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RECENT IMPROVEMENTS IN TIME-DOMAIN EMC MEASUREMENT SYSTEM

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Improved techniques for determining critical resonant frequencies and the current response of internal wiring due to external fields for rotary-wing aircraft are given. The measurement method uses a train of low-level, radiated pulses. These do not disturb other spectrum users, nor do other spectrum users significantly disturb these measurements. The fields are low, a distinct advantage from both cost and personnel hazard standpoints. The problems that should be addressed before the full potential of the technique can be realized are discussed.

Key words: induced currents, natural resonant frequencies, TEM horn antennas, time-domain measurement system, weak source fields.

1.0 Background

The National Institute of Standards and Technology (NIST, formerly NBS) has been developing time-domain techniques and calibration facilities for a number of years [1]. More recently, AVSCOM has supported our efforts to apply these techniques to whole-system measurements for aircraft electromagnetic compatibility (EMC) work [2], an area that is weakly covered by MIL-STD 6051.

The basic idea is to transmit an impulse over a large enough area to expose a complete aircraft to a radiated electromagnetic field. The scattered or reflected response of the aircraft can be sensed with a receiving antenna, digitized, recorded, and processed by any of several mathematical algorithms to give the spectral response. These data contain information on the natural resonant frequencies of the airframe, frequencies that will significantly enhance currents induced on internal wiring within the airframe. These frequencies should be examined carefully in any EMC testing.

An extension to this basic idea is to use another receiving system to directly measure current waveforms induced on internal wiring by this external field. If these measured current-time functions can be related to the external electromagnetic (EM) field and if several other criteria can be satisfied, it may be possible to substitute conducted injection testing for radiated susceptibility testing. This has great potential since whole-system radiated susceptibility testing cannot be done at present.

There are several essential components required for such a system. Many of these have now been developed and tested. Some additional key steps need further work. These issues will be discussed later.

Working in the time domain offers some very important advantages over working in the frequency domain. In the frequency domain, it is necessary to measure both amplitude and phase in order to reconstruct a waveform. Amplitude is easy to measure, but phase is difficult to measure. If we work only with amplitudes, for example, we may assume that the intervening networks are minimum-phase in order to be able to deduce phase from amplitude [3]. This assumption is hard to justify. In the time domain, the recorded time series contains all the information in the waveform.

Conversions to the frequency domain are subject only to limitations of the mathematical algorithm selected.

Another important advantage of working in the time domain is the capability to avoid interference with other spectrum users. This can be implemented by use of a train of low-power, periodic pulses and fiber-optic triggering to achieve selective coherence. Fiber-optic trigger lines from a clocked pulse generator to the transmitter and to each of the receiving systems allow these receiving systems to be synchronized with the transmitted pulses and incoherent with the rest of the electromagnetic environment. This allows averaging -- effectively trading time for power. The train of pulses are of such low power that they cannot be detected 100 m away from the transmitting antenna. External fields do not interfere with our measurement system since they are not coherent with our transmitted pulses.

Advantages of working with small signals as opposed to strong signals are: first, wave shapes of small signals have better repeatability than those of strong signals needed for single-event time domain systems such as those used presently in nuclear electromagnetic pulse (EMP) testing, and second, possible hazards to personnel are less for lower fields than for higher fields.

There are limitations to the applicability of these time-domain techniques. The spatial arrangements among source antennas, aircraft and receiving systems must remain constant during the measurement time; otherwise the repeatability needed for the averaging is lost. Therefore, for the same reason, moving aircraft, even with the rotor turning, cannot be characterized this way. The periodicity of the train of pulses (small time jitter) must be maintained to great accuracy, but this is easy to achieve with currently available equipment, so it is not a practical limitation. The scattered signals and induced currents must be strong enough to be detected within a practical time interval for averaging. The area where the measurement system and aircraft are located must be clear of reflective obstructions to minimize distortions of the desired received signal. Since the received waveforms are analog, they must be filtered adequately, relative to the sampling rate, before being digitized to prevent aliasing. Aliasing is the contamination of low frequency signals by the "folding down about the Nyquist frequency" of higher frequency signals when data are converted from analog to digital form. Special, linear-phase filter designs are needed so as not to distort the waveforms.

These techniques have been applied at three locations using helicopters. The first measurement system was used at Ft. Rucker, Alabama, in 1986. An improved measurement system was used at Western Army Area Training Site (WAATS) near Tucson, Arizona, and at Ft. Huachuca, Arizona, in 1988. This document discusses the more recent work.

2.0 Measurement Systems

The complete measurement system consists of one transmitting system and two receiving systems. All systems usually operate simultaneously. Both receiving systems record time-series waveforms which are generated in response to the train of impulses from the transmitting system. A block diagram of these systems is shown in figure 1. A photograph, figure 2, shows a helicopter, both transmitting and receiving antennas, and an edge of the van where the balance of the system is located. The fiber optic line is protected by a rope and cinder blocks. The source consists of a step generator that drives a transverse electromagnetic (TEM) horn antenna. This step generator is triggered via a fiber optic line by the same pulse generator that synchronizes the receiving systems. The antenna radiates a series of fast rise time (2 ns) impulses of electromagnetic energy. A variable time delay proportional to separation distances is added to the receiving systems so that coherent detection of the transmitted signal is possible.

The transmitting and receiving antennas have flat amplitude and linear phase characteristics. This allows radiation and reception of pulses with very little distortion of the waveform. Their design is essentially a tapered TEM horn [4]; they are about 2 m in length. This is sufficient to extend their low-frequency range down to about 5 MHz. These antennas are supported on non-metallic tripods and guyed with nylon ropes to add stability during windy conditions such as may be caused by a hovering aircraft. These support structures are essentially transparent to EM fields. The antennas can be mounted on the tripods to give either vertical or horizontal polarization.

The first receiving system (outside the aircraft) detects the signal reflected from the aircraft. This waveform contains a combination of damped sinusoids which have the natural resonant frequencies of the aircraft excited by the transmitted impulse. A time-averaging sampling oscilloscope is used as the receiver. Reflections from objects other than the aircraft may be rejected by 'time windowing,' that is selecting portions of a received time waveform.

If a reflecting object other than the aircraft is located so that its reflected signal arrives at the same time as a signal reflected from the aircraft, the waveform contain both signals, and the analysis is much more difficult. This sets the requirement for an unobstructed test area. This clear area should be approximately a circle of radius 4 times the separation distance from the transmitting antenna to the aircraft under test and centered on the aircraft's axis of rotation.

The received signals are filtered, digitized, and stored on disk for subsequent processing. The digitized, time-domain waveforms are checked at time of recording to see that proper scale settings, for example, are used on the digitizing oscilloscopes, so as to adequately record the waveforms. Usually, the same settings are maintained throughout a set of measurements. The oscilloscope settings are recorded as part of the data file.

The second receiving system (inside the aircraft) measures the current induced on a particular wire or bundle of wires. Again, the response is a time series of damped sinusoids. This system consists of a current clamp, amplifier, filter, and a sampling digitizing oscilloscope. A laptop computer is used to record the data on disk. Data are transferred from the oscilloscope to the laptop computer using an RS-232 link and stored on disks. These data are then processed later using the same procedures that are used for data from the first receiving system.

Since these data are digitized before they are recorded, the input signals must be filtered before recording to prevent aliasing errors. A special set of linear-phase filters which have cutoff frequencies of 64, 128 or 256 MHz is used. The current clamp has a frequency response only slightly higher than the 128 MHz filters, so in this case the 128 MHz filters are used for most digitizing.

A reference waveform should be recorded with the aircraft not present; this can be subtracted from other waveforms recorded when the aircraft is present in order to remove direct antenna-to-antenna coupling as well as other specific characteristics of the measurement site. This technique imposes a requirement that may be difficult to meet -- maintaining relative physical position of all objects over the duration of the measurements. This may be difficult during windy conditions or if movement of extraneous objects occurs in the immediate vicinity. It also requires stability of the triggering circuit and pulse generator, which is usually not a problem. It is not possible to take a reference signal for the second receiving system; what is recorded (using the antenna from the first system) is the unperturbed field strength when the aircraft is removed. This may be used to develop a transfer function which relates induced current inside the aircraft to external field strength.

An exception to the use of time windowing occurs when analyzing induced currents inside the aircraft using the second receiving system. The waveform is determined by the effects of intervening media, structure, and cabling -- usually no part of the waveform should be discarded since there is not sufficient spatial separation to allow us to distinguish what object or effect is causing which portion of the time signal.

