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ANALYSIS OF SHOCK PULSES

FOR

ENVIRONMENTAL TESTS

FINAL REPORT

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ANALYSIS OF SHOCK PULSES FOR ENVIRONMENTAL TESTS

ABSTRACT

Specifications for shock testing of components that will be used on the Space Shuttle vehicles require very high acceleration levels. A special shock machine has been built for testing of rocket components to determine if they can meet the specified accelerations. Calibrations of transducers and methods to monitor the shock tests has raised several signature-analysis questions.

In this report, calibration capabilities of shock accelerometers are found to be limited to 10,000g. Equivalency of the mechanical shock test and the rocket pyrotechic shock are examined, and two simple relationships for equivalency are proposed. Five different pulse signature-analysis techniques are tested on analytical and experimental pulse data and recommendations are made for the signature technique which most clearly identifies the magnitude of the impulse applied to the test specimen.

I. INTRODUCTION

The Dynamics Test Branch at Marshall Space Flight Center, NASA, has the responsibility for shock environmental testing of components for the solid propellant rockets of the Space Shuttle Program. Sections of these rockets will be separated after completing a launch of the shuttle vehicle and then parachute down to the recovery site. The sections of the rocket are separated by means of ignition of a pyrotechnic cord that causes the fasteners at the joint to fail. The shock at the point of burning is estimated to be up to 300,000g. This is the source of a shock environment that components mounted on the rocket must be able to survive.

The specifications for the environmental testing of components permit two methods of testing: 1) a single pyrotechnic shock on a full-size model of the support fixture connected to the component under test, or 2) two mechanical shocks on each of three axis of the component. The upper limit for mechanical shocks is 53,000g on the available shock testing machine. The mechanical shock is further specified to have the following shock-response spectrum: rise of 12 dB/octave from 50 to 100 Hz, rise of 6 dB/octave from 100 to 4,000 Hz and flat at maximum g for test from 4,000 to 10,000 Hz. The Dynamics Test Branch MSFC/NASA has the task of conducting these environmental tests of the flight components, and they have chosen the second method of mechanical shocks applied on the three axis of the component. The modified-shock testing machine at MSFC prepared for these tests is shown in Figure 1.

The first question to be explored was: What is the limit of shock calibration for accelerometers in the U.S.A.? Shock calibration services are available as a mechanical shock on a single axis at the National Bureau of Standards. The absolute calibration of shock accelerometers, as of 7/75, covers amplitudes from 15g to 5,000g and a half-sine pulse duration from 0.5 to 40 msec. Amplitudes up to 10,000g can be calibrated by special request. For more information one should contact Mr. John D. Ramboz or Mr. Charles Federman at NBS.

The second question was: What are the best ways to monitor the shock tests in order to avoid the possibility of over stressing or damaging the component under test? Currently the shock testing facility is using Endevco Shock Transducer Model 2740A, a digital event recorder to monitor peak amplitudes versus time and Spectrum Dynamics Shock Spectrum unit Model 320 to monitor the shock spectrum response versus frequency. This report is a study of different methods of pulse examination available for monitoring shock tests.

II. IMPULSE THEORY REVIEW FOR PYROTECHNIC SHOCK AND MECHANICAL SHOCK MACHINE

The following is a development of the equations that apply to this impulse problem. Two cases are considered as follows:

1) A pyrotechnic shock that results from a high pressure applied for a short time between masses M_1 and M_2. After the shock the masses depart from each other with velocities V_1' and V_2' respectively.

2) Shock machine consisting of two masses M_3 and M_4 move towards each other with velocities V_3 and V_4, impact each other and move away from each other with velocities V_3' and V_4'.

Both M_2 and M_4 have the component under test attached and within the component there is a mass m supported in an elastic element k. The over stressing of the component is represented by the strain of the elastic element or as (Z_2-Z_a) the displacement of m relative to the larger mass M_2or M_4. M_1 and M_2 represent the two sections of the rocket seperated by the pyrotechnic cord and M_3 and M_2 represent the shock testing machine main moving head and the smaller magnesium table elastically suspended on the moving head. A sketch of the two cases considered are shown in Figure 2,a) and b).

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IMPULSIVE FORCE EQUIVALANCY

The equation for the change in momentum caused by an impulsive force F(t) is as follows:

$$\int_0^t F_i(t)\ dt = M_i\ (V_i - V_i') \qquad (1)$$

where F_i = the force acting on mass M_i

i = 1,2,3 or 4 for the different mass considered.

The acceleration measured via the shock accelerometer can be related to the impulsive force by the relationship

$$M_i \int_0^t A_i(t)\ dt = \int_0^t F_i\ (t)\ dt \qquad (2)$$

In order to make the mechanical shock test equivalent to the pyrotechnic shock the following equality should be satisfied:

$$M_4 \int_0^t A_4(t)\ dt = \int_0^t F_2(t)\ dt \qquad (3)$$

where M_4 = the magnesium shock table mass plus the component under test

$A_4(t)$ = the acceleration of the shock table,

$F_2(t)$ = the pyrotechnic pressure times the area of contact between the cord and the stucture.

If the final relative seperation velocity of the two rocket components is known, equation (3) could be written as

$$M_4 \int_0^t A_4(t)\ dt = M_2(V_2 - V_2') \qquad (4)$$

where

$V_2 - V_2'$ = the relative velocity of seperation

Also one can have an equivalency from the change of the velocity measured at the mechanical shock table as follows:

$$M_4(V_4-V_4') = M_2(V_2-V_2') \tag{5}$$

Component Strain Equivalency

The criterion for damage is assumed to be the displacement of the elastic element k within the component under test. If the kinetic energy change caused by the velocity change of the rocket section is absorbed by this spring as elastic stored energy then the displacement of the spring can be derived from the following relationships:

Total energy balance of the top of the rocket during impact is given by the following equation:

$$(M_2+m)\ V_2^2(0)/2 + \int_0^{Z_2} F(t)\ dZ_2 = M_2V_2^2(t)/2 + mV_a^2(t)/2 + k(Z_2(t) - Z_a(t))^2/2 \tag{6}$$

The force term F(t) may be replaced by $(M_2+m)dV_2/dt$ as follows:

$$(M_2+m)\ V_2^2(0)/2 + (M_2+m)\int_0^{V_2} V_2\ dV_2 = M_2V_2^2(t)/2 + mV_a^2(t)/2 + k(Z_2(t) - Z_a(t))^2/2 \tag{7}$$

Performing the integration and simplifying we find the relative displacement of the spring to be:

$$Z_2(t) - Z_a(t) = \frac{m}{k}\left(V_2^2(t) - V_a^2(t) \right)^{1/2} \tag{8}$$

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Similarily the total energy balance of the moving head of the mechanical impact machine can be written

$$(M_4 + m)V_4^2(0)/2 + (M_4 + m)\int_0^{V_4} dV_4(t)\ dZ_4/dt = M_4V_4^2(t)/2 +$$

$$mV_b^2(t)/2 + k(\ Z_4(t) - Z_b(t)\ )^2/2 \qquad (9)$$

This equation reduces to the following relative displacement

$$Z_4(t) - Z_b(t) = \frac{m}{k}(\ V_4^2(t) - V_b^2(t)\ )^{\frac{1}{2}} \qquad (10)$$

On can simplify the right side of equation (8) and (10) by assuming the following:

1) Both impulsive forces occur in approximately the same time interval. (See Fig. 2, $t_2 - t_1$)

2) The worse possible situation will occur when the mass m lags behind the foundation mass by the time interval $t_2 - t_1$. If this happens, then $V_a(t) = V_2(0)$ and $V_2(t) = V_2'$ or $V_b(t) = V_4(0)$ and $V_4(t) = V_4'$. (See Fig. 2 for definition of symbols)

These assumption for the equivalency of period and the worse case mean that the component sensitive element will have the same relative displacement, i.e. strain, when the following equation is satisfied:

$$V_2^2(t_2) - V_2^2(t_1) = V_4^2(t_2) - V_4^2(t_1) \qquad (11)$$

To summarize, two methods of constructing an equivalent shock environment have been examined. The equivalent change in momentum

is given by equation (5) and the equivalent worse case strain of a sensitive element is given by equation (11). From these equation it appears that the best control variable to monitor during the mechanical shock testing is the change in velocity over the impact period.

III. ANALYTICAL STUDY OF PULSE SIGNATURES

The following methods of analysis have been used in pulse studies and were tested for their applicability to the task of monitoring and controling the repeatability of the mechanical shock tests:

1) Acceleration display with respect to time,
2) Shock response spectrum,
3) Fast Fourier Transformation,
4) Acceleration peak amplitude distribution,
5) Velocity display with respect to time.

An analytical pulse study was made to determine the sensitivity of methods 2) and 3) listed above for the display of different shock conditions. Combinations of trial pulses were selected as possible problems that could occur during a mechanical shock test. Problems such as repetitive pulses and narrow or wide pulses following the principal impulse can be missed on the accelerometer output display when there is structral ringing, but they would amount to over testing of the component. The principal pulse selected for the analytical study was a half sine wave 4,000 g peak height and

0.25 msec wide. This gives a shock pulse response spectrum similar to the one specified for the mechanical shock testing. The analytical pulses were selected as follows:

1) a half sine pulse 4,000 g peak and 0.25 msec wide,
2) three half sine pulses 4,000 g peak and 0.25 msec wide,
3) two half sine pulses, one 4,000 g peak and 0.25 msec wide and the other 3,000 g peak and 0.5 msec wide,
4) two half sine pulses, one 4,000 g peak and 0.25 msec wide and the other 4,000 g peak and 0.125 msec wide.

The computed shock response spectrum and the FFT results are shown in Figures 3 through 6. An overlay is provided on each figure to indicate the pulse train analyzed. There is a noticable difference in the shock and the FFT signatures between Figure 3 for the principal pulse and the following three figures. On close examination, one can see the effects of different pulse trains in the frequency and amplitude distribution.

The significant point that this analytical study shows is that more than one pulse will not have a linear accumulative effect on the frequency domain signatures. The shock spectrum maximum has increased by approximately two between Figures 3 and 4, and there is a slight increase of the maximum value of the shock spectrum between Figure 5 and 6.

IV. EXPERIMENTAL RESULTS

Four experimental runs were analyzed for this report. The experimental tests were taken on October 18, 1976, at the MSFC Shock and Vibration Laboratory. Tests 1 and 2 were acceleration measurements on a bare table as shown in Figure 1, and Tests 4 and 5 were acceleration measurements at the top of a right angle welded fixture bolted to the table.

Photographs of the accelerometer outputs with respect to time and plots of the shock response spectrum from the Spectrum Dynamics Model 320 unit are shown in Figures 7 through 10. Simultaneously, the accelerometer output was recorded on an Ampex Model PR 2200 magnetic tape recorder. These recordings were taken back to Nashville for digitization and further computer analysis.

Each experimental pulse was analyzed with the five methods listed in Section III. The results of the analysis are shown in Figures 11 through 22. The amplitude axis for the accelerometer output display is in digital step units. If these numbers are multiplied by 40.65, the axis will then be in g units.

V. DISCUSSION OF RESULTS AND CONCLUSIONS

The digitization rates for each test are listed in Table 1. The performance of the frequency signature analysis methods was noticably different for Test 4 which was digitized at 1/4 the rate of the other tests. Thus, one can say that the higher sampling rate does make a difference and that the leading edge portion of the pulse train is to be preferred for computational studies.

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The computed shock response was made for a 5% damped SSDF resonator and is labled SHOCK on the respective figures. The on site plot of the response spectrum is labled SHOCK MSFC. For the 2.5 microsec per sample data, there is reasonable agreement between the SHOCK and SHOCK MSFC curves. The differences are assumed to be related to the gain factor used and a correction would move the curves vertically. The response spectrum for Tests 4 and 5 are noticably lower in the frequency range between 1 and 5 KHz when the spectrums are compared to Tests 1 and 2.

The Fast Fourier Transform results in Tests 1 and 2 indicate that the principal frequency of the pulse is at 2 KHz and secondary frequencies are seen at 3.0,3.7, and 4.6KHz. When the right angle support fixture was added, Tests 3 and 4, the 2 KHz frequency seems to be absorbed and the secondary frequencies are 3.0, 4.0 and 5.0 KHz. This is a good feature about the FFT signature in that it points out how the mounting fixtures may be changing the vibration environment of the component under test.

The distribution of peak amplitudes signature is a good means for classification of the total ring-down pulse package. But, it does not appear to have an application as a shock test monitor and control technique.

