REMOVING RESONANCES IN AUTOMOTIVE CRASH TEST INSTRUMENTATION

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Summary. Unwanted resonances can make analysis of crash instrumentation extremely difficult. These resonances are a natural part of the acceleration measurements and in many cases are allowed to be present to maintain the needed high-frequency responses. Crystal accelerometers are, for instance, essentially undamped, and have resonance humps 40 dB above unity in order to maintain a flat response to approximately one-half the resonance or natural frequency of the accelerometer. This resonance also allows the phase angle response to be close to zero well out towards the natural frequency.

Additional resonance problems exist in the mounting brackets, or as frame resonances which carry little or no information. The process of removing them, however, can produce extreme errors in both amplitude and phase.

The SAE J211a Recommended Practice recommends four channel classes for impact tests: c1asses 60, 180, 600, and 1000. The frequency response is flat to +1/2, -1 dB to these frequencies, and to +1, -4 dB to the break frequencies of 100, 300, 1000, and 1650 Hertz. The filter rolloff is nominally 12 dB/octave (second order) from these break points.

Second order filters are normally used for impact tests since accelerometers have second order response. This filtering will provide satisfactory results, if no resonance is present at less than several times the class frequency. Often the next lower class is used to remove a resonance, a step that may cause large errors. A better solution is to follow the typical class filter with a sharper cutoff filter that will remove the resonance without affecting the amplitude and phase of the initial impulse.

A method that determines when data is lost by excessive filtering is presented and demonstrated on two crashes. One crash has a resonance about 15 times higher than the class; one is less than 3 times higher.

Introduction. Data for analysis was obtained from the Ford crash instrumentation system as described by Jachman*. The analog tapes were sampled at 50 kilosamples/second, digitized, filtered (using digital filtering techniques with 12, 24, and 36 dB/octave), converted to engineering units, listed, and displayed on a Cal Comp plotter. The digital filter routine used 251 filter weights and a transform size of 2048. They were flat to ±1/2 dB to the break point and within ±2dB of the final slope to below 30 dB. The data was taken from vehicle structural accelerations located on the frame at the door post. J211a recommends class 60 for total vehicle comparisons and class 180 for integration of velocity or displacement.

In most cases studied, the class 60 filter caused large errors in amplitude as well as phase shifts up to 2 milliseconds. More significantly, the class 60 filter produced a change in the order of the data. When a second order system responds to an impulse, the output will be third order. During the initial impulse of a crash, the accelerometer will respond such that the data is always third order. If excessive filtering occurs, the data will change to second order. Undersampling will do the same thing; that is, if the samples are spaced far enough apart, they will miss the points that make the waveform third order.

The order of data can be determined from its interpolation error when sampled and reconstructed**.

By sampling the analog data at a high sampling rate, samples can be dropped and replaced by linear interpolation during reconstruction. The difference between the reconstructed values and the original samples can then be used to calculate the RMS interpolation error for a reduced sampling rate. Errors for several lower sampling rates can be calculated and an error curve plotted. The slope of this curve, when plotted on log paper, is a function of the order of the data and the interpolation processed used to reconstruct the data. Using linear interpolation (drawing a straight line between samples) the slope will be 1/2 for first order data, 3/2 for second order and 2 for third order and higher orders of data.

When higher orders of interpolation are used, the same process occurs, with the slope increasing by one for each order of data, until the interpolation process is one order less than the data. For all higher orders of data the slope will remain the same.

DATA WITH HIGH FREQUENCY RESONANCE. When the resonance is many times higher than the information, it is, of course, much easier to remove without affecting the data itself. An example with a resonance of about 3000 Hz was chosen as a

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*The Application of Aerospace Techniques to Automotive Crash Test Instrumentation by J. J. Jachman, Page 363, 1973 ITC.

**Sampling and Source Encoding by Lawrence W. Gardenhire, Harris Electronics Systems Internal Report April 1970.

demonstration. The reconstructed waveform, filtered with a class 1000 filter (wideband), is shown in Figure 1. The 3000-Hz resonance can clearly be seen with peaks as high as 200 G's. Had the data not been filtered, the peaks would have exceeded 700 G's. The actual data is more or less represented by the envelope of the 3000 Hz.

Ringing started at 3.36 Ms and 39.6 G's, long before the initial impulse had reached a peak. Interpolation errors for the waveform cannot be determined, since the peak is obscured by the ringing and the noise frequency is high enough to make even the 50 Ks inadequate.

If, however, the waveform is filtered at a break frequency of 300 Hz with a sharp rolloff of 36 dB, the resonance will be removed with the high-frequency noise. The results of this filtering are shown in the solid surve of Figure 2. Note that the peak of the initial impulse occurred at 3.94, or one-half millisecond after the ringing started, and is only -36.39 G's compared with -137.03 G's in Figure 1.

The question now becomes how much filtering can be done without harming the data. The best approach is to study the rise time of the initial impulse. If the rise time remains third order, we have only removed higher frequencies, not the structure of the impulse.