The measurement systems used in Arizona incorporates several improvements over those used previously in Alabama. The antennas are larger, allowing lower frequencies; they are mounted on fiber-glass supports and can be rotated to give either horizontal or vertical polarization of the E field. The antennas can be raised or lowered over a several-meter range. They are structurally stronger, and can be used during substantial wind conditions. Use of optical fiber lines to allow triggering of all systems from our pulse generator is another improvement. This prevents stray coupling along conductive trigger lines.

A special step generator was designed and built on a card attached to the transmitting antenna. The peak voltage across the antenna elements is over 250 V. This is much higher than we could achieve at Ft. Rucker, but the pulse repetition rate had to be sharply reduced. The trade-off of peak voltage versus repetition rate will be considered on future designs. The transmitting antenna differentiates the step function to produce a radiated impulse.

An 80386 personal computer was used to record and process the data. It is a part of the first receiving system. Data from the digitizing oscilloscope of the external receiving system were transferred directly to the computer through the IEEE-488 bus, while data from the portable system inside the aircraft were read from disks into the 80386 computer for processing. The 80386 computer was used to obtain processing speed necessary to perform the mathematical algorithms nearly in real time, without having to use a mainframe computer with a typical one-day delay in obtaining results due to the need to transfer data by modem, process the data in batch mode, and transfer the results back by modem. This enabled us to perform a preliminary assessment of our measured data to see whether results were reasonable. The 20 MHz, 80386 computer with an 80387 coprocessor that we used is about 12 times faster than an 80286 computer with an 80287 coprocessor, yet about 9 times slower than the actual cpu rate of our mainframe computer. The processing time of our computer is approximately 2 seconds for 1024-point fast Fourier transform (FFT) and 4 min for a 46-pole run using the Prony algorithm. Newer computers are even faster.

The response of the receiving antenna is determined using the NIST time-domain range [1].

3.0 Measured Data

The FFT and Prony transforms are two commonly used algorithms that can be used to convert time-domain waveforms into the frequency domain.

The mathematical processing can be done with any of a number of algorithms, but the FFT should be tried first to obtain an overview of the spectral content of the data. Other algorithms can be used in combination with preprocessing to determine other characteristics of the data. The Prony algorithm gives either Q or damping factor, important characteristics for EMC analysis.

The nonlinear techniques suggested by Dudley and Goodman [5] are certainly more powerful than the techniques we used, but in view of the fairly good signal-to-noise ratio we are able to obtain, the increased time and computer power needed may not give substantially better results.

Sometimes it is advantageous to preprocess the data. An example is decimation as suggested by Dudley and Goodman [5]. This consists of using every second, third, or nth data point and padding the end of the waveform with zeros. This enhances the low-frequency resolution of data processed with the FFT at the expense of high-frequency information. The data are also preprocessed to remove any dc offset that might be present in the data. The Prony algorithm fails if there is a substantial dc offset.

The response of the current clamps is determined by using cw currents of known amplitude at various frequencies. The frequency response is fairly flat from 10 to 50 MHz, is down about 3 dB at 80 MHz, and takes a sharper drop above 120 MHz. The system calibration is a function of all of the components of the receiving system in addition to the current clamps. This includes the recording oscilloscope, filter, amplifier, laptop computer, mathematical algorithms, and the required interface parameters of the personal computer. Some care must be used in converting power spectral density into units of current. The level at which the cw calibration is performed is valid only at that level on a linear current scale. By using a logarithmic scale (dB), we can adjust a current density scale to match this calibration point, and the nonlinear current,squared relation to power reflected through the $20\log(i_2/i_1)$ and $10\log(P_2/P_1)$ allows direct readings of current density values. A second vertical scale for cw current is needed. Current induced from a cw (discrete frequency) source should be used to determine this logarithmic current scale. The two scales may be made identical by selecting the frequency interval used by the FFT and giving the current spectrum density function in terms of dB relative to 1 $\mu A/\sqrt{x}$ Hz, where x is the width of the FFT frequency interval.

Two recorded waveforms show raw and preprocessed data. Figure 3 shows a raw waveform from the receiving antenna while figure 4 shows the same waveform decimated using a factor of 4. Figure 5 shows the spectral response of the decimated time waveform obtained from the FFT. Examples of measured power spectrum density (related to square of current) from various wires within the helicopter were obtained from processed data and are shown in the remaining figures. Figure 6 shows the null response of the current clamp, that is, when it was not coupled over any wire. Some clamps respond to electric field, thus confounding the data unnecessarily. Figure 7 shows power spectrum density in a particular wire, while figure 8 shows the power spectrum density in this same wire, but with the rotor at a different position. Figure 9 shows a much stronger power spectrum density induced in a different single wire; the aircraft was excited by a vertically polarized E field. Figure 10 shows power spectrum density in another wire. Figure 11 shows power spectrum density induced in a bundle of wires. Figure 12 shows power spectrum density variations in one wire at 6 different static positions of the rotor.

We tried to address a number of measurement conditions of the aircraft under test. Some of these conditions are elevation of aircraft, position of rotor, effect of power cords, whether the door(s) are open or closed, and effect of a turning rotor. All of the measurements gave inconclusive results for a number of reasons. Some differences were observed due to each of these variations. More carefully controlled experiments with larger variations of conditions are needed in order to resolve their effects. Some of our observations include these:

> The effect of a power unit or cord can be eliminated by use of battery operated equipment.
>
> The effects of elevation were measured for 0 and 15 cm elevations. This increase in elevation was achieved by rolling the helicopter up wooden ramps onto plywood on top of foam blocks 15 cm thick. There are some repositioning errors in addition to this change in elevation; the measured effects were clearly discernible, but produced variations in amplitude of 3 dB or less in most cases.
>
> The effect of an open door versus a closed door caused very minor changes, 2 dB, in measured results but this may be case- and door-specific.
>
> The effect of different rotor positions was easiest to see (figure 12). Large changes in the waveform were apparent as the rotor was moved through 6 different angles of rotation. Over most of the spectrum of interest, the changes in measured current were less than 4 dB, but at a few frequencies, were as much as 10 dB as shown in figure 13. The frequencies where results were most affected seem to occur at multiples of half-wavelengths of principal dimensions of the helicopter such as tip-to-tail of body or rotor diameter. For example, 45.75 MHz gives a $5/2\lambda$ of 53.8 f (16.4 m), the approximate diameter of the main rotor, and 58.25 MHz gives a $3\ \lambda$ of 50.75 f (15.5 m), the length from the nose-tip to the center of the tail rotor.

4.0 Needed Improvements

There are a number of practical improvements that are easy to make and will speed up the measurement considerably. One example is the use of more current clamps so that only connectors need to be switched rather than relocating a single current clamp to many locations. Another example is to use two sets of antennas so that polarizations could be changed without having to remount one set of antennas. The effect of azimuthal variations will have to be evaluated to see whether the small displacement necessary for using two sets of antennas has any significant effect. How effective this will be depends on the number of measurements to be made.

The trade-off between peak pulse power radiated and repetition rate of the impulses needs to be weighed carefully. Probably it is more advantageous to increase the repetition rate than the pulse power. Stability of waveform can probably be maintained better with lower-power pulses.

The method of processing and/or preprocessing the data to convert from time to frequency domain may be improved if poorer signal-to-noise ratios are encountered in future applications, but the present techniques are adequate when applied judiciously. This is an area where improvements may be desirable but are not essential to the implementation of the measurement technique to present applications.

These are relatively simple problems with obvious solutions. But there are several areas where improvements are needed in order to achieve the full potential of this measurement technique and perhaps fill this gap.

Consider that whole-system, radiated, electromagnetic susceptibility testing cannot be done effectively on an aircraft. Electromagnetic (EM) fields cannot be radiated across the spectrum at high enough power for susceptibility testing without disrupting other spectrum users. Electromagnetic fields generated inside an enclosure such as an anechoic chamber or mode-stirred chamber can be used to immerse the aircraft in specified fields, but the aircraft cannot be operational. This means that avionics are not completely operational, so key failure criteria are not available, and their response to these EM fields remains unknown. This leaves a critical inability to make effective radiated susceptibility tests on large, whole systems. This leaves a crucial gap for newer weapon systems that rely heavily on the proper functioning of sensitive and complex electronic systems to perform their missions.

