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OFFSHORE TECHNOLOGY REPORT - OTO 2000 009

Structural Response Measurements During Gas Explosions in a Test Rig Representing an Offshore Module

Date of Issue : June 2000

Project : 3790

OFFSHORE TECHNOLOGY
REPORT - OTO

Structural Response Measurements During Gas Explosions in a Test Rig Representing an Offshore Module (Work Carried Out Under Contract to the HSE Agreement No. D3790)

EXECUTIVE SUMMARY

It is important for safety engineers to be able to predict the effects that a gas explosion in an offshore module would have on the structure. This report describes structural response measurements carried out during large scale explosion experiments at BG Technology Spadeadam test site, under contract to HSE. The large scale explosion experiments were conducted as a part of a Joint Industry Project being funded by a number of organisations. Measurements were made during six experiments.

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1. INTRODUCTION

To date, structural response to full scale explosion experiments has been studied to only a very limited extent and no full scale data is currently available that would allow an assessment of out of balance loading or dynamic response to be made.

This report describes:

- Measurements of the structural response of a large scale explosion rig at the BG Technology Spadeadam Test Site. These measurements, carried out under contract to HSE, were made during large scale explosion experiments conducted by BG Technology as a part of a Joint Industry Project being funded by a number of organisations. Measurements were made during six tests and the data has been provided to the HSE for analysis.
- An analysis of data obtained from accelerometers.
- Measurements and analysis of data from a series of modal tests carried out on the large scale explosion rig.

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2. EXPERIMENTAL ARRANGEMENT

2.1. TEST RIG

The explosion test rig used in these experiments was originally constructed during the "Blast and Fire Engineering for Topside Structures Phase 2 " [1] project managed by the Steel Construction Institute and subsequently used for the programme of explosion experiments for the HSE [2]. The rig was designed to represent, at full scale, the confinement and congestion within a typical offshore module containing items of process plant and pipework. The rig structure was designed and built to withstand significant explosion overpressures and allow for changes of module layout.

The design of the rig structure was based on a strong framework with beams on 4m centres onto which panels could be fitted to provide the required confinement.

Each wall panel was constructed as a 300 x 300 x 12.5 mm box section frame, 3.56 m high by 3.46 m wide. A horizontal box section, of the same type used for the frame, was welded across the mid-height of the frame for additional stiffening. Flat 10 mm plate was welded into the open areas of the frame to make a flat internal surface. On the outside of the panel, a 10 mm thick corrugation was welded vertically inside the frame as additional stiffening. The flat plate was plug welded to the troughs in the outer corrugation at nominally 400 mm intervals. The design of the panels took advantage of previous experience obtained from the design and use of an explosion chamber at Spadeadam and the framework was designed to be capable of withstanding a static overpressure of 3.5 bar within the rig. In order to securely anchor the test rig, the main framework was fixed to steelwork which was embedded in a thick concrete test pad.

A mezzanine deck, comprising of a steel support frame covered with serrated open bar grating, was located at mid-height throughout all of the test rig and was designed to be similar to those found in typical offshore modules.

During all the experiments described in this report, the test rig was 28m long, 12m wide and 8m high. The confinement of walls and roof was fixed during all of the tests; the rig configuration is shown in Figure 1.

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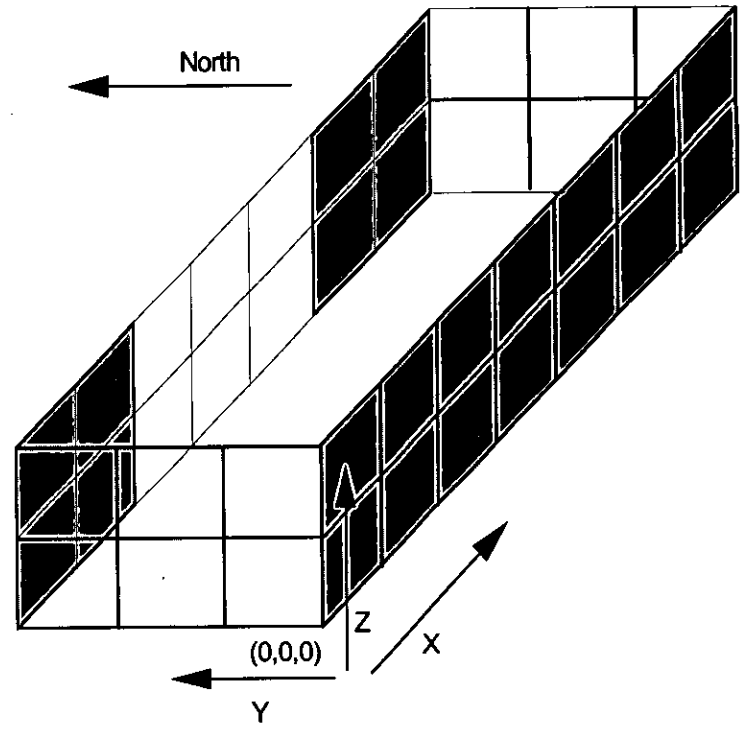

