recommendations were implemented.

Recommendations

1. Develop an improved, stiffer, fail safe clamp.
2. Eliminate all joints between the actuator and the clamp. Use a solid connection between the actuator push rod and the clamp to eliminate the problem of the jam nut loosening.
3. Develop a higher sample rate force feedback controller which also includes programmable voltage and current limiting.
4. Develop a stiffer, higher force output actuator to allow use over wider well spacing and to propagate higher frequency spectrums across highly attenuating formations.
5. Modify the impedance of the actuator drive coil to operate at higher voltage and lower current in order to minimize wireline losses. Use a higher voltage power supply.
6. Modify the internal construction of the actuator, including improved bearings and coil support, to increase device reliability. Use better insulated coil wire and prevent Terfenol rod from rubbing on coil. Include a temperature sensor in the coil.

Conclusion

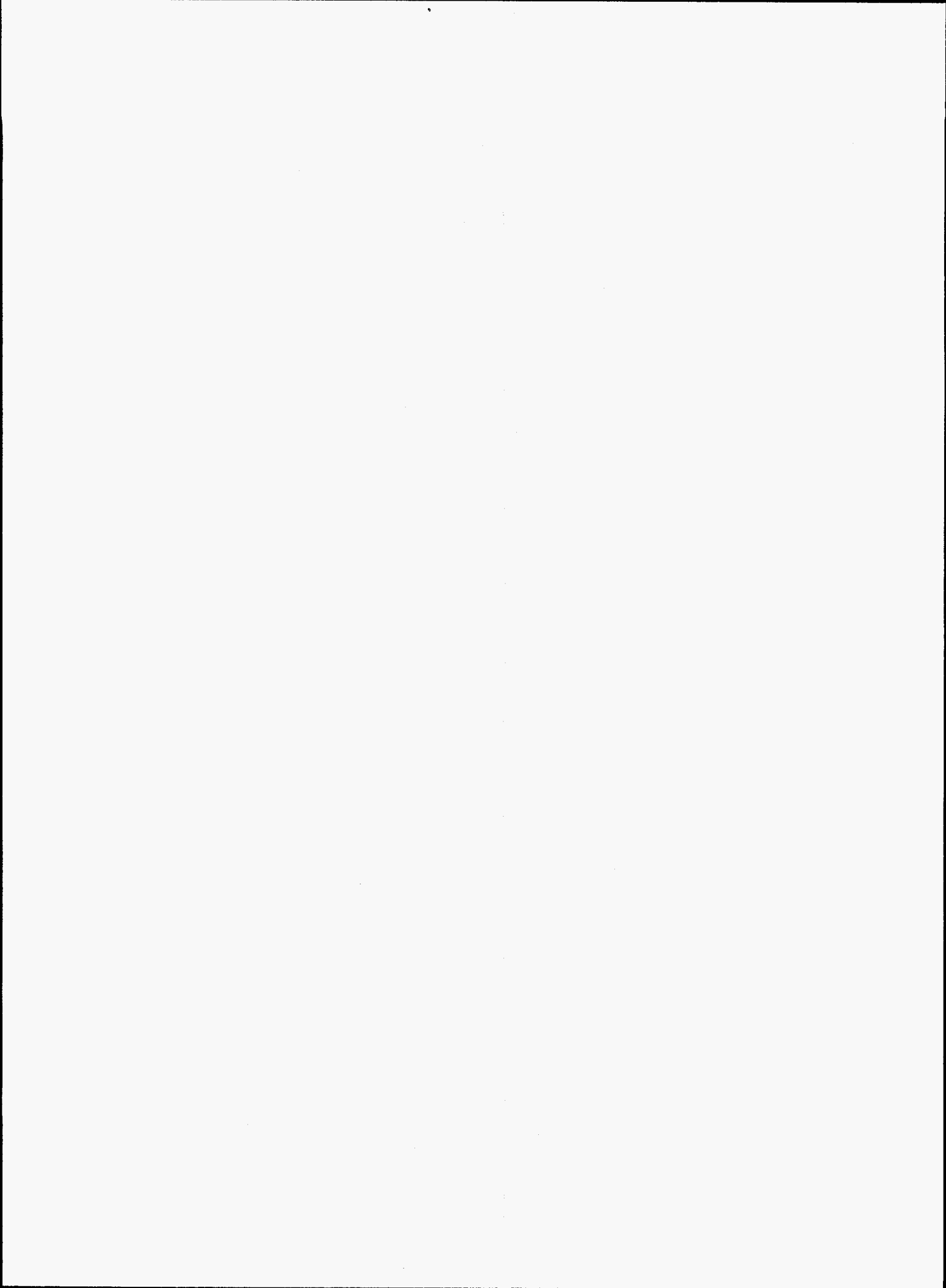
All of the goals of the project were met. A swept frequency seismic source was developed and demonstrated which is applicable for high resolution imaging in environmental applications, and also has potential use in oil, gas, and mining applications. The source is small, easy to deploy, clamped, can be used in wet or dry PVC or steel cased wells, has an easily modified output, has a broad frequency range which is both high enough for good resolution and low enough to propagate through loose soil. The tool is ruggedized for use in downhole environments, and operates on a standard wireline. The tool was successfully demonstrated, both in loose gravel at a shallow environmental location, in shallow rock at an oil field test site, and in a deep well. The source compared very well in side by side tests with other borehole sources. The source has enough force to use between typical monitoring well separations of 200+ feet. Recommendations were made for additional improvements to the source.

APPENDIX-

- APPENDIX A: Project Personnel**
- APPENDIX B: ETREMA Reaction Mass Actuator Final Report**
- APPENDIX C: Comparison of Lower-Frequency (<1000 Hz) Downhole Seismic Sources for use at Environmental Sites**
- APPENDIX D: ETREMA Product Literature**
- APPENDIX E: Effect of Source Frequency Spectrum on Correlated Data**
- APPENDIX F: DOE Reporting Requirements**

APPENDIX A: Project Personnel

Bob Cutler	Sandia 6116	Project leader 4/93 through 9/94
Gerry Sleaf	Sandia 9136	Project leader 10/92 through 4/93, prototype design
Russ Keefe	Sandia 6116	Laboratory and field test support, data plotting
Greg Elbring	Sandia 6116	Field test at Hanford
Bruce Engler	Sandia 6116	Hardware design, field test support, data plotting
Pat Drozda	Sandia 6116	Field test support
Chad Harding	(formerly) Sandia 6114	Field test planning
Marion Scott	Sandia 1307	Former Supervisor dept. 6114
Harry Morris	(formerly) Sandia 6116	Laboratory test support
Ron Franco	Sandia 2664	Electronics support
Carl James	K-Tech	Laboratory test support
Toby Hansen	Etrema	Actuator design, fabrication, test
Dale Cox	Conoco	Field test support



APPENDIX B: ETREMA Reaction Mass Actuator Final Report



ETREMA PRODUCTS, INC.
Subsidiary of Edge Technologies, Inc.

DATE:

October 15, 1993

DOCUMENT TITLE:

ETREMA Reaction Mass Actuator Final Report

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A. Introduction

The Reaction Mass Actuator (RMA) has been successful in achieving its design goals. The RMA's housing length is 11.75 inches and diameter is 3 inches. RMA component interface is provided by a 3/4 - 16 UN threaded push rod. Total unit mass is 14.3 kg. Subtracting out the non-moving mass components, the RMA dynamic mass is 13.7 kg. Reaction output force of the RMA meets the design goal of 400 lb force +/- 6 dB between the frequencies of 150 - 2000 Hz. Output force production should not be compromised from operating temperatures ranging from 15 to 30^o C.

Under normal operating circumstances, input current should not exceed 5.66 A RMS. The RMA in general will not require current inputs larger than 5.66 A RMS at frequencies of 200 Hz or higher to meet the 400 lb force +/- 6 dB specification. To meet the specification given at 150 Hz, requires somewhat higher input current of 8 A RMS.

B. Actuator Operation

The RMA has been designed to provide peak dynamic force of 400 lbs over a band of frequencies between 150 - 2000 Hz. This has been accomplished by the prototype, however, the continued success of the device depends on two main issues when operated in the field.

The first issue is that the device is rated for a maximum peak acceleration of 30 g's (30 g's with an equivalent dynamic mass of 13.7 kg translates to a dynamic force of 906 lbs). Accelerations larger than this may result in damage to the ETREMA TERFENOL-D @ rod inside. The primary reason for this limitation is due to the compressive preload applied to the rod will be exceeded in dynamic operation. When the preload is exceeded, the TERFENOL-D experiences tensile forces which make it extremely susceptible to cracking and damage.

The second issue is the special magnetic circuit will degrade in performance when excessive heat is present in the device. To prevent magnetic circuit degradation, the device is not to be operated in environments exceeding 70^o C. It follows also that in environments cooler than 70^o C the skin temperature of the RMA housing is not to exceed 70^o C.

C. Actuator Testing

The RMA was tested by bolting the push rod to a 1 inch thick steel plate. The plate was then bolted to a very massive steel vibration mount. An accelerometer was placed on various locations of the plate. The RMA was run to excite the mounting plate and determine the modal characteristics of the plate and how it would affect the data collected later. With this task achieved, the accelerometer was placed on the center of the tungsten reaction mass. The data presented was collected following the guidelines established by the contract.

Figure 1 is a graph of the peak output force vs. drive frequency at a constant drive voltage of 20 V RMS. Noticeable on this graph is the absence of 10 - 90 Hz data. Data collected in this frequency band fell into the noise region of the accelerometer. The noise acceleration value was near 50 mg's. Data collected from the RMA in the frequency band had values ranging from 5 - 30 mg's. Referring to Figure 1, it can be seen that there is a strong resonant peak. The frequency of resonance peak was determined to be 635 Hz.

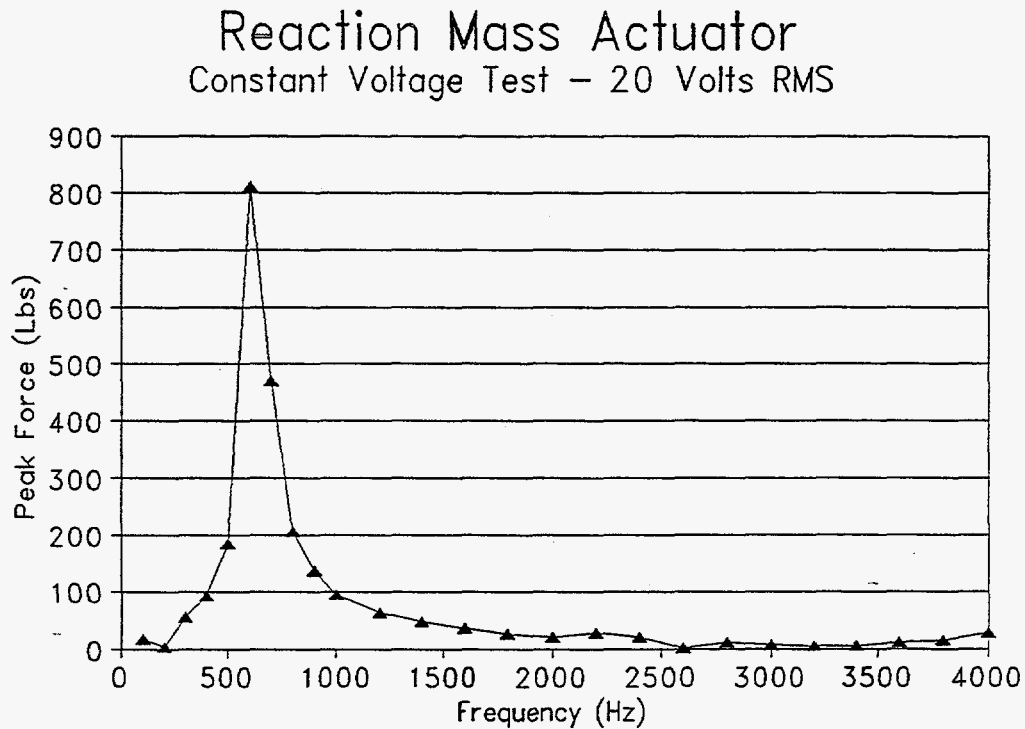


Figure 1: RMA Output Force vs. Frequency at constant Input Voltage of 20 V RMS.

Data represented in Figure 2 is the RMS drive current in the RMA when the constant voltage tests were conducted. The data shown is of the frequency band of 100 - 4000 Hz. The data following in Figure 3 is the RMS drive current in the RMA for the low frequencies of 12.5 - 90 Hz using a constant voltage of 5 V RMS.

Reaction Mass Actuator
Constant Voltage Test

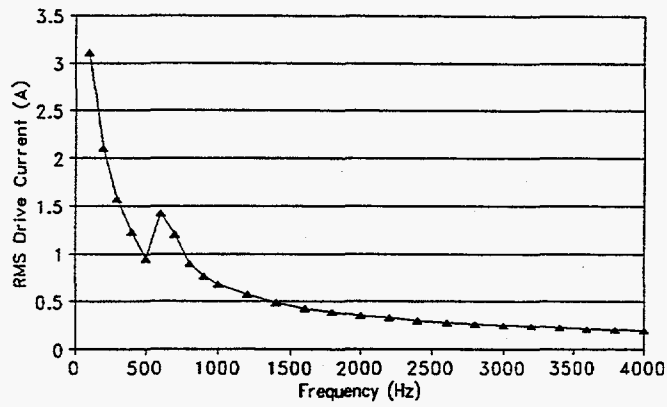


Figure 2: Measured RMS Input Current vs. Frequency for a Constant Drive Voltage of 20 V RMS

Reaction Mass Actuator
Constant Voltage Test

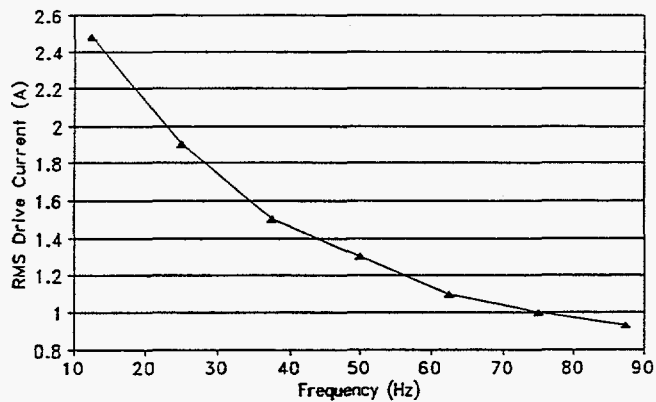


Figure 3: Measured RMS Input Current vs. Frequency for a Constant Drive Voltage of 5 V RMS

Figure 4 is the RMA's peak output force vs. frequency holding the input current constant. The data points taken at 500 and 600 Hz had input currents less than 2.16 A RMS specified on the graph. The input current was lowered at these frequencies to prevent damage to the device, i.e. not to exceed 30 g's peak acceleration. The actual input currents at 500 and 600 Hz were 2.06 and 1.69 A RMS, respectively. There are two peculiar trends represented by the data. There is a small peak at 2200 Hz and a dip around 3000 Hz. These abnormalities in the curve are suspected to be caused by a resonance and anti-resonance of the mounting plate. These abnormalities in the curve should show up at different frequencies when the RMA is tested using a different mounting system.