The velocity display was calculated by numerical integration of the acceleration data. Notice that most of the fixture resonance acceleration was removed by the integration and a clear indication of the input shock was produced. Rise time is defined as the time for a wave to pass from 10 percent to 90 percent of the peak response. The ΔV value shown on the relevant figures is the magnitude of

the initial step change in velocity. The average acceleration is 0.8 x ΔV / rise time. Notice that the ΔV values and the average accelerations are reasonably close for the two tests under similar conditions.

For a half sine pulse of acceleration the peak acceleration is 1.159 times the average acceleration as defined above. The calculated average accelerations can be corrected if one assumes that a half sine pulse is a good representation of the input pulse. The corrected accelerations computed from the velocity display data are shown in Table 2. This table also shows the corrected acceleration in the equivalent digital steps in order to facilitate comparison with the acceleration display data. Looking back at the acceleration plots one can see that the calculated peak acceleration from the velocity plots would possibly agree if the high frequency structural ringing were not present. This example demonstrates that the acceleration plots could be giving erroneous shock information when the structural resonant period is similar to or shorter than the shock pulse period. This seems to be the case with the mechanical shock test data examined in this report.

The acceleration peaks derived by the different signature analysis methods are shown in Table 1.

In summary, of the five signature analysis methods examined the velocity display and the average acceleration calculation appear to be the best means for unambiguous monitoring and control of the mechanical shock tests.

Table 1. Experimental Test Results of Peak Acceleration Amplitudes

Test No.	Digital Sample rate	Time plot Acceleration	Frequency plot FFT	Frequency plot Shock	Velocity plot Avg. Acc.
	μsec	g	g	g	g
1	2.5	3,000	3,700	4,000	1,973
2	2.5	3,450	3,800	4,300	2,115
4	10.0	2,600	2,700	4,600	1,162
5	2.5	3,600	2,850	3,900	1,159

Table 2. Correction of Average Accelerations Based on an Assumed Half Sine Input Shape.

Test No.	Average acceleration	Corrected acceleration	
	g	g	digital steps
1	1,973	2,286	56
2	2,115	2,451	60
4	1,162	1,346	33
5	1,159	1,343	33

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FIGURE 21. SHOCK SPECTRUM AND FFT SPECTRUM; TEST 5

FIGURE 22. A) VELOCITY STEP AND B) PEAK ACCELERATION DISTRIBUTION; TEST 5

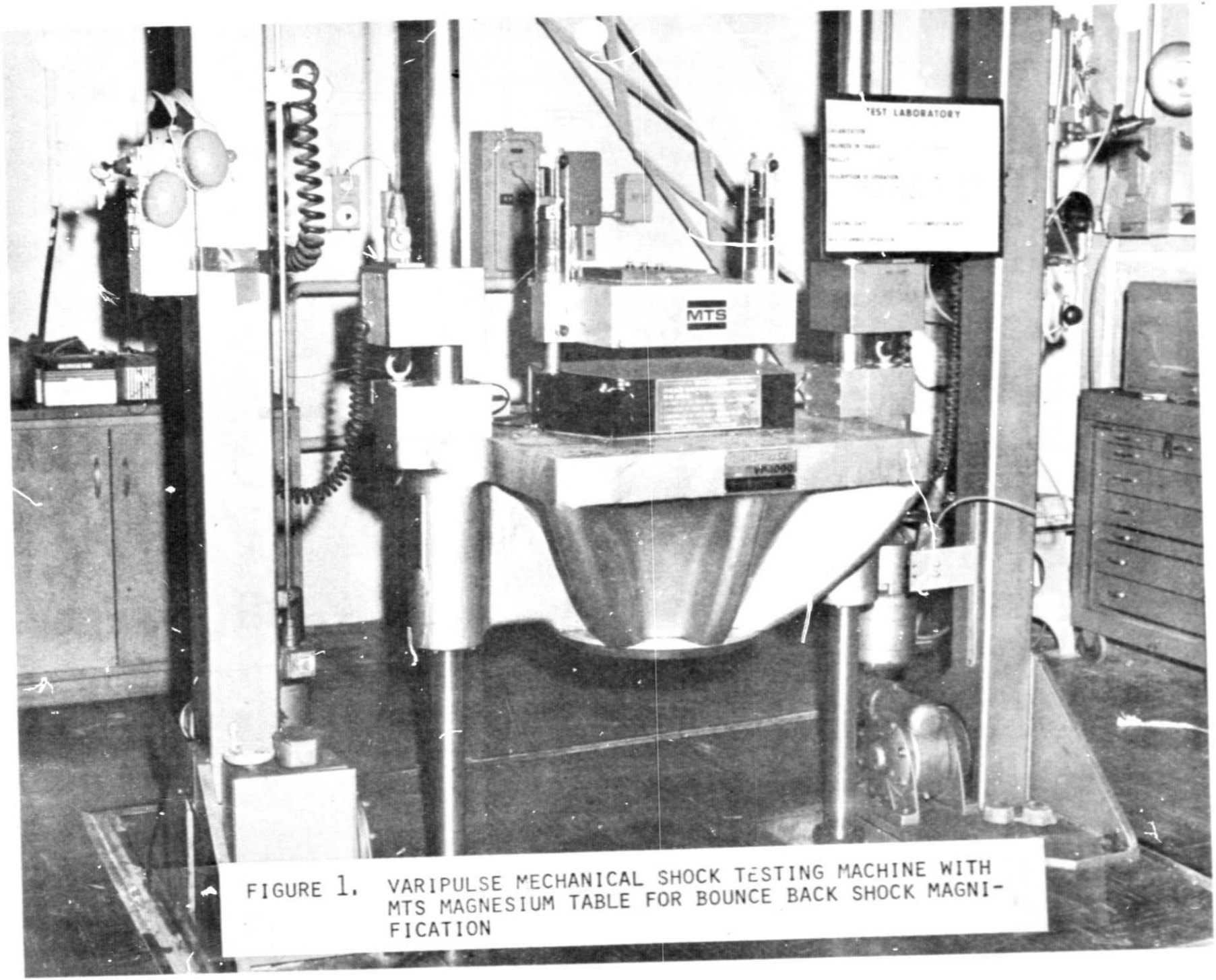
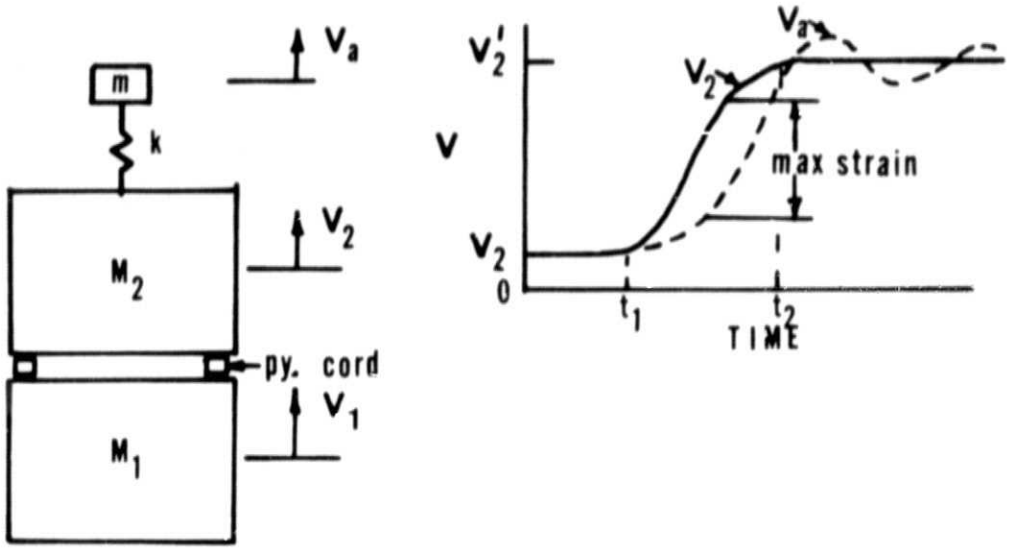
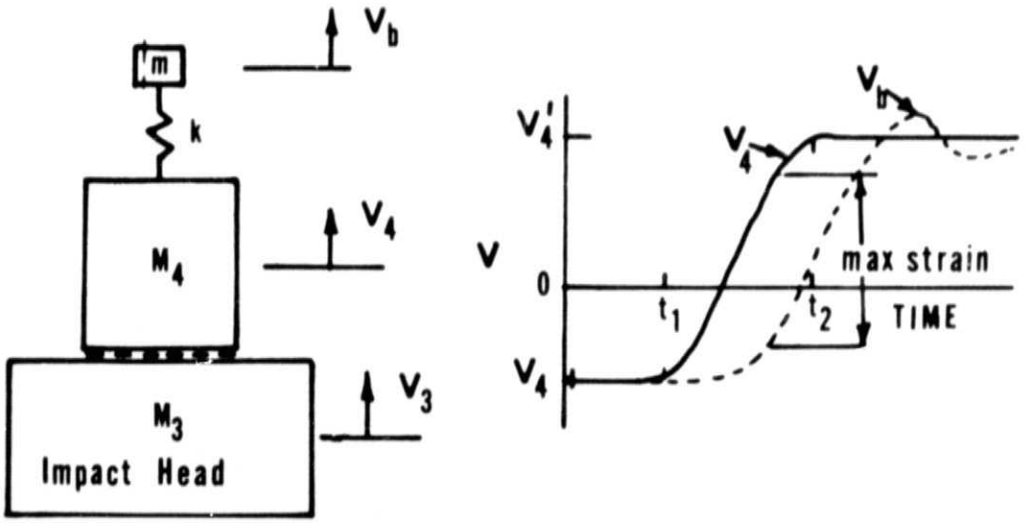


FIGURE 1. VARIPULSE MECHANICAL SHOCK TESTING MACHINE WITH MTS MAGNESIUM TABLE FOR BOUNCE BACK SHOCK MAGNIFICATION



a) Rocket pyrotechnic impulse



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b) Mecanical impact testing machine

FIGURE 2. SKETCH OF MODEL IMPACT COMPONENTS

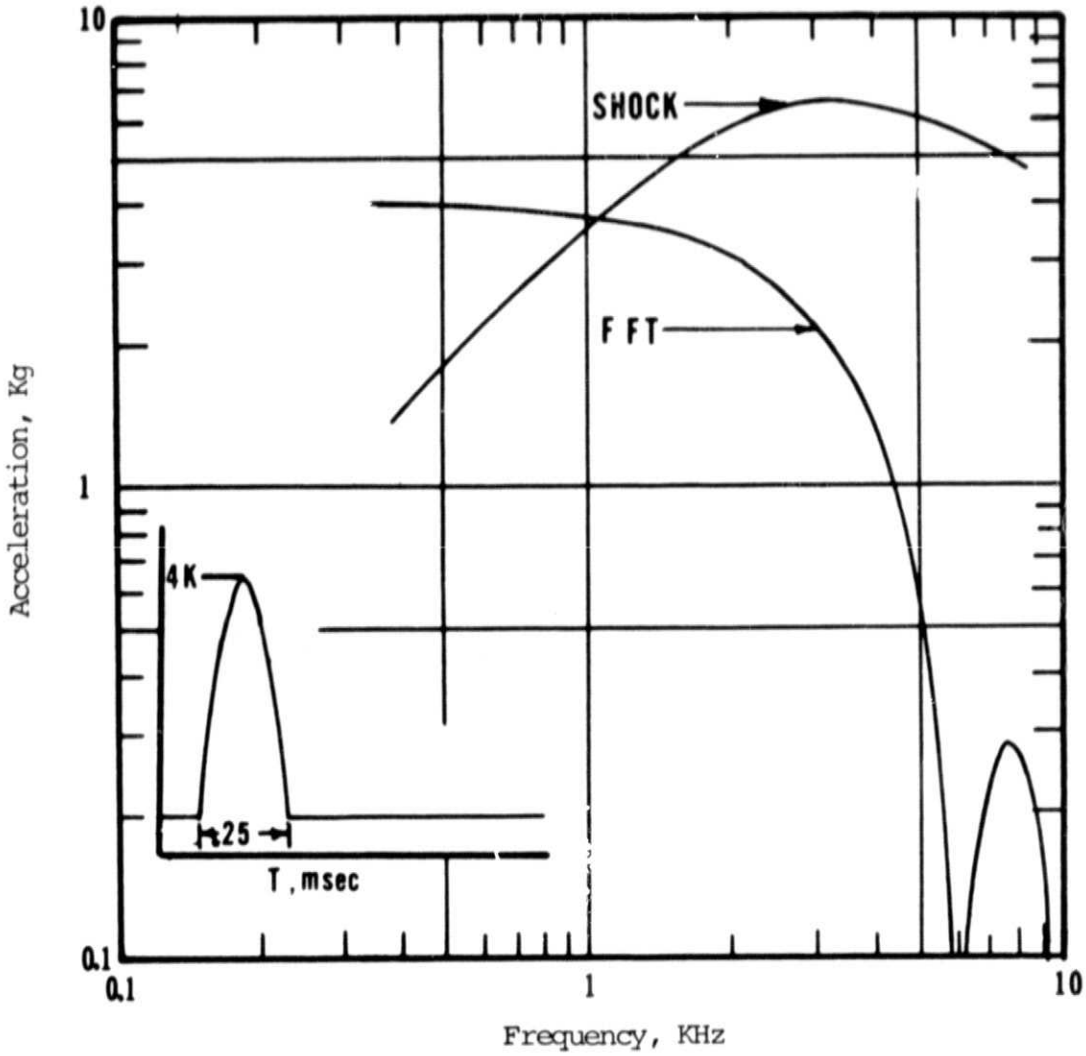

FIGURE 3. SINGLE HALF SINE PULSE; SHOCK RESPONSE SPECTRUM AND FFT SPECTRUM.