The roof was fully confined for all tests

Figure 1
Test rig configuration

2.2. EXPLOSION TEST CONDITIONS

Structural response measurements were made during six experiments. The primary objective of the experiments was to study explosions produced by ignition of a homogeneous mixture of natural gas and air with the volume of the natural gas and air mixture ranging between 10% and 100% of the volume of the explosion rig. The experimental conditions of the six tests are summarised in Table 1.

Table 1
Test conditions for explosion experiments in which structural response measurements were made

Test configuration	Dimensions of cloud (m)			Co-ordinates of corner nearest origin (m)			Percentage of rig filled by the gas cloud
	X	Y	Z	X	Y	Z	
PF 1	8	8	8	12	0	0	19%
PF 2	4	8	8	16	0	0	10%
PF 3	12	12	8	8	0	0	43%
PF 4	12	12	8	16	0	0	43%
PF 5	28	12	8	0	0	0	100%
PF 6	8	8	8	8	0	0	19%

2.3. MODAL ANALYSIS

Modal analysis is the process of characterising the dynamic properties on an elastic structure in terms of its modes of vibration. A mode is the manifestation of energy trapped within the boundaries of a structure that cannot be readily dissipated. As this energy travels back and forth

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within the structure, it causes the structure to deform with various well defined wavelike motions called "mode shapes". These mode shapes occur at various natural frequencies of vibration and will also decay in amplitude, (i.e. become damped out), if all external sources of energy are removed from the structure.

A specific natural frequency, damping factor and mode shape can define each mode of vibration. These modal parameters can be determined from a set of frequency response function (FRF) measurements acquired by exciting the structure and measuring its response at various points across its surface.

A FRF defines the response at a location due to a force input at another location over a frequency range.

A modal analysis was conducted on the arrangement of the large scale explosion rig used during the explosion tests. The purpose of this analysis was to provide information for data analysis and numerical model (such as finite element) evaluation. The modal analysis was conducted to identify mode shapes, natural frequencies and damping factors of the entire large scale explosion rig and a separate analysis on one of the wall panels used to provide confinement to the test rig.

"Tap testing" was employed to excite the large scale explosion rig and the wall panel. This is a fast method for gathering data at many different locations around a test object. Since it is relatively quick to carry out measurements, it is possible to generate a higher resolution of measurement locations than could be achieved using a mechanical shaker.

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3. INSTRUMENTATION

The instrumentation within the test rig for both the explosion and modal testing was located at positions whose co-ordinates are given in Tables 2 to 7, using a co-ordinate system with its origin at the inside south west corner of the rig, see Figure 1.

3.1. INSTRUMENTED CYLINDER

In order to investigate the feasibility of estimating the flow velocity generated by explosions in the test rig, an instrumented horizontal cylinder was mounted in one of the open vent areas of the rig. The cylinder was 3.8m long and 0.1m in diameter, and was strongly supported 2m above the level of the concrete pad and instrumented with strain gauges and an accelerometer to measure the load on the cylinder. The details of the cylinder, supports and instrumentation are shown in Figure 2 to Figure 4.