Can energy be injected into parts of the whole system as a viable substitute for radiated susceptibility testing? The time-domain system can be used to obtain current response of internal wiring due to external fields over the frequency range allowed by the antennas and other ancillary equipment. But this is for one orientation of the aircraft relative to the transmitting antenna. For each of an infinite possible number of relative orientations, there will be a different current response, since fields are vector quantities and couple energy differently depending on these relative orientations. The aircraft is a receiving antenna of unknown characteristics: patterns vary with frequency; differing delay times cause variations in waveshapes. But the aircraft resonances are independent of variations of azimuth. We may be able to develop statistical methods that give an upper bound for currents that will not be exceeded regardless of the relative orientation. An experiment must be designed to take data at an extensive number of azimuths such as may be obtained using a turntable. Methodology for determining the minimum number of azimuths would then be needed. Then conductive injection could be used to reproduce this current bound (which would still be a function of frequency) as a conducted EM susceptibility test that would be equivalent to worst-case radiated EM susceptibility testing, regardless of the relative orientation of source and the aircraft. This current must be tied to the unperturbed field strength in order to relate the injection current to the equivalent field strength. This can be done by measuring the unperturbed field strength with no aircraft present. Once the relationship between external field strength and induced (upper bound) current is established, the levels can be scaled upward as long as the coupling mechanisms between the airframe and the internal wiring are linear, that is, capacitive, resistive, or inductive. The avionics may not be linear, but the injection can linearly simulate increasing field strength. This process could significantly reduce cost of testing since current injection costs much less than radiated susceptibility testing.

Bulk current injection is a method of injecting current into a bundle of wires that has been espoused by Nigel Carter [6] and analyzed with considerable care by M.F Sultan [7]. This method has tremendous advantages for both recording and injecting in that the wire bundles often contain many conductors. Measuring the current in each conductor takes n times as much time as a single bulk measurement where the current clamp is placed over the whole bundle and net current is measured instead of measuring current in n individual wires. Of even more potential importance is the use of bulk current when injecting, since not only is the same time saving achieved but also the problem of interaction is avoided -- injecting one wire may not have the same effect as injecting 2, 3, or n wires simultaneously. But are bulk current techniques valid? Current measurements have been made on individual wires where the current in the individual wire exceeded the current measured in bulk. The question whether the current induced by external fields can be measured and simulated by injection must be studied by theoretical and experimental methods.

If bulk current injection is not valid, or is only valid under a limited number of conditions, another question must be resolved. Does current injected on n wires one at a time have the same effect as injecting all wires simultaneously? Probably not, especially for cases where several conductors have identical resonance frequencies. This undoubtedly will depend on the specific characteristics of each avionics unit, particularly its linearity. This information is usually unknown or very difficult to determine.

In one special case, testing electroexplosive device (EED) response to nuclear EMP, only linear scaling and current bounding problems are relevant, since current response is needed in only one wire.

Another question is determining the amount of perturbation caused by the measurement system used to make the current measurements. The present system required ac power; battery operation would reduce the additional wiring needed to provide power.

For applications where space is too limited to contain the second receiving measurement system, such as inside an attack helicopter or small missile, additional work is needed to develop a fiber optic telemetry system to allow recording the induced current waveforms at some out-of-the-way, nearby site. The current probes and amplifiers could fit inside a much smaller volume than is needed for the present system.

Each type of aircraft or model of aircraft with different wiring is unique. Each should be tested separately.

5.0 Acknowledgments

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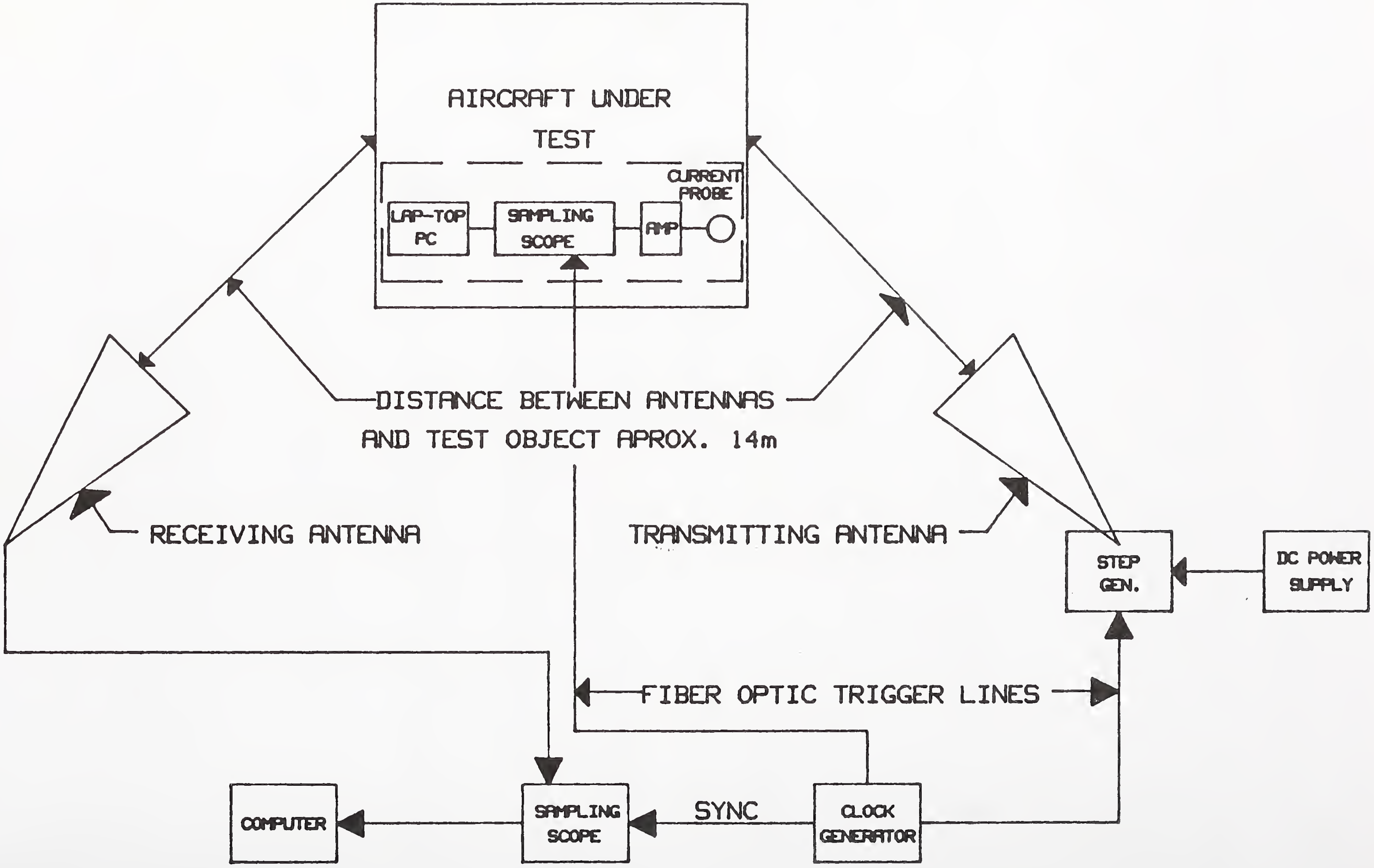

Figure 1. Time-domain measurement system.

Figure 2. The measurement system deployed using an OH-58 helicopter as a test system. Fiber optic line, on ground, is protected by rope supported on cinder blocks.