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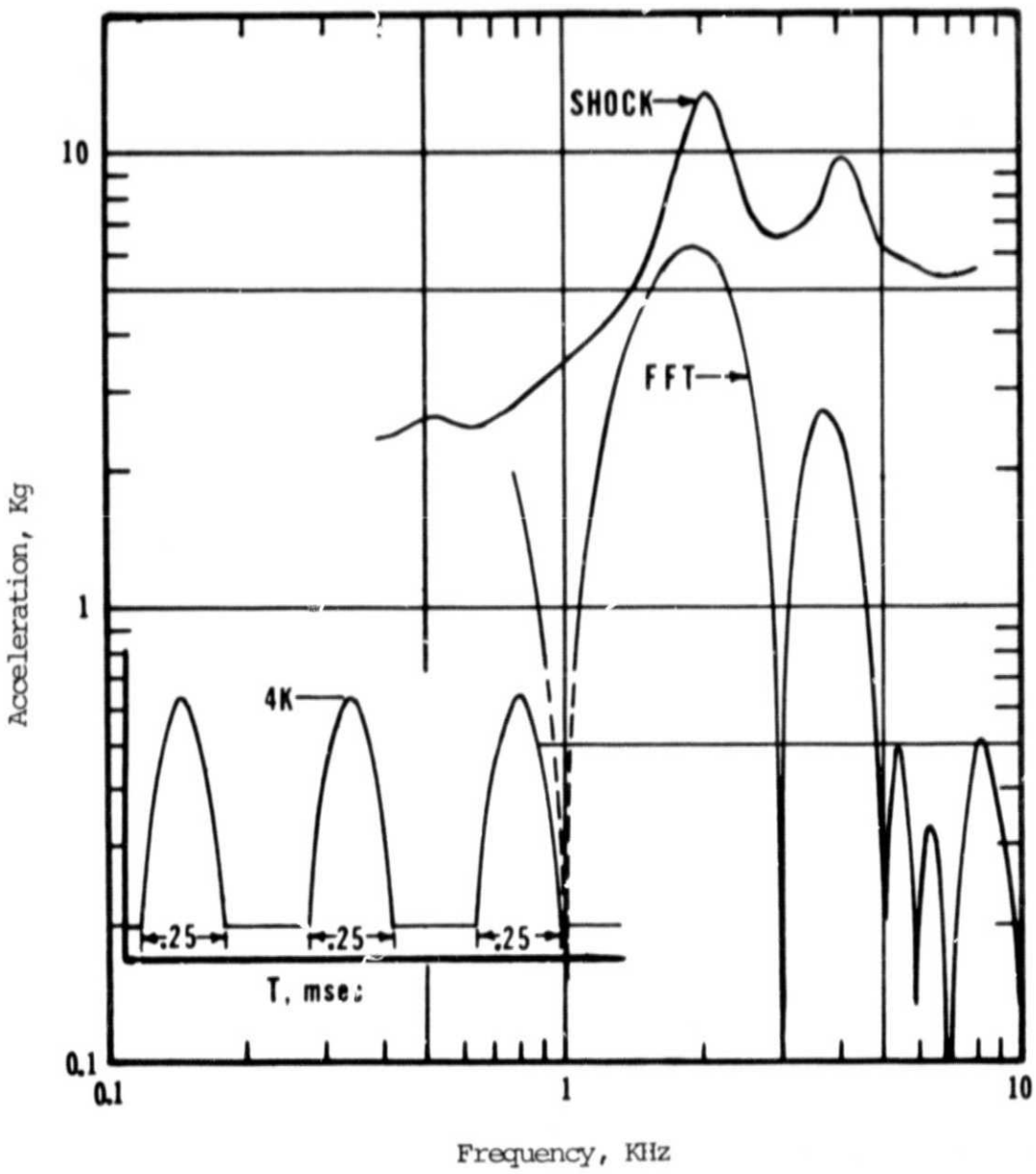

FIGURE 4. THREE IDENTICAL HALF SINE PULSES; SHOCK RESPONSE SPECTRUM AND FFT SPECTRUM.

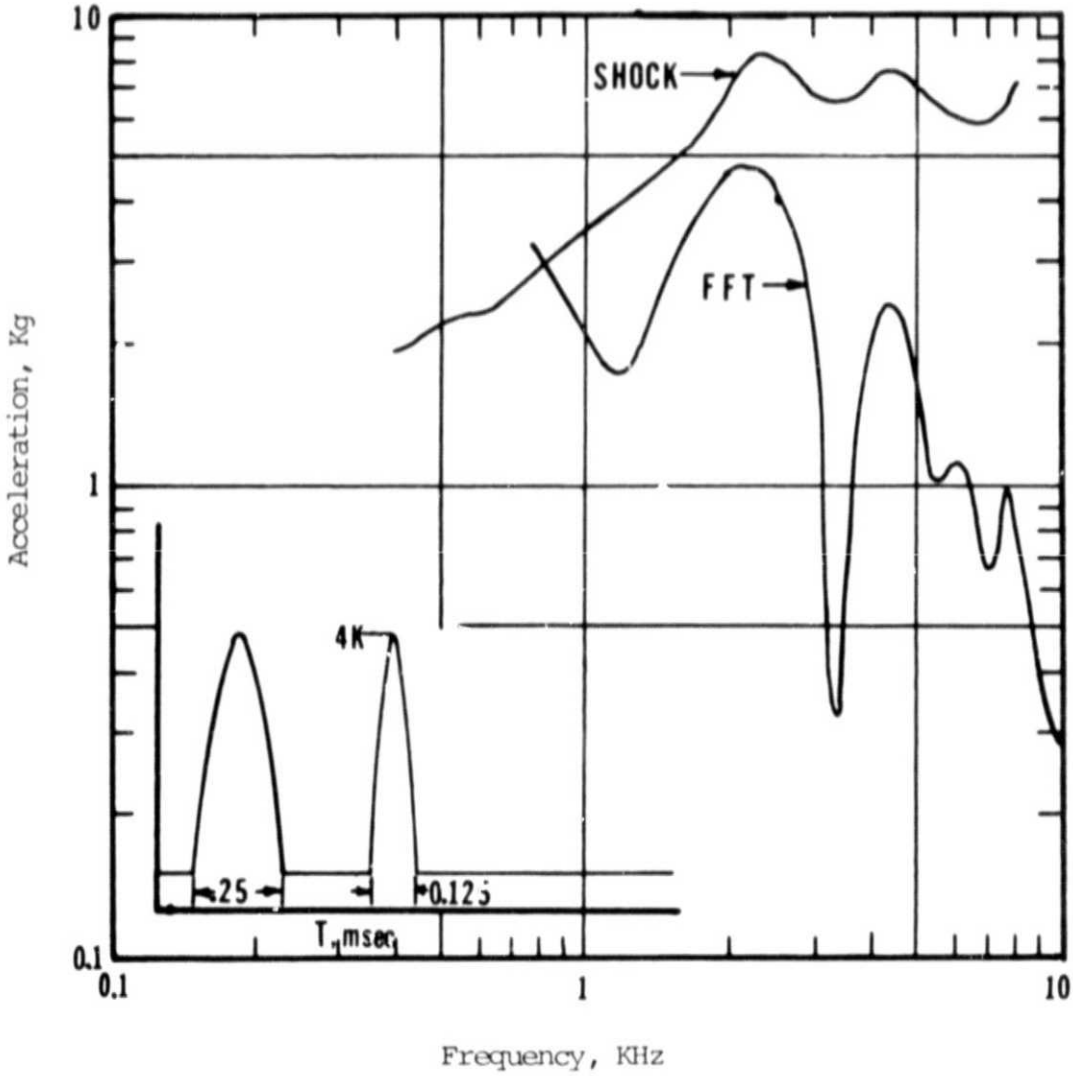

FIGURE 5. TWO HALF SINE PULSES OF DIFFERENT WIDTHS SHOCK RESPONSE SPECTRUM AND FFT SPECTRUM.

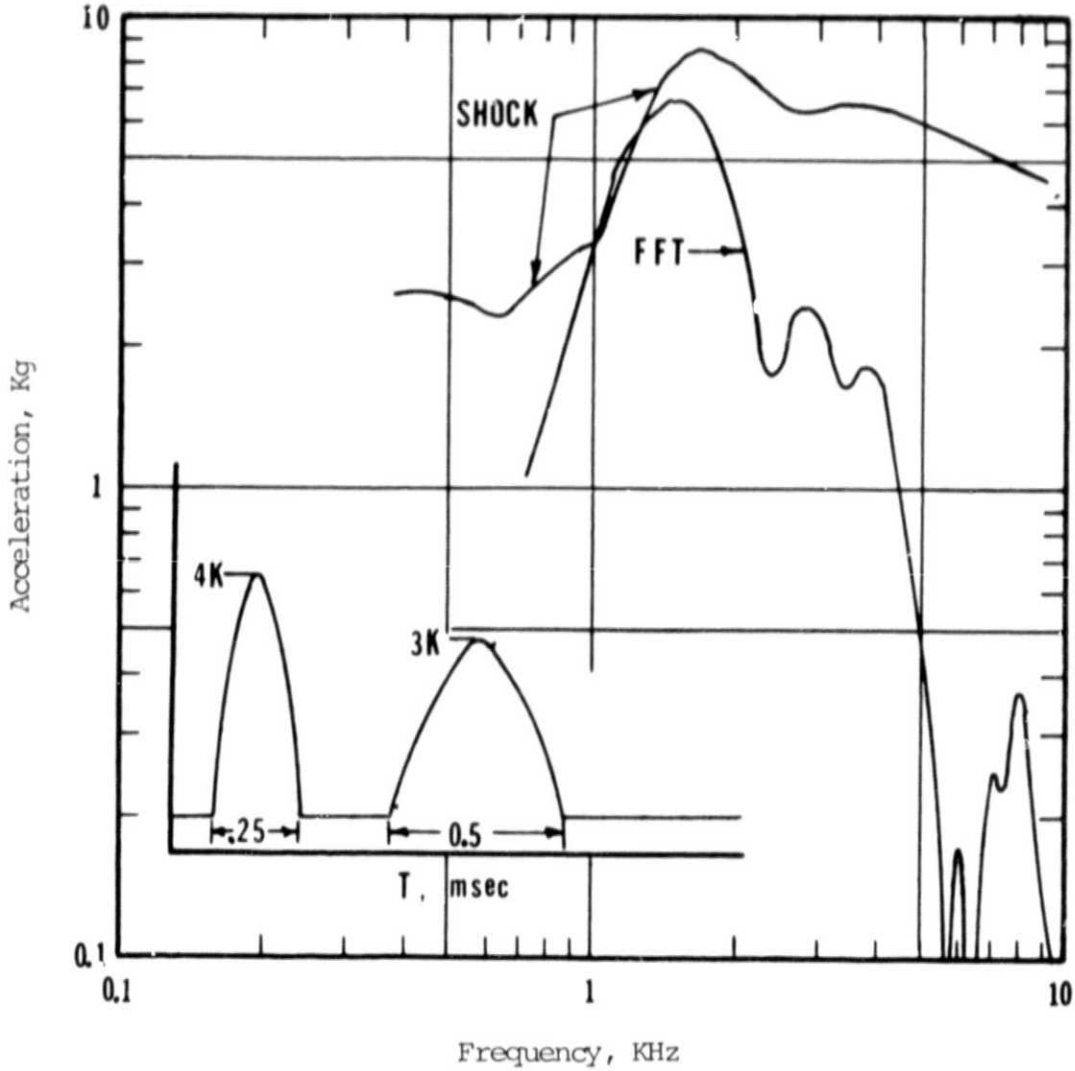

FIGURE 6. TWO HALF SINE PULSES OF DIFFERENT HEIGHT AND WIDTH; SHOCK RESPONSE SPECTRUM AND FFT SPECTRUM.