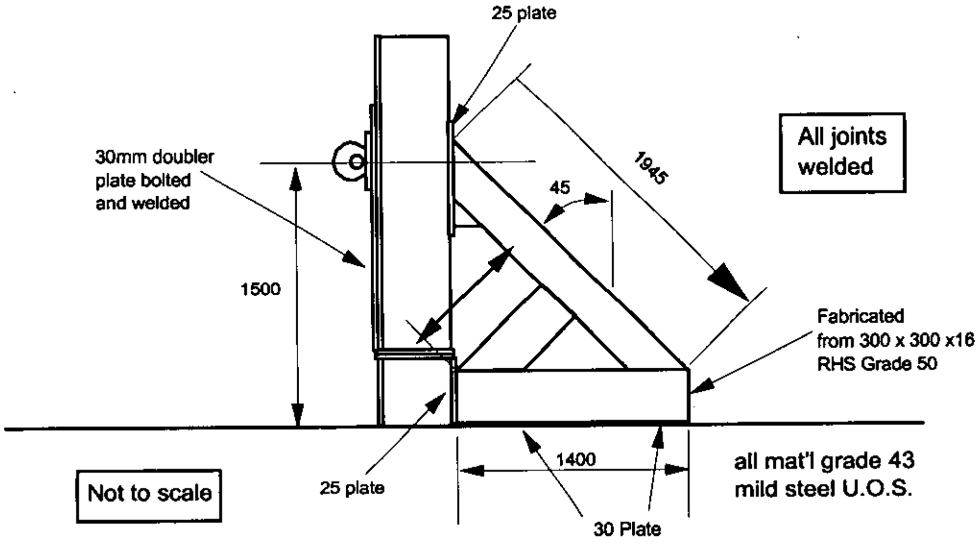

Figure 2
Cylinder and supports general arrangement

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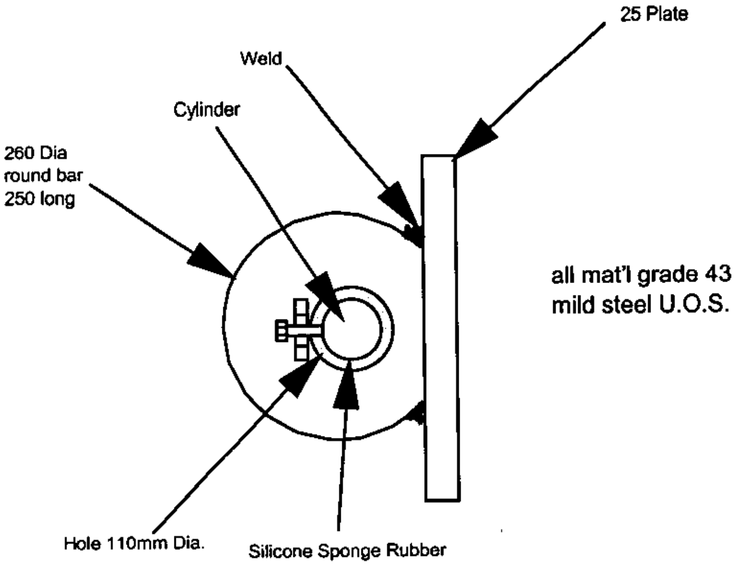
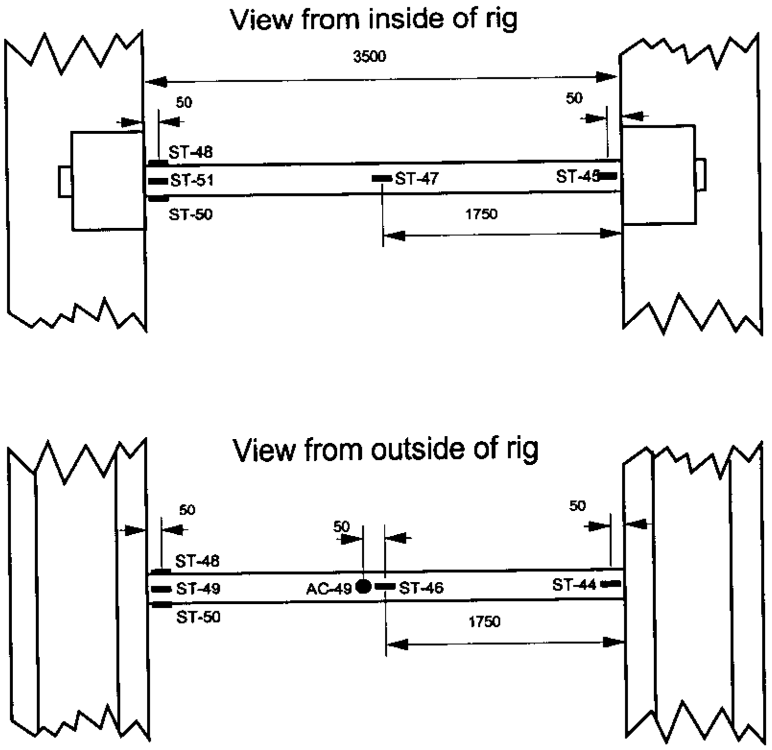