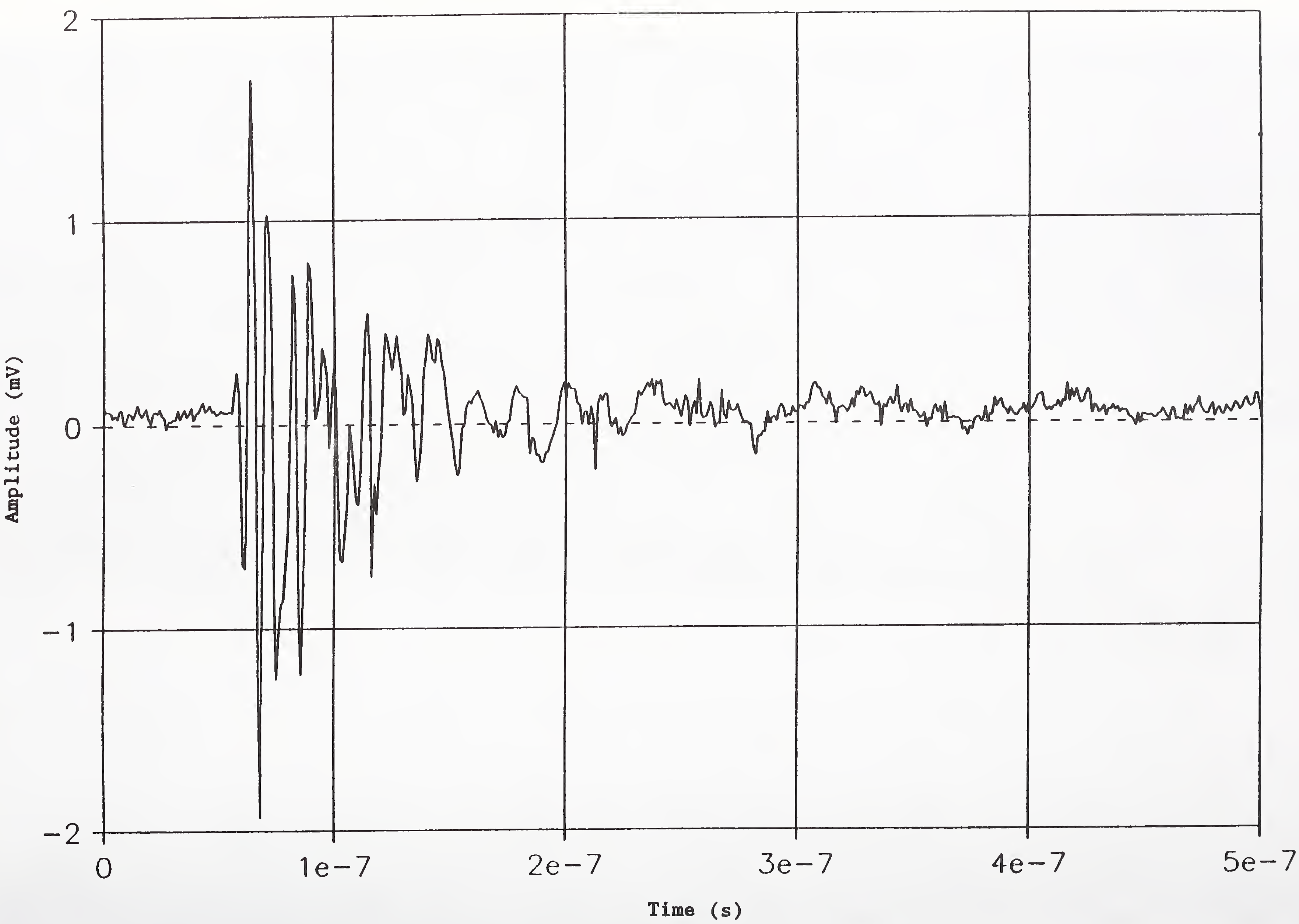

Figure 3. Recorded time waveform from receiving antenna.

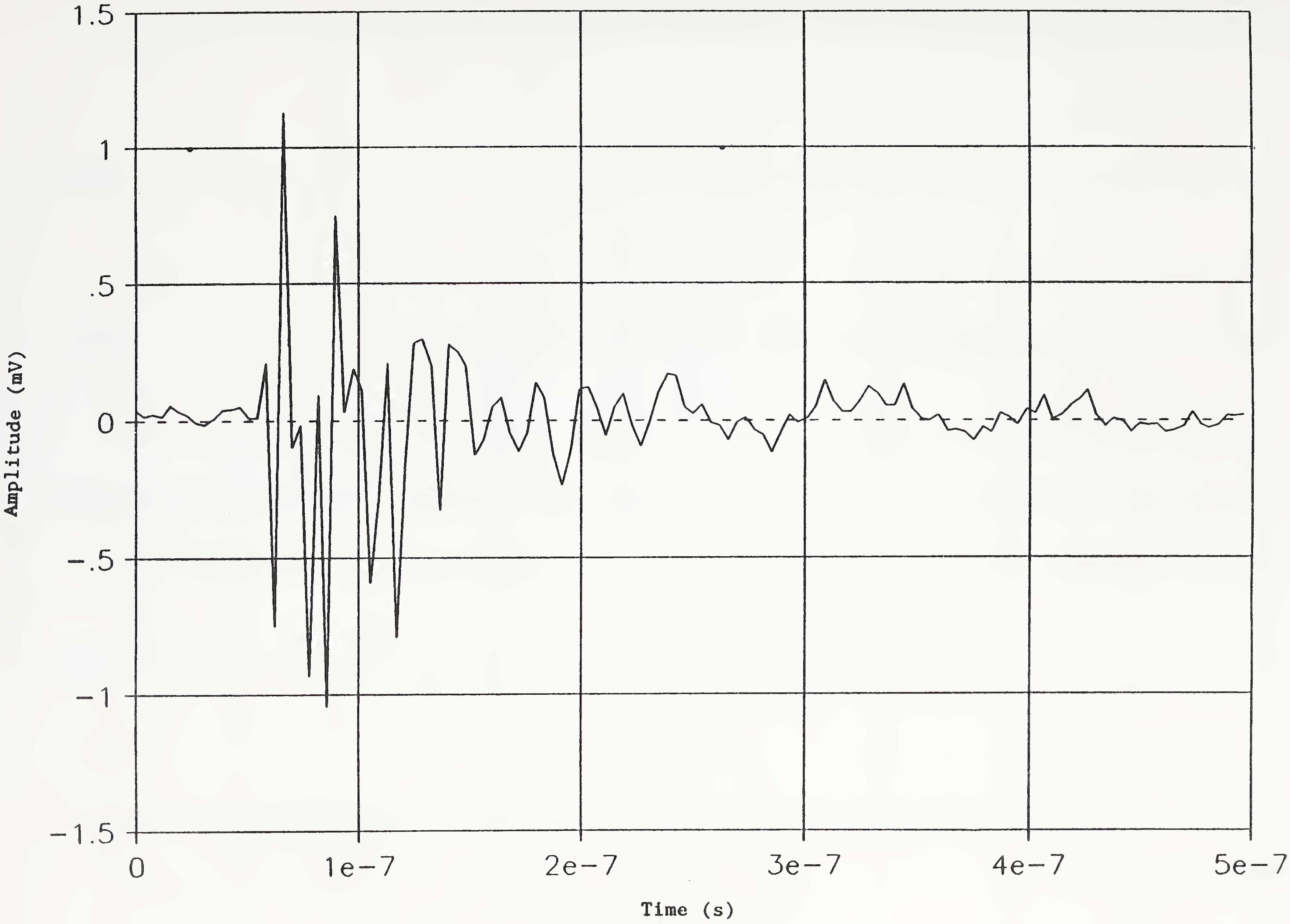

Figure 4. The same waveform as fig. 3, but decimated using every fourth point.