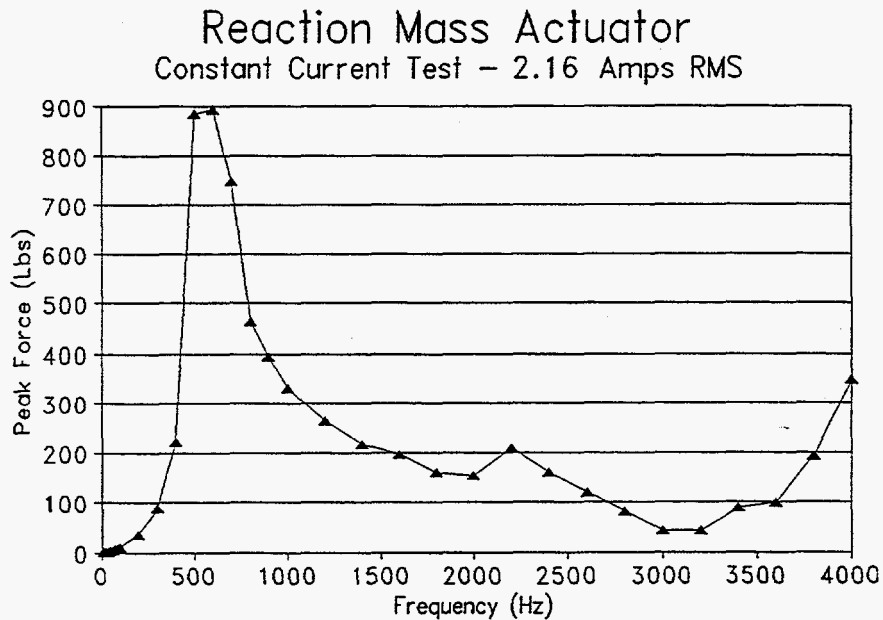


Figure 4: RMA Peak Output Force vs. Frequency at a Constant Current Input of 2.16 A RMS

Figure 5 is the corresponding RMS input voltage required to achieve the 2.16 A RMS represented for the data in Figure 4. Note that the voltages at 500 and 600 Hz are lower due to the lower input current.

Reaction Mass Actuator
Constant Current Test - 2.16 Amps RMS

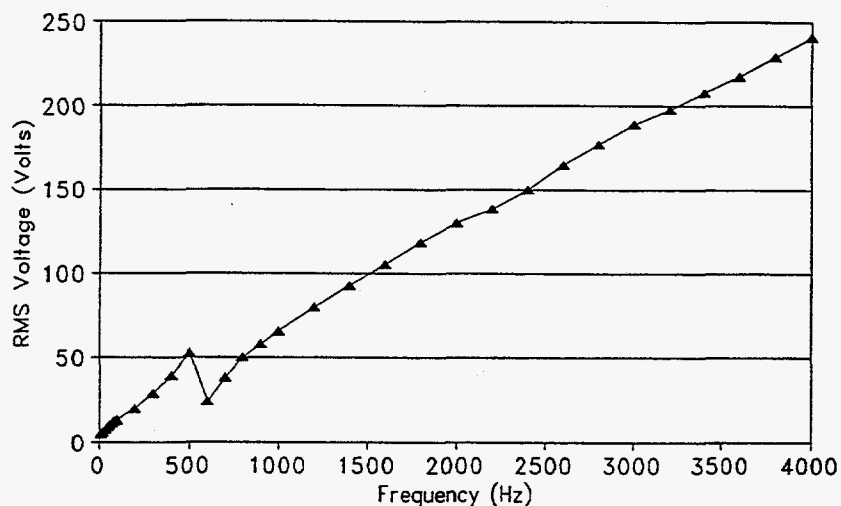


Figure 5: RMS Voltage vs. Frequency for Figure 4.

Data shown in Figure 6 is a plot of the RMA constant output force vs. frequency test. The values represented may appear disappointing when viewed from a design output goal of 400 lbs force. However, these values are conservative from what can be achieved by the RMA. The conservative nature of the values represented was caused from experimental difficulties in drawing power from the electrical outlets in the laboratory. After one main circuit breaker was blown conducting this test, it was decided to lower the power draw and illustrate the constant force properties of the RMA at some lower level. It is known that the data point at 2000 Hz is the maximum output force of the device at that frequency because maximum power was delivered by the amplifier to the RMA. The design goal of 400 lbs force should be achieved at frequencies ranging from 400 to 1900 Hz when input power is not as restrained as it was during this test. It is evident that at 150 and 200 Hz, a constant force of 300 lbs force was not achieved. This is due mainly from the small contribution the frequency has to acceleration at those frequencies. However, the data at those frequencies illustrates the RMA's ability of meeting the 400 lbf +/- 6 dB spec (since - 6 dB translates to approximately 100 lbf). Figure 7 is the corresponding input RMS current required to achieve the constant force output of Figure 6.

Reaction Mass Actuator Constant Output Test

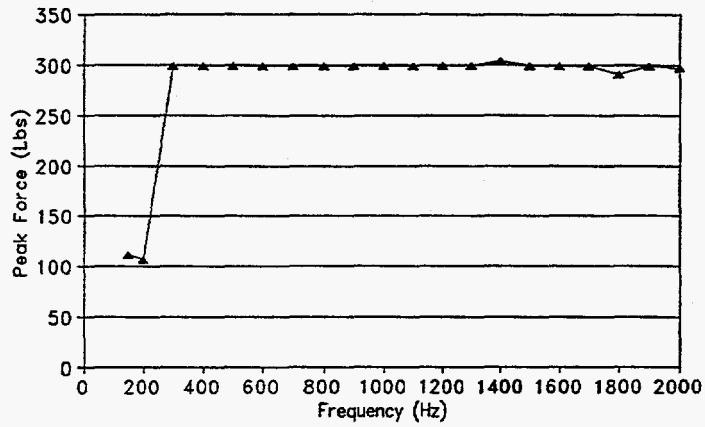


Figure 6: RMA Output Force vs. Frequency.

Reaction Mass Actuator Constant Output Test

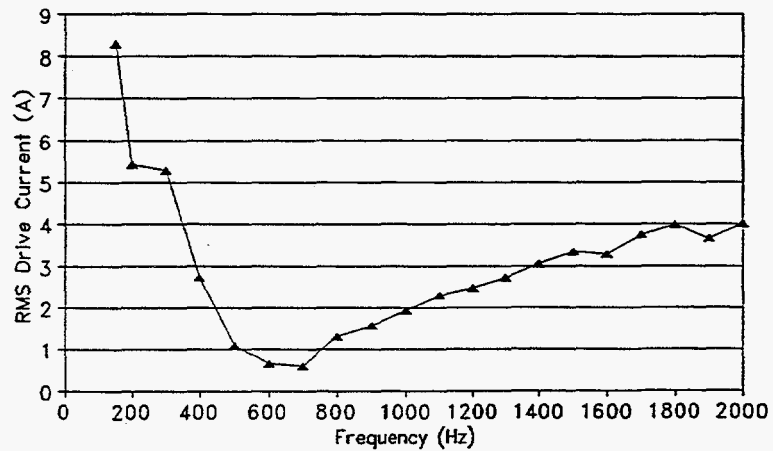


Figure 7: Required RMS Input Current for Figure 6.

The final graph, Figure 8, is the impedance of the device as a function of frequency.

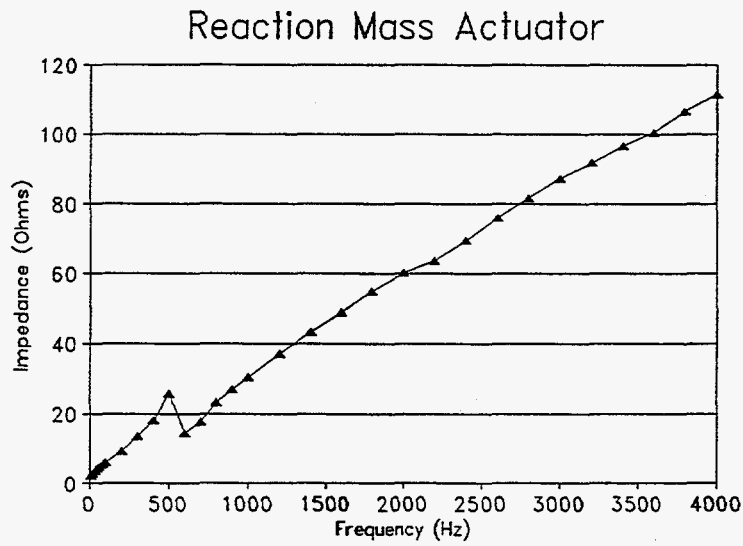
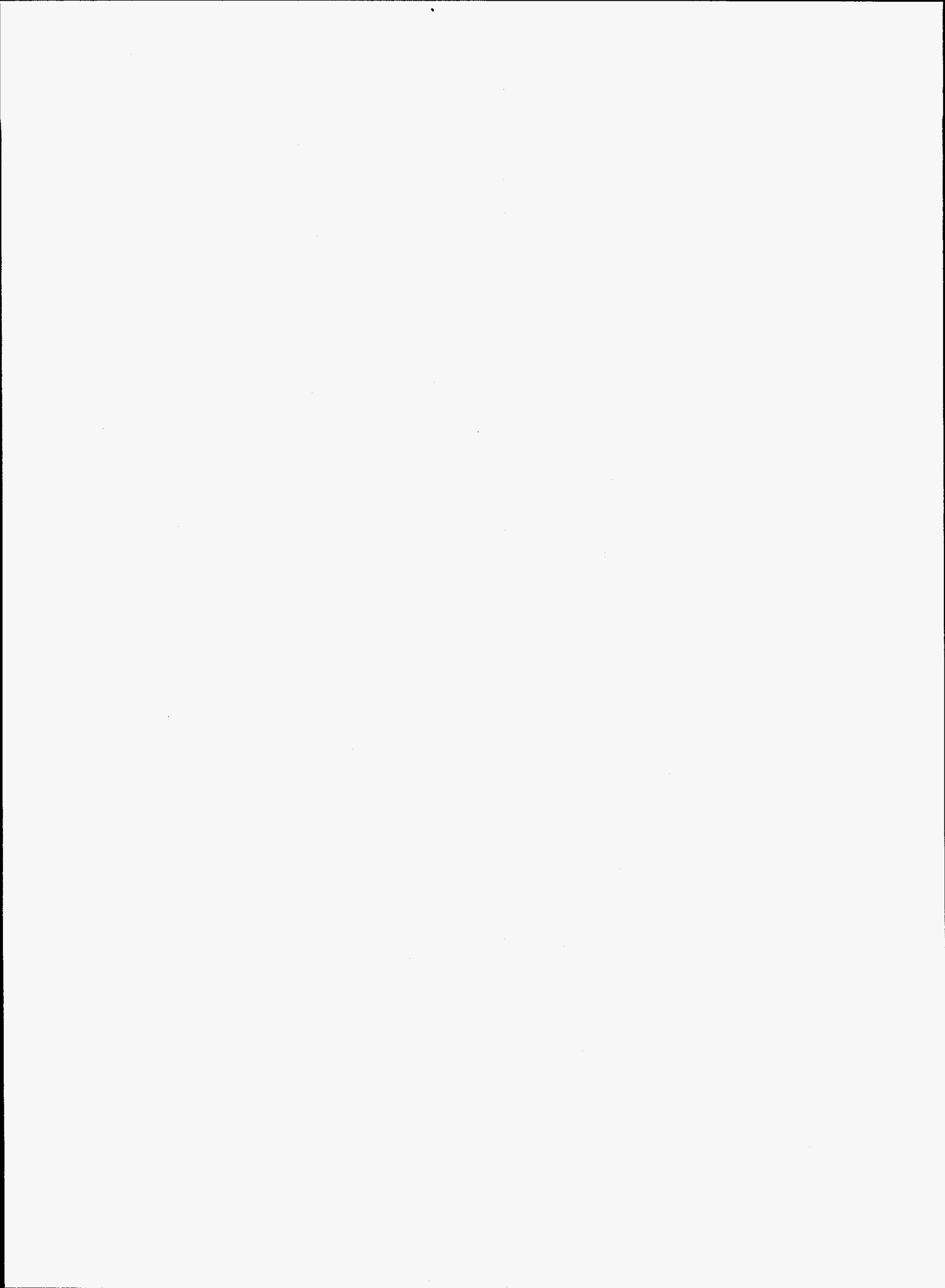


Figure 8: RMA Electrical Impedance vs. Frequency.



APPENDIX C: Comparison of Lower-Frequency (<1000 Hz) Downhole Seismic Sources for use at Environmental Sites

COMPARISON OF LOWER-FREQUENCY (<1000 Hz) DOWNHOLE SEISMIC SOURCES FOR USE AT ENVIRONMENTAL SITES*

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ABSTRACT

In conjunction with crosswell seismic surveying being done at the Hanford Site in south-central Washington, four different downhole seismic sources have been tested between the same set of boreholes. The four sources evaluated were the Bolt airgun, the OYO-Conoco orbital vibrator, and two Sandia-developed vertical vibrators, one pneumatically-driven, and the other based on a magnetostrictive actuator. The sources generate seismic energy in the lower frequency range of less than 1000 Hz and have different frequency characteristics, radiation patterns, energy levels, and operational considerations. Collection of identical data sets with all four sources allows the direct comparison of these characteristics and an evaluation of the suitability of each source for a given site and target.