Figure 3
Cylinder mounting arrangement


View from inside of rig

View from outside of rig

Figure 4
Cylinder instrumentation locations

3.2. OVERPRESSURE MEASUREMENTS

Overpressure measurements during the explosion tests were made at twelve positions inside the test rig (P numbers). The locations of these transducers are given in Table 2. These transducers were located close to some strain gauges (see Section 3.4 below) as shown on Figure 5. This was to allow correlation of the pressure pulse against the response of the structure.

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Table 2
Pressure transducer positions

Pressure transducer	Co-ordinates (m)		
	X	Y	Z
PI-26	4.00	0.00	2.20
PI-27	3.90	1.80	4.10
PI-28	1.10	4.00	4.10
PI-29	6.20	4.00	3.80
PI-30	4.00	9.80	3.80
PI-31	4.00	12.00	2.20
PI-32	4.00	5.80	3.80
PI-33	10.20	4.00	3.80
PI-34	14.20	4.00	3.80
PI-35	18.20	4.00	3.80
PI-36	22.20	4.00	3.80
PI-37	26.90	4.00	4.10

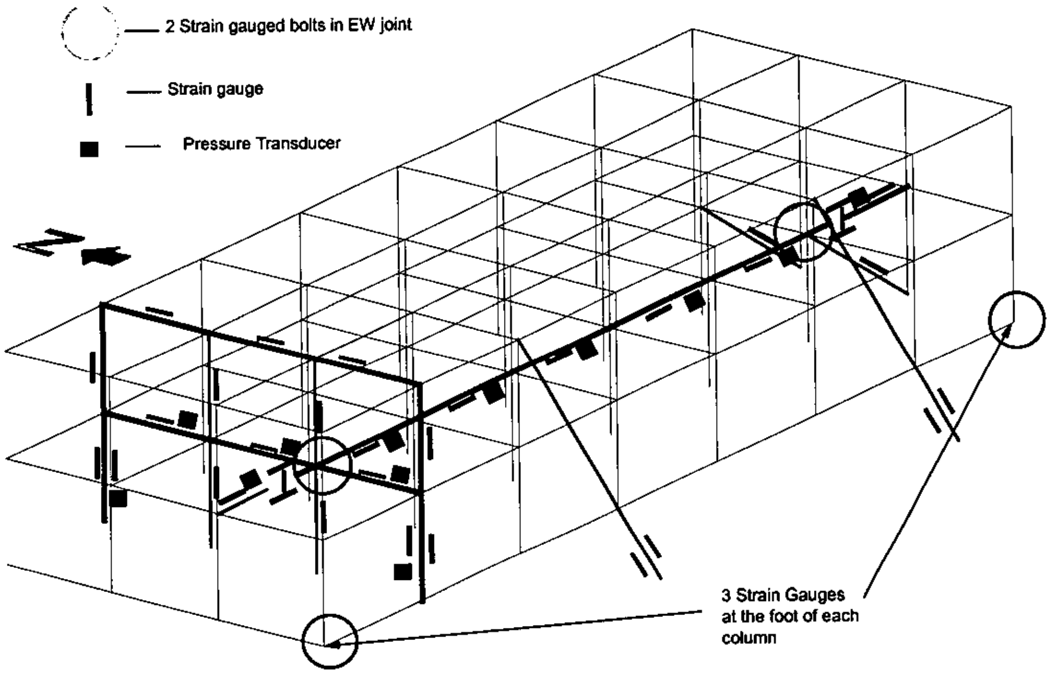

Figure 5
Positions of strain gauges and pressure transducers

The overpressure measurements were carried out using PCB type M102A06 pressure transducers with in-built F.E.T. amplifiers. The specification of these transducers is:

♦ Pressure range:	0 - 35 bar
♦ Resonant frequency:	>500 kHz
♦ Response time:	1μs
♦ Nominal Sensitivity:	145mV/bar
♦ Linearity:	1%

The sensitive faces of the transducers were nominally flush to the floor, roof or side surface in which they were mounted, and they were covered with a layer of silicon grease and aluminium foil, to reduce the effects of thermal radiation on the transducer measurements.

