ANALYSIS OF STRUCTURAL RESPONSE MEASUREMENTS – PHASE 3B SPADEADAM

APPENDIX B

CLEANING OF RECORDED TIME HISTORIES

CONTENTS

EXECUTIVE SUMMARY

The overpressure time histories recorded from the full-scale testing at Spadeadam are characterised by the expected profile of the positive and negative overpressure phases and an overlying high frequency record. It is demonstrated elsewhere in the report that the overlying overpressures are most likely to be a result of the local structural response, and are not a characteristic of the explosion. This Appendix to the report discusses the removal of the extraneous data from the recorded time histories; demonstrates the validity of removing the extraneous data; and presents an algorithm for the automated cleaning of the recorded data. Figure 1 shows a typical recorded overpressure from the September 1999 testing; this clearly shows the extraneous higher frequency measurements. It has also been identified that the magnitude of the noise affects the ease with which the time-histories can be cleaned.

The cleaned explosion overpressure time-histories present two major benefits:

1. The headline overpressure is greatly reduced;

2. The number of time-points required for structural analysis can be reduced to manageable proportions; and

3. There is validity in the use of the cross-correlation coefficient to control the filtering, however this has to be applied in the context of the significance of any noise seen on the measured time-histories.

1. INTRODUCTION

The overpressure time histories recorded from the full-scale testing at Spadeadam are characterised by the expected profile of the positive and negative overpressure phases and an overlying high frequency record. It is demonstrated elsewhere in the report that the overlying overpressures are most likely to be a result of the local structural response, and are not a characteristic of the explosion.

This Appendix discusses the removal of the extraneous high frequency overpressures from the recorded time histories; demonstrates the validity of removing the extraneous high frequency overpressures; and presents an algorithm for the automated cleaning of the recorded data. Figure 1 shows a typical recorded overpressure from the September 1999 testing; this clearly shows the extraneous higher frequency measurements.

2. DATA SMOOTHING TECHNIQUES

Several techniques are available for smoothing or filtering recorded time-series; each has its advantages and disadvantages. For the purposes of this project three techniques have been used and compared.

2.1. TIME SMOOTHING

Time smoothing or time averaging is a computationally simple technique. It consists of averaging data values either side of the time being considered. The smoothing is normally carried out using a square window that is in averaging the data each data point is given equal weight. There are however other windowing techniques which derive from signal processing, these techniques reduce the weighting of the data points based on the distance that the point is from the time being considered. The three most common, Welch, Hann and Bartlett are considered in this report. These are considered within Section 3.6.

The disadvantage of this method is that it in effect only crops the amplitudes of the time-series and it does not necessarily remove unwanted frequencies consistently.

2.2. FREQUENCY FILTERING

The frequency domain method of data filtering has been adopted widely throughout this report, principally because the meaning of the technique is readily understood. The logic behind the technique as applied is relatively simple. The time-history is transformed to the frequency domain by means of a Fourier transform.

Once in the frequency domain the time-series is characterised by real and imaginary components of amplitude over a range of frequencies. These frequencies range from 0Hz to the Nyquist frequency for the recorded data. The Nyquist frequency can be shown to be the highest frequency that can be recorded within a time-series of a given time interval and is defined as $1/2\Delta t$, where Δt is the time interval of the recording.

For the overpressure time-histories presented in this report, the time interval is 2.0×10^{-5} seconds, the Nyquist frequency is therefore 25kHz. The filtering is effected by first the transform to the frequency domain, then zeroing the real and imaginary components of the frequency amplitudes for those frequencies to be removed. The resulting frequency domain Fourier data is then inverse transformed back to the time-domain.

The disadvantages of this process are primarily the computing required for the Fourier transform and the inverse Fourier transform and the fact that harmonics are found to overlie the resulting filtered time-history. The processing disadvantage is reduced by the use of the Fast Fourier Transform (FFT) technique and the speed of modern desktop computers.

The FFT process introduces a problem of its own in that the time-series to be transformed must consist of a number of terms which is an exact power of two. With the Spadeadam recordings consisting of 47,520 data points, the FFT is carried out on 65,536 data points. This results in a frequency interval of 0.76Hz.

The main advantage of this process is that it is obvious what has been done; the time-history has been filtered over a clearly defined frequency band.

2.3. WAVELETS

The wavelet transform is a relatively modern process. The transform is similar to the Fourier technique in that the input time series is transformed from the time-domain. The target domain is an arbitrary domain in that it has no physical meaning, unlike the frequency domain, which is the target of the Fourier transform.

The resulting wavelet amplitudes are then filtered by a normalisation process. The procedure is to remove all coefficients with normalised amplitudes less than a selected ratio. These coefficients are zeroed and the inverse transform applied. The result is a smoothed time history.

The major disadvantage with the wavelet transform is the fact that the intermediate domain is undefined. The filtering process does not have an obvious physical meaning. Whilst there is some wrap-around interference from the mathematical process being applied; the transform does not suffer from significant residual harmonics as are seen in the Fourier transform. Computationally, the process is reasonably efficient.

3. TIME HISTORY CLEANING

3.1. IDENTIFYING THE EXTRANEOUS DATA

It has been shown that it is a reasonable conclusion that the motion of the structure has imposed the extraneous recorded pressures onto the explosion overpressure recording. For an explosion history with a 200ms positive phase, the implied frequency is 2.5Hz. This is at the lower end of the structural frequency range. (The structural response frequencies are discussed elsewhere in this report.) The frequency response imposed on the recorded time-histories by the structure will therefore overlap the response of the actual explosion pressure history. If data is removed from the overpressure time-histories indiscriminately therefore, it is certain that the useful explosion overpressure data will be lost.

Conversely, if frequencies are removed above the normal structural-response range, say all above 50Hz, then there is likely to be residual pollution of the recordings. It is therefore necessary to identify a technique that will allow recorded data to be removed from the overpressure time histories in the crossover range. Whilst it is clear that some pollution of the overpressure data will remain whatever frequency range is selected for filtering, it would be useful to be able to remove as much as is possible.

3.2. DATA CLEANING

The method of data cleaning selected uses the same logic regardless of the filter employed. The technique developed compares the cleaned time-history to the original to demonstrate that the original overpressure history is reasonably retained. The assumption is made that the linear cross correlation coefficient for any two time-histories can be used to demonstrate that they both represent the same set of measurements.

3.2.1. Linear Cross Correlation Coefficient

The linear cross correlation coefficient is defined as a measure of the association between two sets of variables. For pairs of quantities x_i and y_i, the cross correlation coefficient r is given by:

$$r = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2}\sqrt{\sum_i (y_i - \bar{y})^2}}$$

Where

$\bar{x}$ is the mean of x_i

$\bar{y}$ is the mean of y_i

Equations missing?

The value of r lies between –1 and 1. If the absolute value of r is 1 then the data sets are fully correlated, if r is 0, they are fully uncorrelated. The value of r says nothing about the source of the data. It could be possible for example to demonstrate that the sales of cookery books and the attendance at football matches are correlated, when clearly they are not. Clearly, in the case of adjusting the measured time-histories, this is not a concern, as we are working with one data set.

3.2.2. Operational Concept

The concept of using the cross correlation coefficient to identify when the modified time-histories are significantly different from the original has been tested. There is no hard and fast rule which identifies two data sets as being well correlated, or any means of attaching a significance to the correlation. The only fixed rules are ±1 and zero. Taking *r* of 0.95 does not for instance indicate 95% correlation. In seismic engineering, seismic accelerograms that have *r* of 0.3 are described as "statistically independent". (ref asme 4-86, etc.) The perceived wisdom among engineers using the cross correlation coefficient as a measure of association is that the significance associated with values of *r* varies with the process being examined.

Clearly, given a method of smoothing the data and the ability to calculate *r*, it is possible to iteratively adjust or clean the data. By this method, the data can be cleaned of extraneous polluting frequencies, whilst a measure of the change from the original can be made. The main disadvantage of the technique is that there is no hard and fast rule applicable to the use of the cross correlation coefficient as a target value.

3.3. EXAMINATION OF THE SEMI-AUTOMATIC PROCESS

The cleaning process has been examined by considering three time-histories taken from different tests carried out during September 1999:

Table 1
Tests and transducers examined

Test	Pressure Transducer	Recorded Data Points (Record Length)	Peak Overpressure (mb)
2	PI-33	55040	68.81
3	PI-29	47520	749.2
5	PI-37	44064	1776.5

These three overpressure time-histories are presented in Figures 3 to 5. For the purposes of this part of the work, it is not important that the time-histories are taken from different transducers. The three time-histories have been cleaned using frequency smoothing and time averaging techniques, to target values of correlation coefficients of 0.85, 0.90, 0.95 and 0.98. The time-histories were also re-sampled during the process this is discussed and reported in Section 3.6 below.

3.3.1. Frequency Filter

Table 2
Automated frequency filtering

Transducer	*r*	Overpressure (mb)	Reduction (%)	Cut-off Frequency (Hz)	Comment
PI-33	0.98	65.83	4.3	1806.3	
(Test 2)	0.95	59.98	12.8	1689.1	
	0.90	48.38	29.7	1287.5	
	0.85	39.10	43.2	1139.1	
PI-29	0.98	512.4	31.6	139.0	
(Test 3)	0.95	369.4	50.7	32.8	
	0.90	285.6	61.9	6.9	
	0.85	245.7	67.2	5.3	
PI-37	0.98	1754.3	1.2	4470.8	
(Test 5)	0.95	1129.4	36.4	1326.8	
	0.90	918.5	48.3	808.0	
	0.85	455.5	74.4	16.8	

See Figures 3 to 5.

Table 3
Automated frequency filtering – re-sampled data

Transducer	*r*	Overpressure (mb)	Reduction (%) Over Filtered Data[1]	Time-Interval	Comment
PI-33	0.98	52.08	20.9 (24.3)	2.200×10^{-4}	5004 Resulting points
(Test 2)	0.95	59.05	1.6 (14.2)	2.600×10^{-4}	4234 Resulting points
	0.90	44.22	8.6 (35.7)	3.000×10^{-4}	3670 Resulting points
	0.85	28.57	26.9 (58.5)	3.600×10^{-4}	3058 Resulting points
PI-29	0.98	399.1	22.1 (46.7)	1.028×10^{-2}	93 Resulting points
(Test 3)	0.95	367.7	0.5 (50.9)	2.000×10^{-2}	48 Resulting points
	0.90	278.9	2.3 (62.8)	2.000×10^{-2}	48 Resulting points
	0.85	244.7	0.4 (67.3)	2.000×10^{-2}	48 Resulting points
PI-37	0.98	1754.3	0.0 (1.2)	2.000×10^{-4}	4407 Resulting points
(Test 5)	0.95	888.9	21.3 (50.0)	4.400×10^{-4}	2003 Resulting points
	0.90	918.4	0.0 (48.3)	8.600×10^{-4}	1025 Resulting points
	0.85	443.8	2.6 (75.0)	2.000×10^{-2}	45 Resulting points

[1] The "Reduction over filtered data" is a further reduction of the resulting overpressure following the initial filtering. The values in parenthesis are the reduction over the original data.

3.3.2. Time Smoothing

Table 4
Automated time filtering

Transducer	*r*	Overpressure (mb)	Reduction (%)	Smoothing Window Width (ms)	Comment
PI-33	0.98	50.80	26.2	0.40	
(Test 2)	0.95	39.10	43.2	0.56	
	0.90	28.00	59.3	0.72	
	0.85	27.80	59.6	0.86	
PI-29	0.98	480.7	35.8	5.70	
(Test 3)	0.95	348.3	53.5	27.00	
	0.90	238.7	68.1	118.60	
	0.85	188.6	74.8	162.70	
PI-37	0.98	1641.2	7.6	0.18	
(Test 5)	0.95	1019.7	42.6	0.64	
	0.90	841.0	52.7	1.32	
	0.85	422.6	76.2	56.40	

See Figures 6 to 8.

Table 5
Automated time filtering – re-sampled data

Transducer	*r*	Overpressure (mb)	Reduction (%) Over Filtered Data	Time-Interval	Comment
PI-33	0.98	49.80	27.6	2.600×10^{-4}	4234 Resulting points
(Test 2)	0.95	37.60	45.4	3.000×10^{-4}	3670 Resulting points
	0.90	27.70	59.7	3.800×10^{-4}	2897 Resulting points
	0.85	27.50	60.0	5.200×10^{-4}	2117 Resulting points
PI-29	0.98	374.5	50.0	1.054×10^{-2}	91 Resulting points
(Test 3)	0.95	348.2	53.5	2.000×10^{-2}	48 Resulting points
	0.90	233.1	68.9	2.000×10^{-2}	48 Resulting points
	0.85	188.4	74.9	2.000×10^{-2}	48 Resulting points
PI-37	0.98	1312.2	26.1	2.400×10^{-4}	3672 Resulting points
(Test 5)	0.95	994.3	44.0	5.400×10^{-4}	1632 Resulting points
	0.90	770.7	56.6	3.380×10^{-3}	261 Resulting points
	0.85	421.7	76.3	2.000×10^{-2}	45 Resulting points

3.3.3. Comparison of Frequency Filter and Time Smoothing

Table 6
Comparison of frequency and time smoothed data

Transducer	*r*	Frequency Filter		Time Smoothing	
		Overpressure (mb)	Reduction (%)	Overpressure (mb)	Reduction (%)
PI-33	0.98	65.83	4.3	50.80	26.2
(Test 2)	0.95	59.98	12.8	39.10	43.2
	0.90	48.38	29.7	28.00	59.3
	0.85	39.10	43.2	27.80	59.6
PI-29	0.98	512.4	31.6	480.7	35.8
(Test 3)	0.95	369.4	50.7	348.3	53.5
	0.90	285.6	61.9	238.7	68.1
	0.85	245.7	67.2	188.6	74.8
PI-37	0.98	1754.3	1.2	1641.2	7.6
(Test 5)	0.95	1129.4	36.4	1019.7	42.6
	0.90	918.5	48.3	841.0	52.7
	0.85	455.5	74.4	422.6	76.2

3.4. PRE-FILTERING AND THE SEMI-AUTOMATIC PROCESS

The automated filtering technique has been applied to recorded time histories that have been pre-filtered removing all frequencies above 1000Hz. The results of this revised cleaning of the time histories are presented below.