INTRODUCTION

Crosswell seismic imaging is emerging as a viable tool for aiding in the characterization and monitoring of environmental sites. These sites, which are often unsaturated and composed of unconsolidated material, provide a challenge for creating seismic sources small enough to be fielded in standard-sized boreholes, yet still provide enough energy to propagate needed distances and have a high enough frequency content to provide the necessary resolution. Several sources have been developed to meet these needs and comparison of these source is critical to determining the appropriate choice for the restrictions at any given site. In this paper we concentrate on lower-frequency sources, mostly mechanical in nature, that will not yield the resolution of the higher-frequency sources, but should be able to propagate seismic waves farther distances.

Experiment Configuration

The test location used for the source evaluation is an environmental remediation site located in the 200 West area of the Hanford Site in south-central Washington. Data were taken in the vadose zone using existing steel-cased, ungrouted boreholes. The entire survey was in gravel and sand dominated sequences of the flood-deposited Hanford Formation. The source and receiver wells were separated by 70 m. For testing purposes, the particular source being used was held fixed at 15 m depth and the receiver was moved in 1 m intervals from the surface to 20 m depth.

The OYO Geospace downhole three-component accelerometer package, a rigidly clamped receiver, was used to detect the signals generated. Data were recorded on an EG&G ES2420 seismic recording system at a sample rate of 0.5 ms with an anti-alias filter of 720 Hz.

SOURCES

The four sources tested were the Bolt airgun, the OYO Geospace-Conoco orbital vibrator, the Sandia pneumatic vertical vibrator, and the Sandia magnetostrictive vertical vibrator. Of these sources, only the airgun and the orbital vibrator are currently commercially available. Each of these sources varies in frequency and energy

*This work was supported by the United States Department of Energy under contract DE-AC04-94AL85000.

output characteristics, as well as in requirements for operation and the ease of operation itself.

Airgun

The airgun used for this experiment was the Bolt Model DHS-5500. The airgun consists of a pressurized chamber and a quick-release solenoid valve. When triggered, the solenoid valve rapidly releases the gas into the borehole resulting in a pressure pulse that converts to both compressional (P) and shear (S) seismic energy radiating out from the hole. The tool is 5 cm (2 in) in diameter and approximately 61 cm (2 ft) long, depending on the size of the pressure chamber used. There are three pressure chambers available, 82, 164, and 410 cm³ (5, 10, or 25 in³). Gas pressures up to 2000 psi can be used.

The airgun couples through the borehole fluid and, thus, requires a fluid-filled borehole. Because this experiment was conducted above the water table, a packer was placed in the source well below the deepest source depth, and the hole above the packer filled with water to provide the coupling medium needed. Coupling through the borehole fluid and the lack of need for rigid clamping allows the airgun to be rapidly deployed and moved. In addition, the impulsive nature of the source requires only short recording times and very little post-processing of the data.

For this test, a gas pressure of only 500 psi, supplied by bottled nitrogen, was used to avoid any damage to the boreholes, and the largest pressure chamber was installed. The tool was fielded using a standard seven-conductor wireline with an additional high-pressure gas line that was strapped to the wireline as the tool went downhole. Data were recorded for 1.0 s after the trigger pulse, and an accelerometer on the source provided a sharp time break for zero time.

Orbital Vibrator

The orbital vibrator was developed by Conoco, Inc. and is being marketed by OYO Geospace. It consists of an eccentric mass that is spun by a DC motor around a horizontal axis. By varying the voltage to the motor, a sweep of frequencies with both P and S wave components is generated. This source sweep is recorded by an accelerometer mounted in the source. The tool is 10 cm (4 in) in diameter, 76 cm (2.5 ft) long and runs on a standard seven-conductor wireline. Coupling with the formation is again through the borehole fluid, increasing the speed at which the tool can be moved, but requiring the source borehole at this site to be packed off and filled with water as with the airgun. A clamping mechanism for the orbital vibrator is presently under development and will allow it to be used in dry boreholes. Although the unit used for this test was a single motor and mass design, a dual motor and mass design is becoming available and should approximately double the power output of the source.

In this experiment, increasing voltage was applied for 3 s and then removed, allowing the source to spin down for approximately 5 s giving a total sweep length of 8 s. Data were recorded for 8.1 s. The voltage was then reversed causing the mass to rotate in the opposite direction, and a second sweep was recorded in the same manner. Combining the data from the forward and reverse spin directions will allow decomposition of the data into the P and S components, but this has not been done for the data shown in this paper. The frequencies generated range from 90 to 440 Hz (Figure 1).

Processing for all the vibratory sources in this test, including the orbital vibrator, is the same. The data are whitened and a minimum phase filter is derived from the source trace recorded by the sensor on the tool. This filter is applied to all the recorded traces. The data are then crosscorrelated with the source trace and bandpass filtered to include only the frequencies generated by the source as determined by the spectra from the source traces in Figure 1.

Pneumatic Vibrator

The pneumatic vibrator is a prototype source developed at Sandia National Laboratories (Hardee et al., 1987). It consists of a rotary valve connected to a DC motor that controls the porting of compressed gas to a vertical piston chamber. The oscillation of the piston in this chamber generates primarily vertically-polarized S waves and some P-wave energy. The voltage to the rotary valve motor is computer controlled, and a frequency sweep is designed on the computer, relayed to the source, and monitored both by a tachometer on the rotary valve

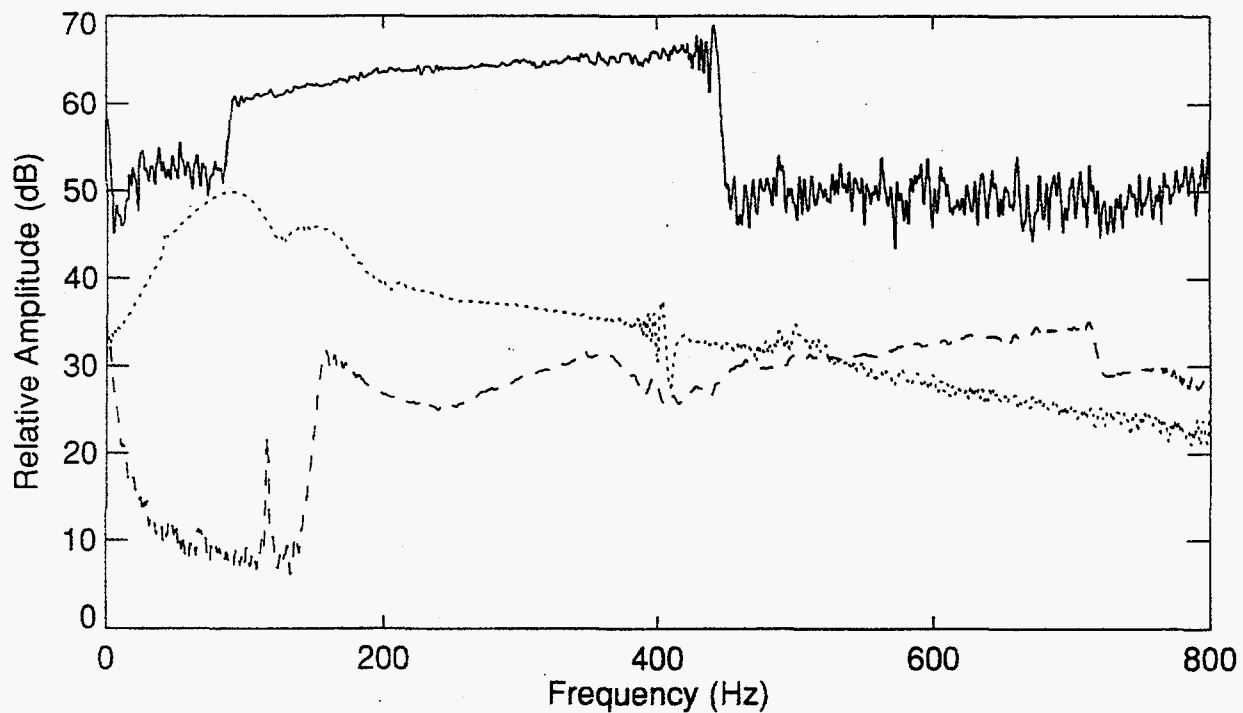


Figure 1: Comparison of source spectra for orbital (solid), pneumatic (dotted), and magnetostrictive (dashed) vibrators. Amplitudes do not correlate between sources due to variations in sensors and recording parameters. Airgun had no sensor to record a source signature.

motor and by a geophone mounted in the tool. The tool is 5 cm (2 in) in diameter and 4.3 m (14 ft) long, most of which is reservoir space for the compressed gas. It is deployed on a standard seven-conductor wireline with an additional high pressure hose that, like the airgun, is strapped to the wireline as the tool goes downhole. A normal operating pressure of 120 psi is supplied from nitrogen bottles at the surface.

Sweeps were run from 40 to 400 Hz (Figure 1) in 7.6 s with data recorded for 8.0 s. A total of four sweeps were run at each source location and the data are stacked together after completing the same processing stream described for the orbital vibrator. The pneumatic vibrator, unlike the airgun and orbital vibrator, is rigidly clamped into the borehole with a clamp located just below the piston chamber. This allows it to function in dry and fluid-filled boreholes, although the time needed to clamp and unclamp significantly slows down the rate at which data can be taken.

Magnetostrictive Vibrator

The magnetostrictive vibrator is another prototype tool being developed at Sandia. This is again a vertical vibrator based on a spring pre-loaded magnetostrictive actuator rod with permanent magnet bias and drive coils and an integral 13.6 kg (30 lb) tungsten reaction mass. It is driven using a programmed amplitude and frequency varying sinusoidal sweep signal through a large audio amplifier. The amplitude variation is used to flatten the spectrum through the frequency sweep and the degree of variation is determined by the signal from an accelerometer mounted in the source. The tool is again deployed on a standard seven-conductor wireline and is 10 cm (4 in) in diameter and 76 cm (2.5 ft) long. It clamps rigidly into the borehole at a much more rapid rate than the pneumatic vibrator, so still deploys fairly rapidly and can be used in fluid-filled or dry boreholes.

Although the source is capable of generating frequencies from 150 to 2000 Hz, the upper end of the sweep was restricted to 720 Hz due to sampling rate and anti-alias filter restrictions. This frequency range was swept in 7.8 s and data recorded for 8.0 s. The same processing stream described for the other vibrators was employed to process the data from the magnetostrictive vibrator, using the data recorded from the accelerometer mounted on the tool for the crosscorrelation process.

COMPARISON OF DATA

The data generated by each of these sources and recorded in the receiver borehole is analyzed in terms of the final signal-to-noise ratio, the relative strength of the P and S waves received, and the overall complexity of the data.

Signal-to-Noise Ratios

Signal-to-noise ratios for the vertical component accelerometer in the receiver package were calculated by taking portions of the signal recorded with both the source and receiver at 15 m depth and transforming them into the frequency domain. Three windows were used: a noise window from .01 s to .09 s, a P-wave arrival signal-plus-noise window from .10 s to .15 s and S-wave arrival signal-plus-noise window from .15 s to .20 s. These windows were shifted forward in time by .01 s for the airgun data due to a discrepancy in the arrival times between the impulse-type data of the airgun and the crosscorrelated data of the vibratory sources. The noise spectra are then plotted along with the P and S wave signal spectra for each of the sources in Figures 2 to 5.

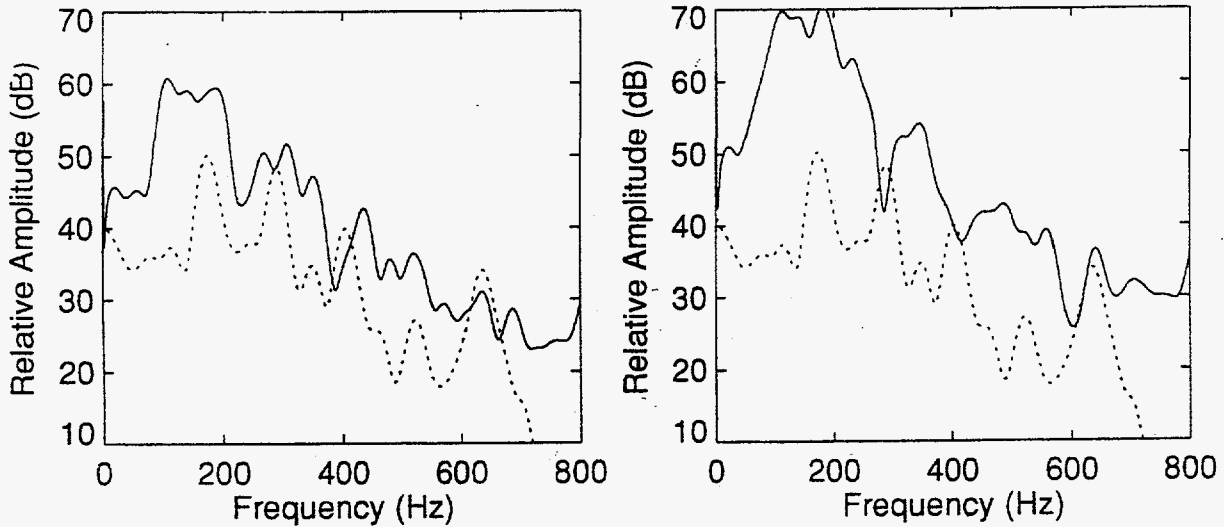


Figure 2: Signal-plus-noise (solid) and noise (dotted) spectra for P (left) and S (right) arrivals for the airgun.

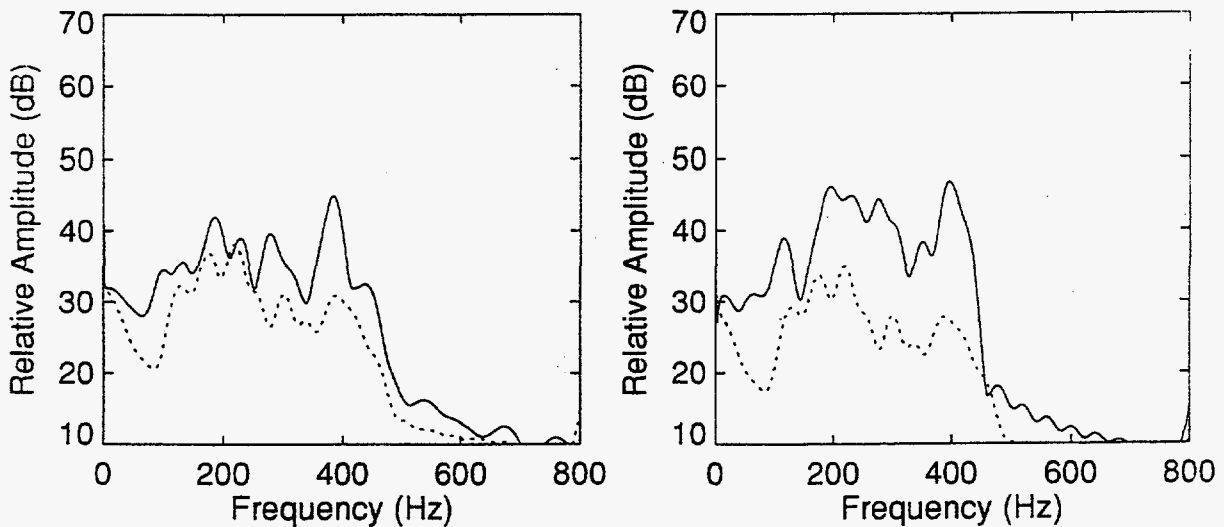


Figure 3: Signal-plus-noise (solid) and noise (dotted) spectra for P (left) and S (right) arrival for orbital vibrator.