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The transducers were connected by coaxial cable to amplifiers close to the rig. There the signal was amplified to maximise its quality, before being transmitted to the control room and recorded on transient recorders.

3.3. ACCELEROMETERS

Six accelerometers were fixed to the test rig at four positions to measure the acceleration of the frame of the rig during the explosion tests (Figure 6).

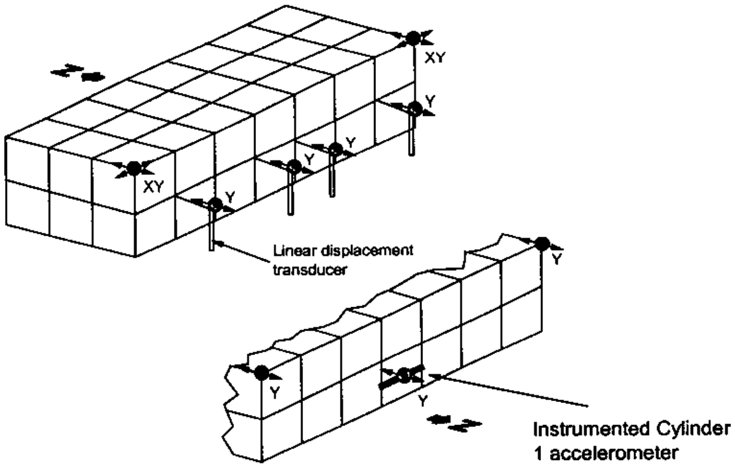

Figure 6
Accelerometer and displacement transducer positions

Table 3
Accelerometer positions

Accelerometer	Axis	Co-ordinates (m)		
		X	Y	Z
AC-39	X	0.0	-0.3	8.3
AC-40	Y	0.0	-0.3	8.3
AC-41	X	28.0	-0.3	8.3
AC-42	Y	28.0	-0.3	8.3
AC-43	Y	4.0	-2.8	4.0
AC-44	Y	12.0	-2.8	4.0
AC-45	Y	16.0	-2.8	4.0
AC-46	Y	24.0	-2.8	4.0
AC-47	Y	28.0	12.3	8.3
AC-48	Y	0.0	12.3	8.3
AC-49+	Y	12.0	11.9	1.6

Four accelerometers were mounted on the supports of the linear displacement transducers to measure the response of the supports during the explosion tests (Figure 6).

One accelerometer was mounted on the instrumented cylinder (Figure 4).

The accelerometers used during these experiments were Endevco type 751-10 and 752-10 transducers. The specification of these transducers is shown below:

Range	500g
Frequency Response	1 to 15,000 Hz
Resonant Frequency	50 kHz

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- Nominal Sensitivity 10mV/g
- Linearity 1%

The accelerometers were stud mounted in PCB 080B10 tri-axial mounting blocks that were stud mounted to the structure. Figure 7 shows details of the mounting. The accelerometers were protected as far as possible from the effects of flame and overpressure by steel covers sealed with silicon rubber.

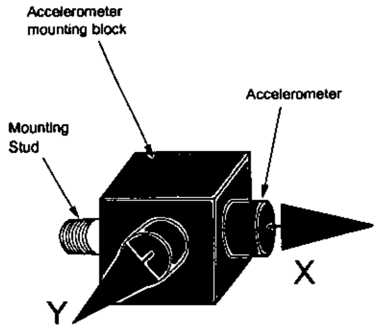

Figure 7
Accelerometer mounting

The accelerometers were connected by coaxial cable to amplifiers close to the rig to maximise signal quality, before being transmitted to the control room and recorded on transient recorders.