The dotted line in Figure 2 shows the reconstructed waveform after a class 60 filter is used (breaks at 100 Hz with 12 dB/octave rolloff). The amplitude has been reduced to 23.97 G's and the peak shifted to 3.51, a 34 percent decrease in amplitude and a 11 percent decrease in phase.

More important, however, is that the order of the rise has changed from third order to second order, and the initial impulse has been lost.

If the interpolation error is calculated for both rise times (at several sampling rates), the two right-hand curves in Figure 3 result. The slope of the 300-Hz data is 2, while the 100-Hz data is 3/2. The interpolation error for a given sampling rate (10 kilosamples/second) increases from 0.095 percent to 0.19 percent; the higher the accuracy, the larger the difference.

In order to avoid this change in order and to see accurately what the accelerometer is responding to, the frequency of the filter must be increased and the rolloff sharpened to remove any resonances or undesired high frequencies. Using a 180-Hz digital filter with a 36-dB/octave slope results in the dotted curve shown in Figure 4. (The 300-Hz data from Figure 2 is shown for comparison). The initial rise has been altered very slightly, as have the peak amplitude and phase. The peak's amplitude of 34.90 G's occurred at 3.86, only a 4 percent decrease in amplitude and a 2 percent decrease in phase. The data is still third order as seen in the left-hand curve of Figure 3. The interpolation error for 10 kilosamples, which decreased to 0.032 percent was to be expected, since the lower break point filter has removed the higher frequencies that required a greater sampling rate.

A second approach to determining interpolation errors provides interesting results. If the time for the amplitude to go from 10 to 90 percent is determined, a rough estimate of the maximum frequency present in the rise can also be determined. This rise time is considered 1/4 cycle of the natural frequency of the device producing the data. This method is not always accurate, but it is quite satisfactory for undamped systems with low noise content. The rise frequency for the three filters were 136, 108, and 95 Hertz. Ten kilosamples would result in 74, 93, and 105 samples/cycle of the rise frequency. The interpolation errors obtained from the tables given by Gardenhire are 0.08 percent, 0.04 percent, and 0.23 percent. These results are quite close to the actual calculated results and show the importance of the generalized sampling rate tables.

The resonance frequency to be removed in the example cited was much greater than the information frequency and therefore easy to remove, even with standard SAE class filters. Although class 180 filter would certainly have accomplished the same results, things would be different if the frequency had been 300 Hz instead of 3000. The next example demonstrates this statement and shows the need for sharper cutoff filters.

DATA WITH LOW FREQUENCY RESONANCE. When the resonance frequencies are close to the filter class, the problem is more difficult. A measurement which contained a 455 Hertz resonance in class 180 data was chosen as a second demonstration. This is only 2.5 times above the class frequency. The resonance can clearly be seen in the reconstructed waveform in Figure 5. Note that the peak to peak amplitude of the 1/2 cycle following 31 ms is approximately 53 G’s. The wide band (class 1000 filter) reconstruction of this 1/2 cycle was 152 G’s. The remaining frequency is particularly disturbing, especially since it completely masks the maximum negative peak about 10 ms.

The filter used in this case was not the standard class 180 electrical filter, rather a digital filter with its break point at 300 Hertz, and thereby closely matching the electrical filter. When a class 60 filter is used most, but not all of the resonance is removed, as seen in Figure 6, the 10 to 90 percent amplitude is reduced to 75 from 113 G’s with a class 180 filter. The rise frequency is also reduced from 163 to 97 Hertz. In this case however, the order of the data did not change, meaning that the initial impulse was low in frequency content.

A filter with a 36 dB per octave slope, breaking at 180 Hertz is a better solution to the problem. This result is shown in Figure 7. The 10 to 90 percent amplitude is 92 G’s, and the rise frequency 110 Hertz. This curve is much easier to read and more nearly represents the actual impulse since the amplification produced by resonance has been removed. The sampling rate for all three examples was 10 kilosamples/second, therefore the interpolation error was very small, 0.018% for the last case. It could be reduced to 1 kilosample/second and would be only 2.0%.

CONCLUSIONS. Removing resonances from Crash Instrumentation is easily accomplished by using sharp cutoff digital filters, with the break frequency slightly less than that of the class filter. It is recommended that this method be added to the SAE J211a recommended practices. The electrical filtering should remain the same as now recommended, and when a resonance is present a second filtering should be done digitally as part of the data processing. This will make the measurements much easier to evaluate and will be more meaningful and will improve the correlation of a given measurement from crash to crash.

For class 180 data the break frequency should be 250 cycles. This means there will be two breaks, the first with a slope of 36 dB per octave and above 300 Hertz the slope will increase to 48 dB/octave, since orders of filter add.

In problem cases where the resonance,is less than 3 times the data class, the break frequency can be lowered, however care must be exercised, such that the order of the data is not changed.