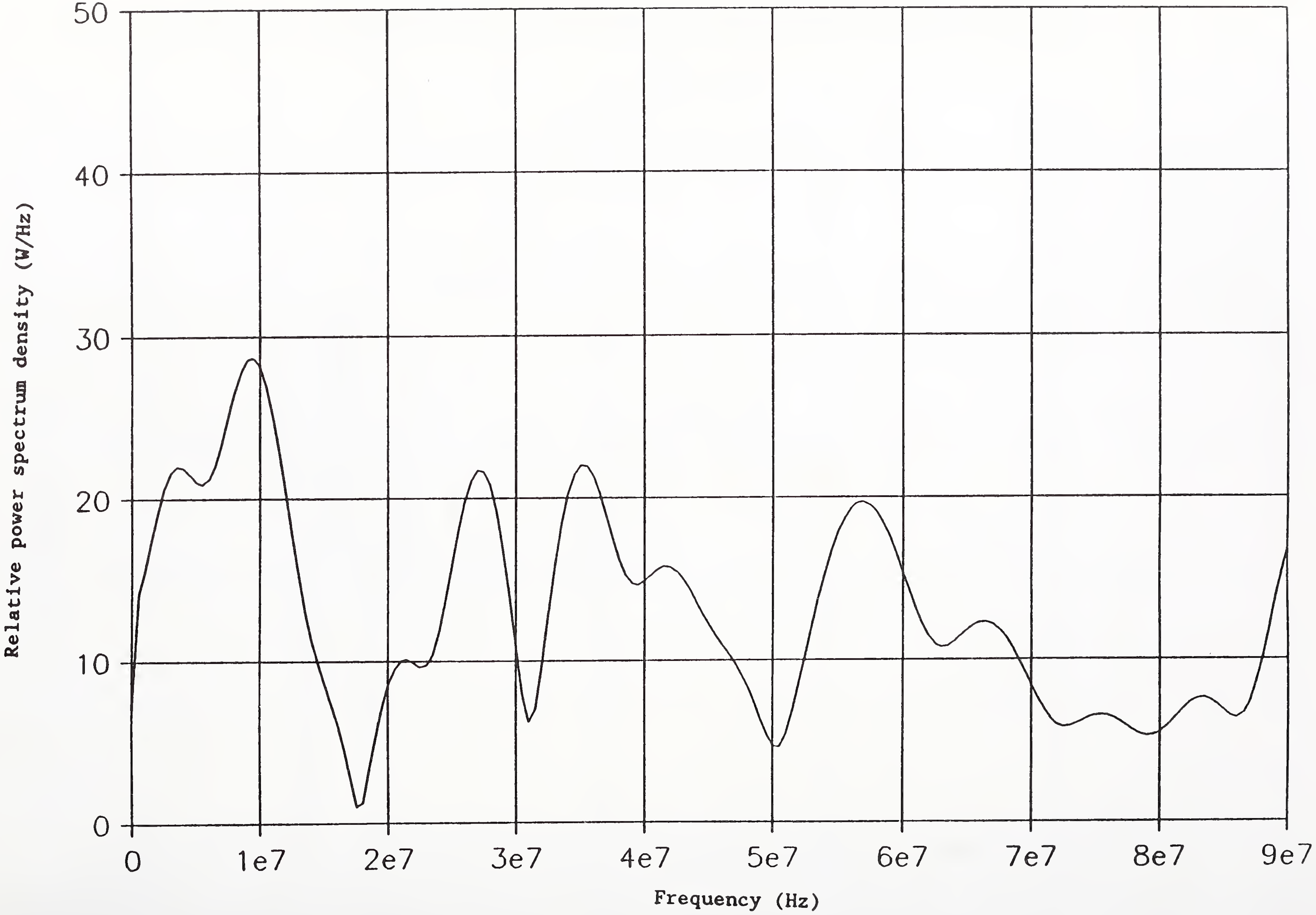

Figure 5. Frequency domain of figure 4 from FFT.

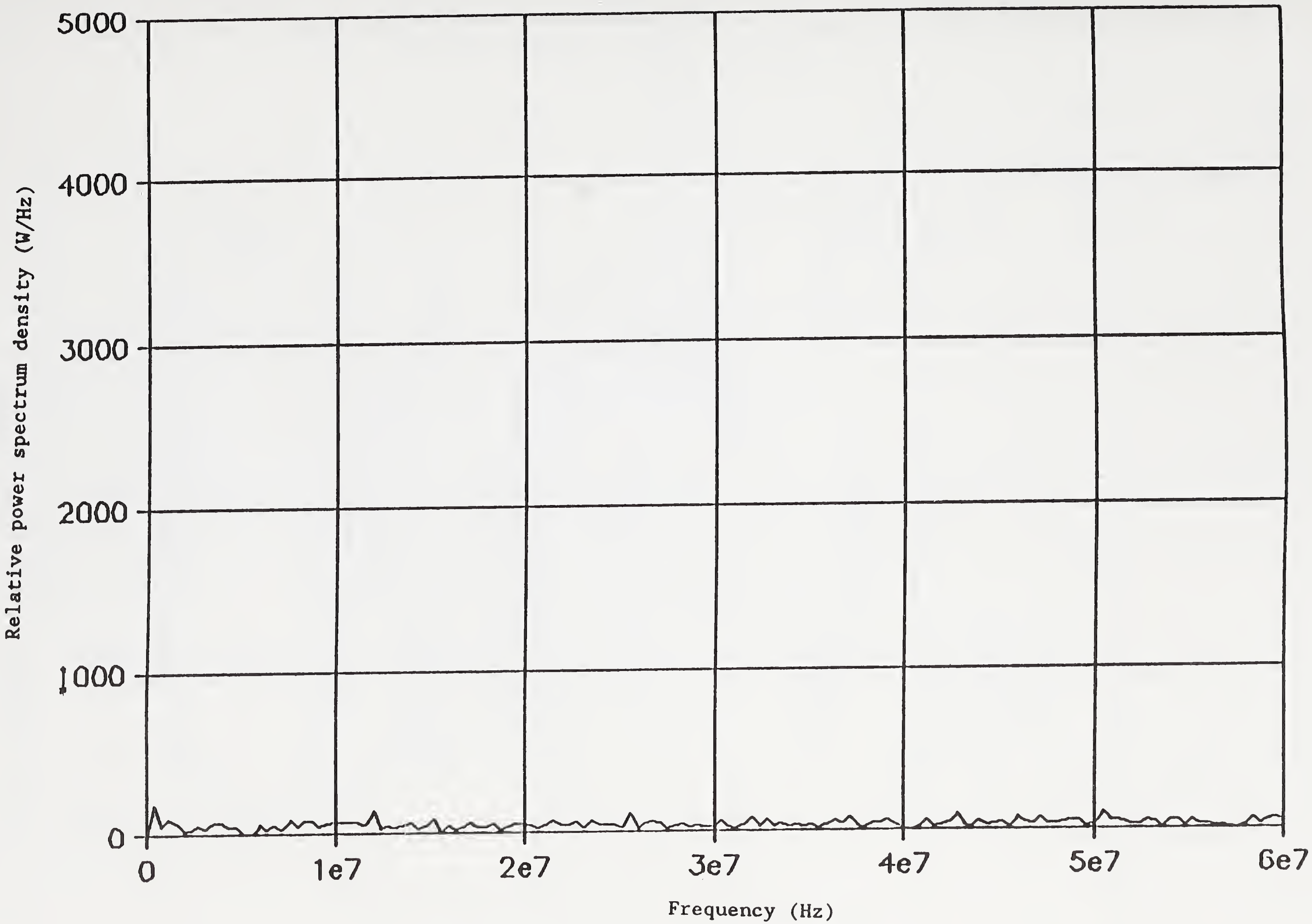

Figure 6. Null response of current clamp (not clamped over a wire).

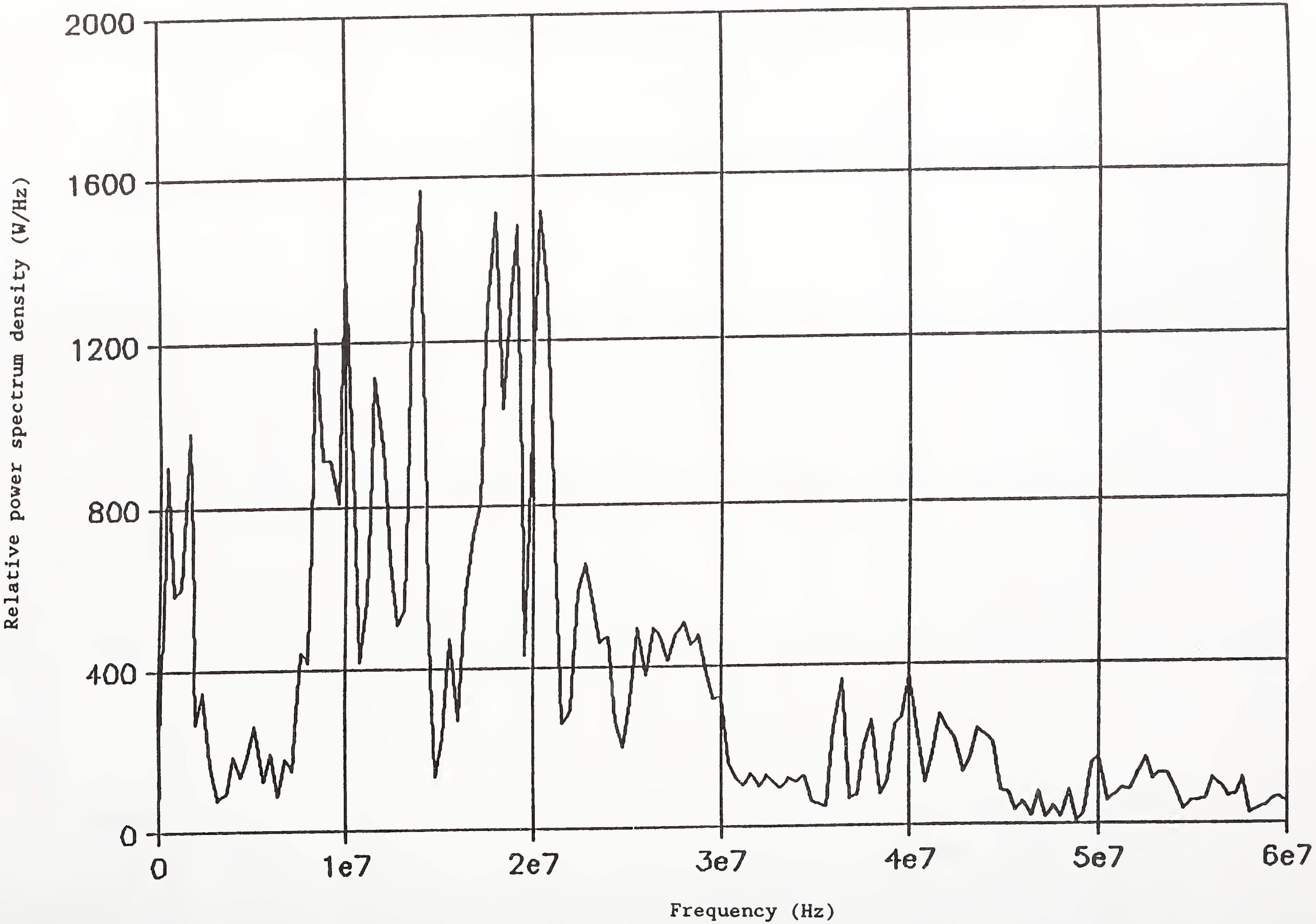

Figure 7. Power spectrum density (relative) obtained by FFT from current time waveform in single wire.