1.1018

TEST ITEM BARE TABLE
IDENT. NO. TEST 1 DATE 10-18-76
ACC. NO. 1 AXIS ___ SPEC. ___
FULL SCALE TIMES 10 Kg

10" Drop
2. 2740A Endevco CA 5 Kg FS = 5 vp
3. ARMS GASKET
4. SD 320 10 vp range + 10 Kg FS
5. ζ = 0.05 1/3 oct. Anal.

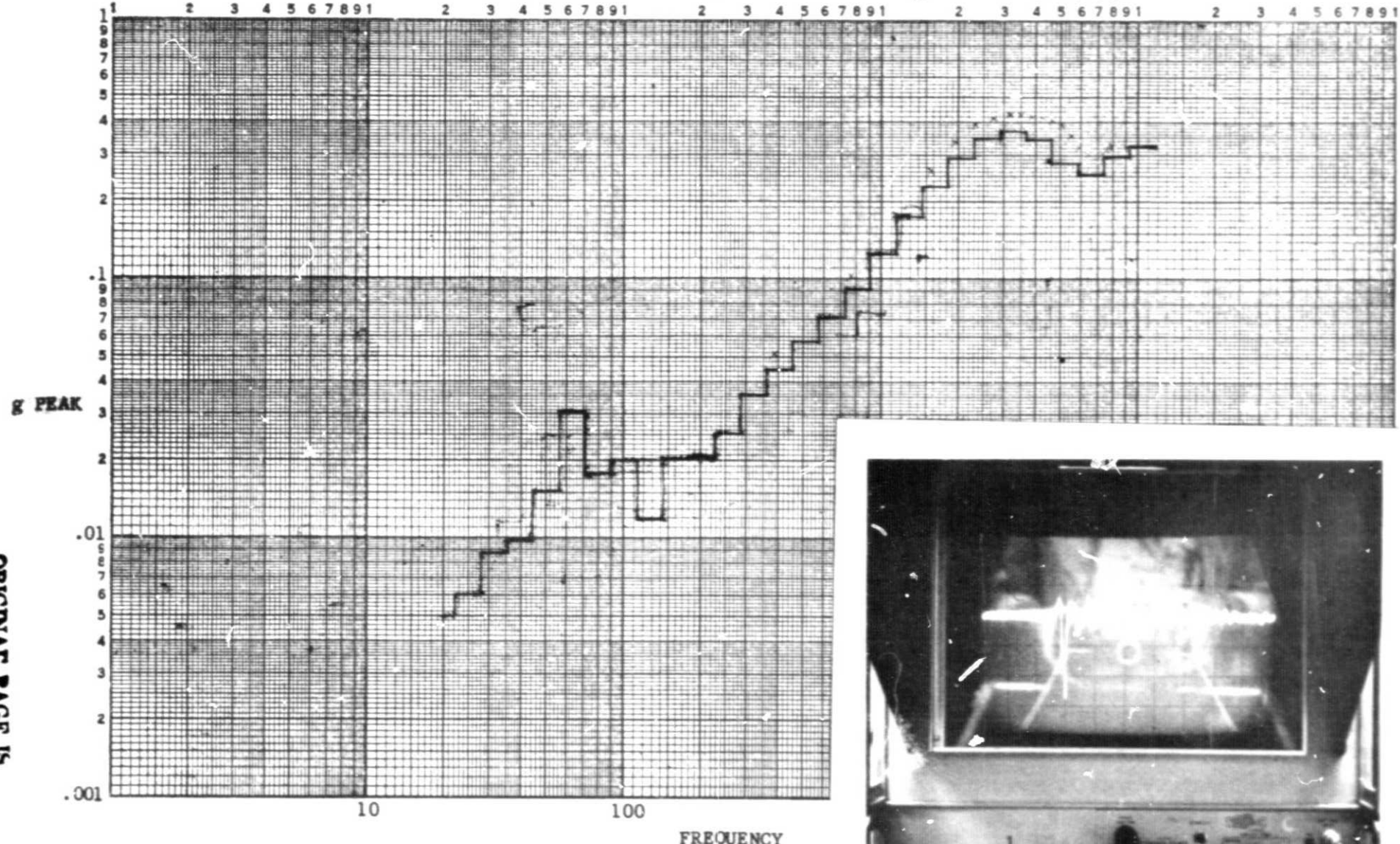

FIGURE 7. EXPERIMENTAL RESULTS MSFC; TEST 1

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TEST ITEM
IDENT. NO. TEST 2 DATE 10-18-76
ACC. NO. 1 AXIS SPEC.
FULL SCALE TIMES 10 Kg