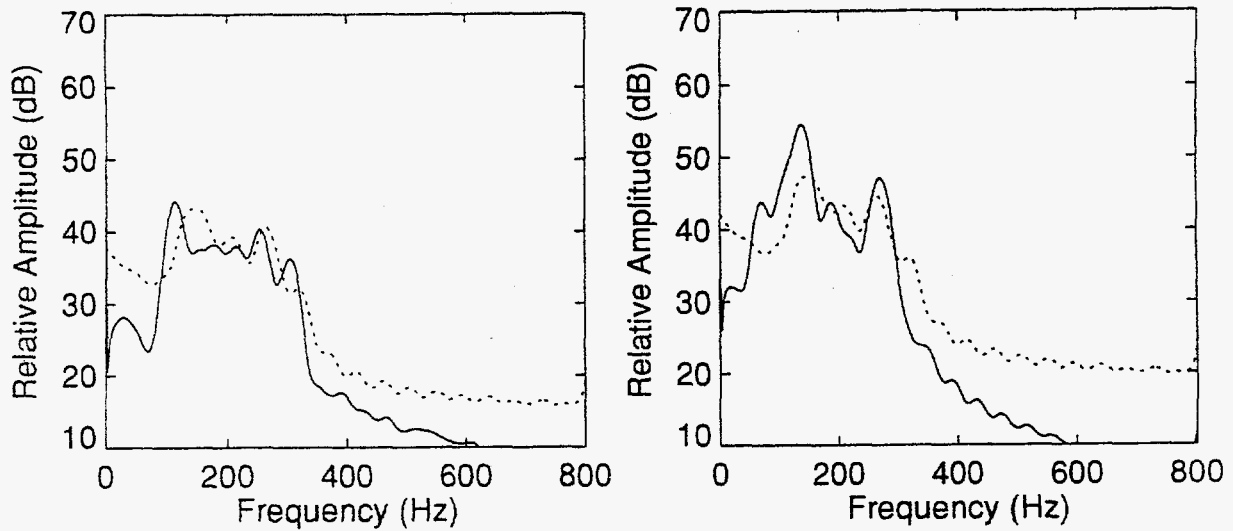


Figure 4: Signal-plus-noise (solid) and noise (dotted) spectra for P (left) and S (right) arrivals for pneumatic vibrator.

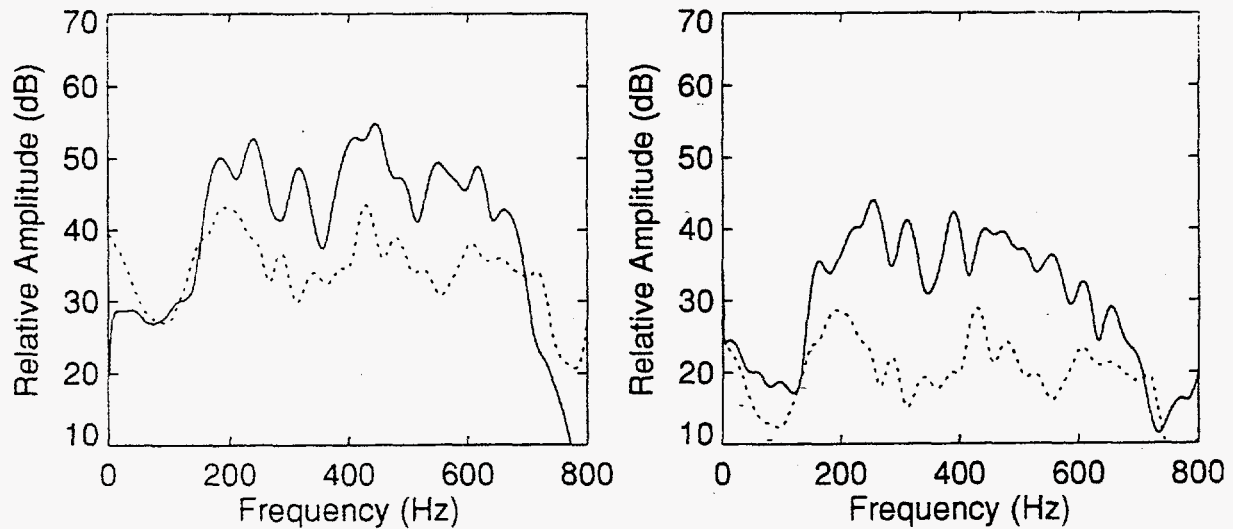


Figure 5: Signal (solid) and noise (dotted) spectra for P (left) and S (right) arrivals for magnetostrictive vibrator.

The amplitude scales on these figures are relative amplitude and are not the same scale from source to source.

For the airgun source (Figure 2), there is in general good signal-to-noise characteristics out to 600 Hz for both the P and S arrival, though the signal-to-noise for the P wave is about half that of the S wave. The majority of the noise is from the ≈ 60 Hz electrical noise and its harmonics. Notch filtering can remove some of this noise, but tends to smear the first arrival energy making first arrival picks more ambiguous.

The orbital source (Figure 3) shows good signal-to-noise characteristics for the S wave across the frequency band generated by the source, but tends to have a much weaker P-wave arrival, especially at the lower end of the frequencies generated. Completing the processing of the data by combining the forward and reverse spin

directions should improve this, but the P-wave arrival will probably still be weak.

The pneumatic source has the worst signal-to-noise characteristics of the sources tested. This source should generate primarily vertically-polarized S-wave energy in the horizontal direction, so it is not surprising that there is no obvious P-wave energy. The S-wave energy, however, still shows poor signal-to-noise ratios, although there is some energy in the 50 to 150 Hz range.

Finally, the magnetostrictive vibrator shows the most favorable signal-to-noise characteristics. As for the pneumatic vibrator, the radiation pattern is such that P-wave energy should be fairly small in horizontal travel paths, but there is still reasonable signal-to-noise for the P-wave arrival over the full source frequency range from 150 to 720 Hz. The S-wave arrival has an even greater signal-to-noise ratio over the same frequency range, although it drops off slightly above 600 Hz.

Individual Traces and Source Gathers

Based on the signal-to-noise ratios, the pneumatic vibrator data were additionally filtered with a bandpass from 30 to 220 Hz. A direct comparison of the vertical component traces recorded with the source and receiver both at 15 m depth for all four sources is shown in Figure 6. These are trace normalized records so direct amplitude comparisons are not possible, but the general signal-to-noise characteristics and the frequency content of the traces from the different sources can be compared.

P and S-wave arrival times are marked on Figure 6 based on the airgun data. The P-wave arrival is most clearly seen on the airgun data and again on the magnetostrictive data. There is some change in character at the P-wave arrival time on the orbital data, but this is not a clear arrival. S-wave arrivals are seen on all four data sets, again most clearly on the magnetostrictive and airgun data.

Arrival times on impulsive sources are picked at the initiation of the energy. On vibratory sources, however, the crosscorrelation process creates a wavelet with the arrival time at the center of the wavelet, not the beginning. With this in mind, a discrepancy in arrival times of about .005 s between the airgun and the vibratory source is seen in Figure 6. This is a result of the processing of the vibratory data and has been noted in previous studies (Howlett, 1991).

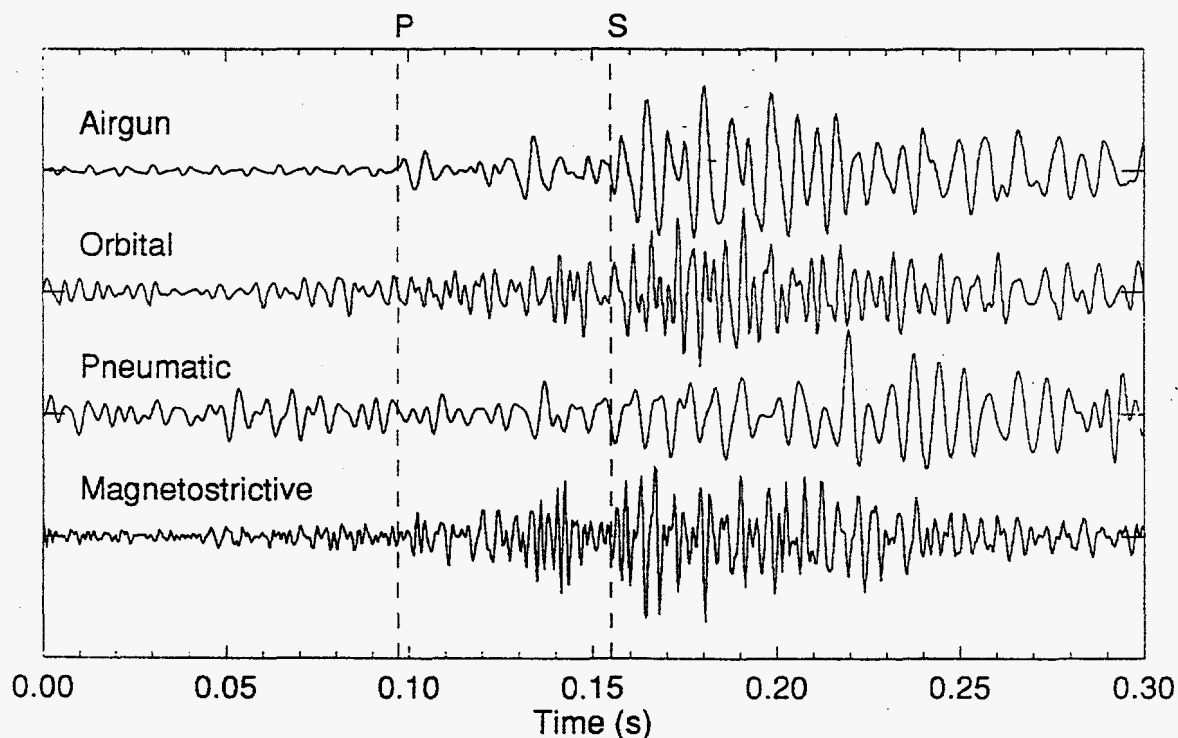


Figure 6: Comparison of trace recorded with both source and receiver at 15 m depth for all four sources.

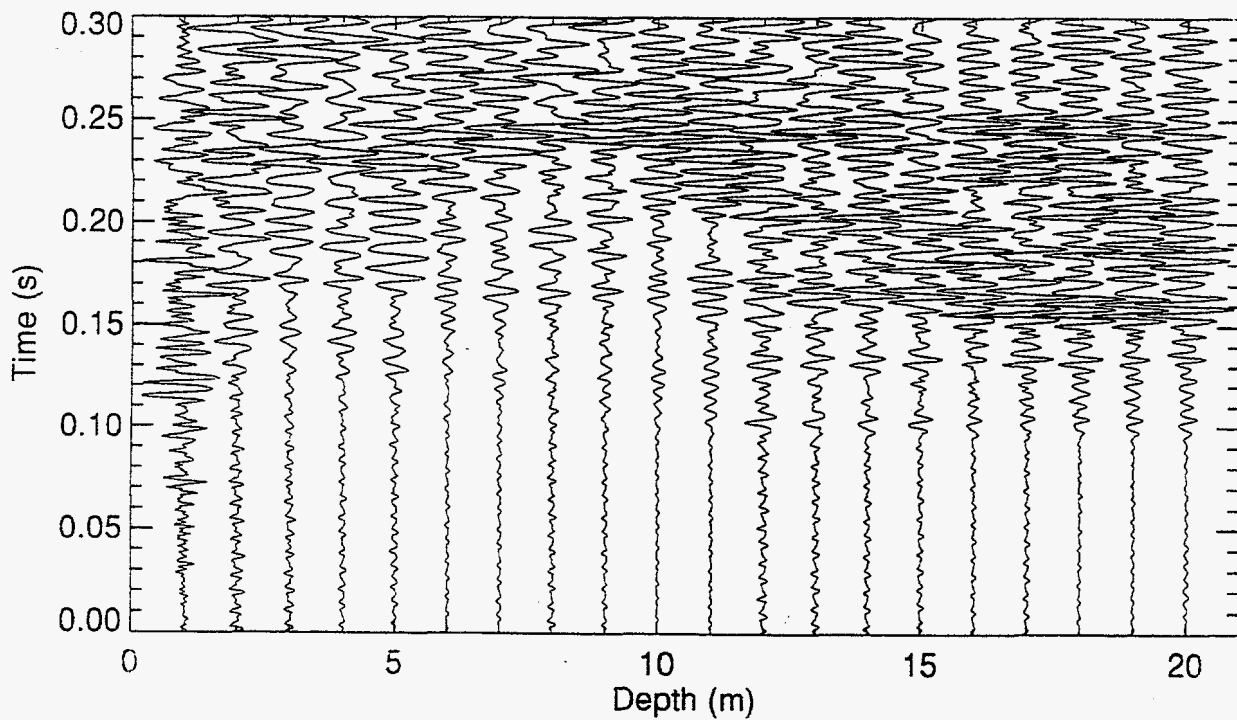


Figure 7: Source gather for data collected with airgun with source at 15 m depth.