3.4. LINEAR DISPLACEMENTS

Four linear displacement transducers were mounted at locations (see Table 4 and Figure 6) on the rig structure to measure the deflection of the structure along the Y-axis. The linear displacement transducers used were Penny and Giles type HLP350, the transducers were attached between the rig and strong steel columns.

Table 4
Linear displacement transducer positions

Linear displacement transducer	Axis	Co-ordinates (m) X	Y	Z
LD-1	Y	4.00	-0.65	4.00
LD-2	Y	12.00	-0.65	4.00
LD-3	Y	16.00	-0.65	4.00
LD-4	Y	24.00	-0.65	4.00

The transducers were energised using a power supply close to rig, the signal from the transducers being taken back to the control room by twisted pair cable and recorded on transient recorders.

3.5. STRAIN GAUGES

Fifty-six strain gauges were mounted on the framework of the rig at a number of locations as shown in Figure 5 and in Table 5. The strain gauges were Measurement Group type CEA-06-W250A-350; their specification is:

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- Strain range 5,000µm/m
- Temperature Range -75° to +95°C

Table 5
Strain gauge positions

Strain Gauge	Co-ordinates (m)			Strain Gauge	Co-ordinates (m)		
	X	Y	Z		X	Y	Z
ST-1	0.00	-0.30	0.25	ST-28	14.00	4.00	3.90
ST-2	0.00	-0.65	0.25	ST-29	18.00	4.00	3.90
ST-3	0.00	-0.30	0.25	ST-30	22.00	4.00	3.90
ST-4	4.00	-0.65	2.00	ST-31	25.30	4.00	4.00
ST-5	4.00	-0.65	6.00	ST-32	25.30	4.10	4.00
ST-6	4.00	2.00	8.65	ST-33	25.30	4.00	3.90
ST-7	4.00	6.00	8.65	ST-34	26.60	4.00	4.00
ST-8	4.00	10.00	8.65	ST-35	8.00	-7.00	1.20
ST-9	4.00	12.65	2.00	ST-36	8.00	-7.20	1.50
ST-10	4.00	12.65	4.00	ST-37	20.00	-7.00	1.20
ST-11	4.00	0.00	2.00	ST-38	20.00	-7.20	1.50
ST-12	4.00	2.00	4.00	ST-39	28.00	-0.30	0.25
ST-13	4.00	3.85	2.20	ST-40	28.00	-0.65	0.25
ST-14	2.80	4.00	3.90	ST-41	28.00	-0.30	0.25
ST-15	2.80	3.90	4.00	ST-42	24.40	3.85	4.15
ST-16	2.80	4.00	4.10	ST-43	24.00	4.15	3.85
ST-17	1.45	4.00	4.10	ST-44	15.70	11.90	1.54
ST-18	4.00	7.85	2.20	ST-45	15.70	11.82	1.54
ST-19	4.00	6.00	3.90	ST-46	14.00	11.90	1.54
ST-20	4.00	10.00	3.90	ST-47	14.00	11.82	1.54
ST-21	4.00	12.00	2.00	ST-48	12.30	11.86	1.58
ST-22	4.00	3.85	5.90	ST-49	12.30	11.90	1.54
ST-23	4.00	7.85	5.90	ST-50	12.30	11.86	1.50
ST-24	4.30	3.85	4.15	ST-51	12.30	11.82	1.54
ST-25	4.30	4.15	3.85	ST-52	26.70	4.00	2.10
ST-26	6.00	4.00	3.90	ST-53	26.70	8.00	2.10
ST-27	10.00	4.00	3.90				

The strain gauges were spot welded to the structure and protected from the effects of the explosion with a rubberised coating and metal foil. The signal from the strain gauges was be taken by twisted pair cable to a bridge termination close to the rig and then to signal amplifiers in an instrumentation turret in the test area. The amplified signal was then taken to the control room where they were recorded on a transient recorder.

3.6. MODAL TEST INSTRUMENTATION

3.6.1. Large Scale Explosion Test Rig

A calibrated hammer was used to strike the structure at one location, but in three orthogonal directions, *fixed excitation method.* The material on the striking face of the hammer was selected to ensure that most of the energy of the impact occurred over the measurement frequency range of 0 - 100 Hz.