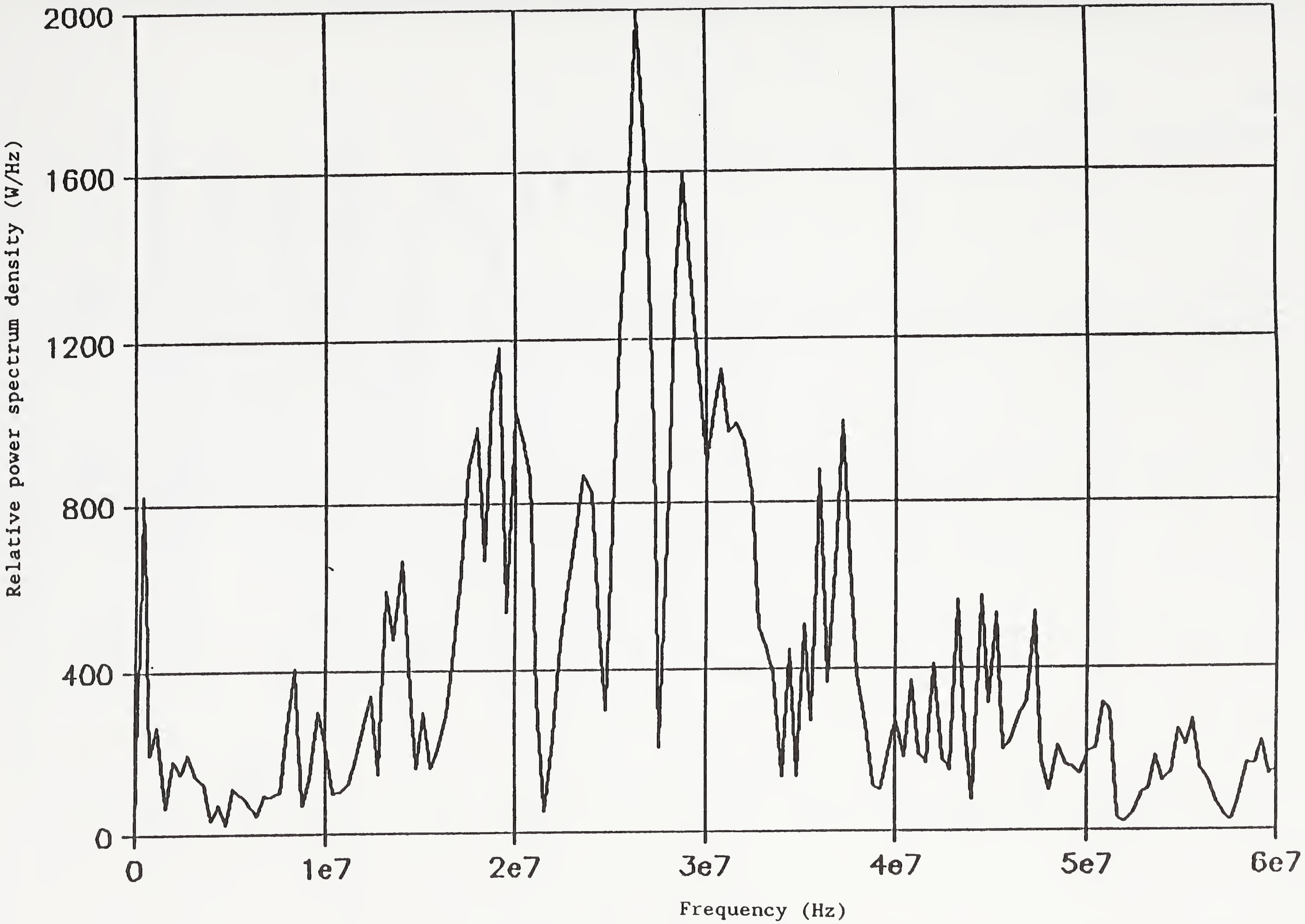

Figure 8. Power spectrum density (relative) obtained by FFT from current time waveform in same single wire as shown in figure 7, but with a different rotor position.

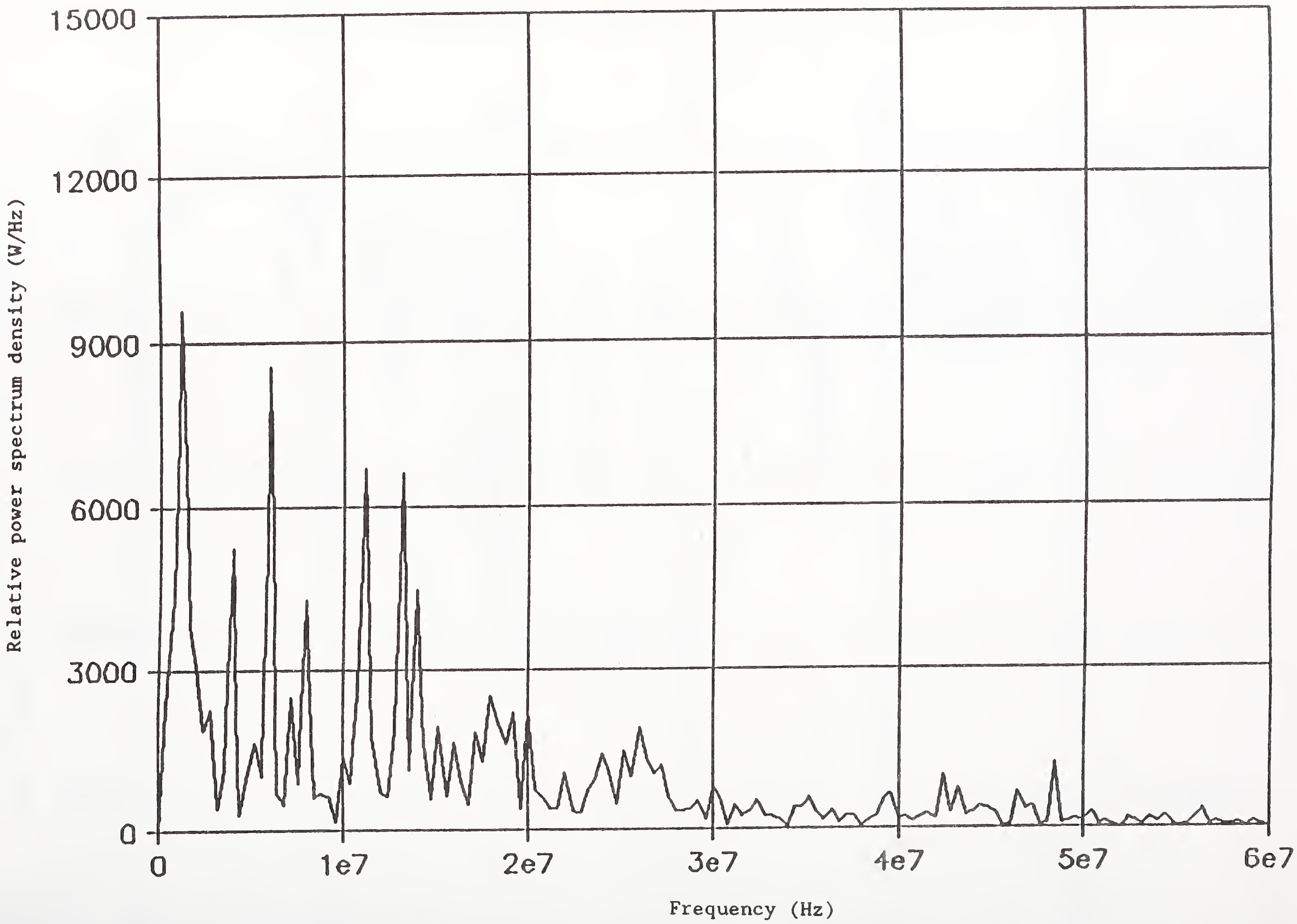

Figure 9. Power spectrum density (relative) obtained by FFT from current time waveform in a different single wire from FFT.