Table 7
Pre-filtering of time histories (1kHz)

Test	Pressure Transducer	Original Overpressure (mb)	Overpressure (mb)	Reduction (%)	Cross Correlation Coefficient
2	PI-33	68.81	27.8	59.6	0.800
3	PI-29	749.2	756.4	-1.0	0.990
5	PI-37	1776.5	962.1	45.8	0.931

Table 8
Automated frequency filtering of pre–filtered data

Transducer	*r*	Overpressure (mb)	Reduction (%)	Cut-off Frequency (Hz)	Comment
PI-33	0.98	28.08	-1.0%	919.7	
(Test 2)	0.95	27.57	0.8%	809.5	
	0.90	21.46	22.8%	5.3	
	0.85	18.62	33.0%	3.8	
PI-29	0.98	389.4	48.5%	64.1	
(Test 3)	0.95	345.1	54.4%	19.1	
	0.90	285.6	62.2%	6.9	
	0.85	245.7	67.5%	5.3	
PI-37	0.98	932.9	3.0%	864.4	
(Test 5)	0.95	838.7	12.8%	590.1	
	0.90	466.6	51.5%	9.2	
	0.85	370.3	61.5%	5.3	

Table 9
Automated frequency filtering of pre–filtered data – re-sampled data

Transducer	*r*	Overpressure (mb)	Reduction (%) Over Filtered Data	Time-Interval	Comment
PI-33 (Test 2)	0.98	28.08	-1.0%	5.600×10^{-4}	1966 Resulting Points
	0.95	27.02	2.8%	1.080×10^{-3}	1020 Resulting Points
	0.90	21.44	22.9%	2.000×10^{-2}	56 Resulting Points
	0.85	18.42	33.7%	2.000×10^{-2}	56 Resulting Points
PI-29 (Test 3)	0.98	366.0	51.6%	1.278×10^{-2}	75 Resulting Points
	0.95	342.6	54.7%	2.000×10^{-2}	48 Resulting Points
	0.90	278.9	63.1%	2.000×10^{-2}	48 Resulting Points
	0.85	244.7	67.6%	2.000×10^{-2}	48 Resulting Points
PI-37 (Test 5)	0.98	867.1	9.9%	6.600×10^{-4}	1336 Resulting Points
	0.95	831.3	13.6%	3.020×10^{-3}	292 Resulting Points
	0.90	465	51.7%	2.000×10^{-2}	45 Resulting Points
	0.85	367.6	61.8%	2.000×10^{-2}	45 Resulting Points

3.5. FIXED FREQUENCY REMOVAL

As a comparison to the automated frequency removal technique, the time-histories have been filtered for all frequencies above 25Hz and all frequencies above 50Hz. In addition, they have been time averaged at 1.5ms and 2.0ms. The four most common methods of windowing data have also been compared. Of these, the square window is the most commonly adopted technique, as it represents a simple averaging of adjacent data items. The other three, Bartlett, Hann and Welch are described below.

Table 10
Fixed frequency filtering of data

Transducer	Filter	Overpressure (mb)	Reduction (%) Over Original Data	Cross Correlation Coefficient to Original Data	Comment
PI-33 (Test 2)	25Hz+	26.1	62.1	0.746	
	50Hz+	26.5	61.5	0.746	
	1.5ms	27.4	60.2	0.717	
	2.0ms	27.1	60.6	0.752	
PI-29 (Test 3)	25Hz+	366.2	51.1	0.945	
	50Hz+	384.7	48.7	0.961	
	1.5ms	590.5	21.2	0.986	
	2.0ms	557.8	25.5	0.985	
PI-37 (Test 5)	25Hz+	489.4	72.5	0.861	
	50Hz+	544.1	69.4	0.865	
	1.5ms	846.4	52.4	0.859	
	2.0ms	819.6	53.9	0.874	

See Figures 9 to 11.

Table 11
Fixed frequency filtering of data – comparison of windowing techniques

Transducer	Filter	Overpressure (mb)	Reduction (%) Over Original Data	Cross Correlation Coefficient to Original Data	Comment
PI-33	2.0ms	27.08	60.6	0.752	Square window
(Test 2)	2.0ms	27.14	60.6	0.763	Bartlett window
	2.0ms	27.10	60.6	0.752	Hann window
	2.0ms	27.18	60.5	0.738	Welch window
PI-29	2.0ms	557.8	25.5	0.985	Square window
(Test 3)	2.0ms	596.1	20.4	0.988	Bartlett window
	2.0ms	618.4	17.5	0.988	Hann window
	2.0ms	582.6	22.2	0.987	Welch window
PI-37	2.0ms	819.6	53.9	0.874	Square window
(Test 5)	2.0ms	826.2	53.5	0.889	Bartlett window
	2.0ms	821.9	53.7	0.892	Hann window
	2.0ms	811.4	54.3	0.874	Welch window

The data windowing processes originate from data processing and are more commonly used during real-time data acquisition. The windowing techniques work by applying weighting to the neighbouring data items, thus deriving a weighted-average. This is intended to reduce the polluting effects of sudden changes in magnitude.

The Bartlett window takes the form:

$$\mathrm{w}_{\mathrm{j}} = 1 - \left| \frac{j - \frac{1}{2}N}{\frac{1}{2}N} \right|$$

The Hann window takes the form:

$$\mathrm{w}_{\mathrm{j}} = \frac{1}{2}\left[1 - \cos\left(\frac{2\pi j}{N}\right)\right]$$

The Welch window takes the form:

$$w_j = 1 - \left(\frac{1 - \frac{1}{2}N}{\frac{1}{2}N} \right)^2$$

Of these windowing methods, the Welch window is the generally recommended technique.

3.6. DATA RE-SAMPLING

The data recorded at Spadeadam uses a 25kHz-sampling rate, which leads to a data series containing over 30,000 values. This is a restrictive record length for finite element analysis of structures subjected to explosion; therefore, the use of the cross correlation coefficient for re-sampling the data has been studied. Using smoothed data this technique has proven to be very efficient, reducing the data set to a few hundred values. Considering the re-sampled data identified in Table 9 above:

Table 12
Reduction in record length following re-sampling

Transducer	*r*	Overpressure (mb)	Re-sampled Time-Interval	Original Record Length	Re-sampled Record Length	Percentage Original Length
PI-33	0.98	52.08	$2.200{\times}10^{-4}$	55040	5004	9.1
(Test 2)	0.95	59.05	$2.600{\times}10^{-4}$	55040	4234	7.7
	0.90	44.22	$3.000{\times}10^{-4}$	55040	3670	6.7
	0.85	28.57	$3.600{\times}10^{-4}$	55040	3058	5.6
PI-29	0.98	399.1	$1.028{\times}10^{-2}$	47520	93	0.2
(Test 3)	0.95	367.7	$2.000{\times}10^{-2}$	47520	48	0.1
	0.90	278.9	$2.000{\times}10^{-2}$	47520	48	0.1
	0.85	244.7	$2.000{\times}10^{-2}$	47520	48	0.1
PI-37	0.98	1754.3	$2.000{\times}10^{-4}$	44064	4407	10.0
(Test 5)	0.95	888.9	$4.400{\times}10^{-4}$	44064	2003	4.5
	0.90	918.4	$8.600{\times}10^{-4}$	44064	1025	2.3
	0.85	443.8	$2.000{\times}10^{-2}$	44064	45	0.1

4. VALIDATION

This Appendix describes the modification of the recorded overpressure time-histories from the Spadeadam testing. Therefore, by definition, the time-histories ultimately presented are different from those originally measured. Care has therefore to be taken to demonstrate that the resulting time-histories are still valid, especially as it is to be recommended that these time-histories be used for the design of structures and plant. Tests have therefore been applied to the resulting data to demonstrate a compatibility with the original data. These tests are designed to demonstrate that although the headline overpressures have reduced, sometimes by significant margins, the time-history being output is an adequate representation of the original from the point of view of structural response.

4.1. INTEGRATION

A simple procedure for demonstrating the correlation between the original data and the filtered data is to integrate the time history, giving a measure of the "impulse" of the load. Figures 12 to 14 show the integrals of the various filtered curves used in this study. The integrated results are compared using cross-correlation coefficients in Tables 14 to 18. The results relating to the as measured raw data have been highlighted.

4.2. TIME-HISTORY ANALYSIS

A simple time-history analysis using three single degree of freedom oscillators has been used to look at the differences induced by the filtering. Three oscillators have been used to represent typical structural frequencies, 2Hz, 4Hz and 8Hz. Tables 19 to 21 show the results of the various runs, including the relative solution times.

Table 13
Key to Table 14

[Key]	[Mean]	[Std Dev]	Array Name
[1]	[95.972015]	[162.0099]	Partial Fill 2 PI- 033 - Auto Freq Filter 0.85 - Int:
[2]	[96.013412]	[162.08646]	Partial Fill 2 PI- 033 - Auto Freq Filter 0.85 - Resampled - Int:
[3]	[95.856627]	[161.87322]	Partial Fill 2 PI- 033 - Auto Freq Filter 0.90 - Int:
[4]	[95.939941]	[161.99175]	Partial Fill 2 PI- 033 - Auto Freq Filter 0.90 - Resampled - Int:
[5]	[95.802507]	[161.80912]	Partial Fill 2 PI- 033 - Auto Freq Filter 0.95 - Int:
[6]	[95.891175]	[161.93389]	Partial Fill 2 PI- 033 - Auto Freq Filter 0.95 - Resampled - Int:
[7]	[95.824256]	[161.83488]	Partial Fill 2 PI- 033 - Auto Freq Filter 0.98 - Int:
[8]	[95.870501]	[161.90513]	Partial Fill 2 PI- 033 - Auto Freq Filter 0.98 - Resampled - Int:
[9]	[95.876234]	[161.89609]	Partial Fill 2 PI- 033 - Auto Time Filter 0.85 - Int:
[10]	[95.798642]	[161.84723]	Partial Fill 2 PI- 033 - Auto Time Filter 0.85 - Resampled - Int:
[11]	[95.834087]	[161.84645]	Partial Fill 2 PI- 033 - Auto Time Filter 0.90 - Int:
[12]	[95.967502]	[162.0408]	Partial Fill 2 PI- 033 - Auto Time Filter 0.90 - Resampled - Int:
[13]	[95.837045]	[161.84998]	Partial Fill 2 PI- 033 - Auto Time Filter 0.95 - Int:
[14]	[95.845827]	[161.88609]	Partial Fill 2 PI- 033 - Auto Time Filter 0.95 - Resampled - Int:
[15]	[95.860762]	[161.87809]	Partial Fill 2 PI- 033 - Auto Time Filter 0.98 - Int:
[16]	[95.88745]	[161.93002]	Partial Fill 2 PI- 033 - Auto Time Filter 0.98 - Resampled - Int:
[17]	[95.643268]	[161.41006]	Partial Fill 2 PI- 033 - Freq Filter: 1kHz+ - Auto Freq Filter 0.85 - Int:
[18]	[95.205293]	[161.04891]	Partial Fill 2 PI- 033 - Freq Filter: 1kHz+ - Auto Freq Filter 0.90 - Int:
[19]	[96.145592]	[162.21559]	Partial Fill 2 PI- 033 - Freq Filter: 1kHz+ - Auto Freq Filter 0.95 - Int:
[20]	[96.174724]	[162.25014]	Partial Fill 2 PI- 033 - Freq Filter: 1kHz+ - Auto Freq Filter 0.98 - Int:
[21]	[96.08941]	[162.149]	Partial Fill 2 PI- 033 - Freq Filter: 1kHz+ - Int:
[22]	[96.080716]	[162.13825]	Partial Fill 2 PI- 033 - Freq Filter: 25Hz+ - Int:
[23]	[96.138223]	[162.20643]	Partial Fill 2 PI- 033 - Freq Filter: 50Hz+ - Int:
[24]	[95.890136]	[161.9129]	Partial Fill 2 PI- 033 - Int:
[25]	[96.054439]	[162.10716]	Partial Fill 2 PI- 033 - Smoothed: 1.5ms - Int:
[26]	[96.028037]	[162.07561]	Partial Fill 2 PI- 033 - Smoothed: 2.0ms - Int:
[27]	[95.989864]	[162.0307]	Partial Fill 2 PI- 033 - Smoothed: 2.0ms Bartlett - Int:
[28]	[95.992685]	[162.03411]	Partial Fill 2 PI- 033 - Smoothed: 2.0ms Hann - Int:
[29]	[96.017528]	[162.06341]	Partial Fill 2 PI- 033 - Smoothed: 2.0ms Welch - Int:

Table 14
Test 2 integrated data cross correlation coefficients

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	10]	[11]	[12]	[13]	[14]	[15]	[16]	[17]	[18]	[19]	[20]	[21]	[22]	[23]	[24]	[25]	[26]	[27]	[28]
[1]	XXX																											
[2]	0.75	XXX																										
[3]	1.00	0.73	XXX																									
[4]	0.64	0.73	0.63	XXX																								
[5]	1.00	0.73	1.00	0.63	XXX																							
[6]	0.51	0.38	0.50	0.82	0.50	XXX																						
[7]	1.00	0.72	1.00	0.62	1.00	0.50	XXX																					
[8]	0.51	0.10	0.50	0.42	0.50	0.77	0.49	XXX																				
[9]	1.00	0.78	1.00	0.67	1.00	0.53	1.00	0.53	XXX																			
[10]	0.36	0.29	0.35	0.05	0.34	0.01	0.34	0.03	0.37	XXX																		
[11]	1.00	0.77	1.00	0.67	1.00	0.53	1.00	0.52	1.00	0.37	XXX																	
[12]	0.73	0.97	0.71	0.60	0.70	0.27	0.70	0.05	0.76	0.41	0.75	XXX																
[13]	1.00	0.76	1.00	0.65	1.00	0.52	1.00	0.52	1.00	0.36	1.00	0.74	XXX															
[14]	0.64	0.73	0.63	1.00	0.63	0.82	0.62	0.42	0.67	0.05	0.67	0.60	0.65	XXX														
[15]	1.00	0.74	1.00	0.64	1.00	0.51	1.00	0.51	1.00	0.35	1.00	0.72	1.00	0.64	XXX													
[16]	0.51	0.38	0.50	0.82	0.50	1.00	0.50	0.77	0.53	0.01	0.53	0.27	0.52	0.82	0.51	XXX												
[17]	1.00	0.54	1.00	0.59	1.00	0.66	1.00	0.77	1.00	0.49	1.00	0.53	1.00	0.59	1.00	0.66	XXX											
[18]	1.00	0.77	1.00	0.54	1.00	0.26	1.00	0.01	1.00	0.66	1.00	0.78	1.00	0.54	1.00	0.26	1.00	XXX										
[19]	1.00	0.79	1.00	0.68	1.00	0.53	1.00	0.53	1.00	0.38	1.00	0.77	1.00	0.68	1.00	0.53	1.00	1.00	XXX									
[20]	1.00	0.77	1.00	0.67	1.00	0.53	1.00	0.52	1.00	0.37	1.00	0.75	1.00	0.67	1.00	0.53	1.00	1.00	1.00	XXX								
[21]	1.00	0.77	1.00	0.66	1.00	0.52	1.00	0.52	1.00	0.36	1.00	0.74	1.00	0.66	1.00	0.52	1.00	1.00	1.00	1.00	XXX							
[22]	1.00	0.75	1.00	0.71	1.00	0.60	1.00	0.56	1.00	0.51	1.00	0.73	1.00	0.71	1.00	0.60	1.00	1.00	1.00	1.00	1.00	XXX						
[23]	1.00	0.80	1.00	0.72	1.00	0.55	1.00	0.54	1.00	0.41	1.00	0.78	1.00	0.72	1.00	0.55	1.00	1.00	1.00	1.00	1.00	1.00	XXX					
[24]	1.00	0.72	1.00	0.62	1.00	0.50	1.00	0.49	1.00	0.34	1.00	0.70	1.00	0.62	1.00	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	XXX				
[25]	1.00	0.80	1.00	0.69	1.00	0.54	1.00	0.54	1.00	0.38	1.00	0.78	1.00	0.69	1.00	0.54	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	XXX			
[26]	1.00	0.80	1.00	0.69	1.00	0.54	1.00	0.54	1.00	0.38	1.00	0.78	1.00	0.69	1.00	0.54	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	XXX		
[27]	1.00	0.80	1.00	0.69	1.00	0.54	1.00	0.54	1.00	0.38	1.00	0.78	1.00	0.69	1.00	0.54	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	XXX	
[28]	1.00	0.80	1.00	0.69	1.00	0.54	1.00	0.54	1.00	0.38	1.00	0.78	1.00	0.69	1.00	0.54	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	XXX
[29]	1.00	0.80	1.00	0.69	1.00	0.54	1.00	0.54	1.00	0.38	1.00	0.78	1.00	0.69	1.00	0.54	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 15
Key to Table 16

[Key]	[Mean]	[Std Dev]	Array Name
[1]	[792.26852]	[1355.7639]	Partial Fill 3 PI- 029 - Auto Freq Filter 0.85 - Int:
[2]	[784.0814]	[1359.2463]	Partial Fill 3 PI- 029 - Auto Freq Filter 0.85 – Resampled - Int:
[3]	[796.35481]	[1361.7684]	Partial Fill 3 PI- 029 - Auto Freq Filter 0.90 - Int:
[4]	[787.38368]	[1364.2551]	Partial Fill 3 PI- 029 - Auto Freq Filter 0.90 – Resampled - Int:
[5]	[786.53875]	[1351.073]	Partial Fill 3 PI- 029 - Auto Freq Filter 0.95 - Int:
[6]	[779.51568]	[1355.5505]	Partial Fill 3 PI- 029 - Auto Freq Filter 0.95 – Resampled - Int:
[7]	[786.74034]	[1351.3224]	Partial Fill 3 PI- 029 - Auto Freq Filter 0.98 - Int:
[8]	[819.57179]	[1413.7299]	Partial Fill 3 PI- 029 - Auto Freq Filter 0.98 – Resampled - Int:
[9]	[786.38121]	[1326.1488]	Partial Fill 3 PI- 029 - Auto Time Filter 0.85 - Int:
[10]	[776.9959]	[1328.0342]	Partial Fill 3 PI- 029 - Auto Time Filter 0.85 – Resampled - Int:
[11]	[786.5122]	[1336.1028]	Partial Fill 3 PI- 029 - Auto Time Filter 0.90 - Int:
[12]	[775.87696]	[1335.7987]	Partial Fill 3 PI- 029 - Auto Time Filter 0.90 – Resampled - Int:
[13]	[786.71995]	[1350.3397]	Partial Fill 3 PI- 029 - Auto Time Filter 0.95 - Int:
[14]	[790.3671]	[1373.2415]	Partial Fill 3 PI- 029 - Auto Time Filter 0.95 – Resampled - Int:
[15]	[786.73159]	[1351.264]	Partial Fill 3 PI- 029 - Auto Time Filter 0.98 - Int:
[16]	[817.36505]	[1407.7658]	Partial Fill 3 PI- 029 - Auto Time Filter 0.98 – Resampled - Int:
[17]	[792.23352]	[1355.7226]	Partial Fill 3 PI- 029 - Freq Filter: 1kHz+ - Auto Freq Filter 0.85 - Int:
[18]	[796.32026]	[1361.7276]	Partial Fill 3 PI- 029 - Freq Filter: 1kHz+ - Auto Freq Filter 0.90 - Int:
[19]	[787.34987]	[1351.9923]	Partial Fill 3 PI- 029 - Freq Filter: 1kHz+ - Auto Freq Filter 0.95 - Int:
[20]	[786.75259]	[1351.3343]	Partial Fill 3 PI- 029 - Freq Filter: 1kHz+ - Auto Freq Filter 0.98 - Int:
[21]	[786.78201]	[1351.371]	Partial Fill 3 PI- 029 - Freq Filter: 1kHz+ - Int:
[22]	[787.55362]	[1352.2472]	Partial Fill 3 PI- 029 - Freq Filter: 25Hz+ - Int:
[23]	[786.59684]	[1351.1491]	Partial Fill 3 PI- 029 - Freq Filter: 50Hz+ - Int:
[24]	[786.86262]	[1351.4649]	Partial Fill 3 PI- 029 - Int:
[25]	[786.74963]	[1351.3277]	Partial Fill 3 PI- 029 - Smoothed: 1.5ms - Int:
[26]	[786.68187]	[1351.2448]	Partial Fill 3 PI- 029 - Smoothed: 2.0ms - Int:
[27]	[786.78065]	[1351.3647]	Partial Fill 3 PI- 029 - Smoothed: 2.0ms Bartlett - Int:
[28]	[786.79347]	[1351.3806]	Partial Fill 3 PI- 029 - Smoothed: 2.0ms Hann - Int:
[29]	[786.7552]	[1351.3341]	Partial Fill 3 PI- 029 - Smoothed: 2.0ms Welch - Int:

Table 16
Test 3 integrated data cross correlation coefficients

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	10]	[11]	[12]	[13]	[14]	[15]	[16]	[17]	[18]	[19]	[20]	[21]	[22]	[23]	[24]	[25]	[26]	[27]	[28]
[1]	XXX																											
[2]	-0.70	XXX																										
[3]	1.00	0.69	XXX																									
[4]	-0.70	1.00	0.69	XXX																								
[5]	1.00	-0.65	1.00	-0.65	XXX																							
[6]	-0.70	1.00	0.69	1.00	-0.65	XXX																						
[7]	1.00	0.73	1.00	0.73	1.00	0.73	XXX																					
[8]	-0.70	0.15	0.68	0.15	-0.63	0.15	0.78	XXX																				
[9]	1.00	-0.70	0.99	-0.70	0.99	-0.70	0.99	-0.70	XXX																			
[10]	-0.73	1.00	0.72	0.99	-0.68	0.99	0.76	0.16	-0.73	XXX																		
[11]	1.00	-0.70	1.00	-0.70	1.00	-0.70	1.00	-0.70	1.00	-0.73	XXX																	
[12]	-0.72	1.00	0.71	1.00	-0.67	1.00	0.75	0.16	-0.72	1.00	-0.72	XXX																
[13]	1.00	-0.70	1.00	-0.70	1.00	-0.69	1.00	-0.70	0.99	-0.73	1.00	-0.72	XXX															
[14]	-0.70	1.00	0.69	1.00	-0.65	1.00	0.73	0.16	-0.70	0.99	-0.70	1.00	-0.70	XXX														
[15]	1.00	0.80	1.00	0.79	1.00	0.79	1.00	-0.27	0.99	0.83	1.00	0.82	1.00	0.80	XXX													
[16]	-0.70	0.17	0.68	0.17	-0.63	0.17	0.79	0.99	-0.70	0.18	-0.70	0.17	-0.70	0.17	-0.24	XXX												
[17]	1.00	-0.70	1.00	-0.70	1.00	-0.70	1.00	-0.70	1.00	-0.73	1.00	-0.72	1.00	-0.70	1.00	-0.70	XXX											
[18]	1.00	0.69	1.00	0.69	1.00	0.69	1.00	0.68	0.99	0.72	1.00	0.71	1.00	0.69	1.00	0.68	1.00	XXX										
[19]	1.00	0.70	1.00	0.70	1.00	0.70	1.00	0.71	0.99	0.73	1.00	0.72	1.00	0.70	1.00	0.71	1.00	1.00	XXX									
[20]	1.00	0.74	1.00	0.73	1.00	0.73	1.00	0.77	0.99	0.77	1.00	0.75	1.00	0.74	1.00	0.77	1.00	1.00	1.00	XXX								
[21]	1.00	0.83	1.00	0.82	1.00	0.82	1.00	-0.34	0.99	0.86	1.00	0.85	1.00	0.83	1.00	-0.29	1.00	1.00	1.00	1.00	XXX							
[22]	1.00	-0.70	1.00	-0.70	1.00	-0.70	1.00	-0.70	0.99	-0.73	1.00	-0.72	1.00	-0.70	1.00	-0.70	1.00	1.00	1.00	1.00	1.00	XXX						
[23]	1.00	0.76	1.00	0.75	1.00	0.75	1.00	0.31	0.99	0.79	1.00	0.78	1.00	0.76	1.00	0.37	1.00	1.00	1.00	1.00	1.00	1.00	XXX					
[24]	1.00	0.60	1.00	0.60	1.00	0.60	1.00	-0.25	0.99	0.63	1.00	0.62	1.00	0.60	1.00	-0.20	1.00	1.00	1.00	1.00	1.00	1.00	1.00	XXX				
[25]	1.00	0.68	1.00	0.67	1.00	0.67	1.00	0.00	0.99	0.71	1.00	0.69	1.00	0.67	1.00	0.04	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	XXX			
[26]	1.00	0.55	1.00	0.55	1.00	0.55	1.00	0.24	0.99	0.58	1.00	0.57	1.00	0.55	1.00	0.30	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	XXX		
[27]	1.00	0.75	1.00	0.75	1.00	0.75	1.00	-0.12	0.99	0.78	1.00	0.77	1.00	0.75	1.00	-0.08	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	XXX	
[28]	1.00	0.77	1.00	0.77	1.00	0.76	1.00	-0.17	0.99	0.80	1.00	0.79	1.00	0.77	1.00	-0.13	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	XXX
[29]	1.00	0.74	1.00	0.74	1.00	0.74	1.00	-0.06	0.99	0.77	1.00	0.76	1.00	0.74	1.00	-0.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 17
Key to Table 18

[Key]	[Mean]	[Std Dev]	Array Name
[1]	[742.34116]	[1646.4075]	P3BPF5a PI- 037 - Auto Freq Filter 0.85 - Int:
[2]	[748.61385]	[1665.7807]	P3BPF5a PI- 037 - Auto Freq Filter 0.85 - Resampled - Int:
[3]	[742.32967]	[1646.4259]	P3BPF5a PI- 037 - Auto Freq Filter 0.90 - Int:
[4]	[741.60887]	[1646.3571]	P3BPF5a PI- 037 - Auto Freq Filter 0.90 - Resampled - Int:
[5]	[742.36649]	[1646.4593]	P3BPF5a PI- 037 - Auto Freq Filter 0.95 - Int:
[6]	[741.86089]	[1646.28]	P3BPF5a PI- 037 - Auto Freq Filter 0.95 - Resampled - Int:
[7]	[742.33847]	[1646.434]	P3BPF5a PI- 037 - Auto Freq Filter 0.98 - Int:
[8]	[742.35218]	[1646.5879]	P3BPF5a PI- 037 - Auto Freq Filter 0.98 - Resampled - Int:
[9]	[741.07184]	[1636.2548]	P3BPF5a PI- 037 - Auto Time Filter 0.85 - Int:
[10]	[748.0672]	[1657.922]	P3BPF5a PI- 037 - Auto Time Filter 0.85 - Resampled - Int:
[11]	[742.33968]	[1646.4297]	P3BPF5a PI- 037 - Auto Time Filter 0.90 - Int:
[12]	[731.04343]	[1622.1939]	P3BPF5a PI- 037 - Auto Time Filter 0.90 - Resampled - Int:
[13]	[742.36514]	[1646.4567]	P3BPF5a PI- 037 - Auto Time Filter 0.95 - Int:
[14]	[742.82539]	[1649.5124]	P3BPF5a PI- 037 - Auto Time Filter 0.95 - Resampled - Int:
[15]	[742.36603]	[1646.4646]	P3BPF5a PI- 037 - Auto Time Filter 0.98 - Int:
[16]	[746.39162]	[1656.275]	P3BPF5a PI- 037 - Auto Time Filter 0.98 - Resampled - Int:
[17]	[732.57691]	[1634.4208]	P3BPF5a PI- 037 - Freq Filter: 1kHz+ - Auto Freq Filter 0.85 - Int:
[18]	[745.85413]	[1649.5764]	P3BPF5a PI- 037 - Freq Filter: 1kHz+ - Auto Freq Filter 0.90 - Int:
[19]	[742.23752]	[1646.3427]	P3BPF5a PI- 037 - Freq Filter: 1kHz+ - Auto Freq Filter 0.95 - Int:
[20]	[742.30608]	[1646.4047]	P3BPF5a PI- 037 - Freq Filter: 1kHz+ - Auto Freq Filter 0.98 - Int:
[21]	[742.32089]	[1646.418]	P3BPF5a PI- 037 - Freq Filter: 1kHz+ - Int:
[22]	[741.97842]	[1646.1048]	P3BPF5a PI- 037 - Freq Filter: 25Hz+ - Int:
[23]	[742.18549]	[1646.2937]	P3BPF5a PI- 037 - Freq Filter: 50Hz+ - Int:
[24]	[742.32759]	[1646.4242]	P3BPF5a PI- 037 - Int:
[25]	[742.29813]	[1646.3856]	P3BPF5a PI- 037 - Smoothed: 1.5ms - Int:
[26]	[742.24837]	[1646.3323]	P3BPF5a PI- 037 - Smoothed: 2.0ms - Int:
[27]	[742.31786]	[1646.4053]	P3BPF5a PI- 037 - Smoothed: 2.0ms Bartlett - Int:
[28]	[742.32868]	[1646.4172]	P3BPF5a PI- 037 - Smoothed: 2.0ms Hann - Int:
[29]	[742.30314]	[1646.39]	P3BPF5a PI- 037 - Smoothed: 2.0ms Welch - Int:

Table 18
Test 5 integrated data cross correlation coefficients

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	[15]	[16]	[17]	[18]	[19]	[20]	[21]	[22]	[23]	[24]	[25]	[26]	[27]	[28]
[1]	XXX																											
[2]	0.76	XXX																										
[3]	1.00	0.84	XXX																									
[4]	0.70	0.79	0.75	XXX																								
[5]	1.00	0.58	1.00	0.74	XXX																							
[6]	0.70	0.79	0.79	0.76	0.79	XXX																						
[7]	1.00	0.57	1.00	0.74	1.00	0.79	XXX																					
[8]	0.70	0.20	0.64	0.40	0.64	0.69	0.64	XXX																				
[9]	1.00	0.76	1.00	0.77	1.00	0.77	1.00	0.68	XXX																			
[10]	0.76	1.00	0.84	0.80	0.58	0.79	0.57	0.20	0.76	XXX																		
[11]	1.00	0.67	1.00	0.80	1.00	0.80	1.00	0.64	1.00	0.67	XXX																	
[12]	0.75	0.31	0.30	0.42	0.27	0.65	0.27	0.77	0.75	0.31	0.60	XXX																
[13]	1.00	0.59	1.00	0.76	1.00	0.80	1.00	0.64	1.00	0.59	1.00	0.34	XXX															
[14]	0.68	0.76	0.76	0.81	0.76	0.54	0.76	0.50	0.77	0.77	0.78	0.53	0.77	XXX														
[15]	1.00	0.56	1.00	0.74	1.00	0.79	1.00	0.64	1.00	0.56	1.00	0.28	1.00	0.76	XXX													
[16]	0.76	0.48	0.69	0.45	0.69	0.79	0.69	0.57	0.70	0.48	0.69	0.72	0.69	0.64	0.69	XXX												
[17]	1.00	0.75	1.00	0.32	1.00	-0.88	1.00	-0.87	1.00	0.75	1.00	0.72	1.00	-0.78	1.00	-0.88	XXX											
[18]	1.00	-0.62	1.00	0.85	1.00	0.82	1.00	0.60	1.00	-0.63	1.00	0.87	1.00	0.83	1.00	0.69	1.00	XXX										
[19]	1.00	0.29	1.00	0.80	1.00	0.80	1.00	0.64	1.00	0.29	1.00	0.74	1.00	0.78	1.00	0.69	1.00	1.00	XXX									
[20]	1.00	0.83	1.00	0.75	1.00	0.79	1.00	0.64	1.00	0.84	1.00	0.27	1.00	0.76	1.00	0.69	1.00	1.00	1.00	XXX								
[21]	1.00	0.79	1.00	0.74	1.00	0.79	1.00	0.64	1.00	0.79	1.00	0.28	1.00	0.76	1.00	0.69	1.00	1.00	1.00	1.00	XXX							
[22]	1.00	-0.75	1.00	0.90	1.00	0.82	1.00	0.66	1.00	-0.76	1.00	-0.67	1.00	0.86	1.00	0.66	1.00	1.00	1.00	1.00	1.00	XXX						
[23]	1.00	0.76	1.00	0.84	1.00	0.80	1.00	0.64	1.00	0.76	1.00	0.76	1.00	0.79	1.00	0.69	1.00	1.00	1.00	1.00	1.00	1.00	XXX					
[24]	1.00	0.57	1.00	0.74	1.00	0.79	1.00	0.64	1.00	0.57	1.00	0.27	1.00	0.76	1.00	0.69	1.00	1.00	1.00	1.00	1.00	1.00	1.00	XXX				
[25]	1.00	0.55	1.00	0.81	1.00	0.81	1.00	0.64	1.00	0.56	1.00	0.84	1.00	0.78	1.00	0.69	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	XXX			
[26]	1.00	-0.51	1.00	0.81	1.00	0.81	1.00	0.64	1.00	-0.51	1.00	0.87	1.00	0.78	1.00	0.69	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	XXX		
[27]	1.00	0.59	1.00	0.81	1.00	0.81	1.00	0.64	1.00	0.59	1.00	0.76	1.00	0.78	1.00	0.69	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	XXX	
[28]	1.00	0.63	1.00	0.81	1.00	0.80	1.00	0.64	1.00	0.64	1.00	0.70	1.00	0.78	1.00	0.69	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	XXX
[29]	1.00	0.54	1.00	0.81	1.00	0.81	1.00	0.64	1.00	0.55	1.00	0.82	1.00	0.78	1.00	0.69	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 19a
Test 2 - PI33 - raw data

	Wall Time:	6	CPU Time:	13733.28
Oscillator	**Value Max**	**Value Min**	**Ratio Max**	**Ratio Min**
2Hz	0.237458	-0.27339		
4Hz	5.36E-02	-7.14E-02		
8Hz	1.17E-02	-1.17E-02		

Table 19b
Test 2 - PI33 – frequency filtered to cross correlation coefficient 0.90

	Wall Time:	5.87	CPU Time:	13768.05
Oscillator	**Value Max**	**Value Min**	**Ratio Max**	**Ratio Min**
2Hz	0.175024	-0.21819	0.737073	0.798109
4Hz	5.47E-02	-7.61E-02	1.02059	1.06637
8Hz	1.55E-02	-1.86E-02	1.32107	1.59395

Table 19c
Test 2 - PI33 – frequency filtered to cross correlation coefficient 0.90 – re-sampled

	Wall Time:	0.38	CPU Time:	919.59
Oscillator	**Value Max**	**Value Min**	**Ratio Max**	**Ratio Min**
2Hz	0.174995	-0.21826	0.736953	0.798348
4Hz	5.47E-02	-7.62E-02	1.02107	1.06667
8Hz	1.55E-02	-1.86E-02	1.32118	1.59357

Table 19d
Test 2 - PI33 – frequency pre-filtered above 1kz & frequency filtered to cross correlation coefficient 0.90

	Wall Time:	5.5	CPU Time:	13775.94
Oscillator	**Value Max**	**Value Min**	**Ratio Max**	**Ratio Min**
2Hz	0.203618	-0.23273	0.857492	0.851293
4Hz	4.84E-02	-6.97E-02	0.904027	0.975757
8Hz	1.03E-02	-5.83E-03	0.880879	0.499057

Table 19e
Test 2 - PI33 – time filtered to cross correlation coefficient 0.90

	Wall Time:	5.55	CPU Time:	13683.7
Oscillator	**Value Max**	**Value Min**	**Ratio Max**	**Ratio Min**
2Hz	0.177397	-0.21771	0.747065	0.796352
4Hz	5.39E-02	-7.54E-02	1.00635	1.0567
8Hz	1.52E-02	-1.83E-02	1.2953	1.56637

Table 20a
Test 3 - PI37 - Raw Data

	Wall Time:	4.77	CPU Time:	11825.05
Oscillator	**Value Max**	**Value Min**	**Ratio Max**	**Ratio Min**
2Hz	1.57353	-1.84195	0	0
4Hz	0.748973	-0.87465	0	0
8Hz	0.195394	-0.23018	0	0

Table 20b
Test 3 - PI37 – frequency filtered to cross correlation coefficient 0.90

	Wall Time:	4.73	CPU Time:	11824.59
Oscillator	**Value Max**	**Value Min**	**Ratio Max**	**Ratio Min**
2Hz	1.6142	-1.87301	1.02585	1.01686
4Hz	0.750982	-0.89414	1.00268	1.02228
8Hz	0.194336	-0.13305	0.994583	0.577997

Table 20c
Test 3 - PI37 – frequency filtered to cross correlation coefficient 0.90 – re-sampled

	Wall Time:	0.01	CPU Time:	12.48
Oscillator	**Value Max**	**Value Min**	**Ratio Max**	**Ratio Min**
2Hz	1.57523	-1.83328	1.00109	0.995296
4Hz	0.708003	-0.8354	0.945299	0.95512
8Hz	0.190783	-0.15297	0.976399	0.664536

Table 20d
Test 3 - PI37 – frequency pre-filtered above 1kz & frequency filtered to cross correlation coefficient 0.90

	Wall Time:	4.82	CPU Time:	11813.7
Oscillator	**Value Max**	**Value Min**	**Ratio Max**	**Ratio Min**
2Hz	1.61415	-1.87295	1.02582	1.01683
4Hz	0.750973	-0.89413	1.00267	1.02227
8Hz	0.194334	-0.13305	0.994577	0.578006

Table 20e
Test 3 - PI37 – time filtered to cross correlation coefficient 0.90

	Wall Time:	4.81	CPU Time:	11828.36
Oscillator	**Value Max**	**Value Min**	**Ratio Max**	**Ratio Min**
2Hz	1.47228	-1.76031	0.935657	0.955681
4Hz	0.593791	-0.7098	0.792807	0.811523
8Hz	0.130935	-0.10384	0.670109	0.451099

Table 21a
Test 5 – PI29 - raw data

	Wall Time:	4.42	CPU Time:	11001.5
Oscillator	**Value Max**	**Value Min**	**Ratio Max**	**Ratio Min**
2Hz	2.5128	-8.49E-02	0	0
4Hz	1.0161	-1.32677	0	0
8Hz	0.275833	-0.28495	0	0

Table 21b
Test 5 – PI29 – frequency filtered to cross correlation coefficient 0.90

	Wall Time:	4.49	CPU Time:	11027.47
Oscillator	**Value Max**	**Value Min**	**Ratio Max**	**Ratio Min**
2Hz	2.46619	-1.36E-02	0.981451	0.160667
4Hz	1.02819	-1.33811	1.0119	1.00854
8Hz	0.276052	-0.28625	1.00079	1.00458

Table 21c
Test 5 – PI29 – frequency filtered to cross correlation coefficient 0.90 – re-sampled

	Wall Time:	0.11	CPU Time:	256.95
Oscillator	**Value Max**	**Value Min**	**Ratio Max**	**Ratio Min**
2Hz	2.46595	-1.36E-02	0.981355	0.160667
4Hz	1.02802	-1.33624	1.01173	1.00713
8Hz	0.275989	-0.28607	1.00057	1.00394

Table 21d
Test 5 – PI29 – frequency pre-filtered above 1kz & frequency filtered to cross correlation coefficient 0.90

	Wall Time:	4.52	CPU Time:	11034.64
Oscillator	Value Max	Value Min	Ratio Max	Ratio Min
2Hz	2.46481	-6.65E-03	0.980901	7.84E-02
4Hz	1.01798	-1.33588	1.00184	1.00687
8Hz	0.296078	-0.26942	1.0734	0.945522

Table 21e
Test 5 – PI29 – time filtered to cross correlation coefficient 0.90

	Wall Time:	4.54	CPU Time:	11027.86
Oscillator	Value Max	Value Min	Ratio Max	Ratio Min
2Hz	2.44131	-1.99E-02	0.971546	0.234086
4Hz	1.03465	-1.34417	1.01826	1.01311
8Hz	0.276175	-0.28692	1.00124	1.00694

5. DISCUSSION

5.1. DATA CLEANING

The results of the work presented in this Appendix shows that it is both possible and valid to clean the recorded time-histories. However, it is clear from the results presented that it is not a clear-cut process. The noise overlying the time-histories is clearly sinusoidal in nature; this is evident from inspection of the plots and from the integration of the recordings. The integrated results lack the presence of the noise; therefore, the noise is self-cancelling. This is a characteristic of a sinusoidal component overlying the more significant data. The source of the noise is discussed elsewhere in this report, where is shown that the sinusoidal nature strengthens the arguments leading to identification.

The cleaning process is however significantly controlled by the relative magnitude of the noise. The September 1999 tests were a particularly useful source of data for this study into the nature and removal of noise, as the explosion intensities were varied by the use of different gas clouds. It has therefore been possible to analyse time-histories where the noise amplitudes subsume the measured explosion. It is seen from the results of the automated cleaning of time-histories, that the technique is more effective where the noise amplitude is significantly less than the overpressure amplitude. To some extent, this is an obvious observation as for the larger overpressure; the explosion time-history dominates the recording.

The influence of the dominance of the noise over recording lead to the premise that the time-history should first be pre-filtered, then the pre-filtered time history should be treated as the raw data. The choice of 1kHz for the pre-filtering was arbitrary, if pre-filtering is shown a reasonable technique; it would be necessary to derive a reasonable lower-bound pre-filtering frequency. Observations would lead to the conclusion that this may be as low as 100Hz.

It is seen from the validation exercises in Section 4 that it is difficult to validate the cleaning of the time-histories where the data is overwhelmed by noise. Tests 2 and 5 both exhibit significant noise. In both cases, the validation of the results is not convincing. For test 3, where the maximum amplitude of the noise is lower than that of the recorded over-pressure, the methods validate well.

5.2. RE-SAMPLING

The re-sampling of the data has significant implications for the analysis of structures subjected to explosion overpressure. The Spadeadam data has been recorded using a time interval of 0.02ms (2×10^{-5}s). As is seen in the results tables, this yields records with greater than 40,000 data points. Whist computer resources have increased in both processing speed and disc storage; the resources required to analyse even the simplest structure for so many iterations are prohibitive outside research organisations. As an example, using the Test 2 data on a the three single degree of freedom oscillators expended the following:

47,520 data points;

11,825 seconds (3.28 Hours) of CPU time; and

280MBytes disc storage.

This on a 450 MHz twin processor Pentium III machine with 512Mbytes memory.

Evidently, demonstrating that the data set can be reduced without losing the explosion characteristics is important. The reduced data set for the Test 3 data resulted in between 48 and 93 time-steps. This dramatic reduction allows the structural analyst to use the measured data, or data derived from the measured data, for design verification analysis without having to use time-intervals which are dictated by the data recording. Depending upon the type of analysis being performed, the analyst will have to introduce further time divisions, however, these divisions can be selected by the analyst, the analysis program or more commonly a combination of the two. Reducing the size of the data record also allows for publishing of the data in a user-friendlier format.