An accelerometer was mounted on the back of the hammer, and this was used to provide a measure of the input force to the structure. The hammer accelerometer was PCB type 353B03,

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with a frequency range from 1 - 9000 Hz, was connected to a single channel PCB amplifier, type 480.

A scaffolding tower was erected to provide access to the reference location on the structure, and prevented the reaction of the test rig to the hammer swing prior to impact.

To measure the test rig structural response to the hammer blows, a magnetic tri-axial block was used to position three accelerometers at different locations around the rig. The FRF measurements at each position were averaged over six hammer blows to improve the signal-to-noise ratio of the FRF. The response accelerometers were Bruel & Kjaer type 4370 accelerometers, with a frequency range from 0.1 - 4800 Hz, and were amplified using type 2635 charge amplifiers.

A "force" and "exponential" window was adopted for the measured force and response spectra, (as is usual with impact modal testing). This provides the best estimate of modal frequencies, but does cause the damping to be overestimated.

Measurement positions were located on the nodes of the test rig beams, and created a nominally 4m spaced grid. FRF measurements were made at all nodes on the mezzanine and roof levels, (Z = 4m, and Z = 8m). It was assumed that nodes at ground level would not deflect since they were directly attached to the subsurface framework, which was buried in approximately 3500 tonnes of concrete.

A list of the node positions is shown below in Table 6. The measurement positions correspond to nodes 33-96. The hammer impact position was at node 93.

[N.B. Nodes 1 - 32 were all at ground level and the response was not measured].

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Table 6
Modal node co-ordinates

Node	Co-ordinates (m)			Node	Co-ordinates (m)			Node	Co-ordinates (m)		
number	X	Y	Z	number	X	Y	Z	number	X	Y	Z
1	0	0	0	35	8	0	4	69	16	0	8
2	4	0	0	36	12	0	4	70	20	0	8
3	8	0	0	37	16	0	4	71	24	0	8
4	12	0	0	38	20	0	4	72	28	0	8
5	16	0	0	39	24	0	4	73	0	4	8
6	20	0	0	40	28	0	4	74	4	4	8
7	24	0	0	41	0	4	4	75	8	4	8
8	28	0	0	42	4	4	4	76	12	4	8
9	0	4	0	43	8	4	4	77	16	4	8
10	4	4	0	44	12	4	4	78	20	4	8
11	8	4	0	45	16	4	4	79	24	4	8
12	12	4	0	46	20	4	4	80	28	4	8
13	16	4	0	47	24	4	4	81	0	8	8
14	20	4	0	48	28	4	4	82	4	8	8
15	24	4	0	49	0	8	4	83	8	8	8
16	28	4	0	50	4	8	4	84	12	8	8
17	0	8	0	51	8	8	4	85	16	8	8
18	4	8	0	52	12	8	4	86	20	8	8
19	8	8	0	53	16	8	4	87	24	8	8
20	12	8	0	54	20	8	4	88	28	8	8
21	16	8	0	55	24	8	4	89	0	12	8
22	20	8	0	56	28	8	4	90	4	12	8
23	24	8	0	57	0	12	4	91	8	12	8
24	28	8	0	58	4	12	4	92	12	12	8
25	0	12	0	59	8	12	4	93	16	12	8
26	4	12	0	60	12	12	4	94	20	12	8
27	8	12	0	61	16	12	4	95	24	12	8
28	12	12	0	62	20	12	4	96	28	12	8
29	16	12	0	63	24	12	4	97	8	-7	0
30	20	12	0	64	28	12	4	98	20	-7	0
31	24	12	0	65	0	0	8	99	-5	4	0
32	28	12	0	66	4	0	8	100	-5	8	0
33	0	0	4	67	8	0	8				
34	4	0	4	68	12	0	8				

3.6.2. Confining Wall Panel

The wall panel selected for testing was on the mezzanine level of the explosion test rig. In terms of the test rig co-ordinates, the lower left corner of the panel, (when viewed from inside the test rig), was located at (20m, 12m, 4m).

Only the response normal to the plane of the panel was examined. This was considered sufficient to identify the conventional "panel" modes of vibration.