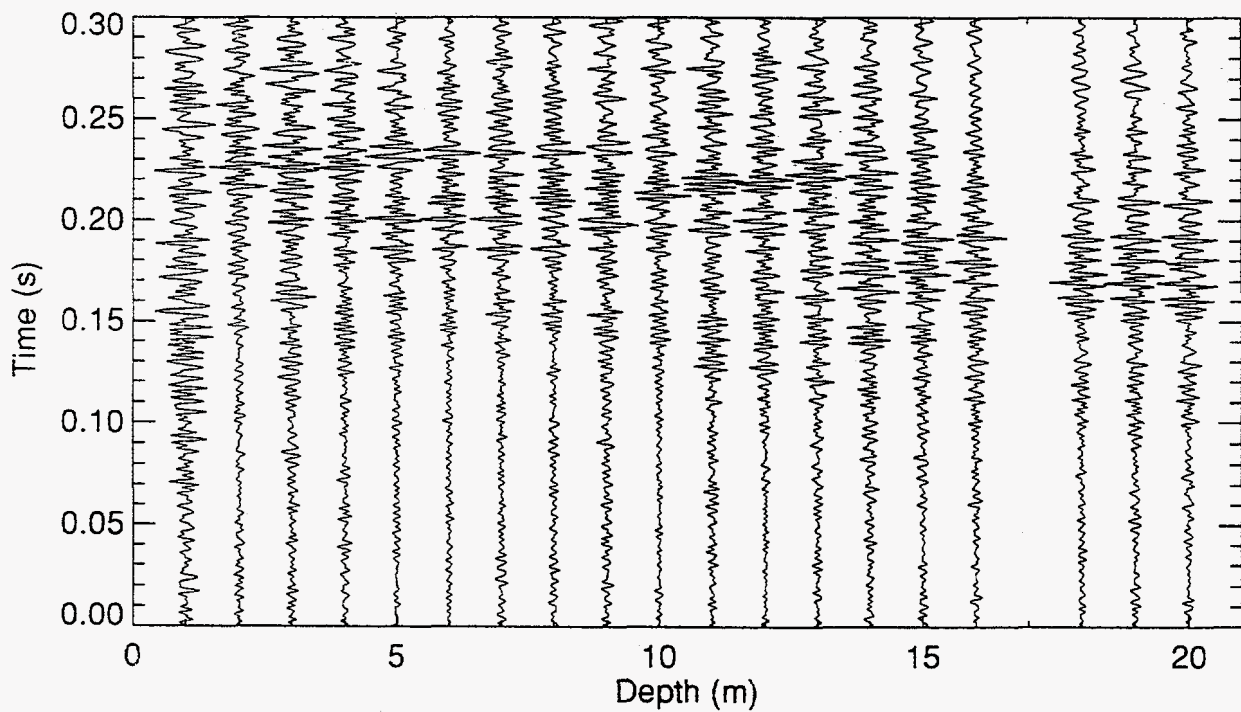


Figure 8: Source gather for data collected with orbital vibrator with source at 15 m depth.

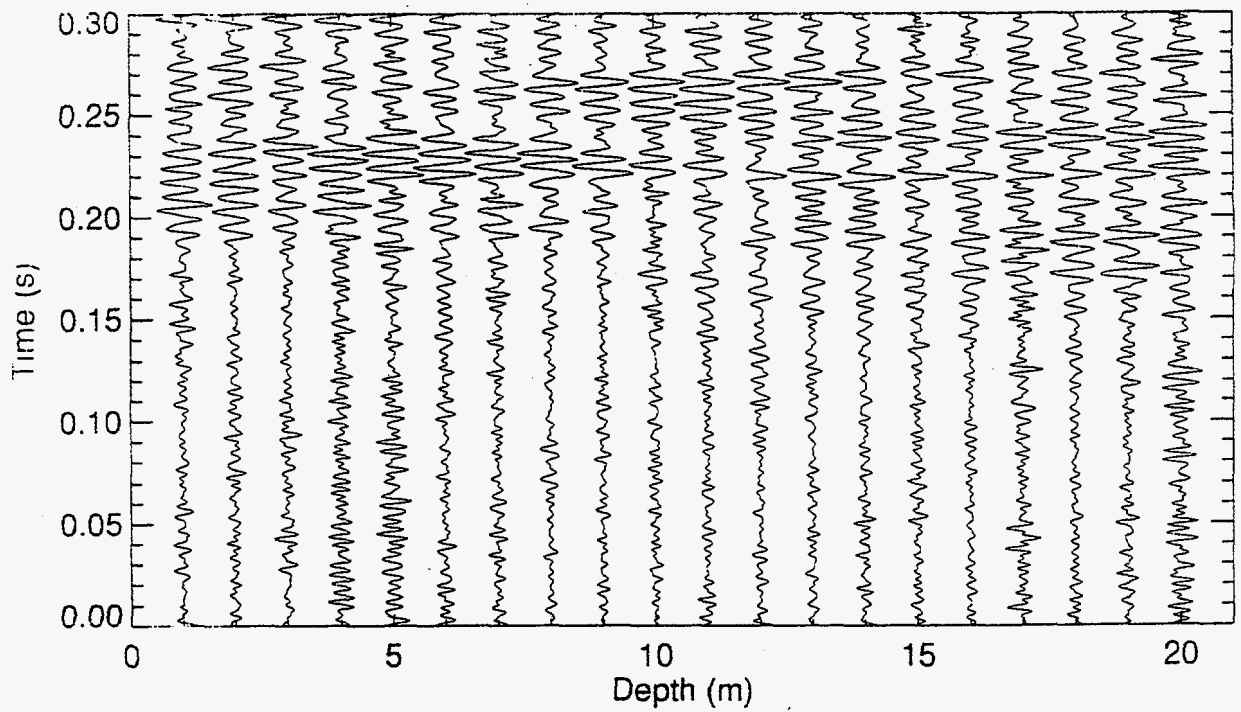


Figure 9: Source gather for data collected with pneumatic vibrator with source at 15 m depth.

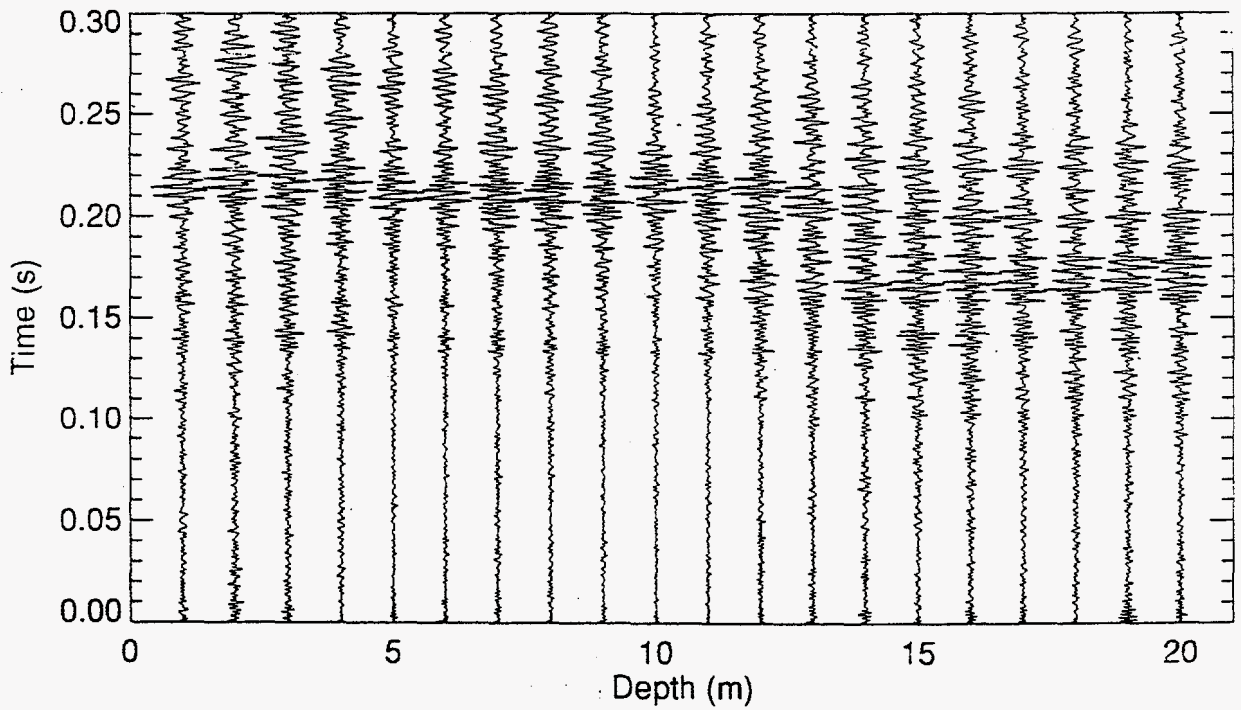


Figure 10: Source gather for data collected with magnetostrictive vibrator with source at 15 m depth.

Source gathers at 15 m source depth for the four sources are shown in Figures 7 to 10. Of these, the airgun and magnetostrictive vibrator show the best P-wave arrival energy across the section at about .10 s, although this arrival becomes more ambiguous for both the sources in the shallower part of the section, but more so for the magnetostrictive source. The P-wave arrival is also present in the deeper parts of the section generated by the orbital vibrator, but is lost in the noise above about 10 m. No evidence of the P-wave arrival is seen on the pneumatic vibrator section.

S-wave arrivals are seen on all four sections at about .15 s below 10 m, but are clearest on the magnetostrictive and orbital vibrator sections. This arrival is also apparent on the airgun and pneumatic vibrator data, but at much lower frequencies. It is uncertain what happens to this arrival above 10 m.

Later arrivals at greater than .19 s are seen on all four section also. There is a general correlation of these arrivals between the magnetostrictive and pneumatic vibrators, although the frequency content and signal-to-noise ratio are significantly less on the pneumatic vibrator section. The airgun and orbital vibrator data show much different later arrivals indicating a significant effect of the source radiation pattern on these arrivals.

CONCLUSIONS

Based on the comparison of frequency spectra and signal characteristics, the magnetostrictive source appears to have the best overall character of the four sources tested, especially for S-wave arrivals. The airgun is dominated by generally lower frequencies, but generates a good P-wave arrival and is easier to field and process, making it an attractive option for quick P-wave surveying. The orbital vibrator also shows good shear wave energy arrivals and, with its ease of operation and generally favorable frequency spectrum, it is still a good source for determining S-wave velocity structure. The pneumatic vibrator performed the worst of the sources and is not recommended if other sources are available.

The restriction of the airgun and orbital vibrator to fluid-filled boreholes can be a potential problem at certain vadose zone sites where water cannot be reliably held in the borehole. This should be taken into account when designing the survey. On the other hand, the clamped sources can prove problematic when weakened casing or PVC or fiberglass casing is involved, and care must be taken to test these clamps in a test casing to ensure that they will not cause any damage to the borehole wall.

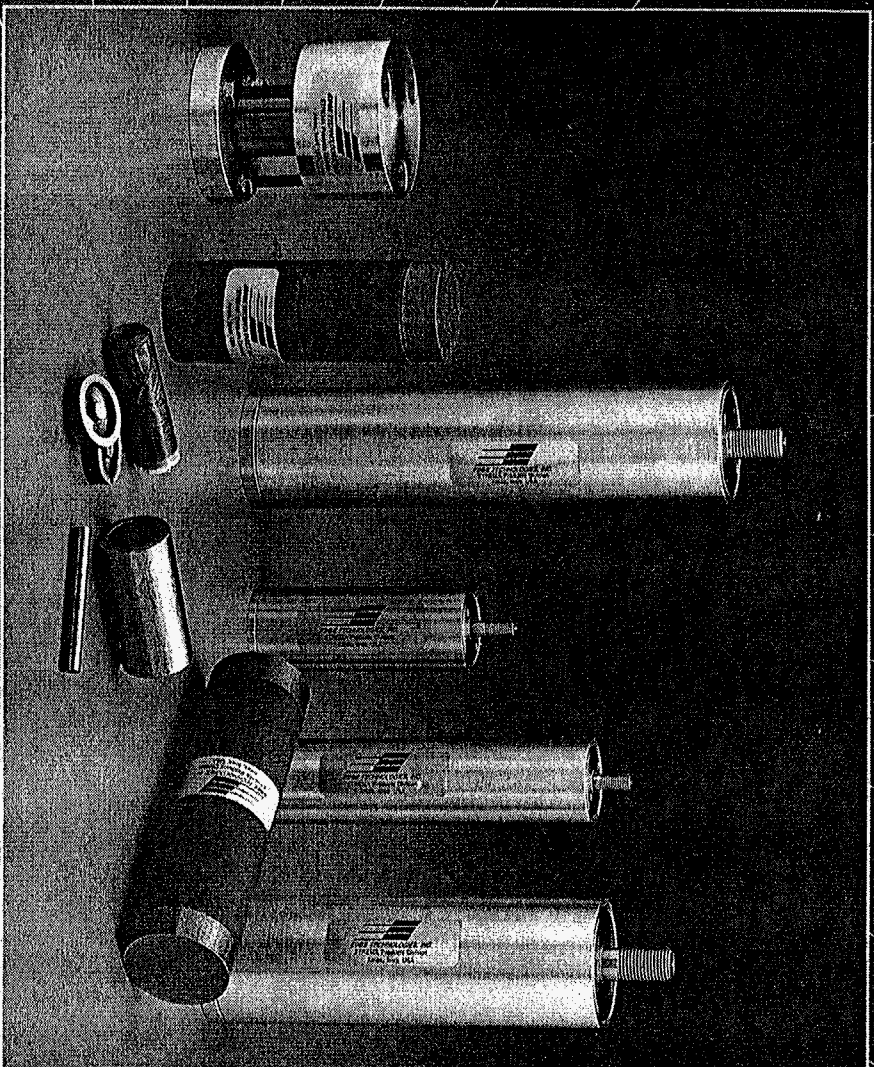
It must be kept in mind that the development of downhole sources is an ongoing process and that improvements in source design, clamping mechanisms, operational parameters, and processing may significantly improve the output of any particular source. This has been discussed in terms of the double motor and mass version of the orbital vibrator, the clamp being developed for this same vibrator, and the greater pressure capabilities of the airgun. All these factors must be taken into account, along with the restrictions of the particular site to be surveyed, when choosing the best source to use.

REFERENCES

- Hardee, H. C., Elbring, G. J., and Paulsson, B. N. P., 1987, Downhole seismic source: *Geophysics*, v. 52, p.729-739.
- Howlett, D. L., 1991, Comparison of borehole seismic sources under consistent field conditions: *Society of Exploration Geophysicists Expanded Abstracts with Biographies*, 61st Annual International Meeting, p. 18-21.