5.3. TIME-DOMAIN VERSES FREQUENCY DOMAIN FILTERING

This work has used three data filtering techniques, time-domain data smoothing, frequency-domain data filtering and wavelet filtering. Of these, the time and frequency domain techniques are the most widely used. These both have advantages and disadvantages:

Frequency-domain filtering is computationally complex in that it requires the data to be transformed from the time-domain to the frequency domain, filtered, then transformed back, utilising the Fourier transform; however

With frequency-domain filtering it is obvious what is being done and this can be immediately associated with known and expected structural responses; and

Frequency-domain filtering has the minor drawback of unavoidably adding harmonics to the filtered data;

Time-domain filtering or data smoothing is computationally simple in that data either side of the data point being processed are simply averaged or averaged using one of the weighted smoothing algorithms; however

The physical nature of the smoothing process cannot be readily allied to the structural response.

Table 6 compares the results of automatic filtering in both the time and frequency-domains. It is seen that the time-domain filtering yields a greater reduction in peak overpressure, and that the re-sampled time-histories are shorter.

Considering the resulting time-intervals for the automatic time filtering, Table 4, the smoothing window widths for Test 3 (PI-29) are 5.70ms, 27.00ms, 118.60ms and 162.70ms, for cross-correlation coefficients of 0.98, 0.95, 0.90 and 0.85 respectively. Assuming these are the periods of oscillation, these would imply frequencies of 175.4Hz, 37.0Hz, 8.43Hz and 6.14Hz. The corresponding frequency filters are 139.0Hz, 32.8Hz, 6.9Hz and 5.3Hz. There is therefore some degree of association between the results from the two tests. This would add to the validity of the cut-off frequencies calculated by the frequency domain technique.

5.4. CROSS-CORRELATION COEFFICIENT

The strength of using the cross-correlation coefficient to measure the degree of correlation between two data sets also appears to be its weakness. Where the amplitude of the noise is significantly less than the amplitude of the measured overpressure, the cross-correlation coefficient can be used to provide a measure of the closeness of the filtered data to the original data. In the tests carried out to validate this work, the filtered time-histories from Test 3 have compared well to the original raw data. In both the integration and analysis tests, the filtered data gives results adequately close to the original to enable confidence to be expressed in there being no loss of response. However, for the Test 2 and Test 5 data, where the noise is of significant amplitude, these correlations do not exist. Indeed, in the analysis results the amplitudes increase when the high frequency data is removed. This may point to the average noise response swamping the actual response.

The results of this work would suggest a cross-correlation coefficient of 0.90 to control filtering, as long as the noise amplitudes are low compared to the explosion overpressure amplitude. As the noise amplitudes become more significant, the target cross-correlation coefficient has to drop. Therefore, for very noisy time-histories cross-correlation coefficients as low as 0.60 may be required. This adds a second subjective layer to the filtering process, which makes automation and subsequent validation more difficult.

5.5. CHANGE IN OVERPRESSURE AMPLITUDE

It is seen from the results in Table 6 that the recorded overpressures can be reduced by as much as 70%. For Test 3, this is a reduction from 749mbar to 286mbar (by frequency-domain filtering) or 239mbar (by time-domain smoothing). These are significant reductions and will have correspondingly significant influences on the necessary structural resistances. These reductions are repeated for the other tests although the cleaning process is not so successful where the noise amplitudes are significant.

6. CONCLUSION

This work leads to the conclusion that it is permissible to remove the extraneous noise from the measured explosion overpressures. In the case where the noise amplitude is significantly lower than the explosion overpressure, the noise can be removed automatically, with reference to the cross-correlation coefficient between the original and modified data. Where the amplitude of the noise is of the same order as that of the measured explosion overpressure, or greater, automatic cleaning is not easily achieved. However, the time-histories can be cleaned by eye. The work has shown that it is safe to use 25Hz as a lower-bound filtering frequency, and the automated processes take this down to below 10Hz. However, based on the information presented here, it would be necessary for the choice of lower-bound frequency to be validated and justified on a case by case basis.

The cleaned explosion overpressure time-histories present two major benefits:

1. The headline overpressure is greatly reduced;

2. The number of time-points required for structural analysis can be reduced to manageable proportions; and

3. There is validity in the use of the cross-correlation coefficient to control the filtering, however this has to be applied in the context of the significance of any noise seen on the measured time-histories.

7. REFERENCES

1 Press, W.H., Teukolsky, S.A., Vetterling, W.T. and Flannery, B.P., *Numerical Recipes in C, The Art of Scientific Computing*, Cambridge University Press, Second Edition, 1996.

2 ASCE Standard, *ASCE 4-86, Seismic Analysis of Safety Related Nuclear Structures and Commentary on Standard for Seismic Analysis of Safety Related Structures,* The American Society of Civil Engineers, September 1986.

3 CREA Consultants Limited, *DynaTool, a Dynamics Toolkit.*

4 ANSYS Inc., *ANSYS A General Purpose Finite Element Analysis Suite.*

8. FIGURES

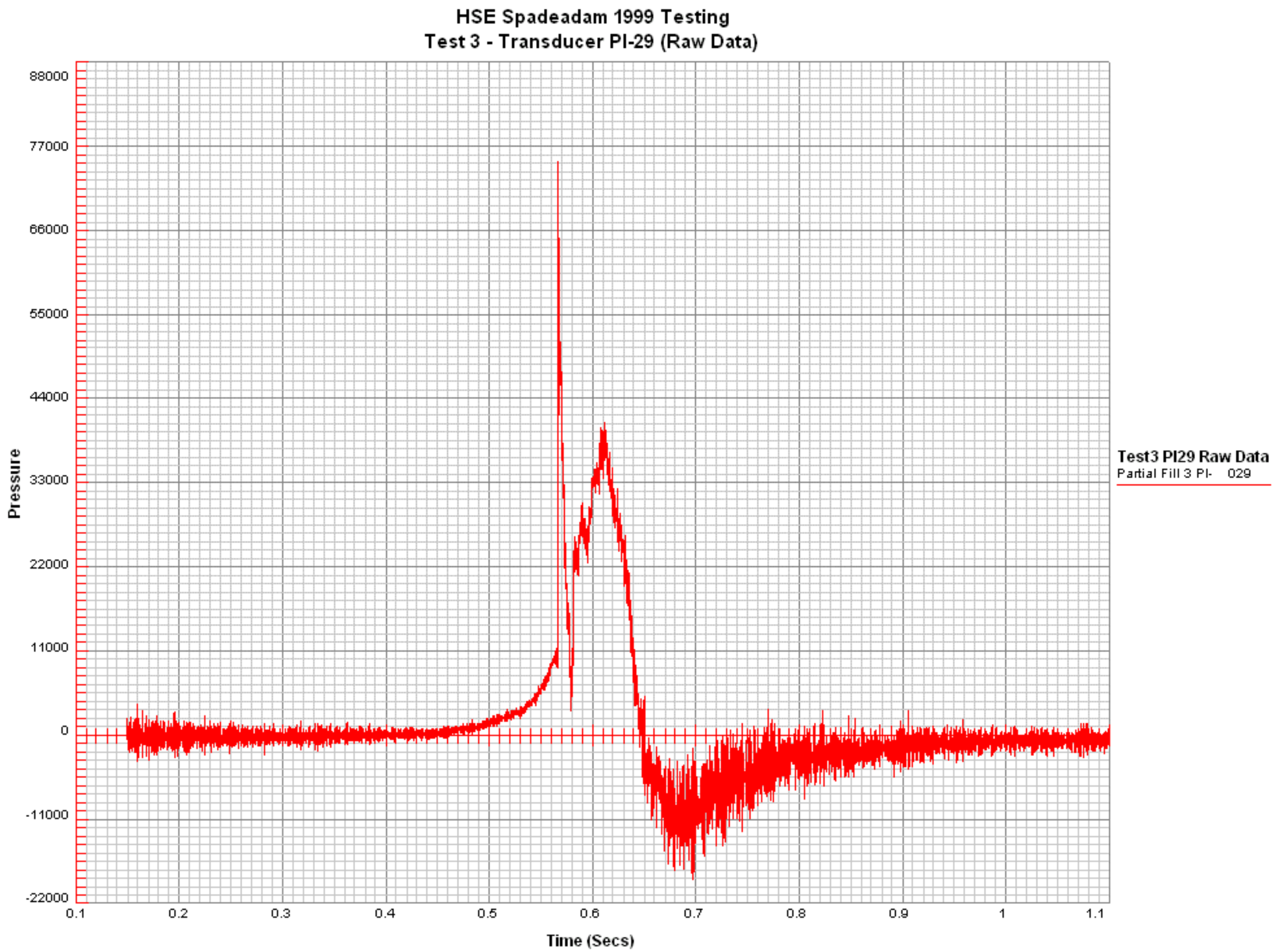
HSE Spadeadam 1999 Testing
Test 3 - Transducer PI-29 (Raw Data)
Pressure
88000
77000
66000
55000
44000
33000
22000
11000
0
-11000
-22000
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
Time (Secs)
Test3 PI29 Raw Data
Partial Fill 3 PI- 029