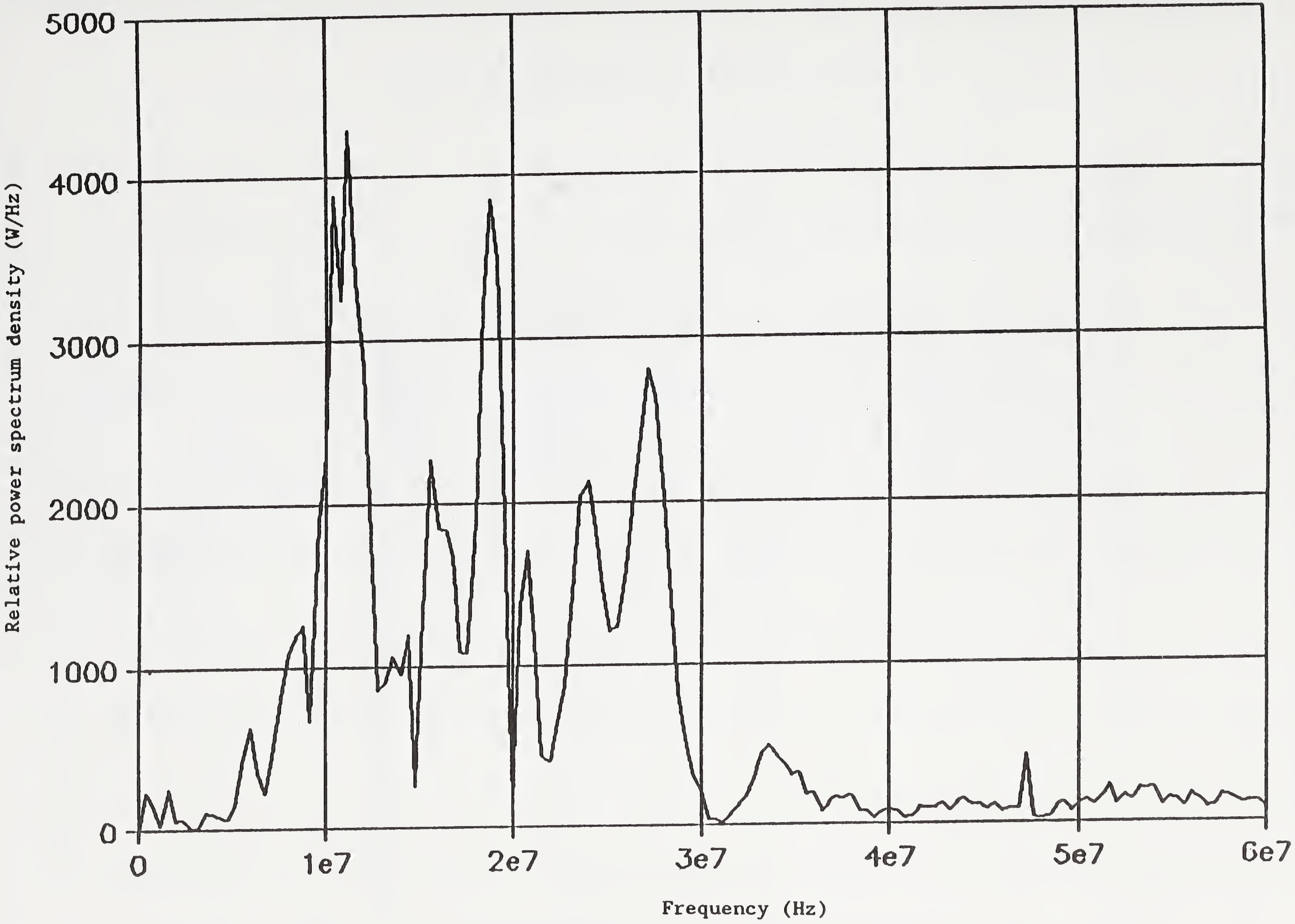

Figure 10. Power spectrum density (relative) obtained by FFT from current time waveform in yet another single wire from FFT.

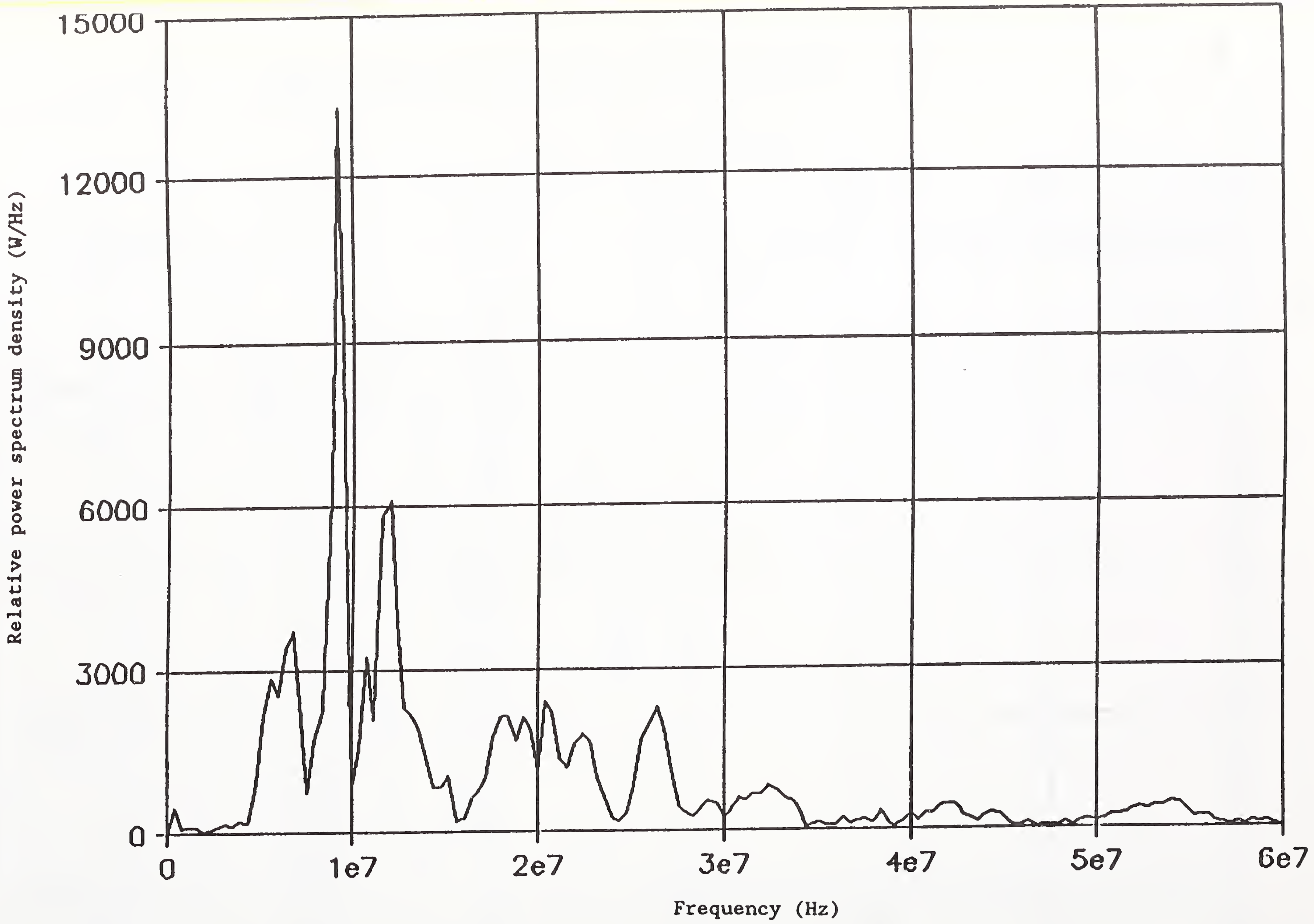

Figure 11. Power spectrum density (relative) obtained by FFT from current time waveform of a bundle of wires.