SAME

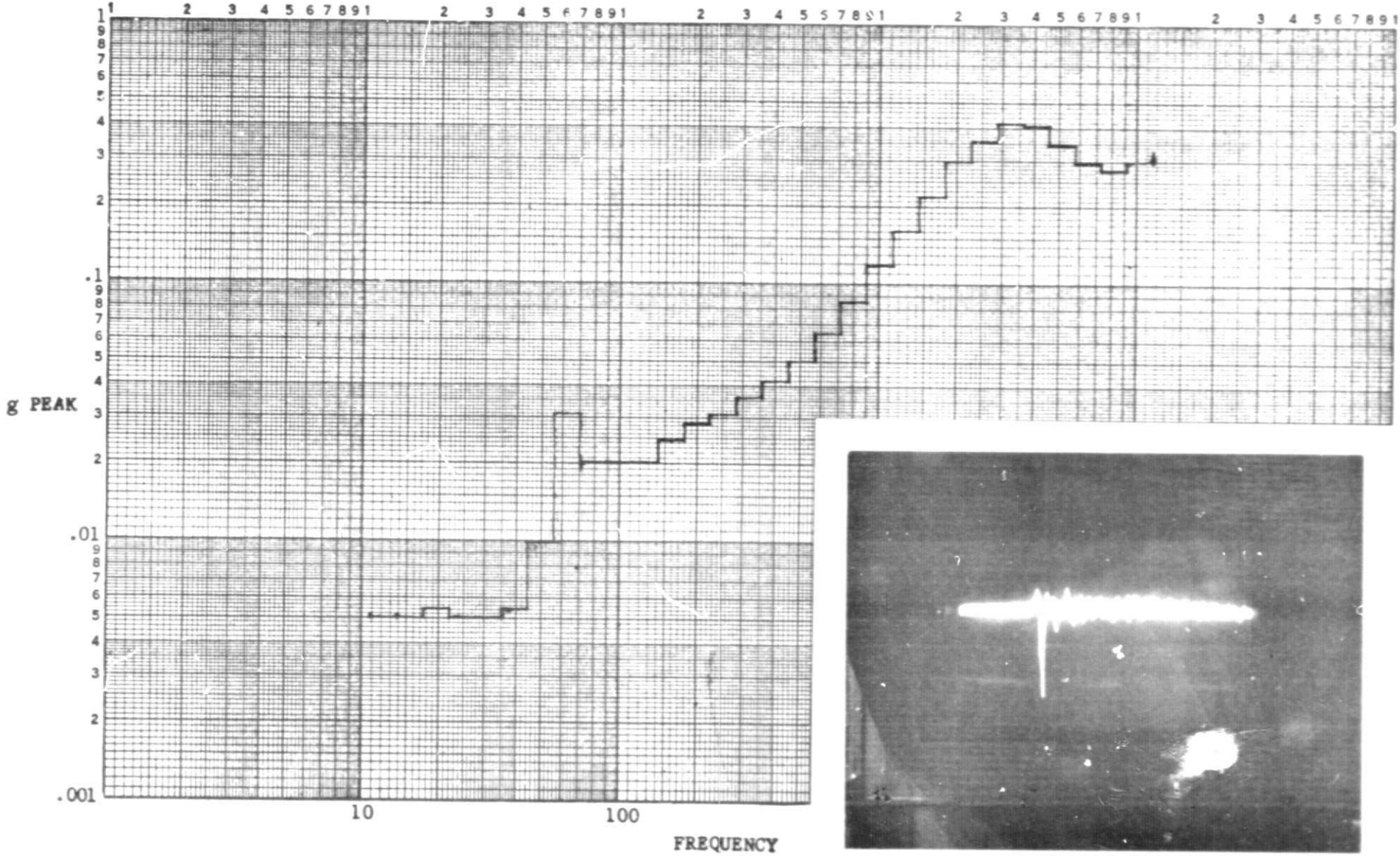

FIGURE 8. EXPERIMENTAL RESULTS AT MSFC; TEST 2

TEST ITEM Rt. Angle Fix.
IDENT. NO. Test 4 DATE 10-18-76
ACC. NO. 1 AXIS ___ SPEC. ___
FULL SCALE TIMES 10K

SAME

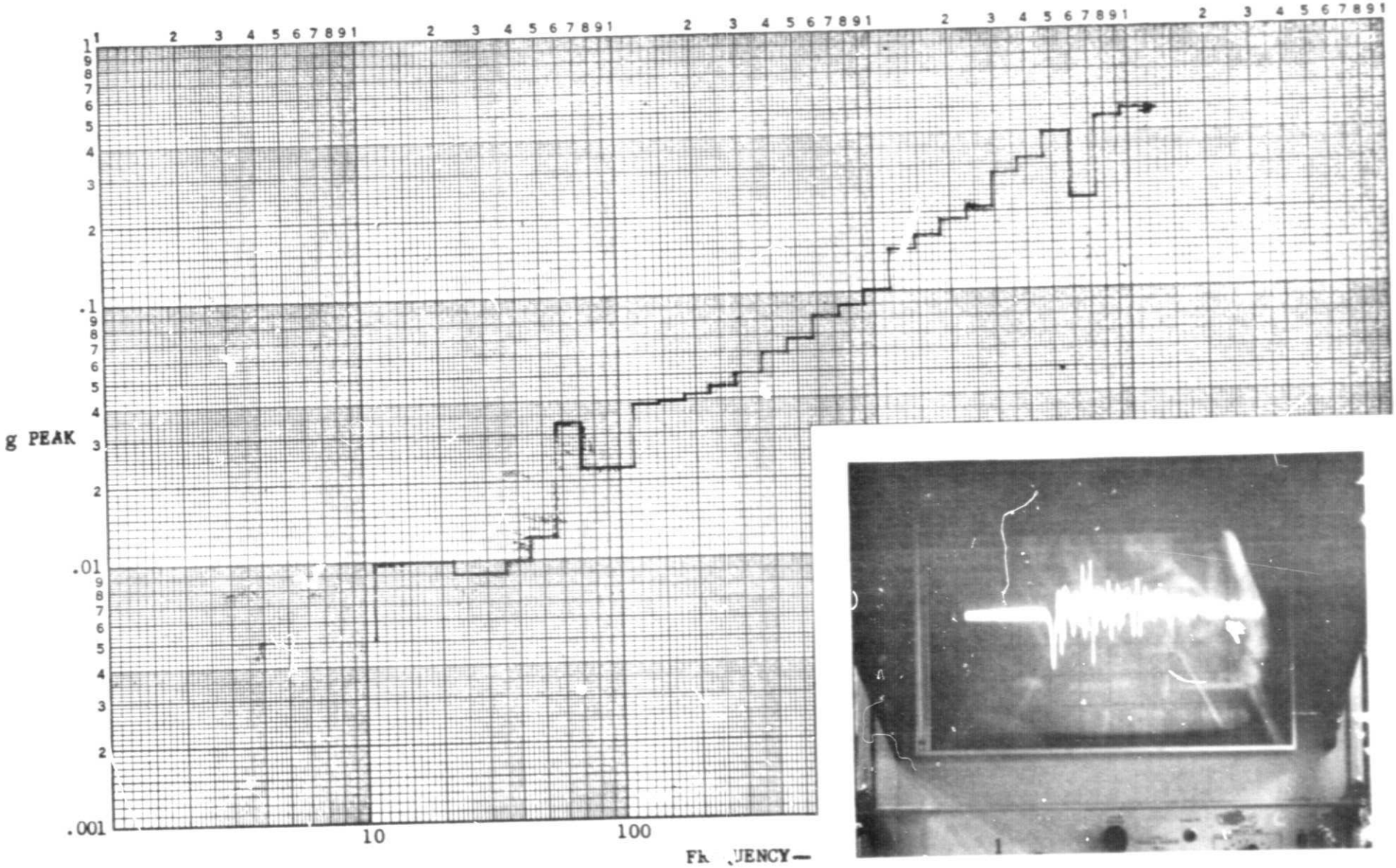

FIGURE 9. EXPERIMENTAL RESULTS AT MSFC; TEST 4

TEST ITEM Rt. Angle Fix
IDENT. NO. KGJ5 DATE 10-18-76
ACC. NO. ____ AXIS ____ SPEC. ____
FULL SCALE TIMES 10K