Figure 1: Typical Recorded Overpressure

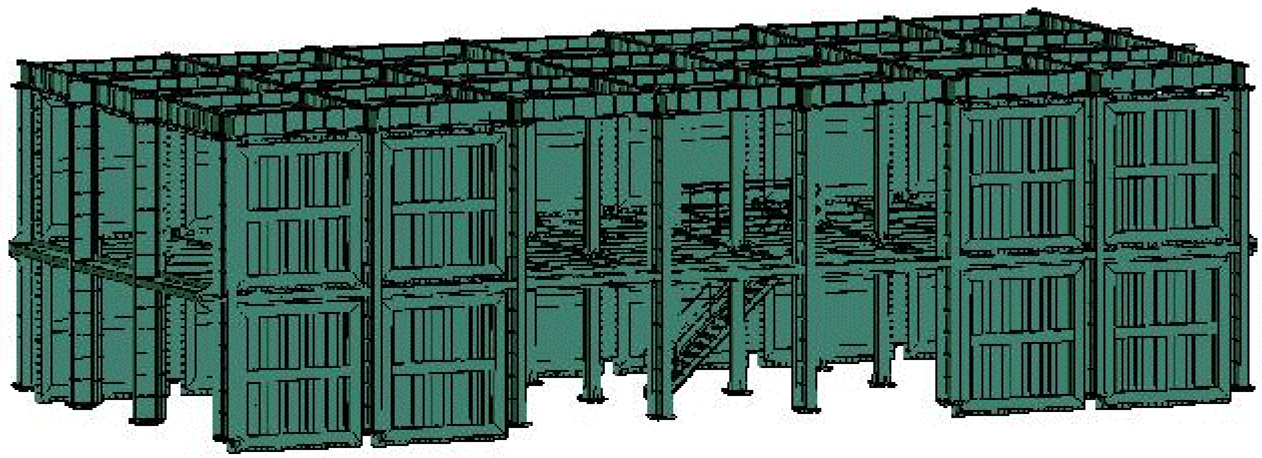

Figure 2: The Spadeadam Test Rig

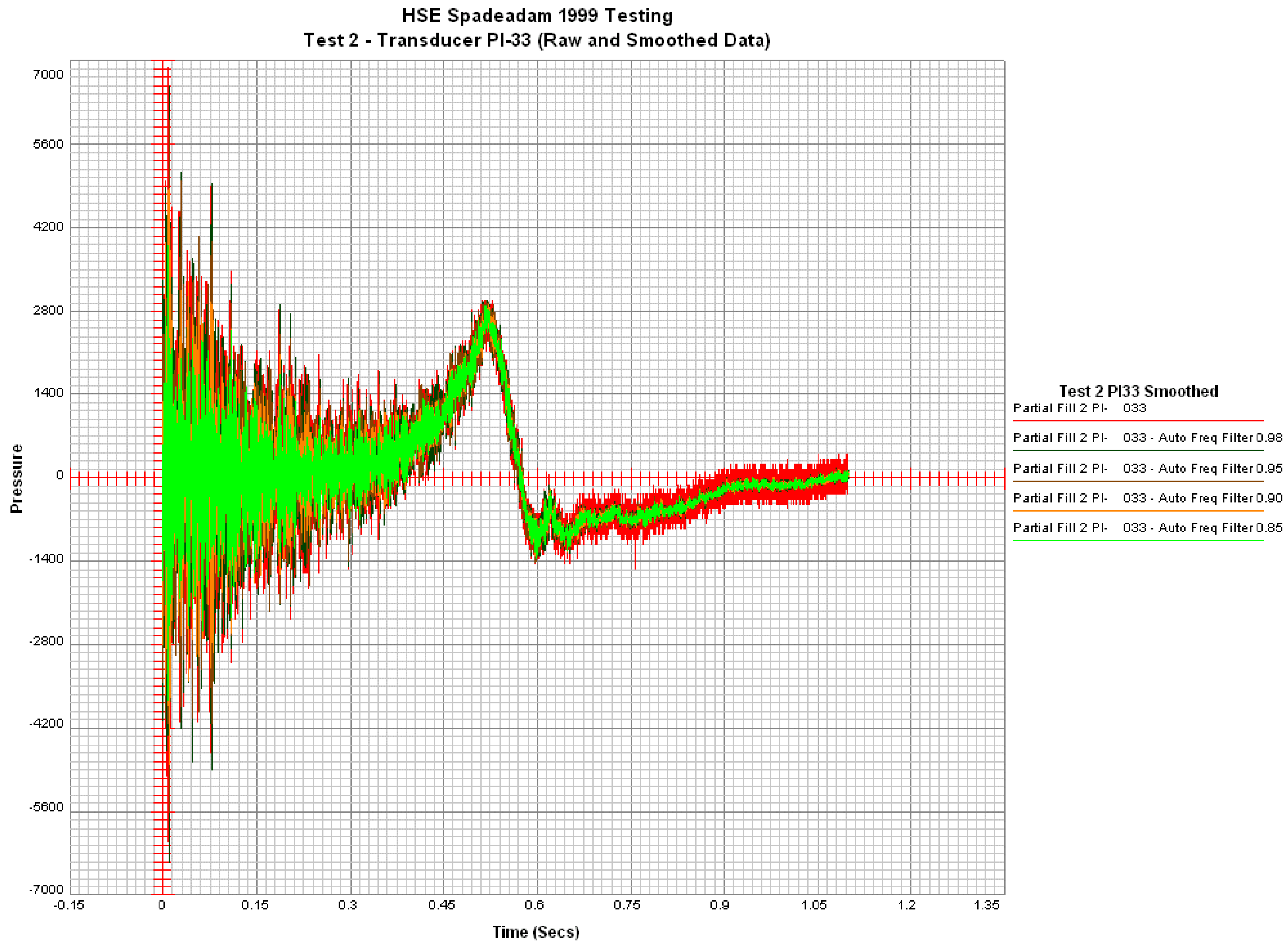

Figure 3: Automated Frequency Smoothing of Test 2

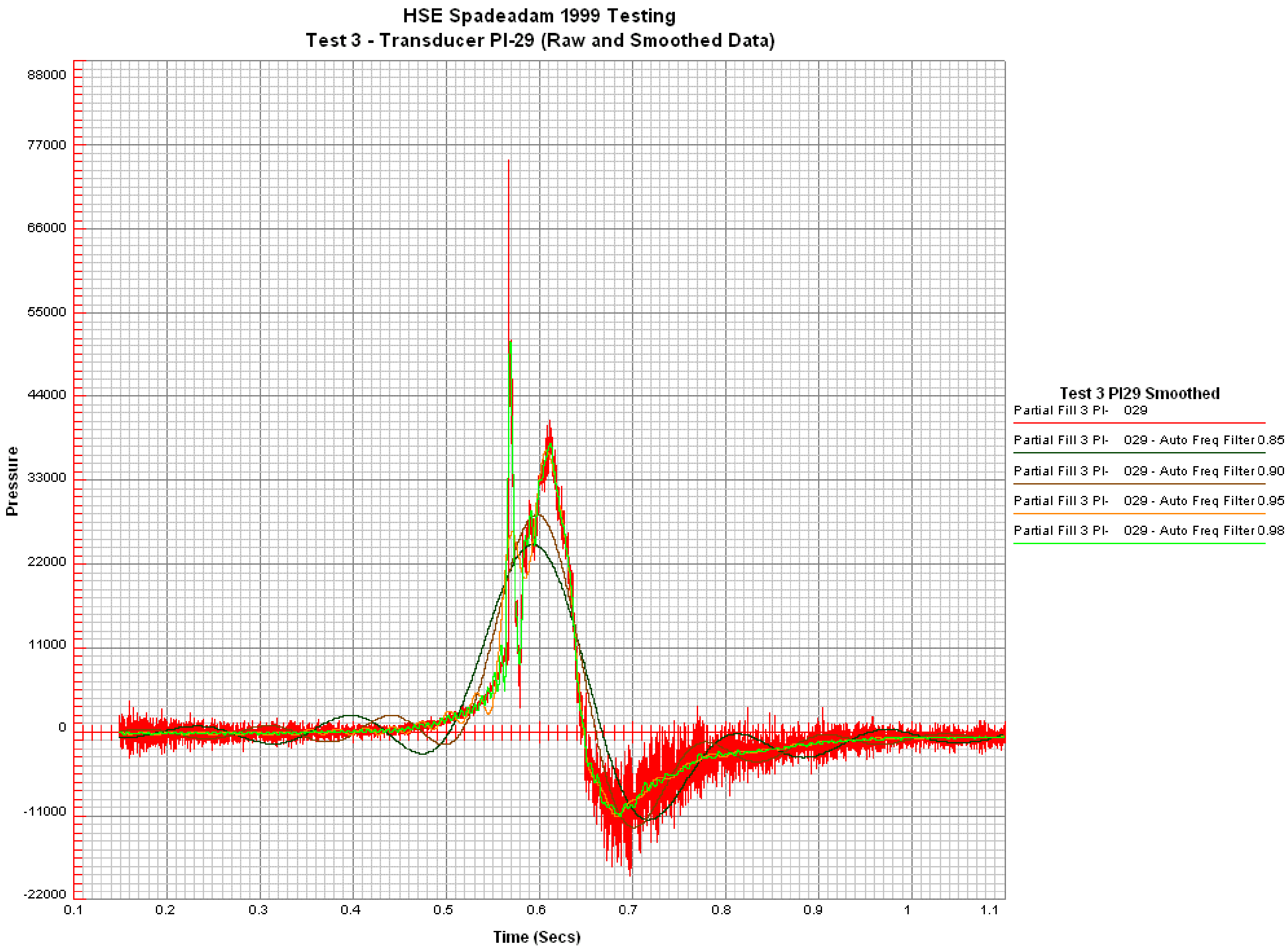

Figure 4: Automated Frequency Smoothing of Test 3

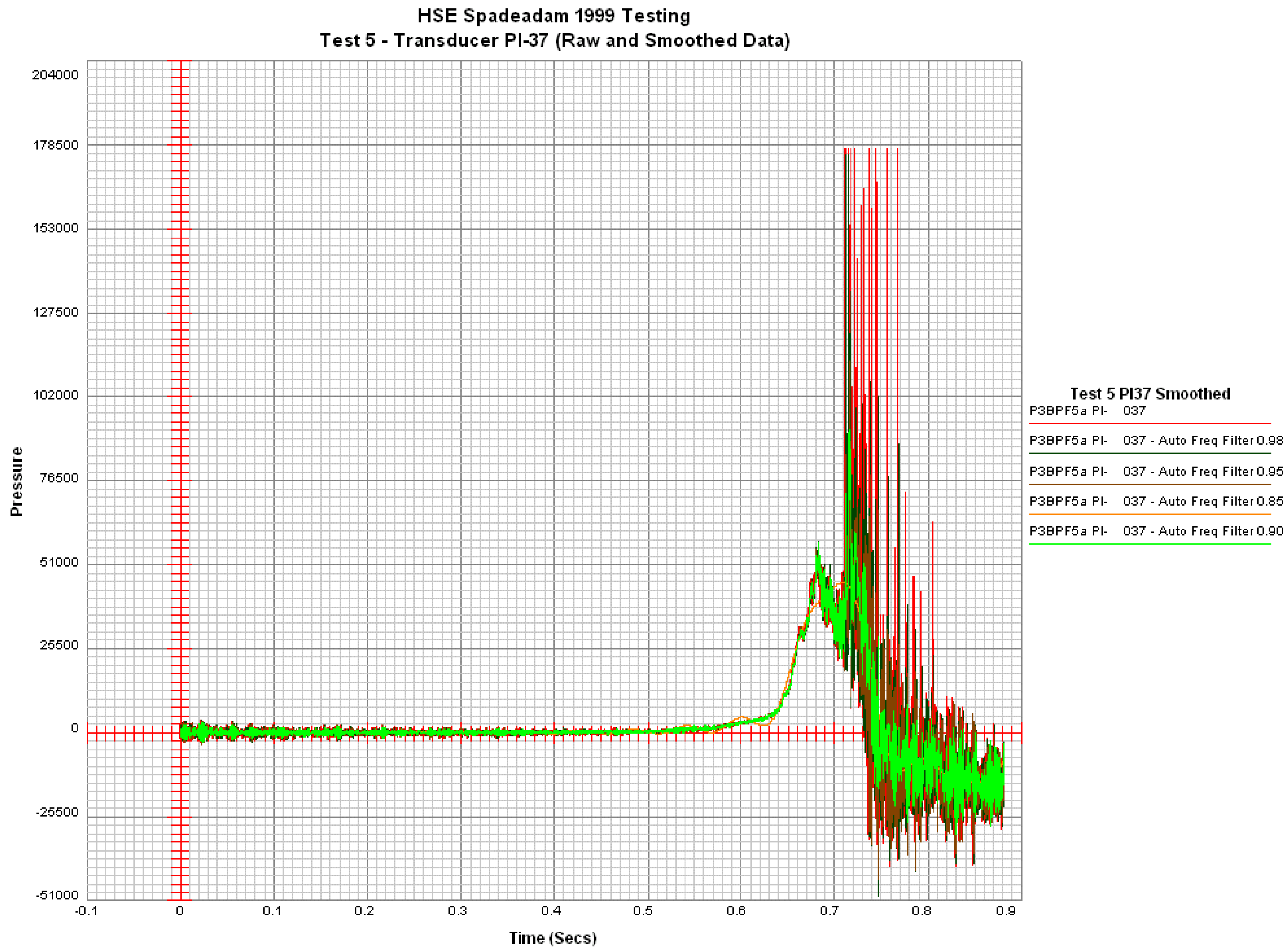

Figure 5: Automated Frequency Smoothing of Test 5