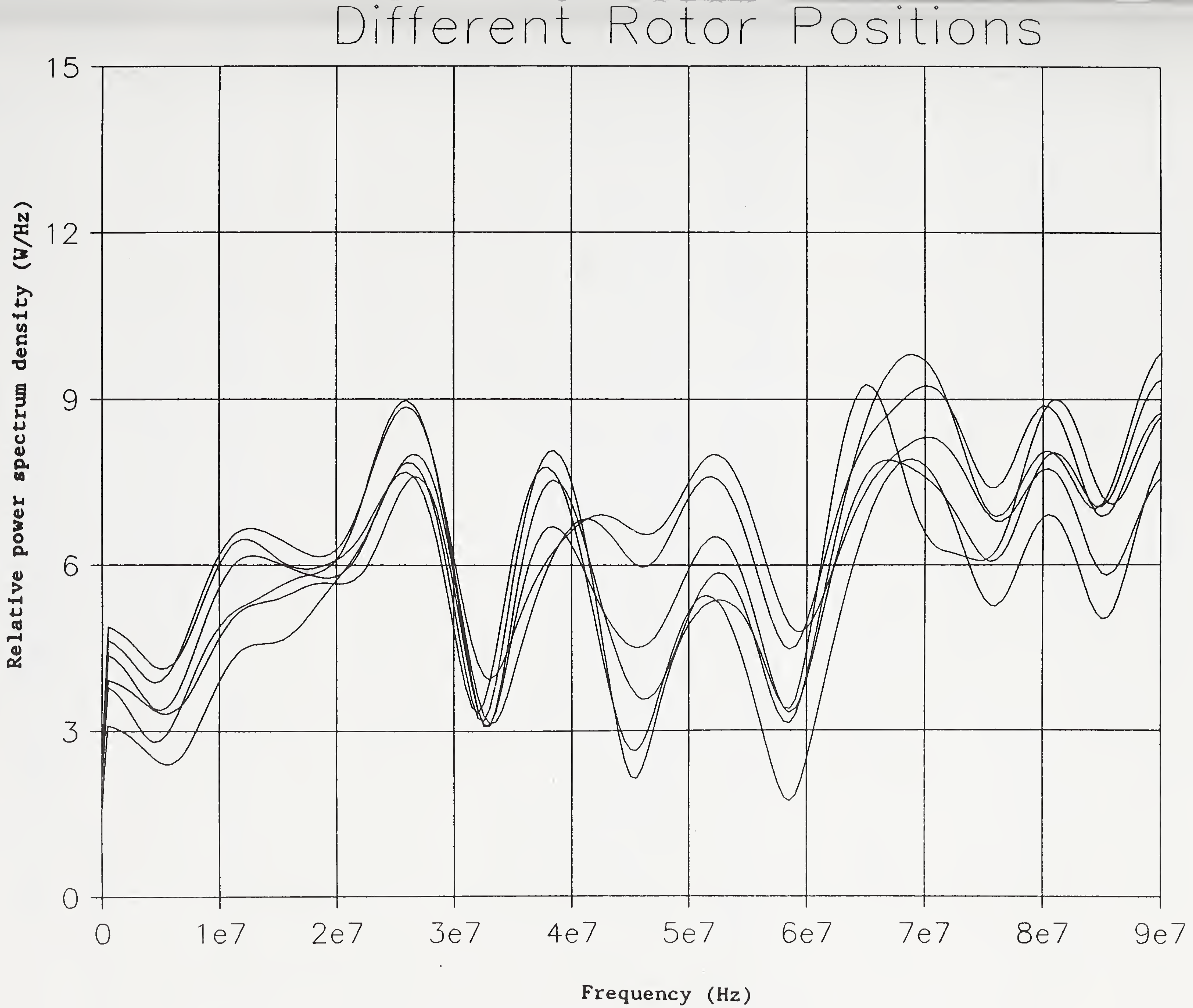
Different Rotor Positions

Figure 12. Power spectrum density (relative) obtained by FFT from current time waveform in same wire at several azimuths of rotor position, static measurements.

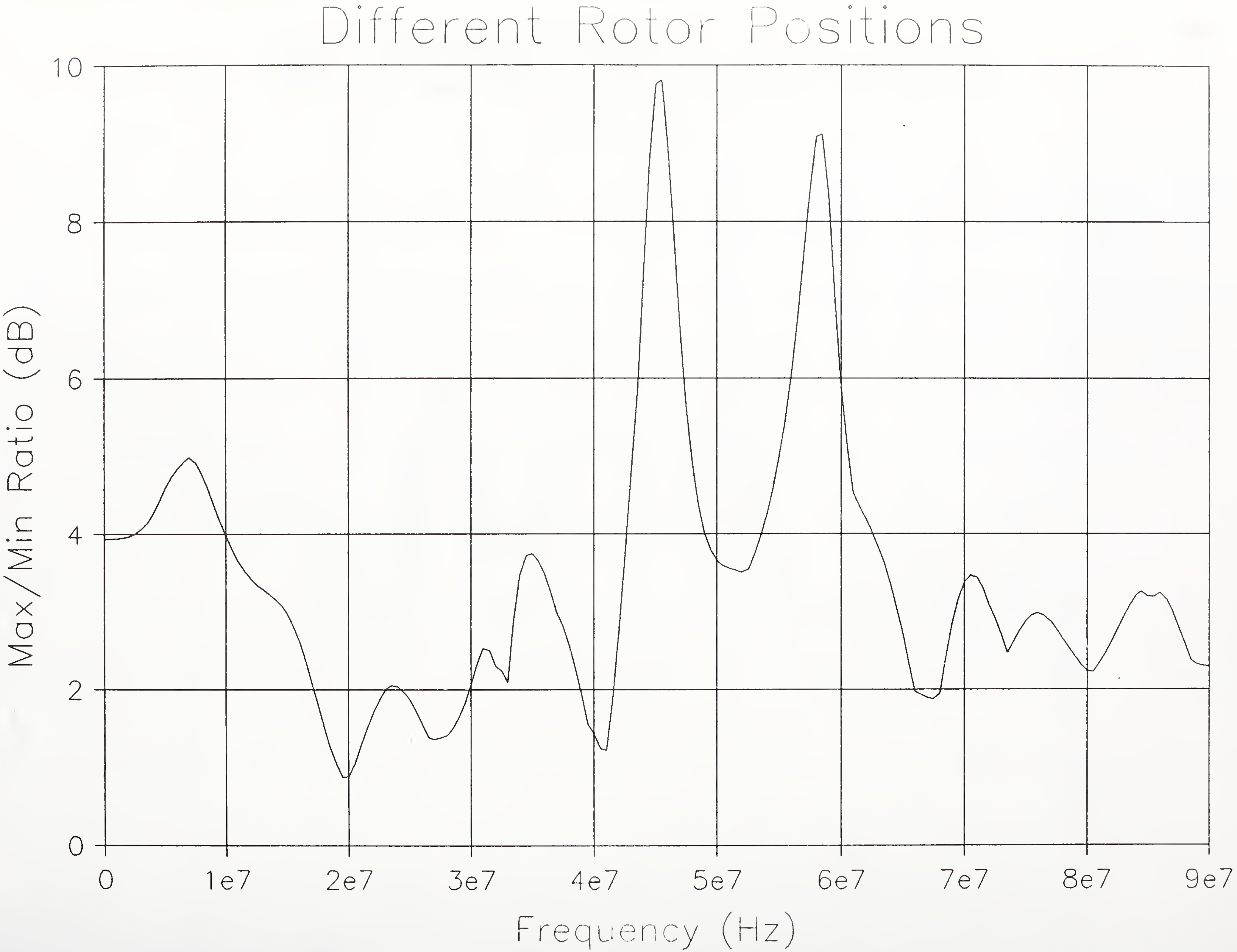

Figure 13. Ratio of maximum-to-minimum power spectrum densities in dB for different rotor positions shown in figure 12.

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11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

Improved techniques for determining critical resonant frequencies and the current response of internal wiring due to external fields for rotary-wing aircraft are given. The measurement method uses a train of low-level, radiated pulses. These do not disturb other spectrum users, nor do other spectrum users significantly disturb these measurements. The fields are low, a distinct advantage from both cost and personnel hazard standpoints. The problems that should be addressed before the full potential of the technique can be realized are discussed.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

induced currents; low-level source fields; natural resonant frequencies; TEM horn antennas; time-domain measurement system; weak source fields.

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