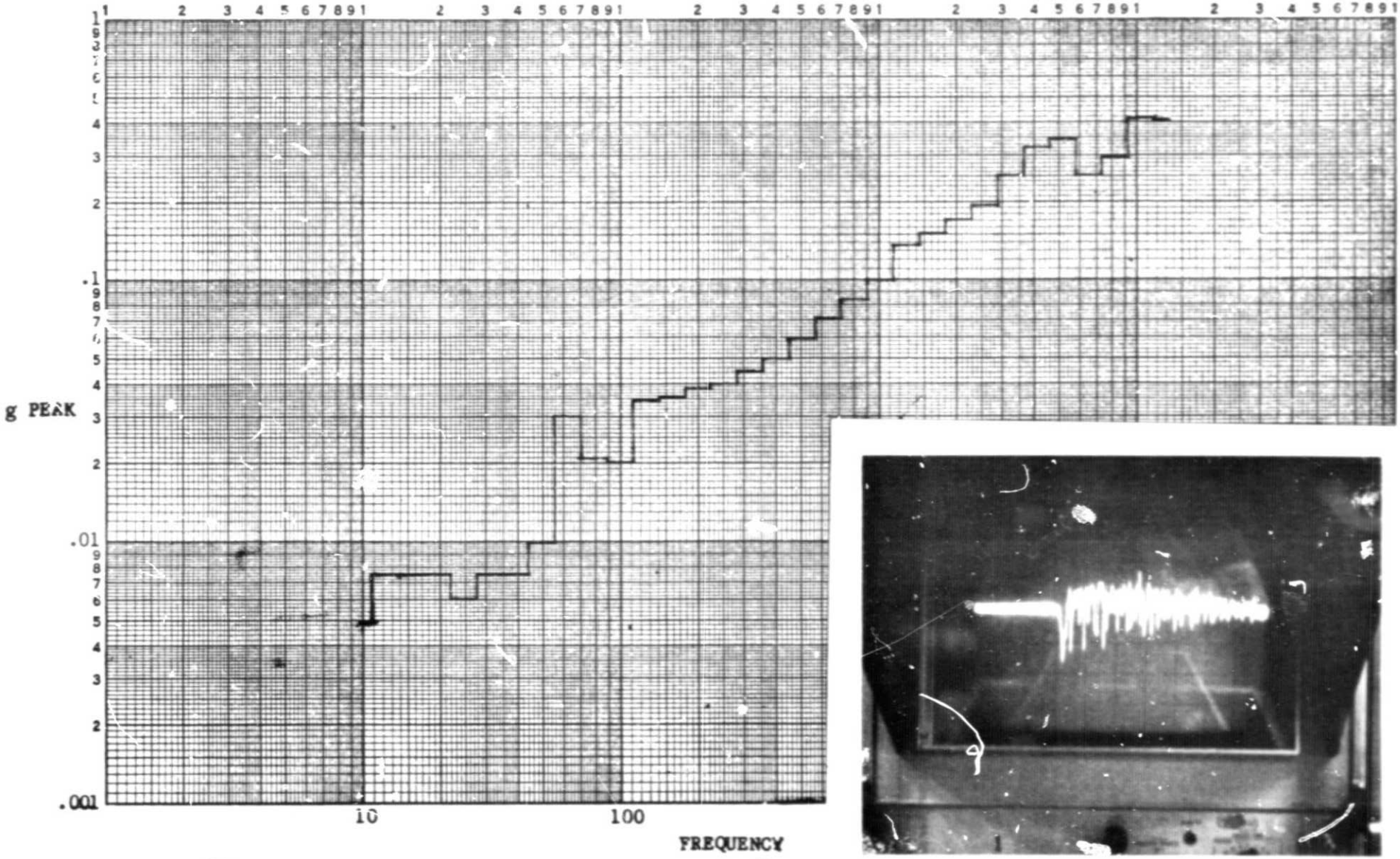

FIGURE 10. EXPERIMENTAL RESULTS AT MSFC; TEST 5

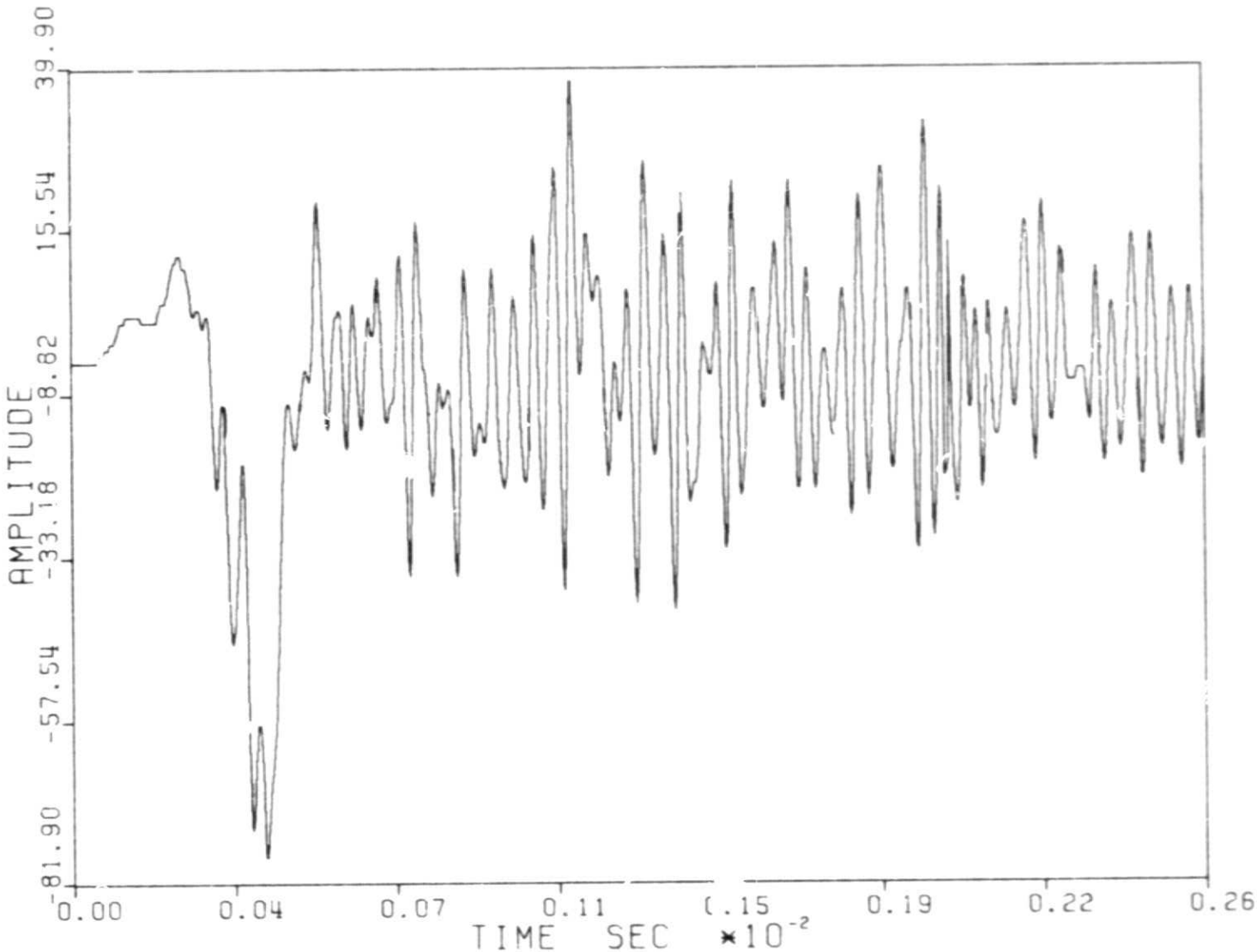

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FIGURE 11. DIGITIZED ACCELERATION PULSE; TEST 1, 1300 POINTS

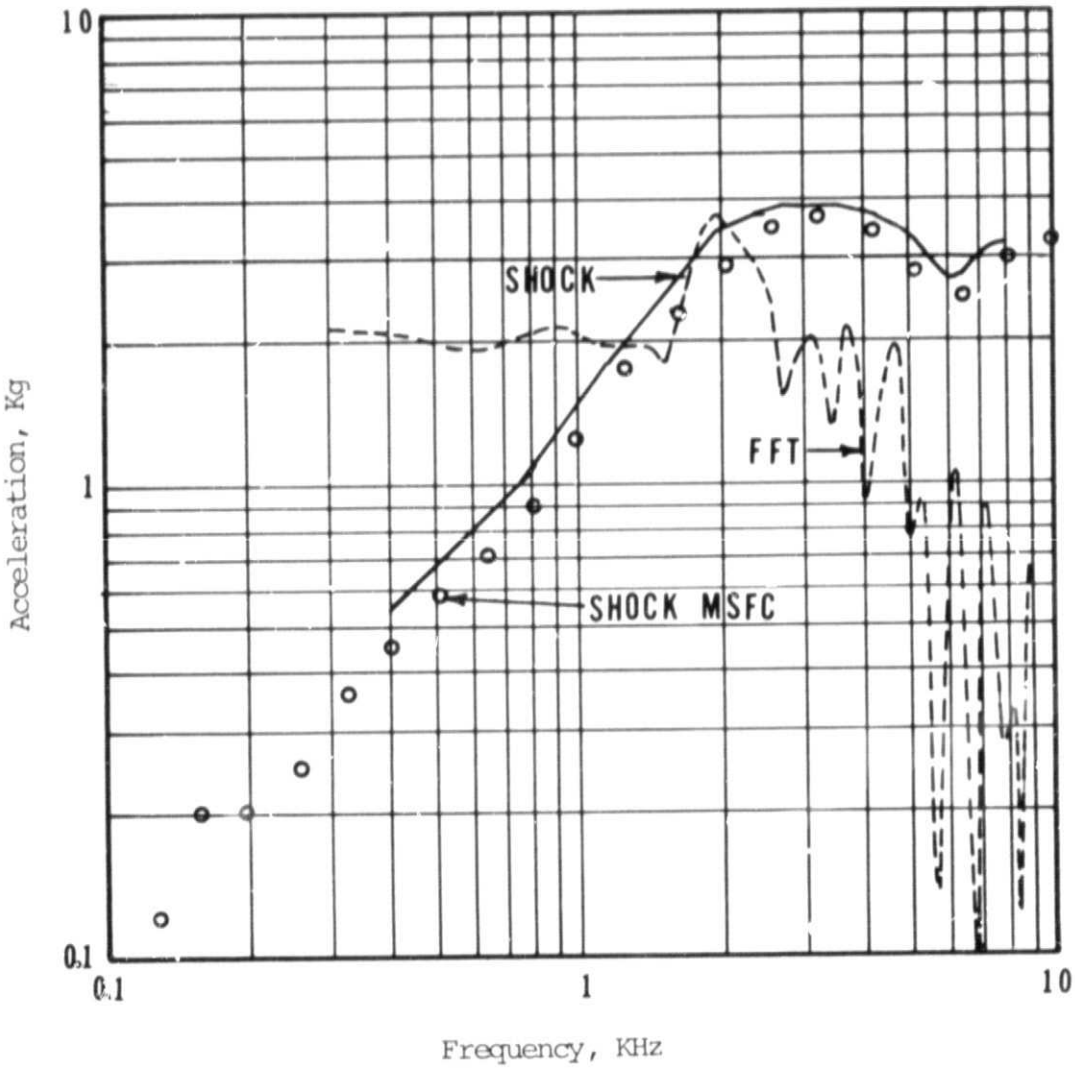

FIGURE 12. SHOCK SPECTRUM AND FFT SPECTRUM; TEST 1

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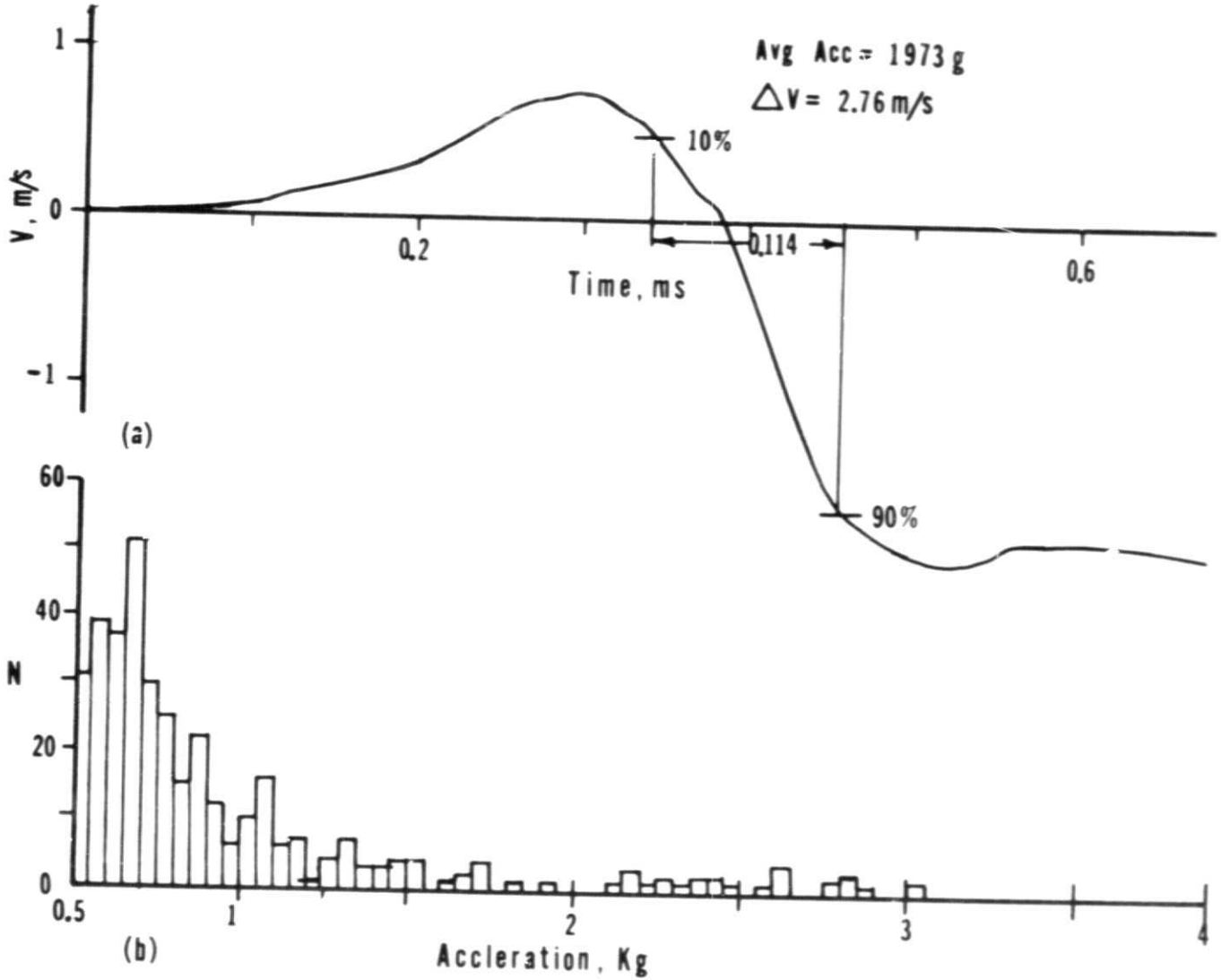