APPENDIX D: ETREMA Product Literature

ETREMA Terfenol-D® Magnetostrictive Actuators



**Performance, Power and Dependability
For Your Most Demanding Design Needs!**

High Force

High Energy Density/High Strain

Low Voltage Operation

Microsecond Response

Micro Control

Broad Frequency Bandwidth

Wide Temperature Range and Stability

No Poling, Aging or Fatigue

ETREMA Products, Inc.

A Subsidiary of EDGE Technologies, Inc.

D-2

ETREMA Terfenol-D[®] Actuators ...

The emerging
choice of
leading-edge
engineers

ETREMA actuators, powered by the magnetostrictive alloy Terfenol-D, can give your system or product a competitive performance edge. For power, speed, control, design flexibility and dependability, no other option comes close. And for a growing number of systems and products, ETREMA Terfenol-D[®] actuators are the only option.

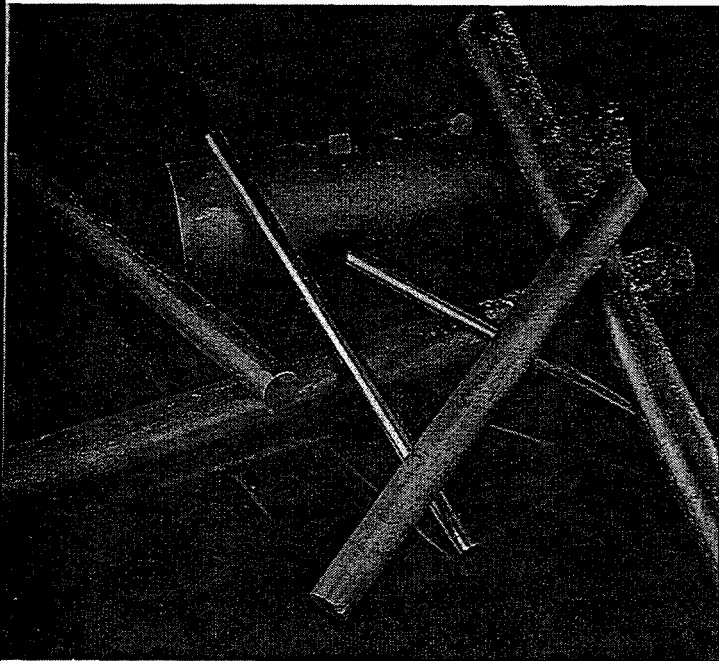
ETREMA Terfenol-D[®] actuators are alone in their ability to achieve high-power linear or oscillatory motion in response to a low-voltage electric current. In addition, ETREMA actuators offer high force and microsecond response times.

Applications of ETREMA actuators include robotics, valve control, micro-positioning and active vibration control. Other applications include fast-acting relays, high-pressure pumps and as high-energy, low-frequency sonic sources.

Terfenol-D

Terfenol-D is an alloy of the metals terbium, dysprosium and iron with the formula $Tb_xDy_{1-x}Fe_y$. Terfenol-D provides the largest strain of any commercially available material. ETREMA Terfenol-D[®] is produced by patented processes.

Standard ETREMA actuators employ Terfenol-D rods of stoichiometry $Tb_{.3}Dy_{.7}Fe_{1.95}$. However, exact stoichiometry can be customized for the properties demanded by each application. For more information on magnetostrictive materials, contact ETREMA Products, Inc.

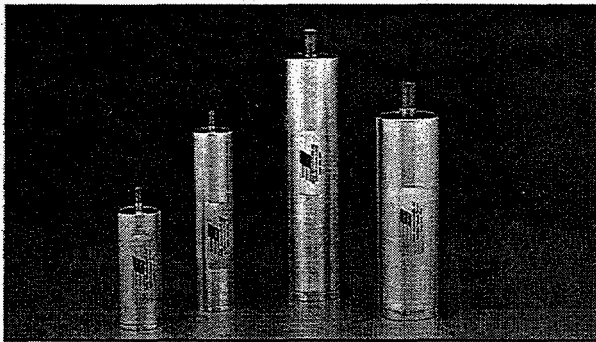


ETREMA Actuators

ETREMA actuators are available in a variety of sizes, magnetically biased or unbiased, with or without a prestress housing.

MP & NP Series

Ready-to-Use Actuators With Prestress Housing



The MP and NP Series ETREMA actuators are supplied ready for use. They include an aluminum housing with internal spring system and push rod supplied with user-specified standard or metric threads.

Actuators are shipped with prestress set to rated load to optimize displacement. Prestress can be adjusted by user to accommodate applied load.

Available options:

- Threaded hole in base
- Threaded hole in push rod
- User-specified solenoid coil

M & N Series

Drive Motor Actuators Without Prestress Housing



The M and N Series ETREMA drive motor actuators are the same internal drivers found in the MP and NP series, but without housing and preload spring assembly. Mechanical preload and alignment must be supplied by the user's device.

Available options:

- User-specified solenoid coil

COMPLETE ACTUATORS

MP-Series Bidirectional (Magnetically Biased) Actuators						
Catalog Number	Peak-to-Peak Disp. μm	Rated Load N	Unit Length mm	Unit Dia. mm	Required Input Amps	Coil Res. Ohms
50/6-MP	50	490	100	34	± 1.5	6.4
100/6-MP	100	490	150	34	± 1.5	3.7
75/12-MP	75	1750	175	49	± 3	3.5
110/12-MP	110	1750	213	49	± 4	5.0
NP-Series Monodirectional Actuators						
Catalog Number	Rated Disp. μm	Rated Load N	Unit Length mm	Unit Dia. mm	Required Input Amps	Coil Res. Ohms
50/6-NP	50	245	100	34	1.5	6.4
100/6-NP	100	245	150	34	1.5	12.2
75/12-NP	75	875	175	49	3	3.5
110/12-NP	110	875	213	49	4	5.0

DRIVE MOTOR ACTUATORS WITHOUT PRESTRESS HOUSING						
M-Series Bidirectional (Magnetically Biased) Drive Units						
Catalog Number	Peak-to-Peak Disp. μm	Rated Load N	Unit Length mm	Unit Dia. mm	Required Input Amps	Coil Res. Ohms
50/6-M	50	490	65	25	± 1.5	6.4
100/6-M	100	490	90	25	± 1.5	3.7
75/12-M	75	1750	103	39	± 3	3.5
110/12-M	110	1750	140	39	± 4	5.0
N-Series Monodirectional Drive Units						
Catalog Number	Rated Disp. μm	Rated Load N	Unit Length mm	Unit Dia. mm	Required Input Amps	Coil Res. Ohms
50/6-N	50	245	65	25	1.5	6.4
100/6-N	100	245	90	25	1.5	12.2
75/12-N	75	875	103	39	3	3.5
110/12-N	110	875	140	39	4	5.0

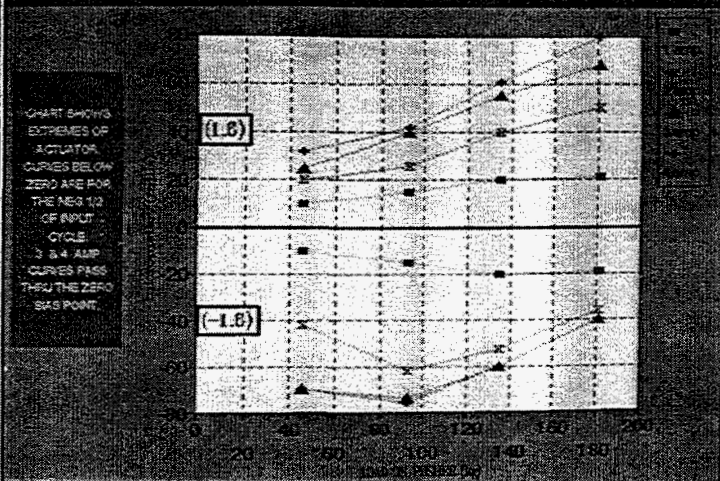
Actuator Performance and Selection Notes

The applications for ETREMA Terfenol-D[®] actuators are restricted only by your imagination. However, for best performance and efficiency, consider the following criteria. Better yet, consult ETREMA engineers when selecting the actuator best suited for each application.

Displacement and Load

FIGURE 1.

110/12-MP actuator response at varying preloads and currents



Displacement and load range are the two specifications most frequently cited by design engineers. Both features are readily calculated for Terfenol-D actuators.

Terfenol-D has the highest strain of any commercially available transducer material, reaching over 0.1% linear motion. With Terfenol-D, displacement is proportional to rod length. A 50mm (2.0 in.) long Terfenol-D rod will easily provide more than 50 μm (0.002 in.) displacement. A 100mm rod will provide twice the displacement, or 100 μm . The first part of the catalog number of each actuator is rated displacement in micrometers.

Load range for each ETREMA actuator is given in Newtons (N). (1 N=.225 pounds) Load range is determined by the cross-sectional area of the Terfenol-D drive rod. The second part of the actuator catalog number is the diameter of the Terfenol-D rod in millimeters.

Displacement and load range are conservatively rated for ETREMA actuators. Higher loads can be driven, but some loss of displacement may occur. Greater displacements also may be achieved, but response may not be as linear.

Directional Response and Magnetic Bias

FIGURE 2.

50/6-N Non-magnetically biased actuator performance

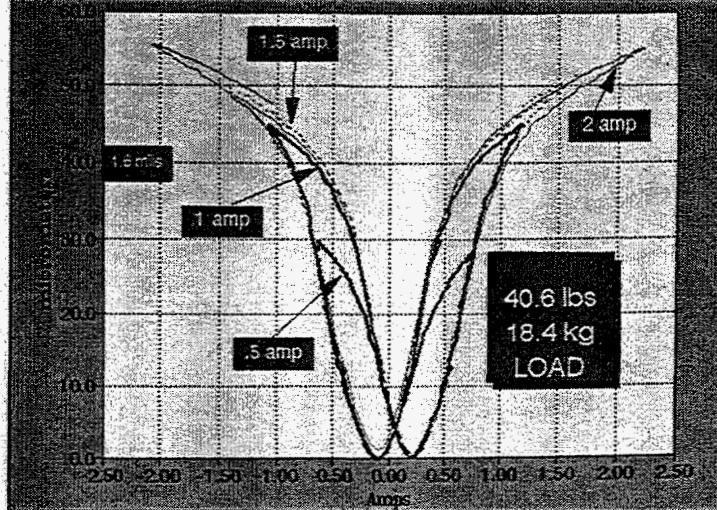
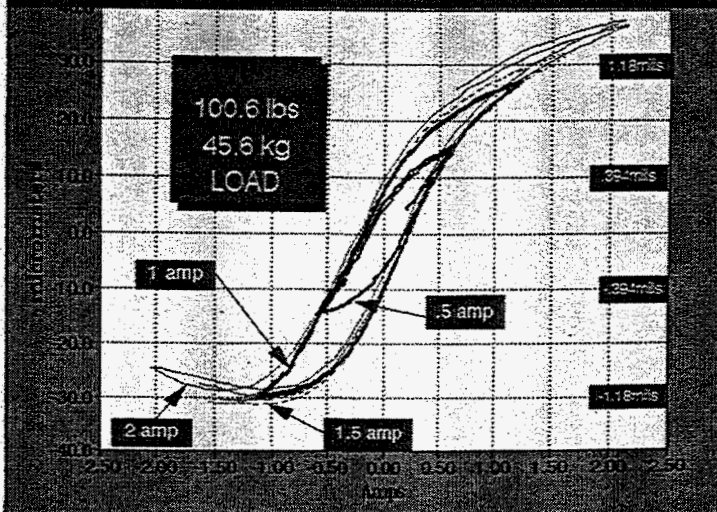


FIGURE 3.

50/6-M Magnetically biased actuator performance



ETREMA Terfenol-D[®] actuators can be either mono-directional (push only) or bidirectional (push-pull). Non-biased actuators push when current is applied, regardless of current direction. All bidirectional ETREMA actuators include permanent magnets sized to cause the Terfenol-D to elongate through one-half the linear range when no power is applied. Current in one direction causes expansion; reversing the current results in contraction.

Magnetic bias is required for linear operation in response to an AC drive signal. Oscillatory applications — including sonar, vibration-damping, anti-noise, pumps,

vibrators and medical sonics — generally require magnetically biased units, too.

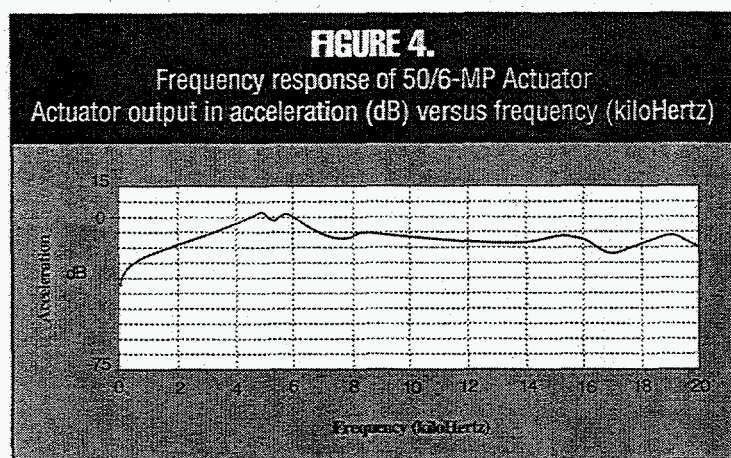
The effect of magnetic biasing can be seen by comparing Figures 2 and 3. These charts show performance curves for the 50/6-N and 50/6-M drivers. The two units are essentially identical, except for inclusion of a permanent magnet in the 50/6-M driver.

Mechanical Prestress

Best performance of Terfenol-D actuators is achieved with application of mechanical prestress. Preload also helps mate components for low-loss transfer of force.

ETREMA Terfenol-D actuators are available with or without a built-in spring system for prestress. In many systems — active vibration-damping, sonic oscillation and some micro-positioners, for example — the user's device often provides the necessary preload and alignment. For such applications, a complete line of drive motors without springs and housing is available.

Frequency Range



Constant response over a broad frequency range has proven to be one of the most useful features of Terfenol-D actuators. Figure 4 shows acceleration versus frequency for a 50/6-MP actuator. Units designed for high-frequency operation may require special attention to coil design and eddy current control. The ETREMA engineering staff can provide more information on frequency range, resonant frequency and other useful specifications for ETREMA actuators.

Coil and Magnetic Circuit Design

While construction of ETREMA actuators is extremely simple and rugged, magnetic circuitry is carefully engineered for maximum efficiency. The standard solenoid coil, for example, has been chosen for low power consumption and best match with standard power supplies. (Essential power requirements are shown in specification tables for each actuator.)