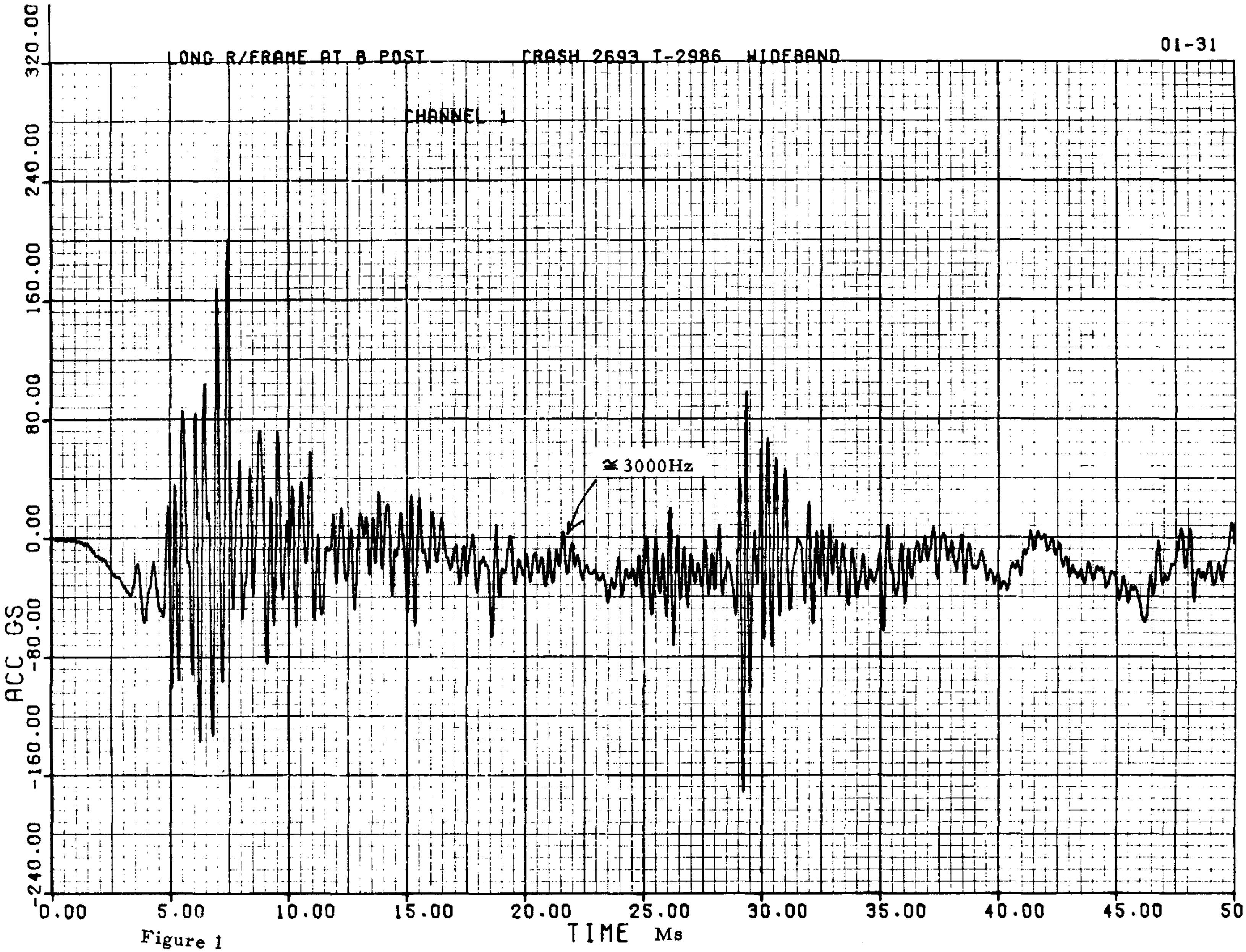
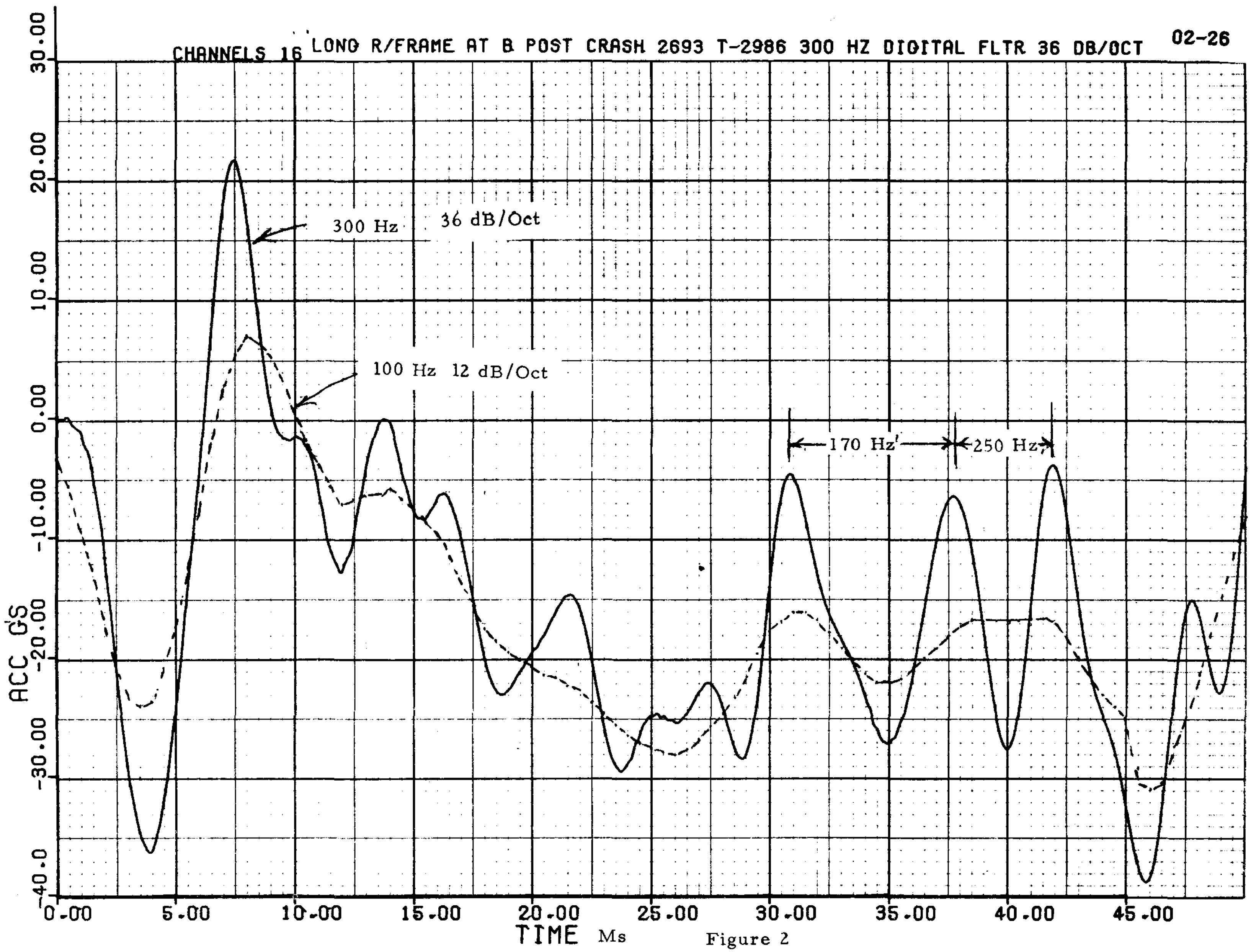