FIGURE 13. A) VELOCITY STEP AND B) PEAK ACCELERATION DISTRIBUTION; TEST 1

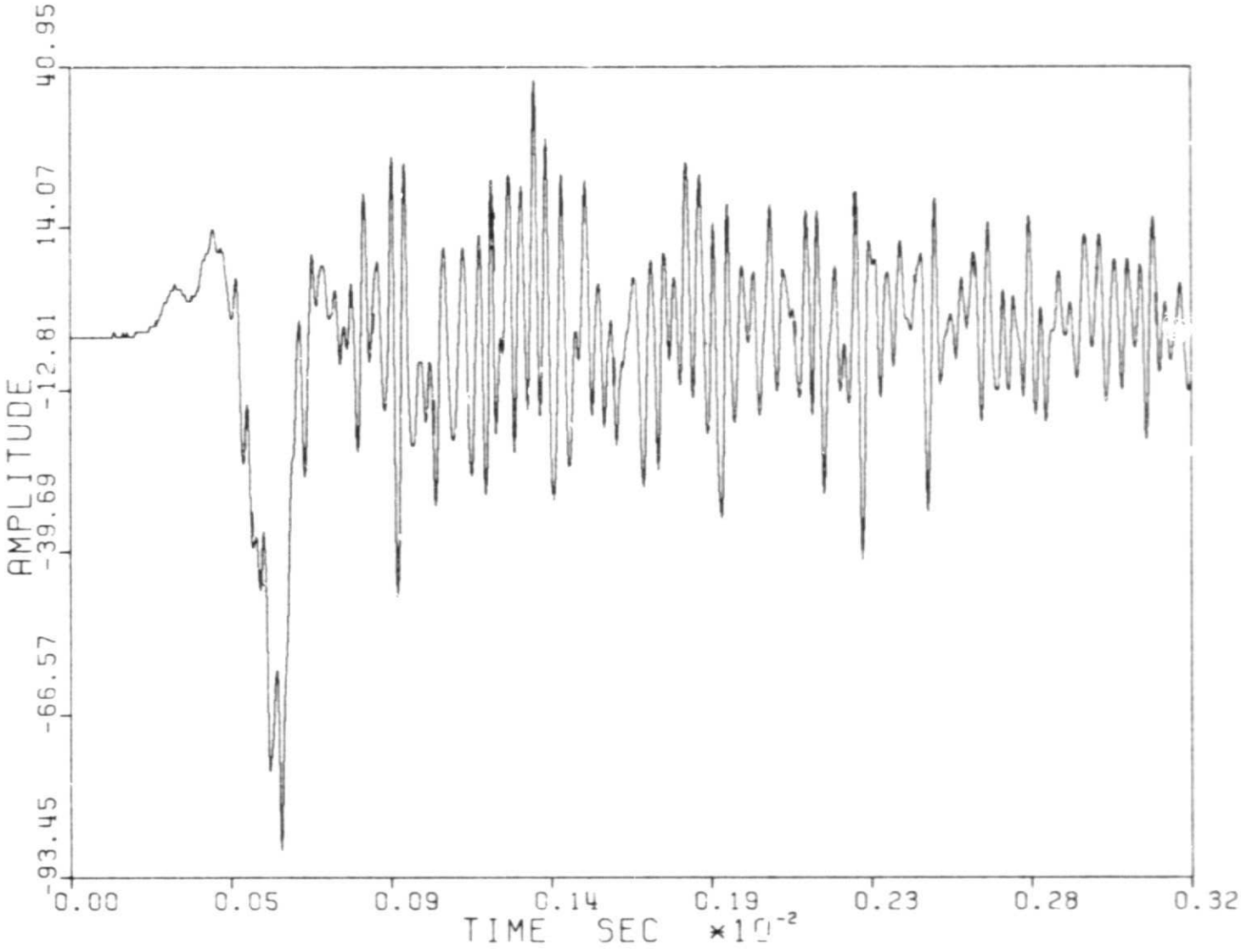

FIGURE 14. DIGITIZED ACCELERATION PULSE; TEST 2, 1040 POINTS

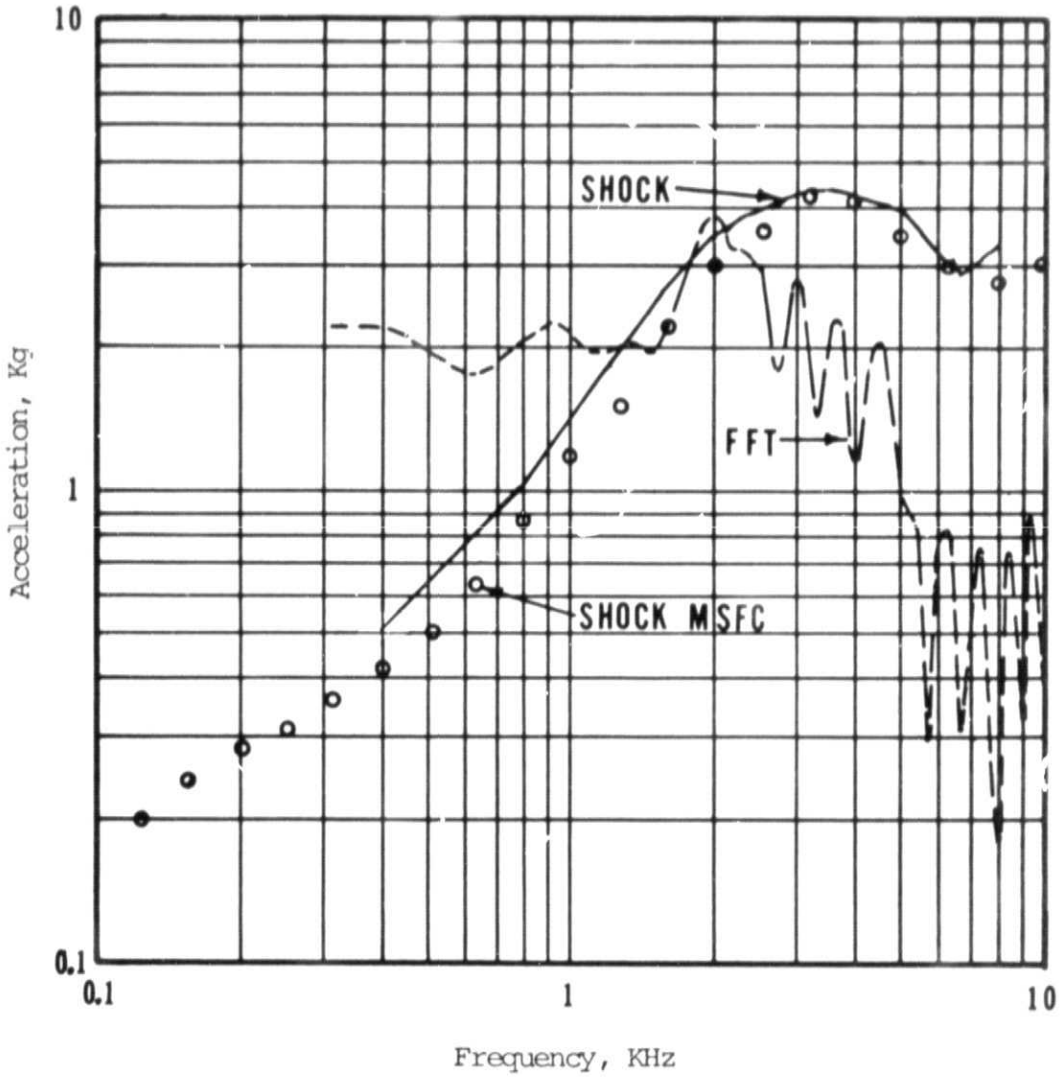

FIGURE 15. SHOCK SPECTRUM AND FFT SPECTRUM; TEST 2

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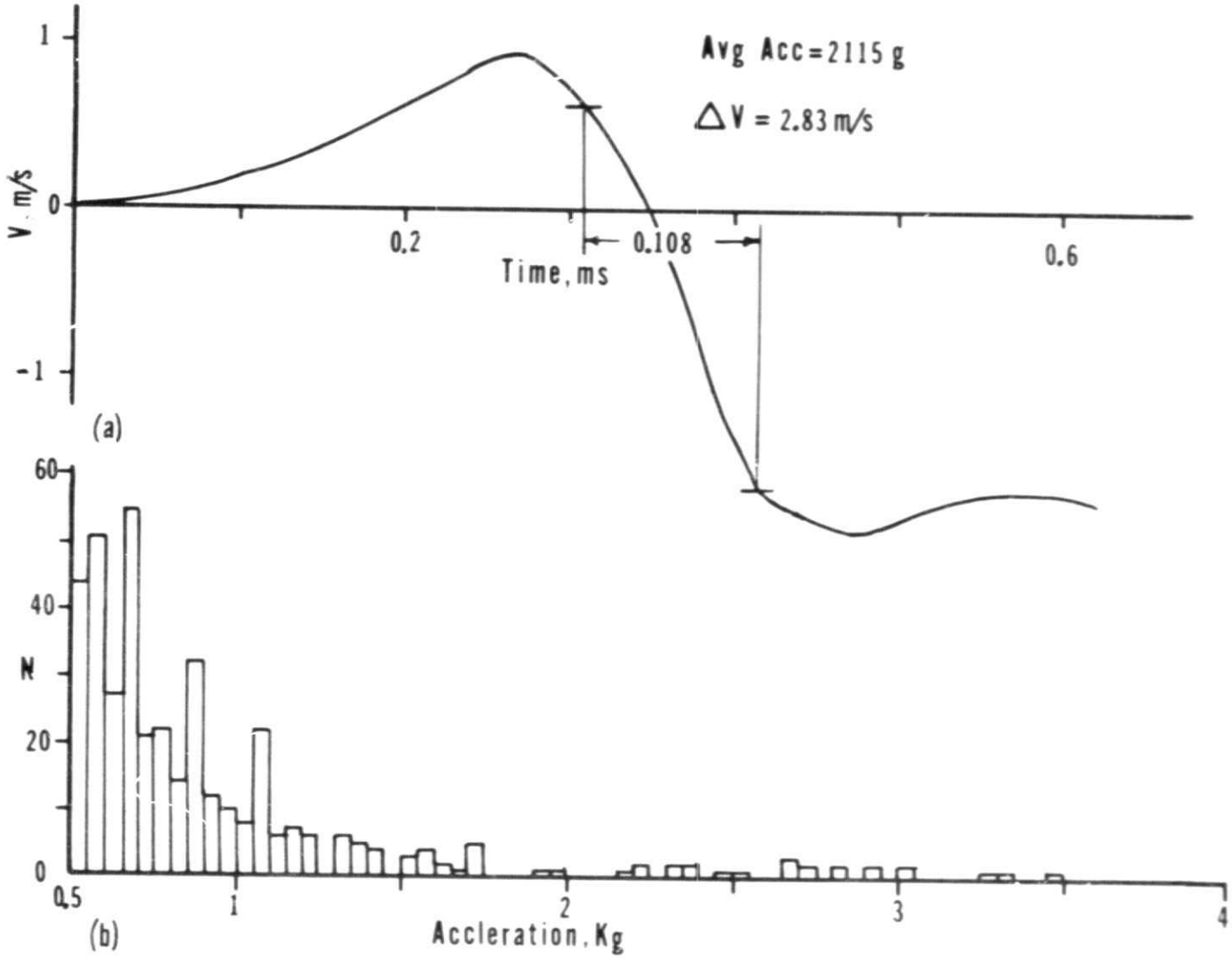

FIGURE 16. A) VELOCITY STEP AND B) PEAK ACCELERATION DISTRIBUTION; TEST 2

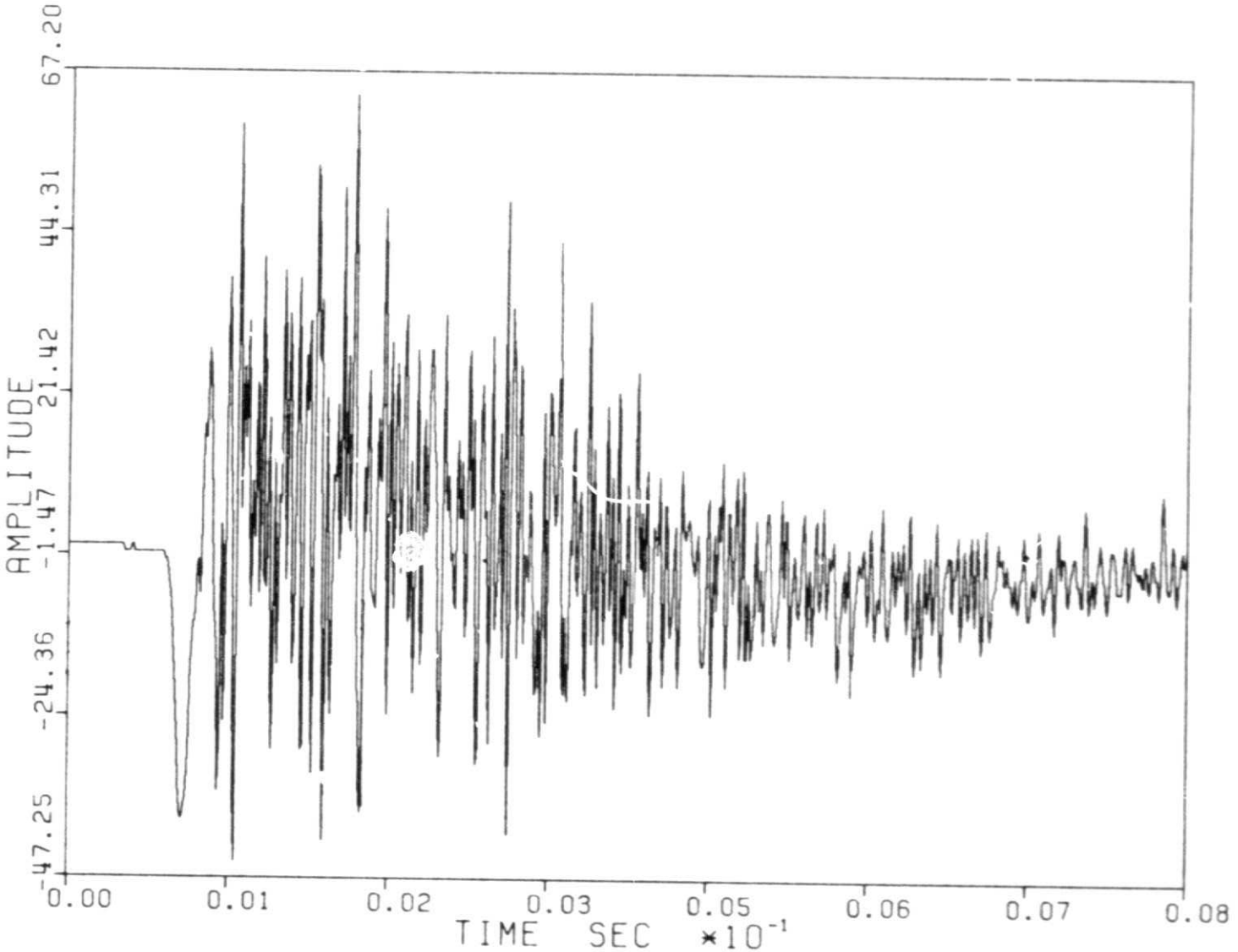

FIGURE 17. DIGITIZED ACCELERATION PULSE; TEST 4, 800 POINTS

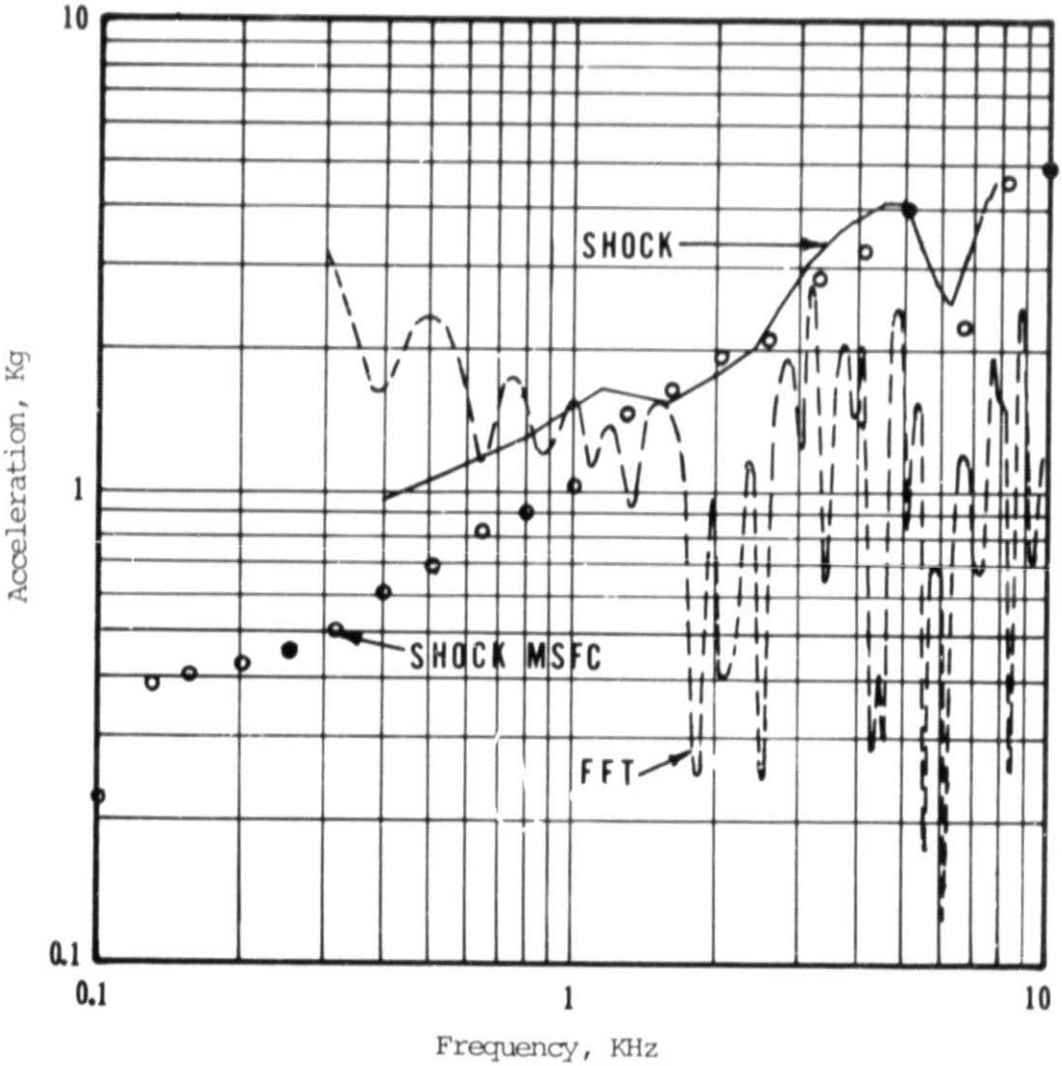

FIGURE 18. SHOCK SPECTRUM AND FFT SPECTRUM; TEST 4

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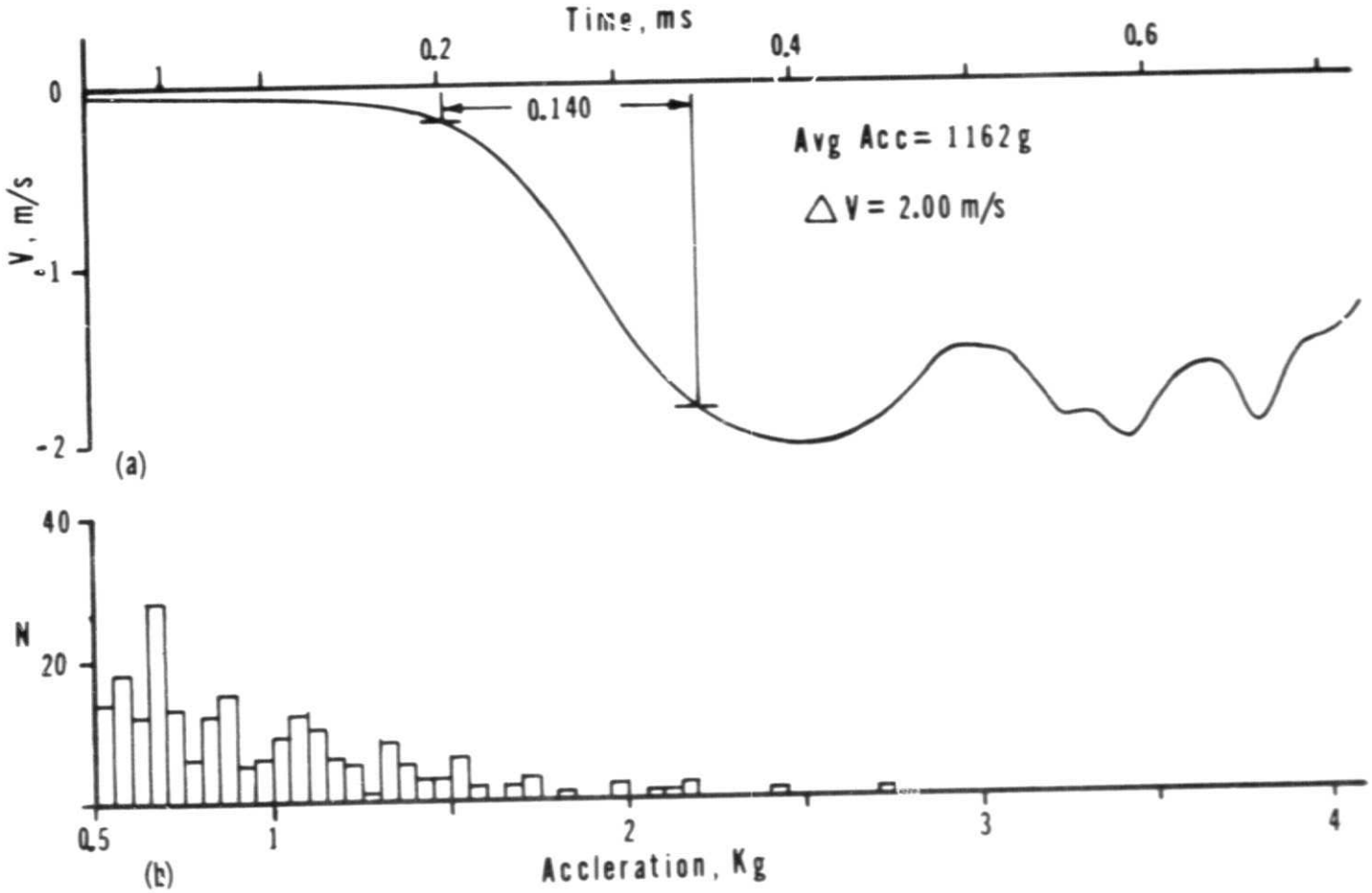