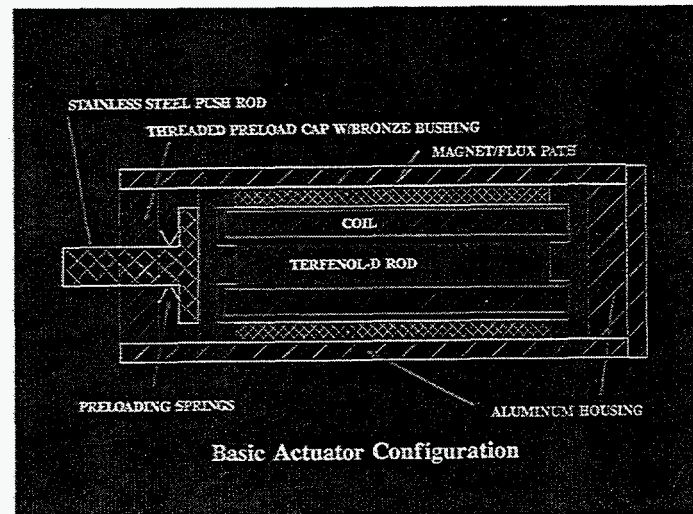
ETREMA engineers can provide actuators with custom coils for high frequency operation or to precisely match specific power supplies.

Reliability

ETREMA Terfenol-D actuators are highly reliable, part due to their minimal number of moving parts. Long term studies of Terfenol-D actuators have found no measurable change after months of operation. In addition, transducer failure modes due to fatigue, cracking, aging and electrode detachment are problems of the past.

Temperature Range

ETREMA Terfenol-D devices can operate at extreme temperatures without significant loss of power. Standard ETREMA actuators are rated for temperatures from -15°C to +100°C. Custom actuators can operate from cryogenic temperatures to 200°C. These require special actuator materials and magnetostrictive alloys.



Custom Actuators and System

ETREMA is a leader in the design and manufacturing of complete custom systems based on Terfenol-D. Our experience allows us to quickly supply Terfenol-D driven products at attractive prices. For solutions to your design requirements, contact our engineering staff.

Long-stroke Actuators

Actuators with strokes of 1.25mm (0.05 in.) and more are available on special order. These actuators are similar in size to standard ETREMA units but employ a stroke-enhancement mechanism. This system converts the high force of Terfenol-D to a longer stroke.

Drivers/Controllers

Driver/controller power supplies are available from ETREMA for optimum operation of standard and custom actuators.

Tension-load Actuators

ETREMA has developed actuator configurations for applications required to function under tension loads. ETREMA can simplify your system design.

Research And Demonstration

The RA-101 is specifically designed for laboratory experimentation and exploration of magnetostrictive transduction. It is constructed to allow easy modification and connection to a variety of laboratory equipment. The unit is magnetically biased and mechanically prestressed.

RESEARCH AND DEMONSTRATION TRANSDUCER/ACTUATOR

Catalog Number	Unit Length mm	Unit Dia. mm	Required Input Amps	Coil Res. Ohms
RA-101	75	60	±1.5	6.4

ETREMA Terfenol-D Actuators Available Now

Standard ETREMA actuators are available now, in large or small quantities. Call us today if you are ready to unleash the full capacity of your product system design.



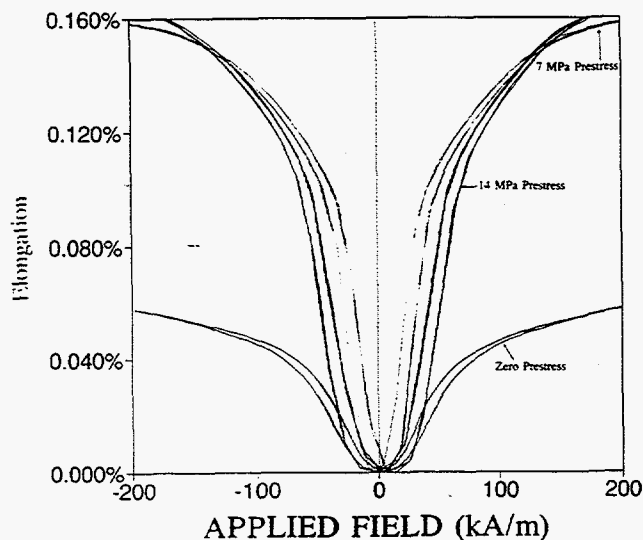
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Subsidiary of EDGE Technologies, Inc.
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APPLICATIONS

ETREMA Products, Inc. is being used by designers around the world to improve the performance and increase the reliability of their products. This exciting new material is now working in the following applications.

- High Force Actuators
- High Force Pumps
- Valve Actuators
- Micropositioning
- Vibration Control
- Chemical Catalysis
- Seismic Sources
- Sonic Welding
- Sonic Cleaning
- Medical Sonics
- SONAR
- Sonic Communications
- High Sensitivity Sensors
- Noise Control

TYPICAL PERFORMANCE OF ETREMA TERFENOL-D®



PHYSICAL PROPERTIES

Young's Modulus	2.5-3.5X10 ¹⁰ N/m ²
Tensile Strength	28MPa*
Compressive Strength	700MPa*
Expansion Coefficient	12X10 ⁻⁶ /°C
Curie Temperature	380°C
Coupling Factor	0.75
Sound Speed	1720m/s

(*1 kpsi = 6.895 MPa)

ETREMA TERFENOL-D® is available in standard rods with diameters from 5mm to 50mm or in specialty shapes and sizes.

ETREMA Products, Inc.
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APPENDIX E: Effect of Source Frequency Spectrum on Correlated Data

The following memo, written by Dale Cox of Conoco, describes the effect of seismic source output spectrum on correlated data.

The received signal from any swept source must be processed to collapse the frequency sweep into a wavelet. The ringing of the wavelet, as well as the width of the wavelet (which affects the ability to distinguish fine time and or distance in an image are both affected by the mid frequency of the received signal, and also by the spectrum of the received signal, measured in octaves.

Figure 1 shows the effects of different octaves of bandwidth given a certain central frequency. The horizontal axis is time measured in periods of central frequency. The vertical axis is amplitude. The bottom curve shows the wavelet associated with a half octave of band width. The other curves show the wavelet associated with 1, 2, 3, 4, 5, and an infinite number of octaves of band width. Infinite octaves simply means that all frequencies from zero to twice the central frequency are present. It is important to remember that all of these wavelets have the same central frequency. What has changed is the number of octaves of bandwidth. Thus the highest frequency increases and the lowest frequency decreases as the number of octaves increases.

The first zero crossing after zero time is exactly the same for each of these wavelets, it only depends on the central frequency. However, the shape of the wavelets changes with an increase of bandwidth. As can be seen, the shape of the wavelet changes very little after 2-3 octaves. Therefore, adding additional bandwidth beyond 3 octaves reaches a point of diminishing returns.

Figures 2-5 show the effects of keeping the highest frequency constant but increasing the bandwidth. 50 milliseconds of data is shown in all cases. A single spike centered at 25 milliseconds was filtered with the bandwidth shown immediately to its right. The filtering was done one half, one, two, three, four octaves, and from 5 Hz to the maximum frequency.

Figure 2 has a maximum frequency of 250 Hz. Figure 3 has a maximum frequency of 500 Hz. Figure 4 has a maximum frequency of 1000 Hz. Figure 5 has a maximum frequency of 2000 Hz. Again in each case we see that the gains after 2-3 octaves of bandwidth is minimal. However, the gains achieved by doubling the maximum frequency is significant.

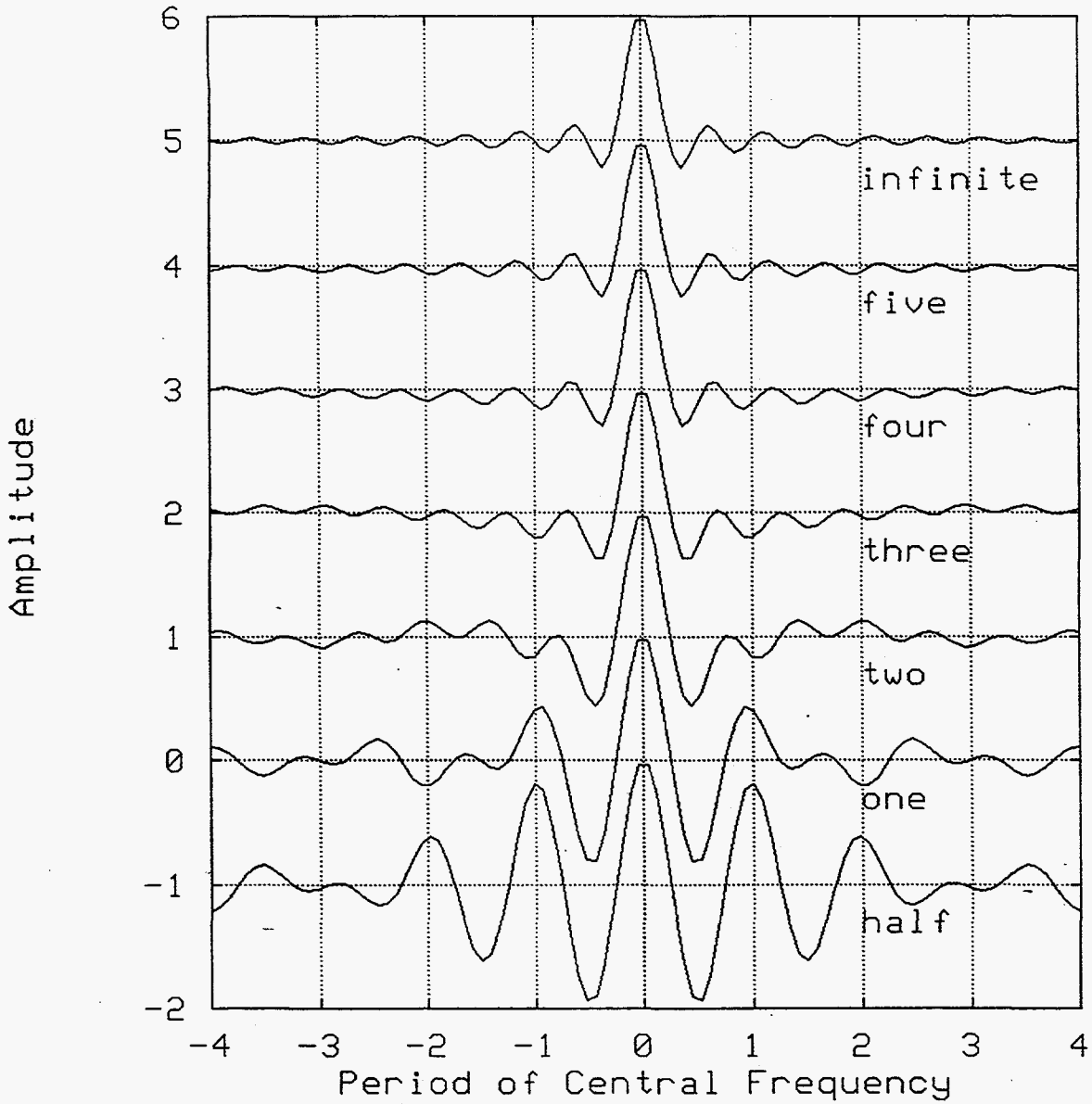
Conclusions:

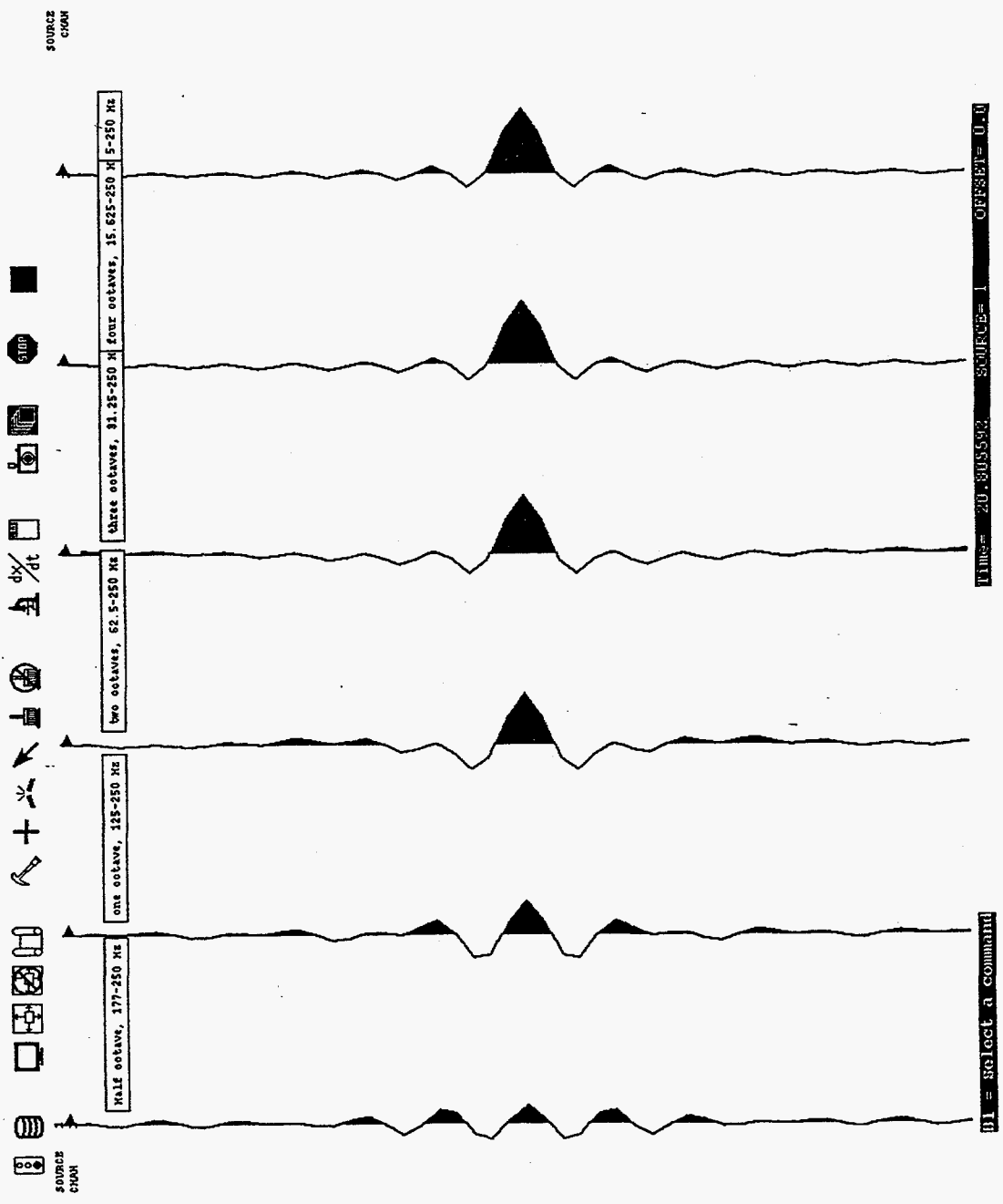
After 2-3 octaves of bandwidth is achieved at a given maximum frequency it is more important to direct efforts to increase the maximum frequency than to increase the bandwidth by extending the lower frequency.