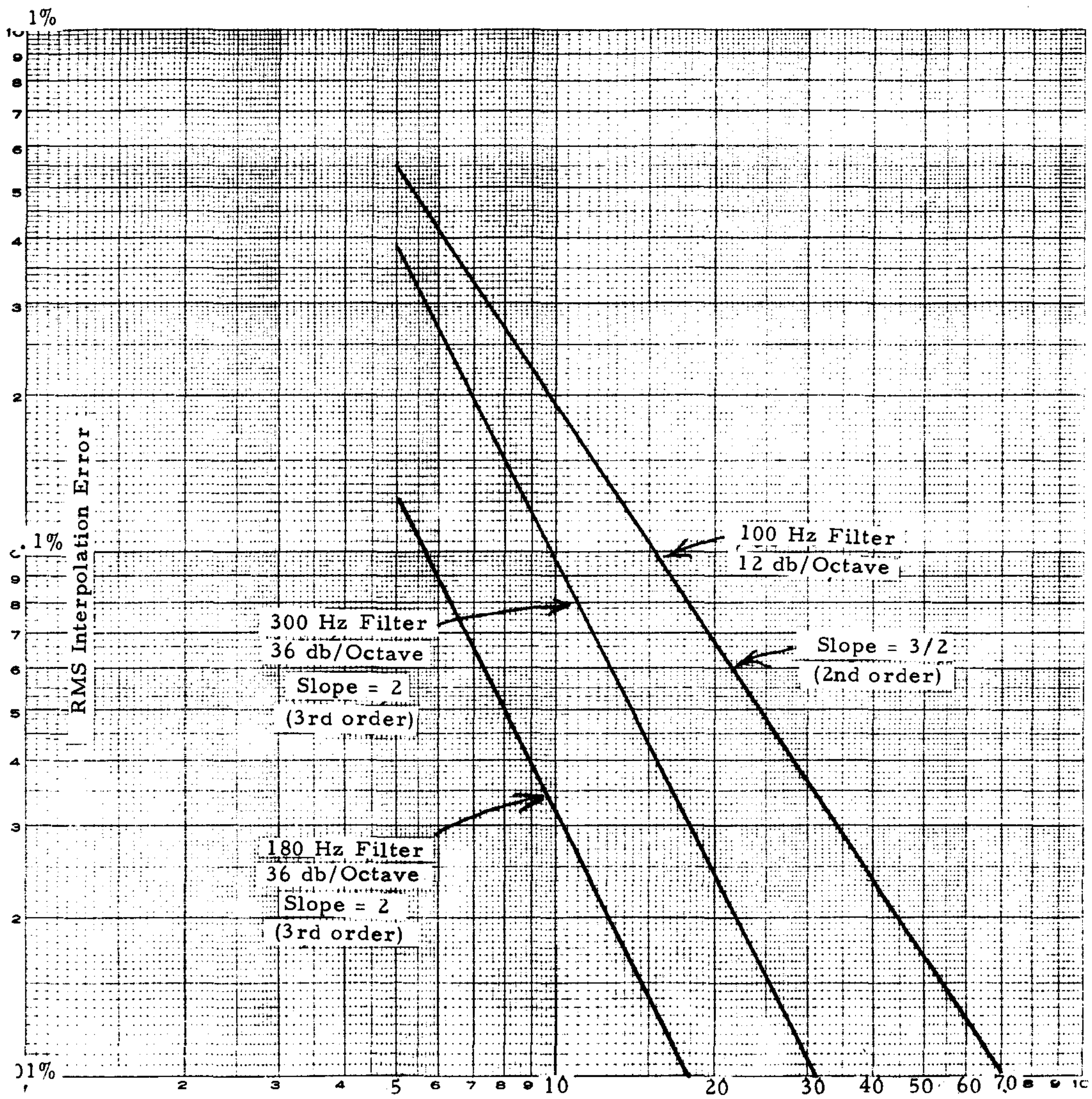