FIGURE 19. A) VELOCITY STEP AND B) PEAK ACCELERATION DISTRIBUTION; TEST 4

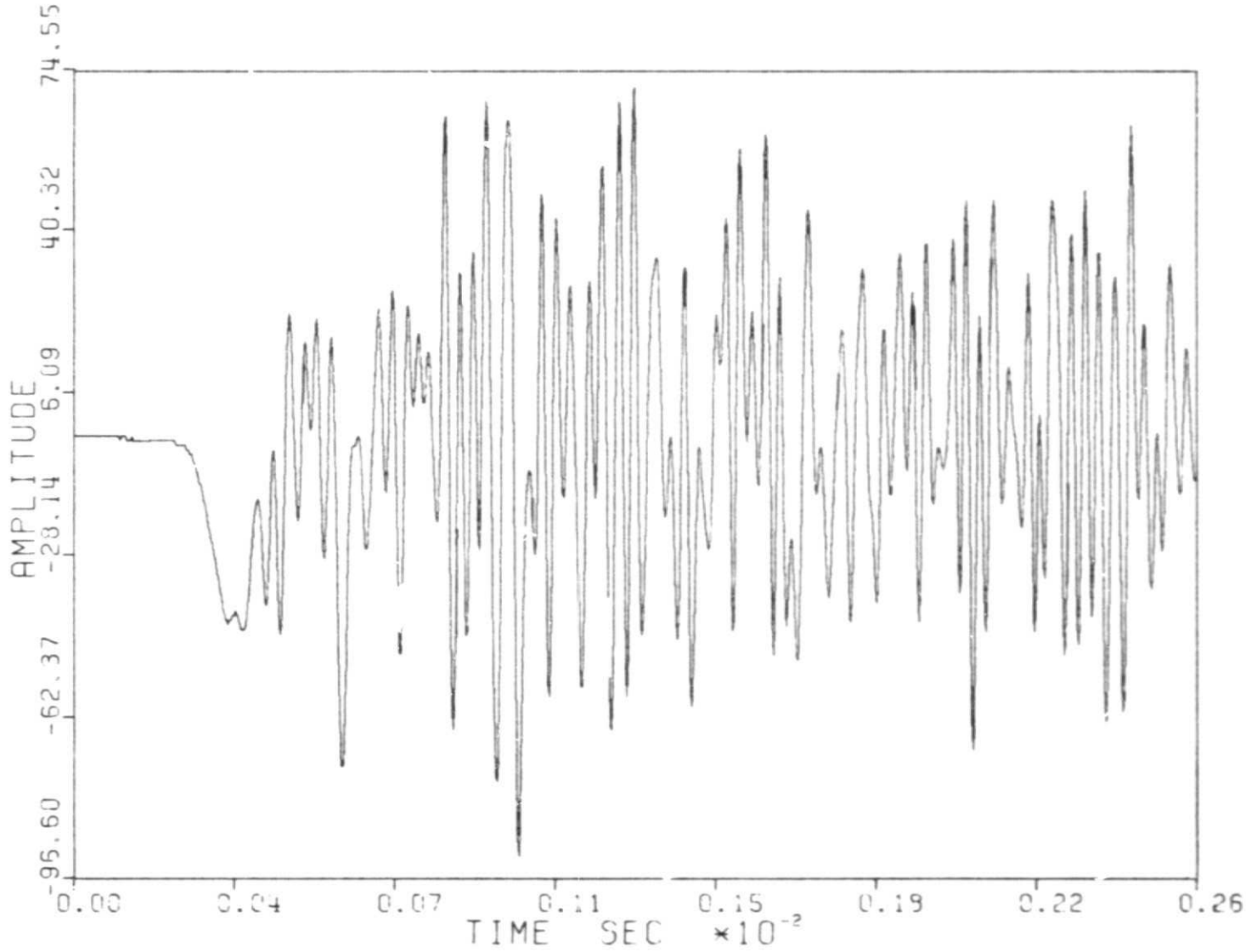

FIGURE 20. DIGITIZED ACCELERATION PULSE; TEST 5, 1030 POINTS

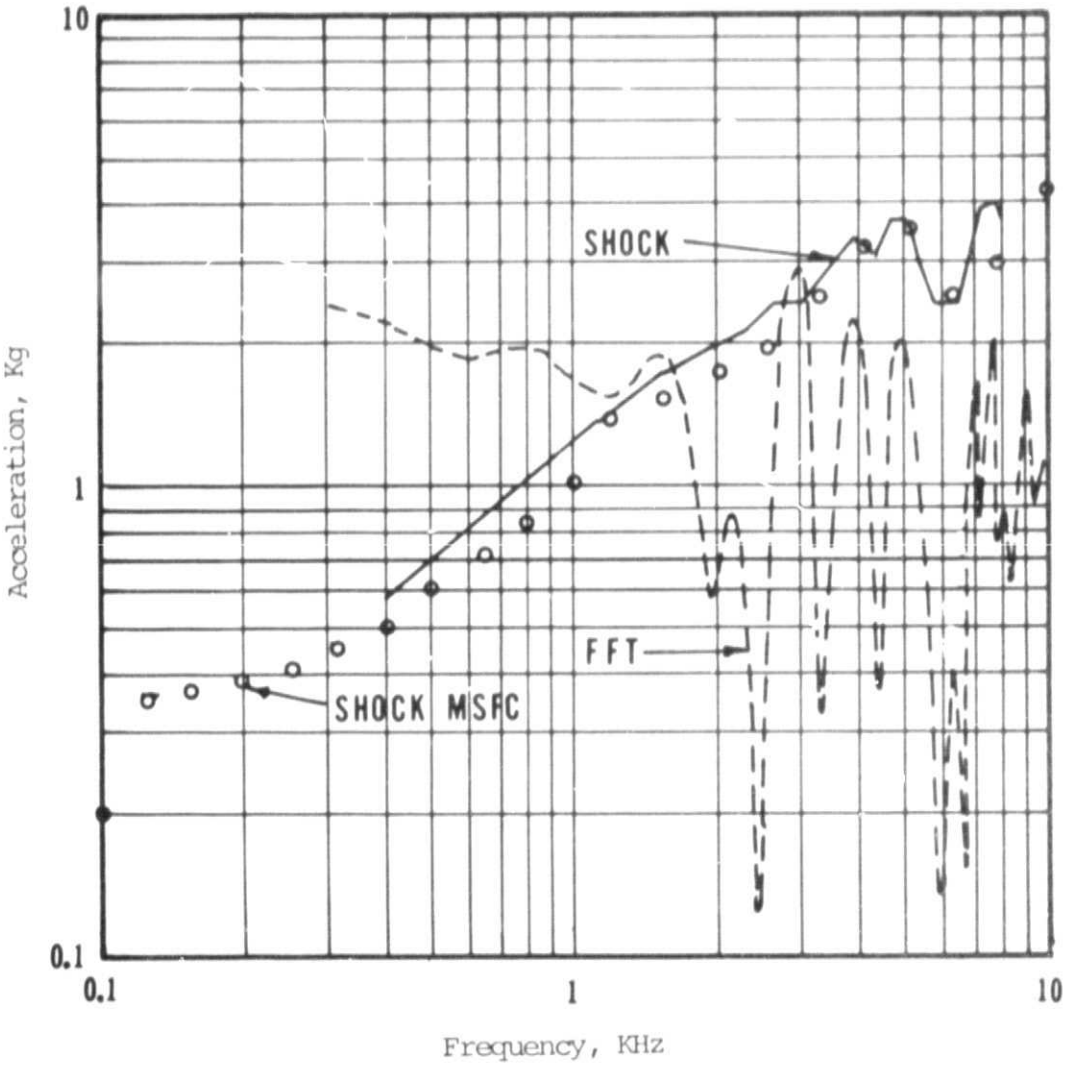

FIGURE 21. SHOCK SPECTRUM AND FFT SPECTRUM; TEST 5

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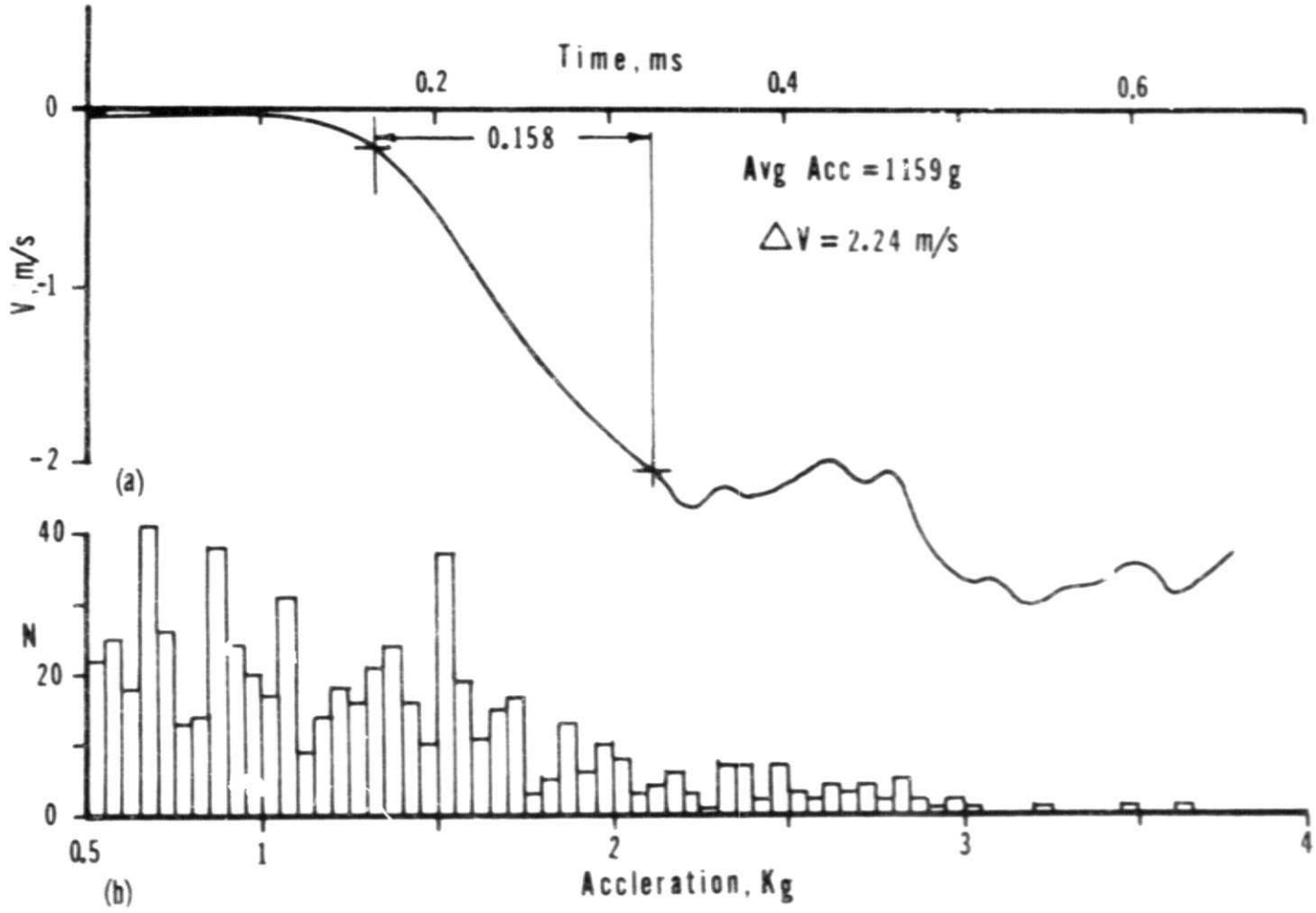

FIGURE 22. A) VELOCITY STEP AND B) PEAK ACCELERATION DISTRIBUTION; TEST 5