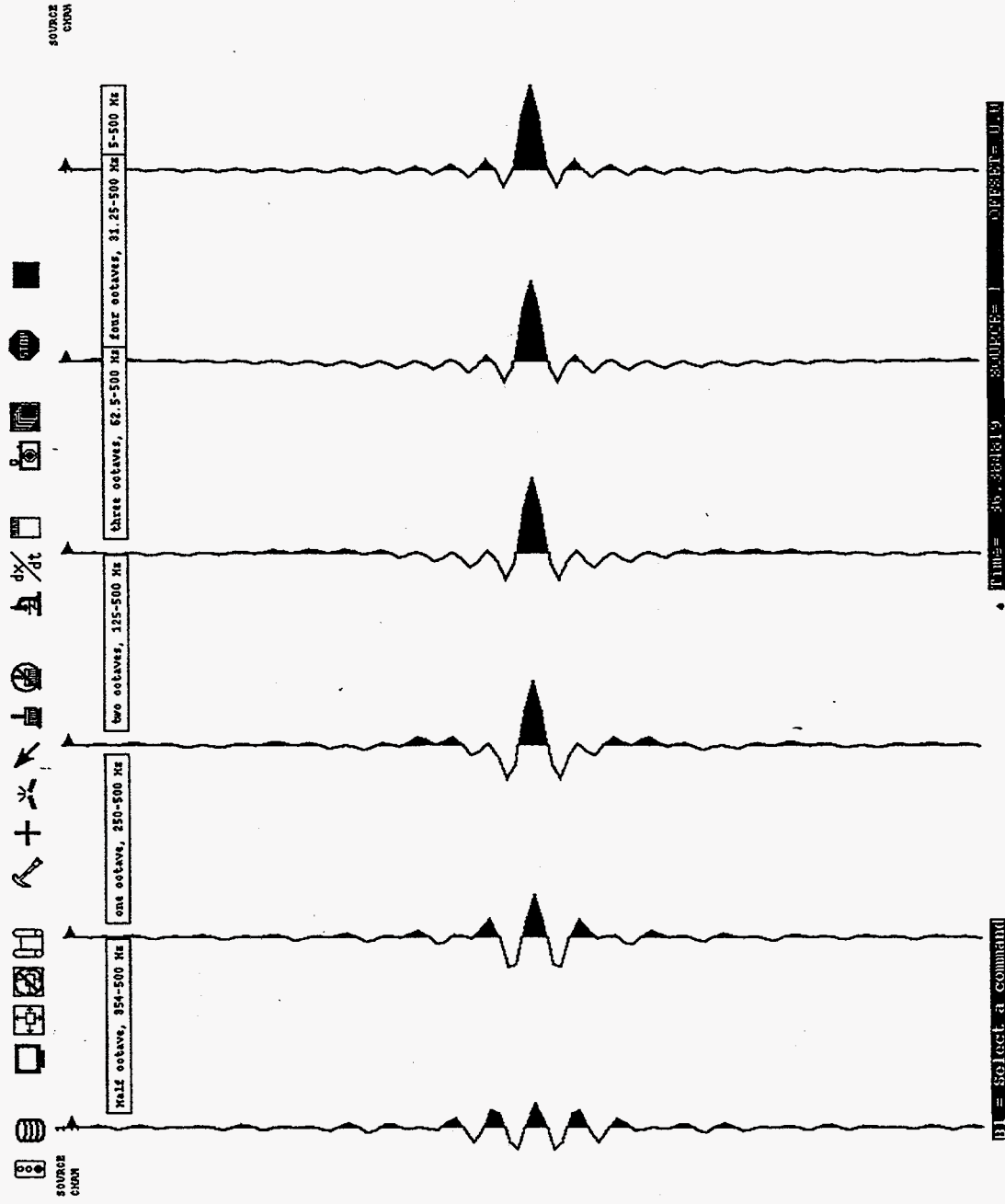
If a highest frequency of at least 250 Hz can be achieved, then the lowest frequency necessary to assure at least 2-3 octaves is in the 20-40 Hz range.

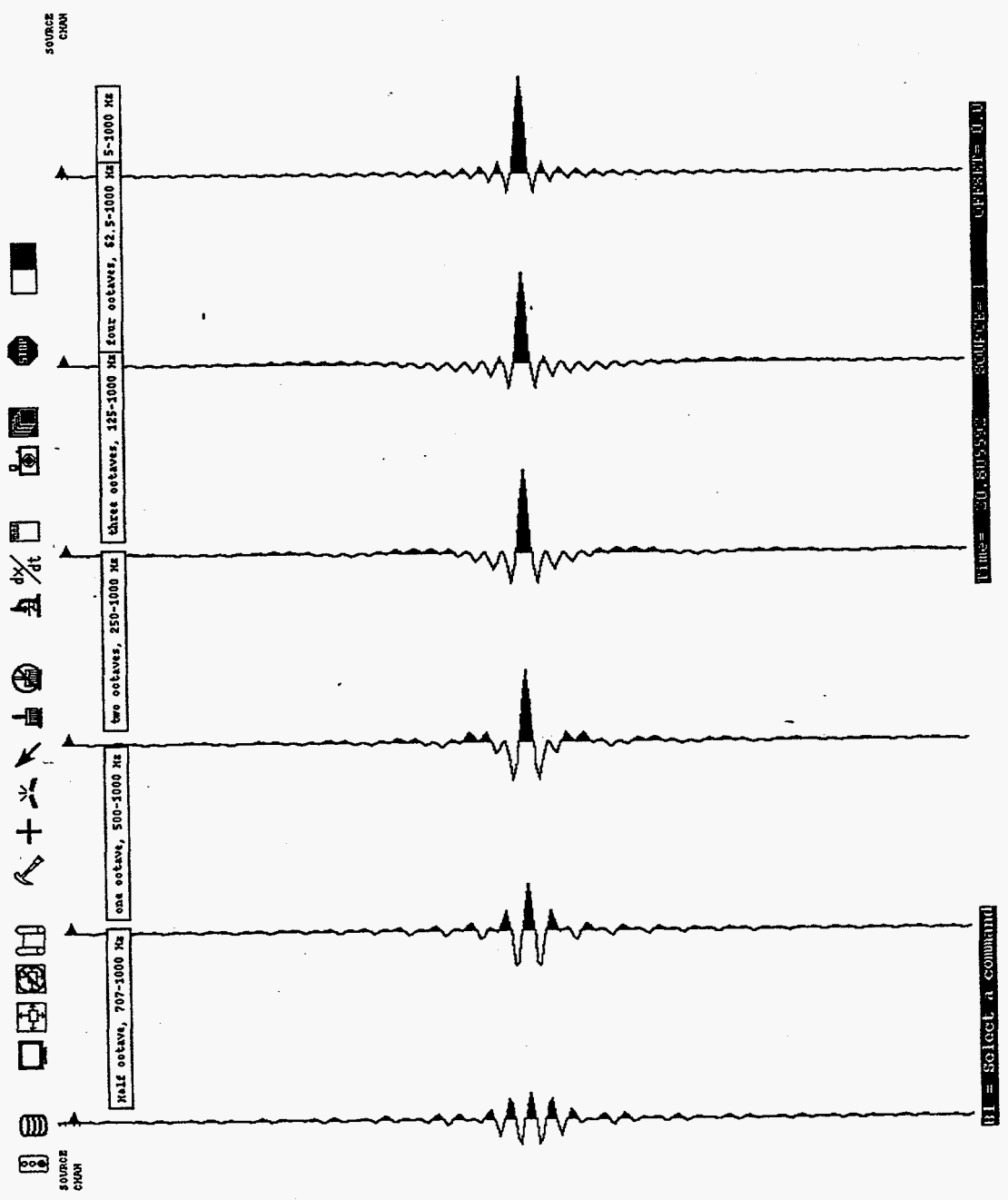
Note that all of this depends on the frequencies received at the seismic receiver, not the frequencies generated at the source. Since some formations severely attenuate higher frequencies, in those cases it is important to generate 2-3 octaves of lower frequency signal, but still with the effort of transmitting as high a frequency bandwidth as the formation will allow. This also argues for a source that will produce a very strong output in order to overcome the formation attenuation at higher frequencies.

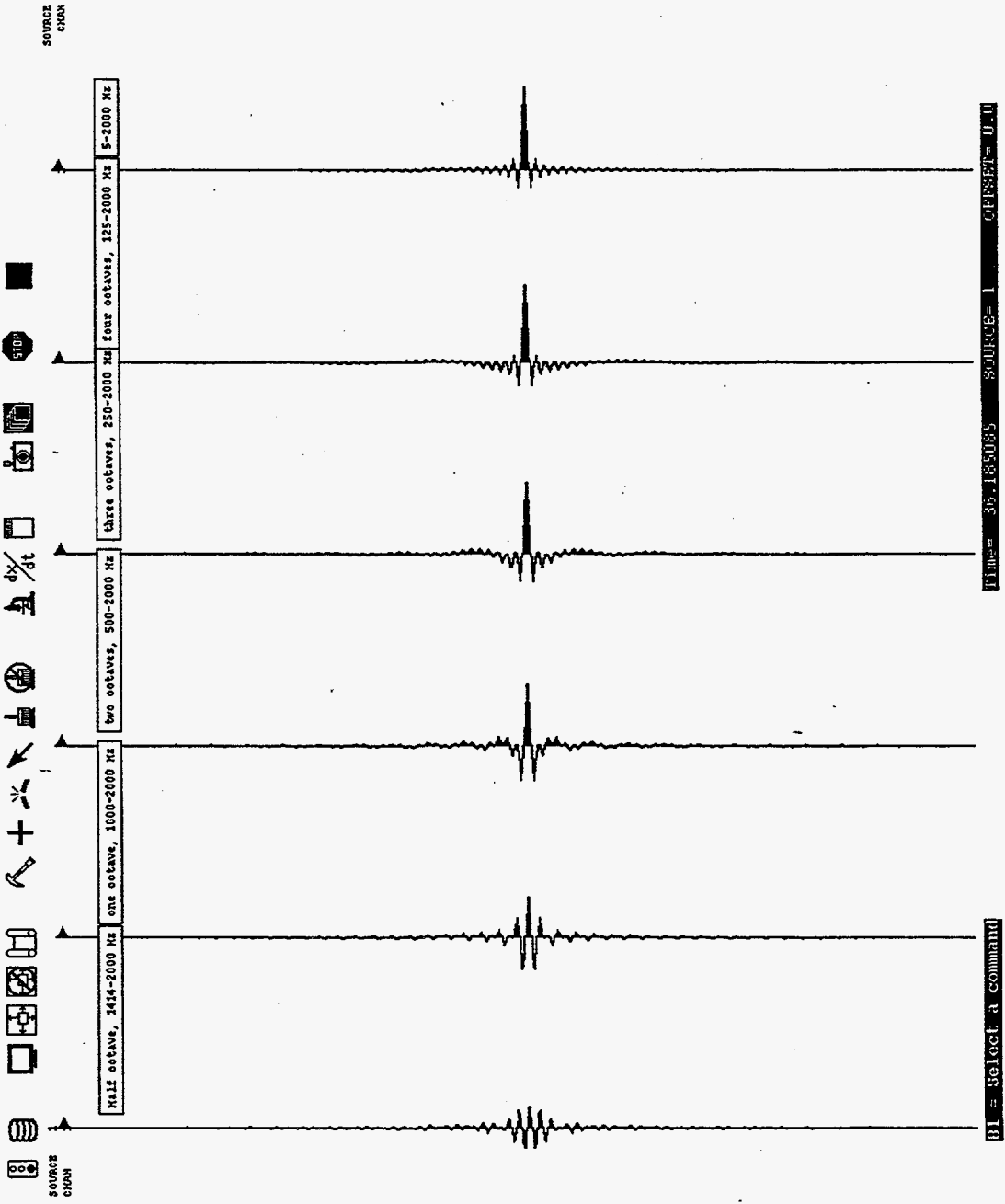
Wavelet Shapes for Various Octaves











APPENDIX F: DOE Reporting Requirements

Can't conf. incomplete info - JEP 5-14-97

List of publications and presentations resulting from the project:

"Comparison of Lower Frequency (<1000 Hz) Downhole Seismic Sources for use at Environmental Sites" by Greg Elbring, SAGEEP Proceedings

List of invention disclosures resulting from the project

A Technical Advance for a Multi-Mode Elastic Wave Generator was submitted on 12/16/93 for a variant of this actuator

Number of patents (applied for or issued) resulting from the project

None

Number of copyrights (for software) resulting from the project

None

Number of students involved in the project

None

Number of post doctoral students involved in the project

None

Number of permanent technical or scientific staff recruited as a result of this project

None

Number of awards (and their names):

None

Number of new non-LDRD funded projects and amounts:

None

Your qualitative assessment about the completion of your final milestones for the year in percent:

100 %

Your qualitative assessment about the direction of the project as a result of research or other findings (Please circle the number of the statement that best describes your results)

- ⇒1 Goals met, hypothesis proved
- 2 Goals partially met, hypothesis modified
- 3 Goals substantially modified, hypothesis redefined
- 4 Goals not met, hypothesis disproved
- 5 Project terminated because _____

References

- 1) "Survey of Borehole Seismic Sources", Technical Task Report, Thomas E. Owen, Southwest Research Institute, San Antonio, Texas, October 6, 1995
- 2) "Development of the Multi-Level Seismic Receiver (MLSR)" Sandia Report SAND94-2162 by G. E. Sleafy et al
- 3) "Comparison of Lower Frequency (<1000 Hz) Downhole Seismic Sources for use at Environmental Sites" by Greg Elbring, SAGEEP Proceedings

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