LONG R/FRAME AT B POST
CRASH 2693 T-2986 WIDEBAND
01-31
CHANNEL 1
≅3000Hz
320.00
240.00
160.00
80.00
0.00
-80.00
-160.00
-240.00
ACC GS
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50
TIME Ms

Figure 1



CHANNELS 16 LONG R/FRAME AT B POST CRASH 2693 T-2986 300 HZ DIGITAL FLTR 36 DB/OCT
02-26
300 Hz 36 dB/Oct
100 Hz 12 dB/Oct
170 Hz
250 Hz
ACC G'S
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
-40.0
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
TIME Ms

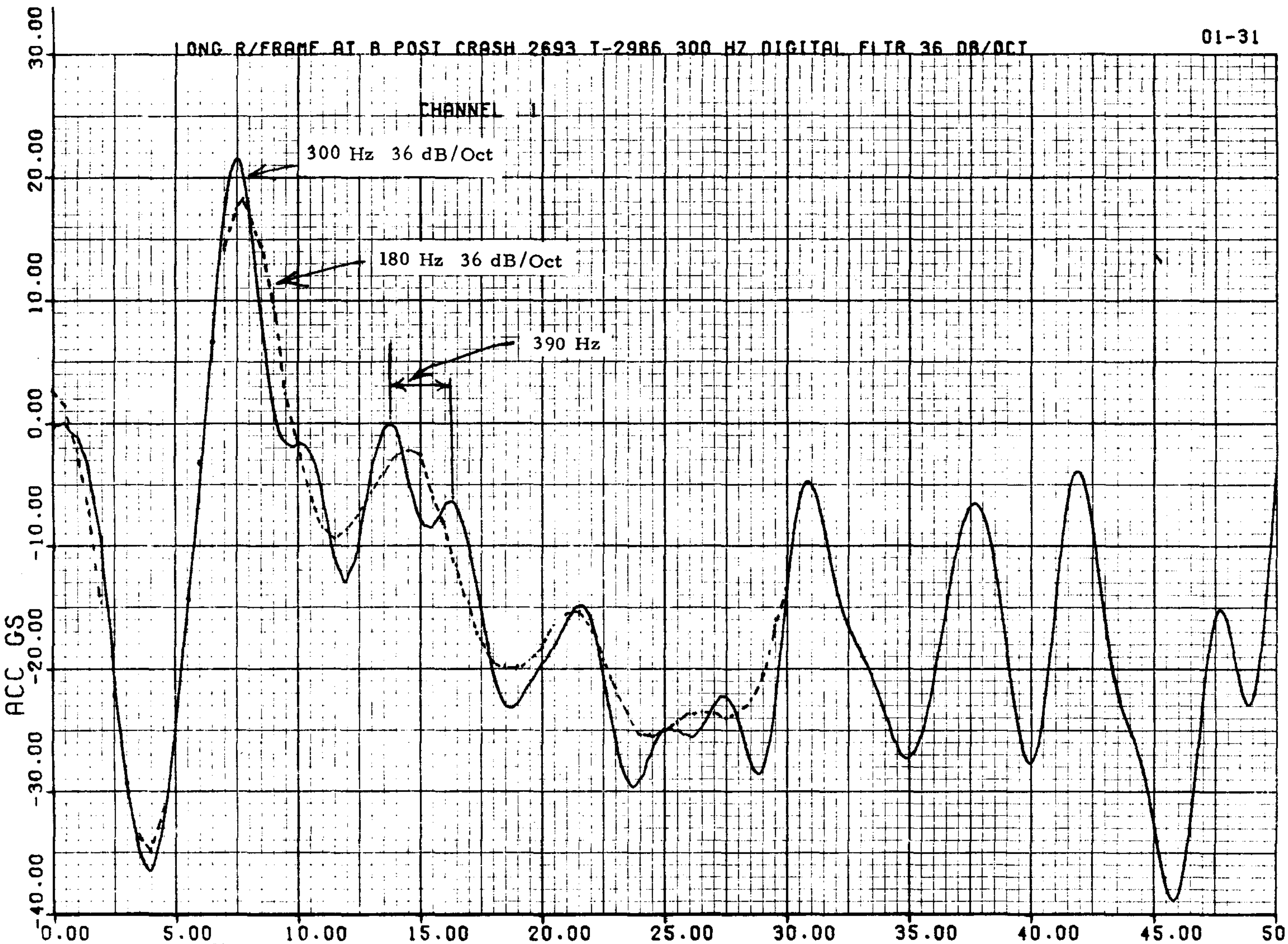
Figure 2



Sampling Rate in Kilosamples/Second

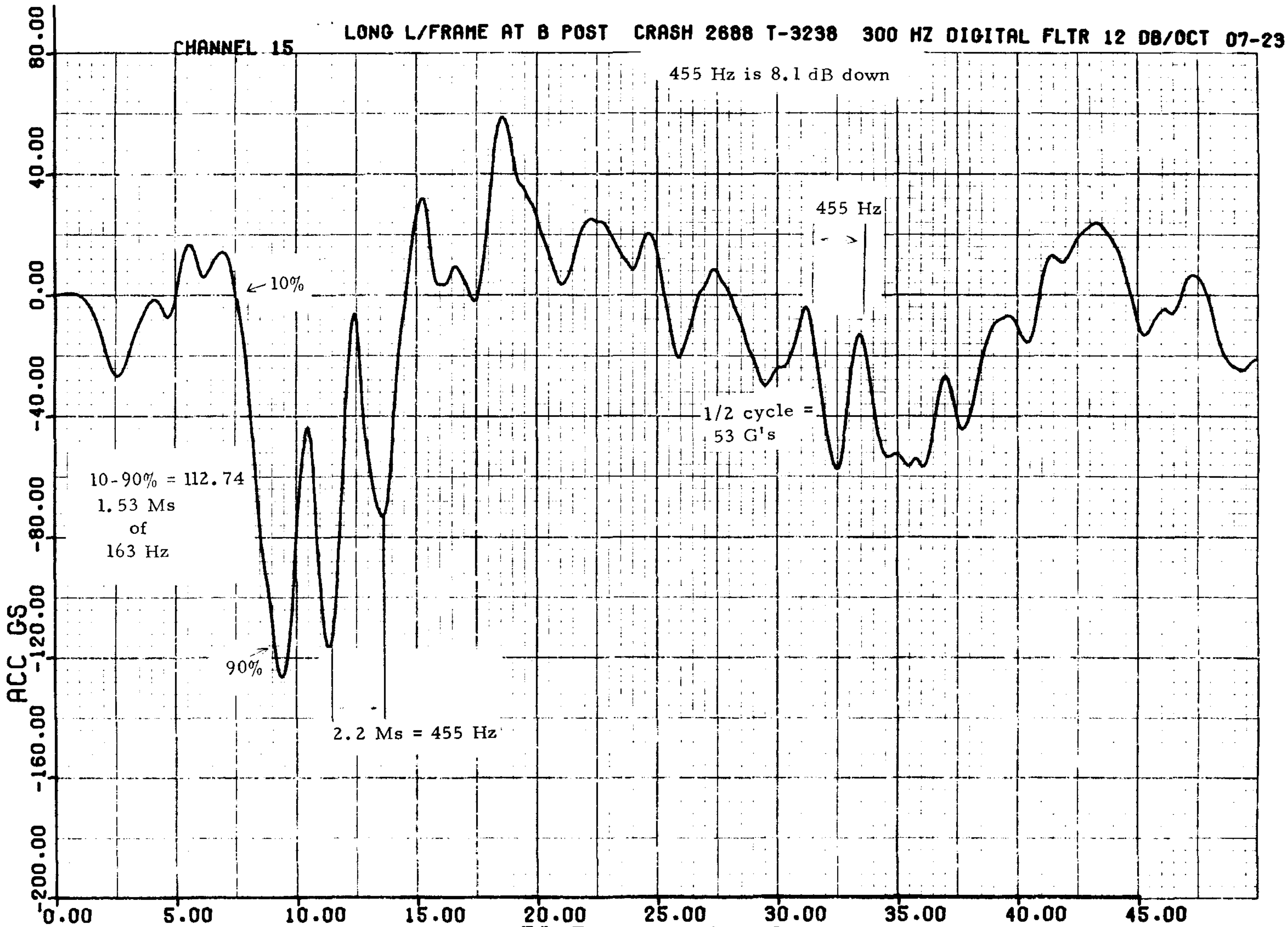
Figure 3 Interpolation Errors of Initial Impulse