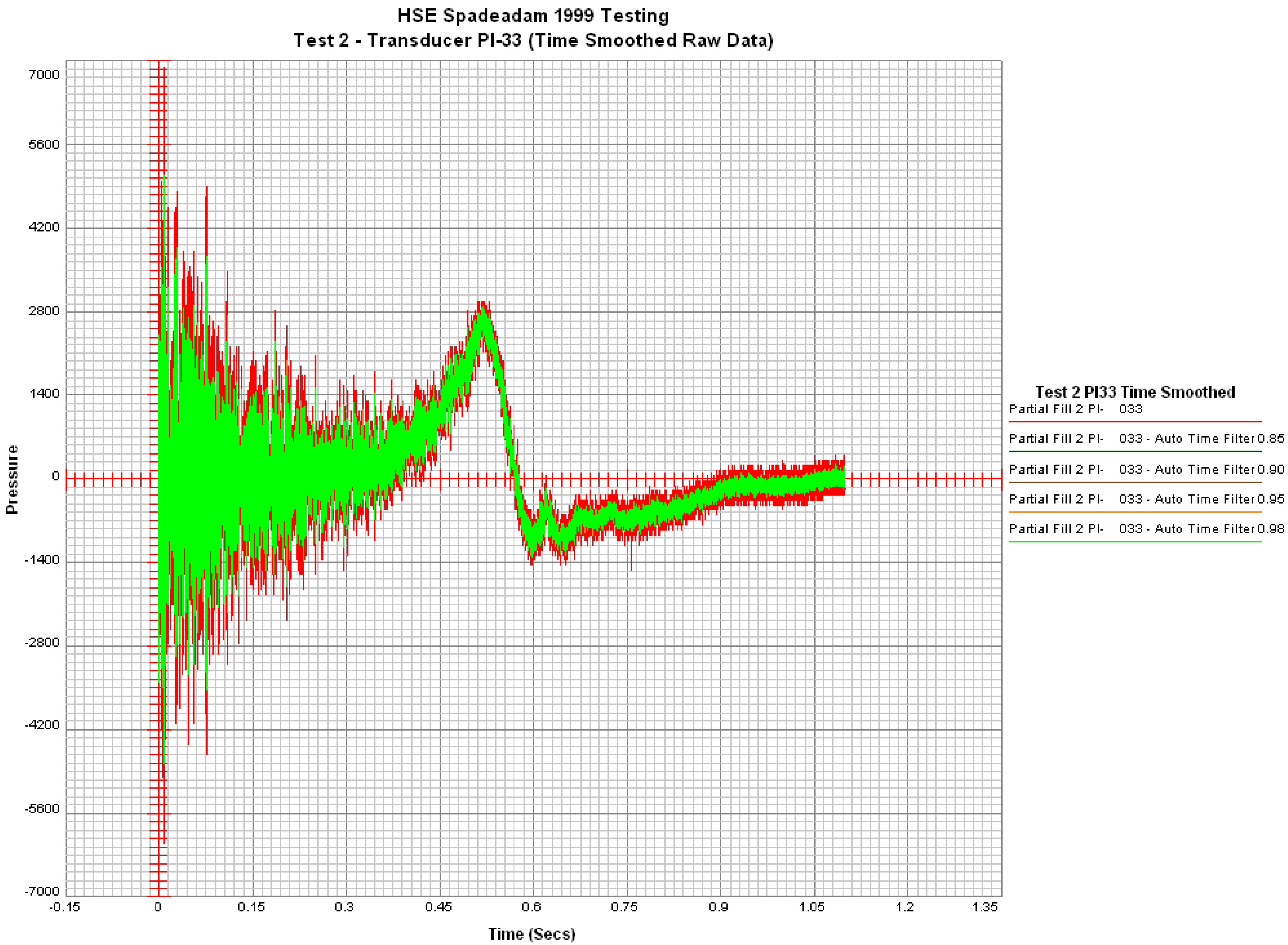

Figure 6: Automated Time Smoothing of Test 2

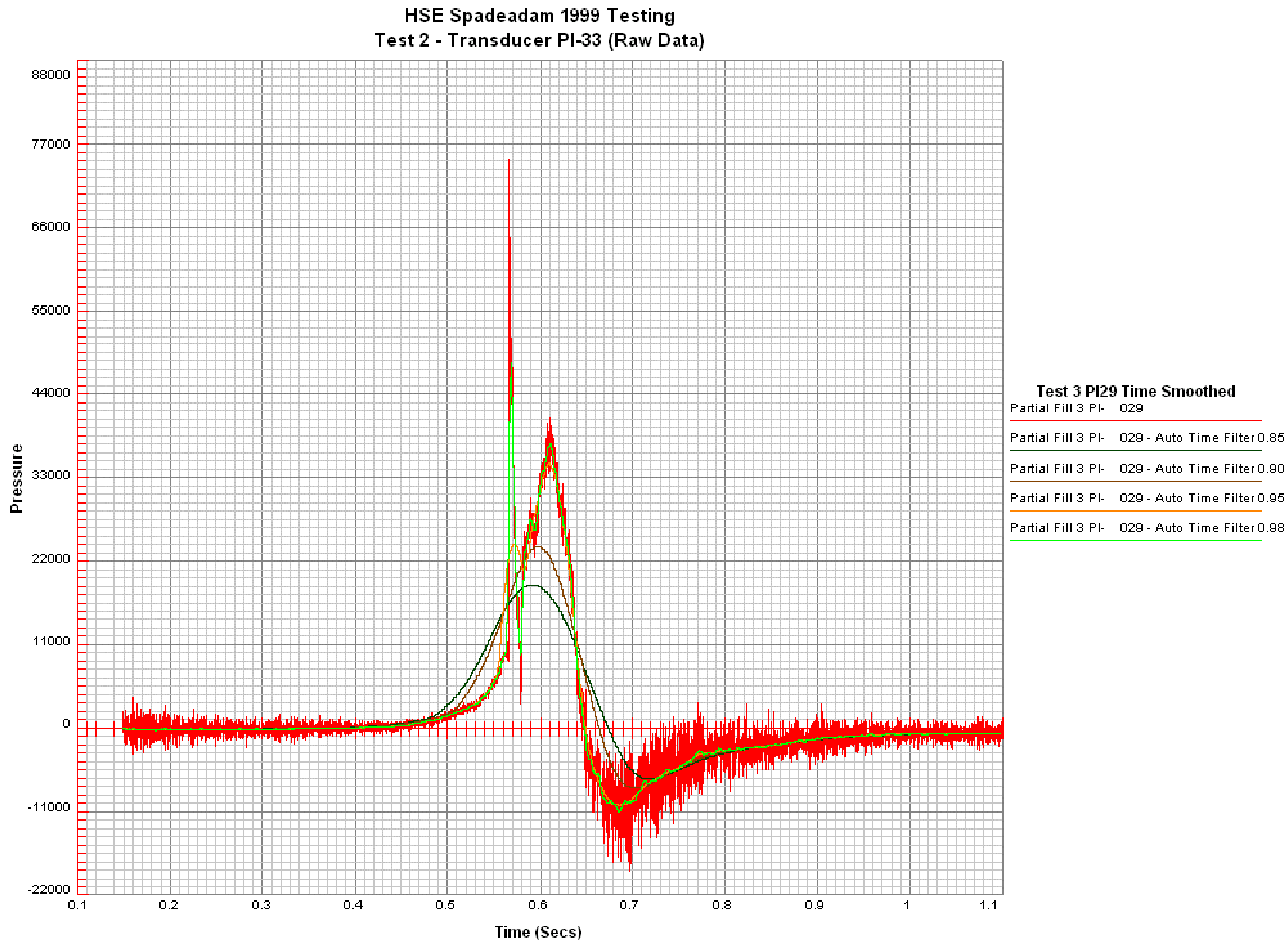

Figure 7: Automated Time Smoothing of Test 3

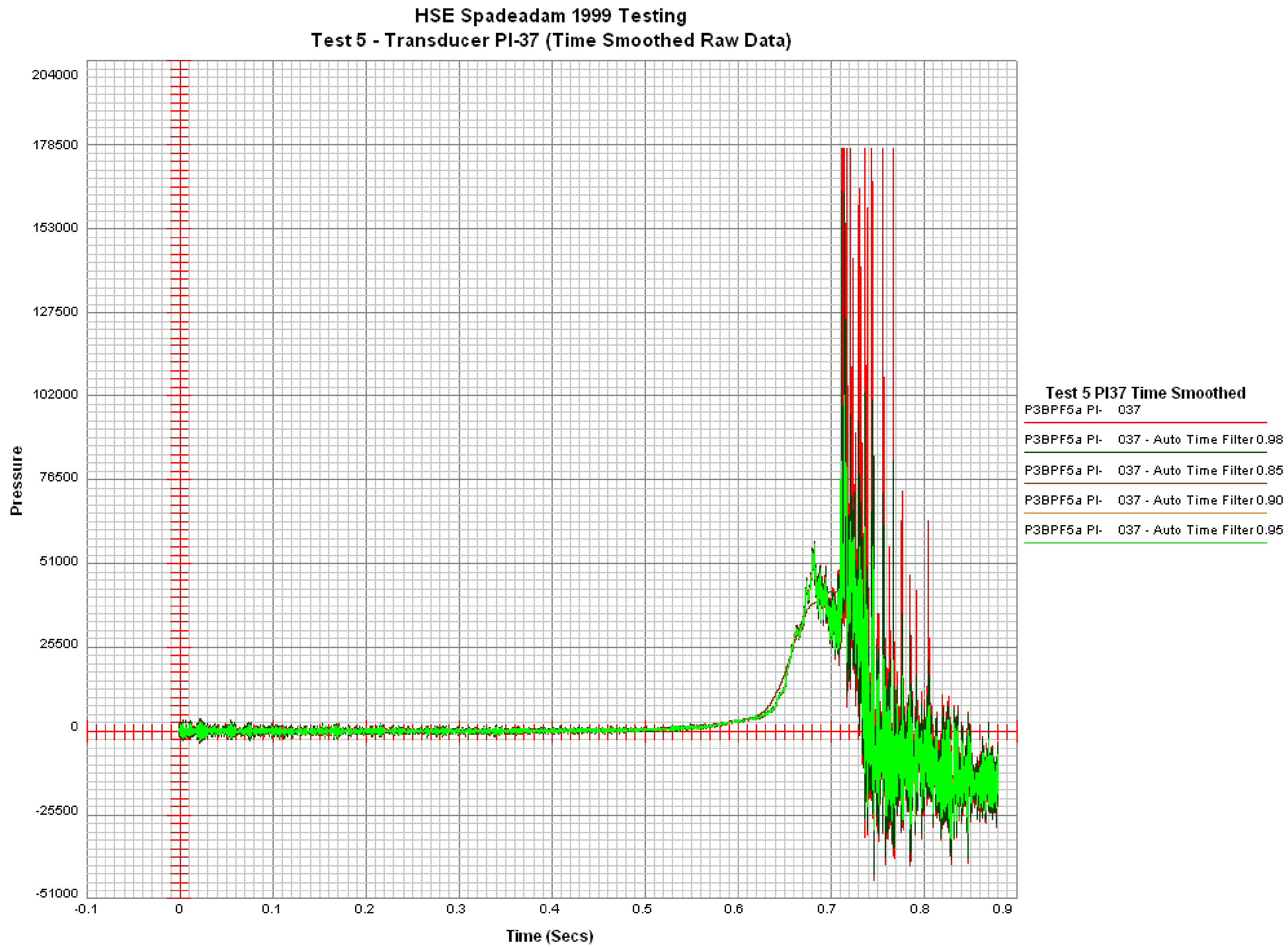

Figure 8: Automated Time Smoothing of Test 5

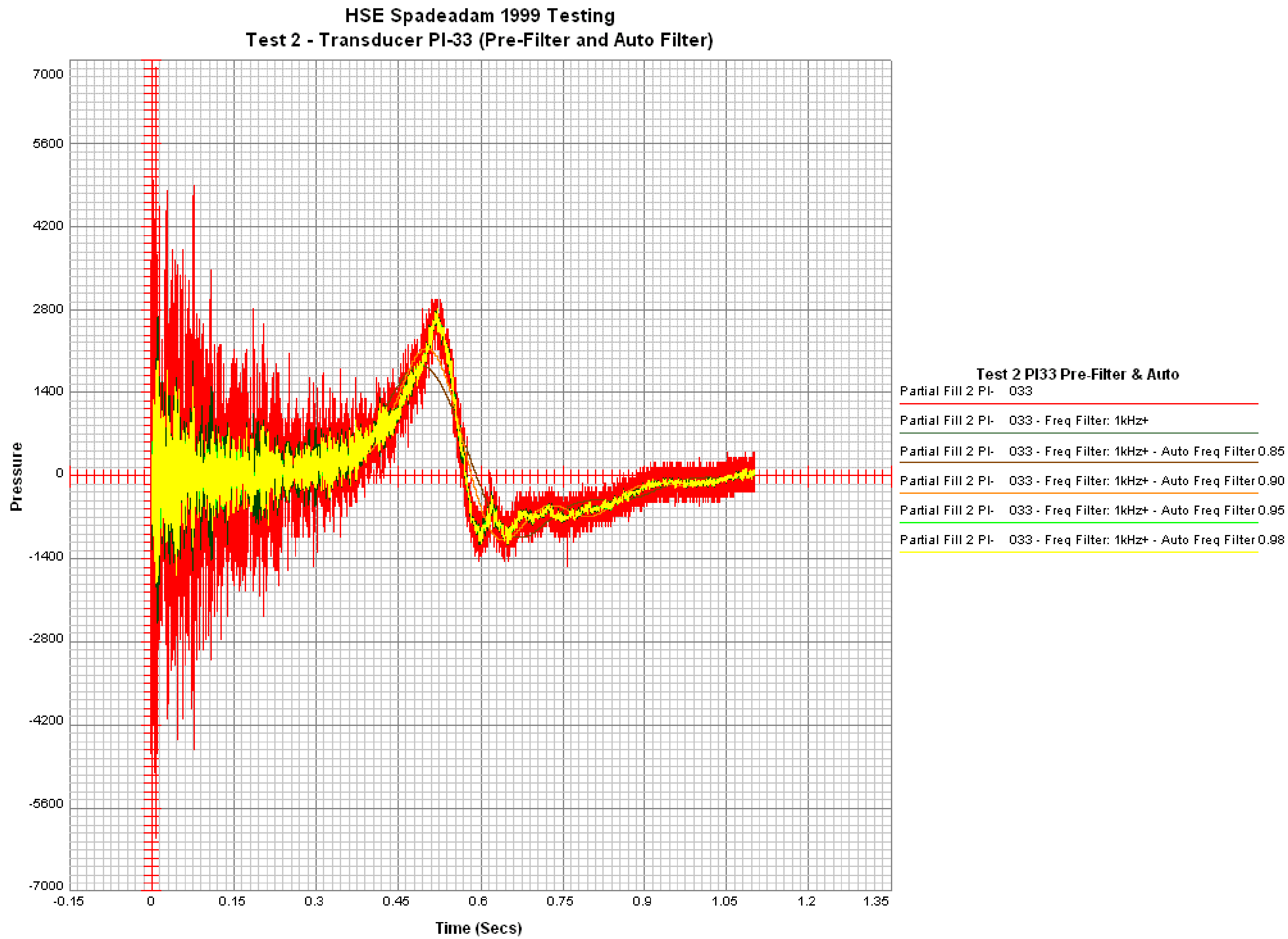

Figure 9: Pre-filter and Automatic Frequency Filtering of Test 2

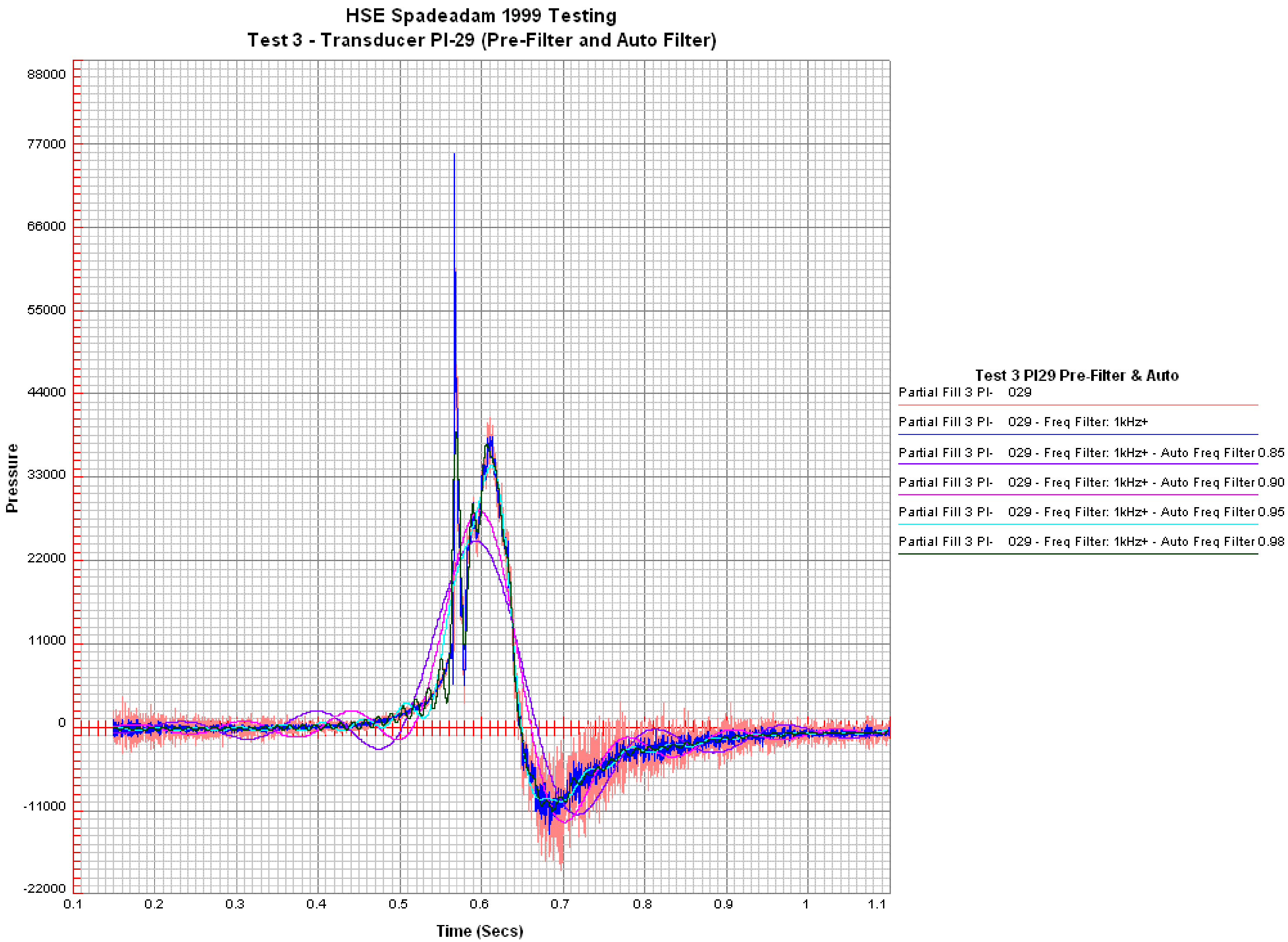