Crash 2693 - Long R/Frame at B Post



LONG R/FRAME AT B POST CRASH 2693 T-2986 300 HZ DIGITAL FLTR 36 DB/OCT
01-31
CHANNEL 1
300 Hz 36 dB/Oct
180 Hz 36 dB/Oct
390 Hz
ACC GS
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
-40.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50
TIME Ms

Figure 4



CHANNEL 15
LONG L/FRAME AT B POST CRASH 2688 T-3238 300 HZ DIGITAL FLTR 12 DB/OCT 07-23
455 Hz is 8.1 dB down
455 Hz
10%
90%
10-90% = 112.74
1.53 Ms
of
163 Hz
2.2 Ms = 455 Hz
1/2 cycle =
53 G's
ACC GS
80.00
40.00
0.00
-40.00
-80.00
-120.00
-160.00
-200.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
TIME Ms

Figure 5

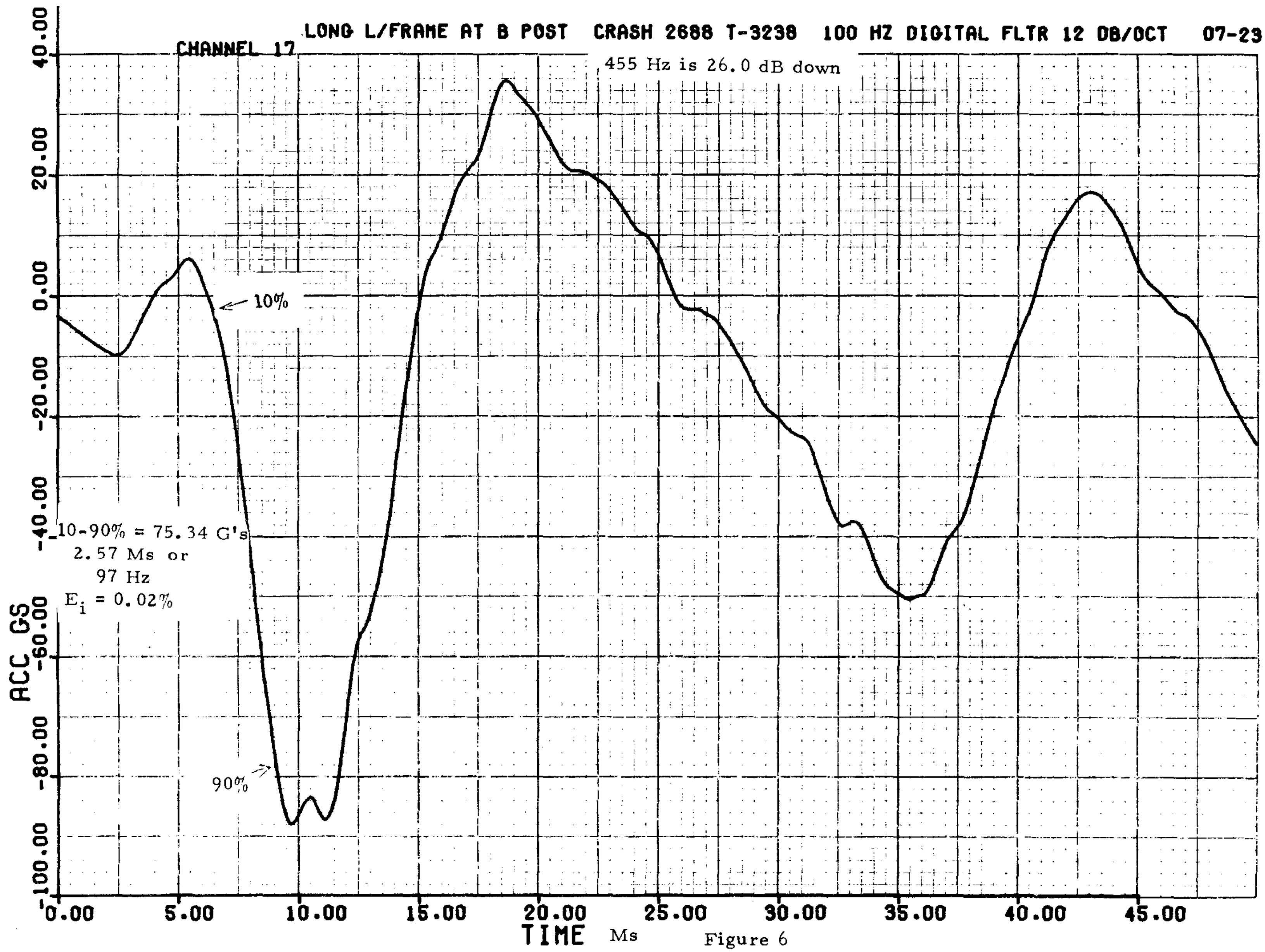
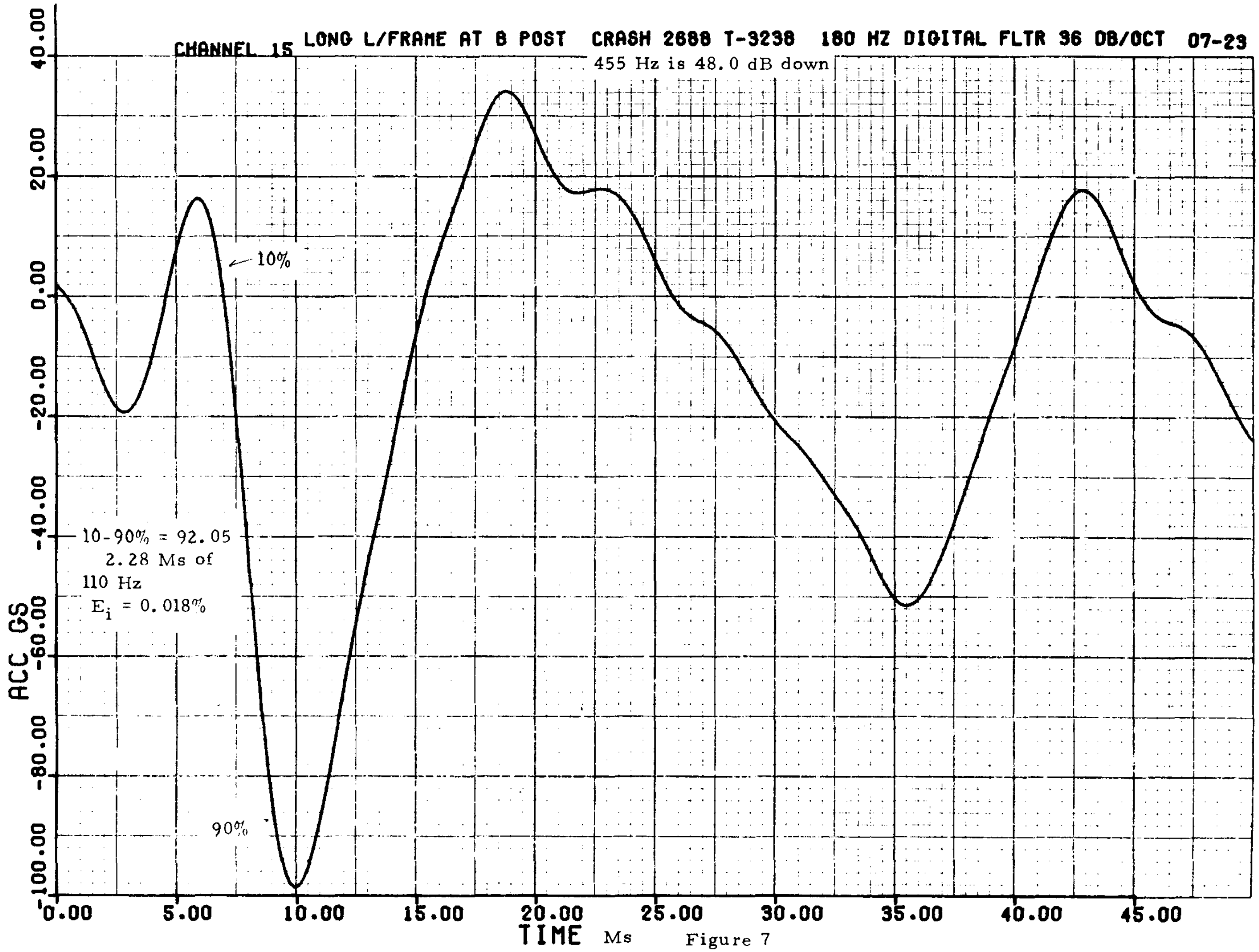

CHANNEL 17
LONG L/FRAME AT B POST CRASH 2688 T-3238 100 HZ DIGITAL FLTR 12 DB/OCT 07-23
455 Hz is 26.0 dB down
10%
90%
10-90% = 75.34 G's
2.57 Ms or
97 Hz
E_i = 0.02%
ACC GS
40.00
20.00
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
TIME Ms

Figure 6


CHANNEL 15
LONG L/FRAME AT B POST CRASH 2688 T-3238 180 HZ DIGITAL FLTR 36 DB/OCT 07-23
455 Hz is 48.0 dB down
ACC GS
40.00
20.00
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
10%
90%
10-90% = 92.05
2.28 Ms of
110 Hz
E_i = 0.018%
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
TIME Ms
Figure 7