Figure 10: Pre-filter and Automatic Frequency Filtering of Test 3

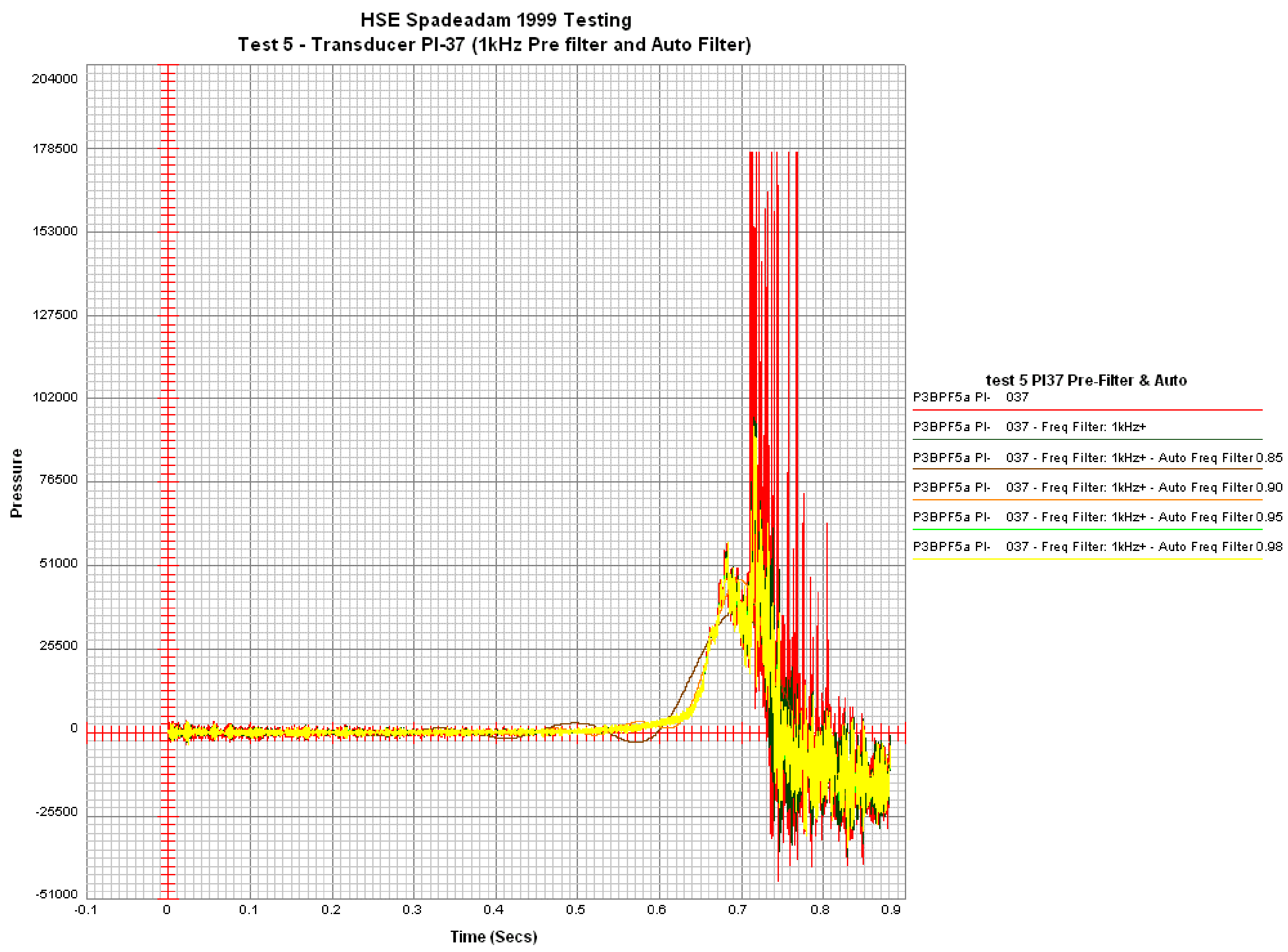

Figure 11: Pre-filter and Automatic Frequency Filtering of Test 5

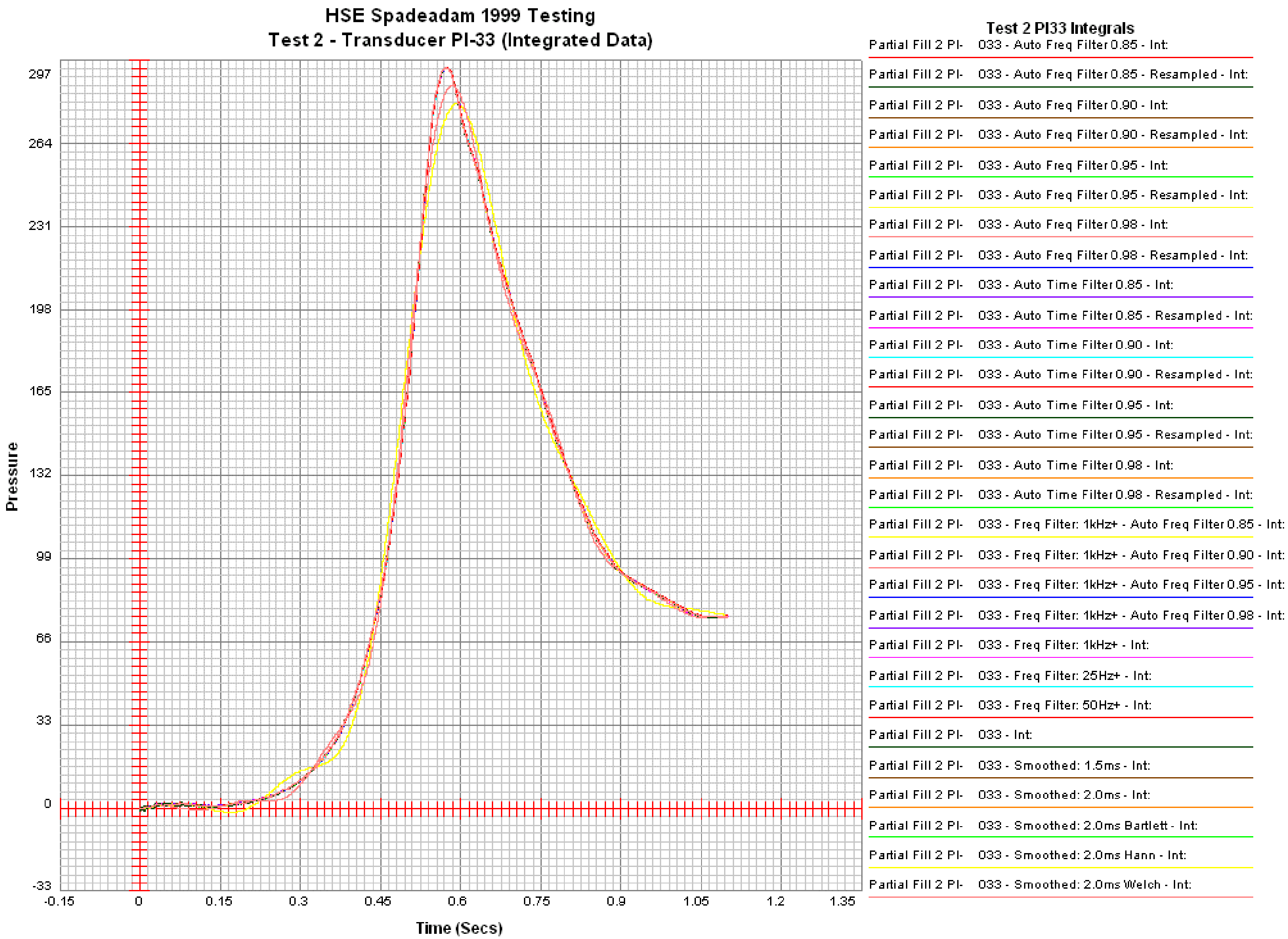

Figure 12: Test 2 Filtered Data - Integrals

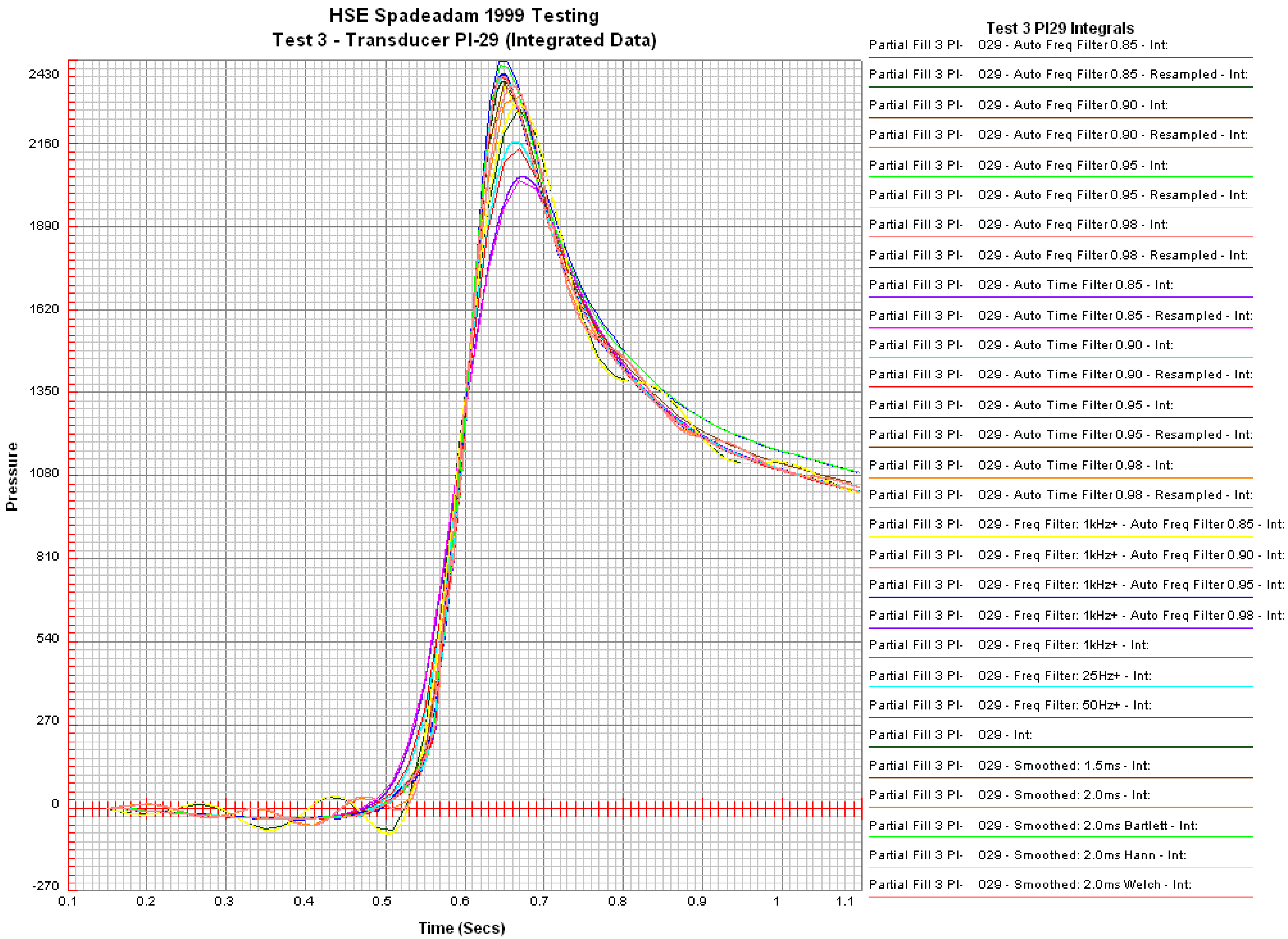

Figure 13: Test 3 Filtered Data - Integrals

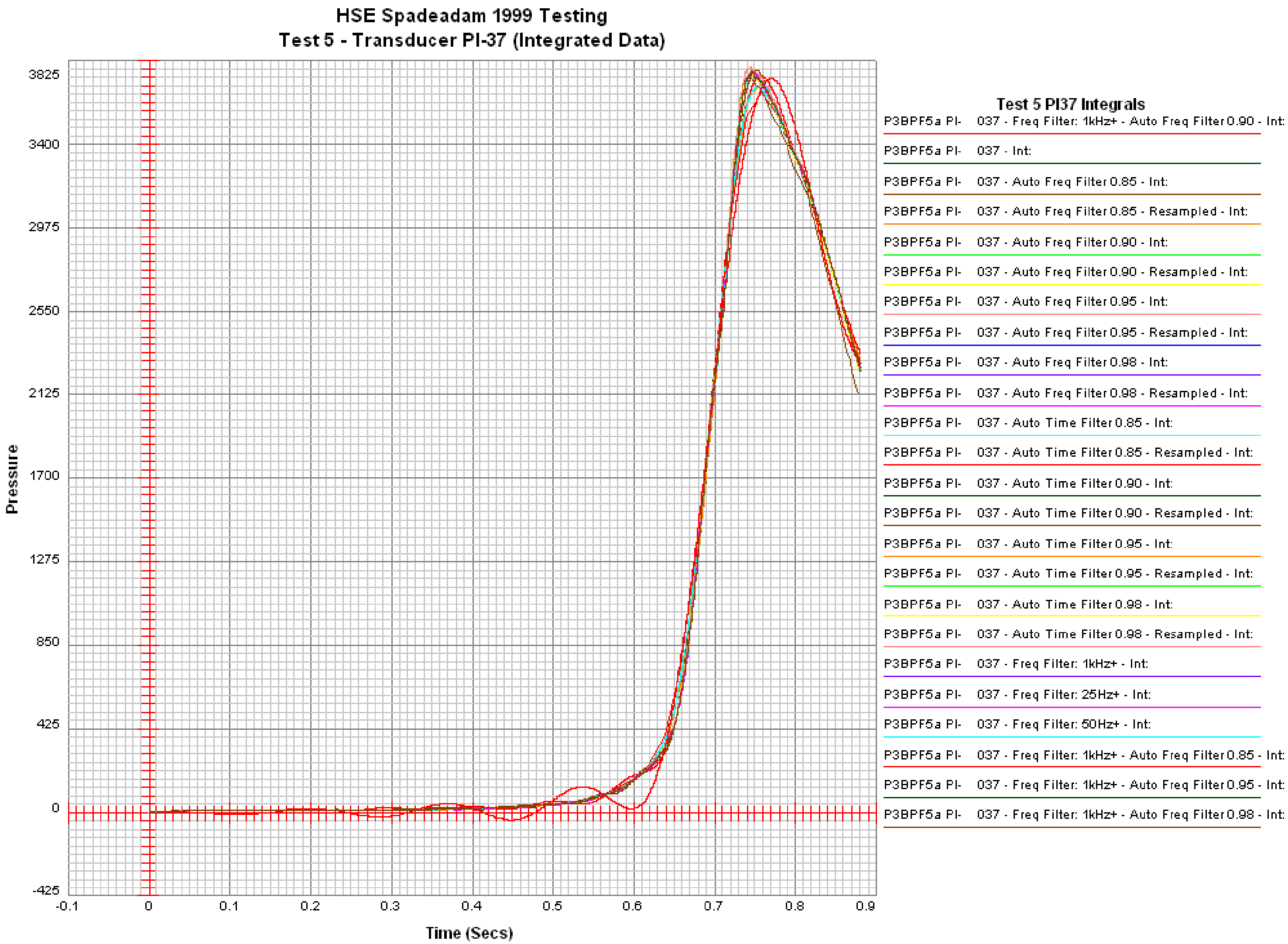

Figure 14: Test 5 Filtered Data - Integrals