The technique for the wall panel was similar to the test rig. A smaller hammer was used to excite modes in the panel, and magnetically mounted accelerometers were used to measure the panel response normal to the plane of the panel. The hammer accelerometer was PCB type 353B03, with a frequency range from 1 - 9000 Hz, was connected to a single channel PCB amplifier, type 480. The response accelerometers were Bruel & Kjaer type 4370 accelerometers,

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with a frequency range from 0.1 - 4800 Hz, and were amplified using type 2635 charge amplifiers.

The accelerometers were kept in fixed reference positions, (*fixed response method*), whilst the hammer was used to strike the panel at different locations.

An orthogonal co-ordinate system was used for the panel, (X direction horizontal, Y direction vertical, and the Z direction perpendicular to the panel).

A nine by nine measurement grid was aligned with the centre of the panel giving 81 measurement positions, with approximate 400 mm grid spacing.

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4. MODAL ANALYSIS RESULTS

The signals from the accelerometers were processed using a 4 channel "Siglab" analyser to provide the FRFs. The modal analysis was performed using "The STAR SYSTEM" software.

4.1. EXPLOSION TEST RIG

To visualise the mode shapes, a wire-frame model of the test rig was created by joining the nodes together. Internal and major external bracing has also been included in the model, and can be seen in Figure 8. For comparison, a photograph of the test rig can be seen in Figure 9.

The FRF measurements were processed to identify likely natural frequencies, and the results curve fitted to produce mode shapes. The modes identified have been listed in Table 7 along with the damping factors calculated at that frequency. If applicable, a description of the mode shape has been included.

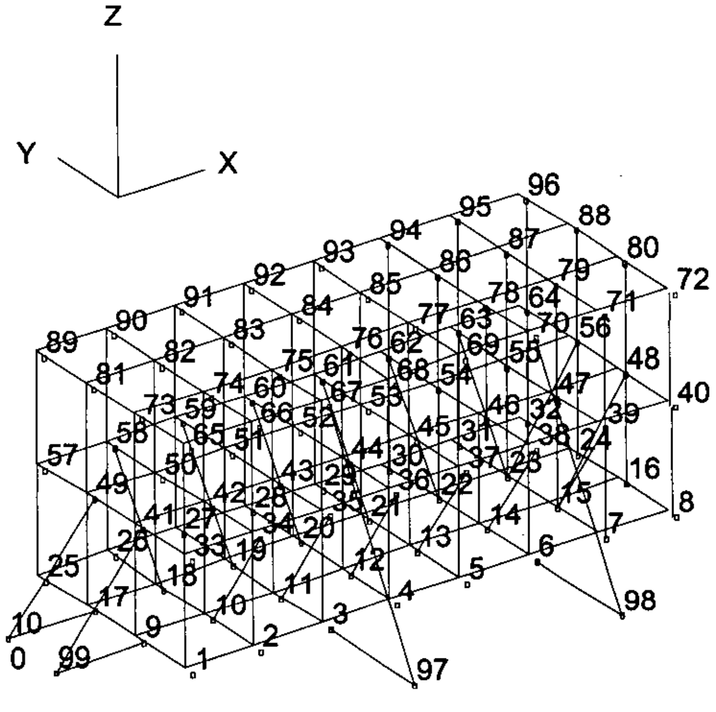

Figure 8
Undeformed "stick model" of explosion test rig

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Figure 9
Large scale explosion test rig

The natural frequencies of the four identified modes are listed in Table 7. The damping values, expressed as a percentage of critical damping are also presented, however, these values should be used with caution for the following reasons;

- The damping will have been over estimated because of the use of exponential window when determining the FRF measurements, as discussed in 3.6.1.
- The damping calculation assumes that the damping is viscous, i.e. increasing in proportion to velocity. In practice, this may not be a good representation of the bolted structure, which may have a significant component of friction damping. In this case, the equivalent viscous damping is a function of the amplitude of vibration.

A great number of peaks were present within the FRF measurements, reflecting the complexity of the structure. Many of the peaks above 50 Hz correspond to local modes within the structure, where only part of the structure responds to the applied load. Only those peaks that could clearly be identified as global modes have been reported.

In addition to the local modes, there were also many travelling waves excited within the structure. These travelling waves were often the largest peaks in the FRF measurements. An example of one of the FRF measurements is shown in Figure 10.

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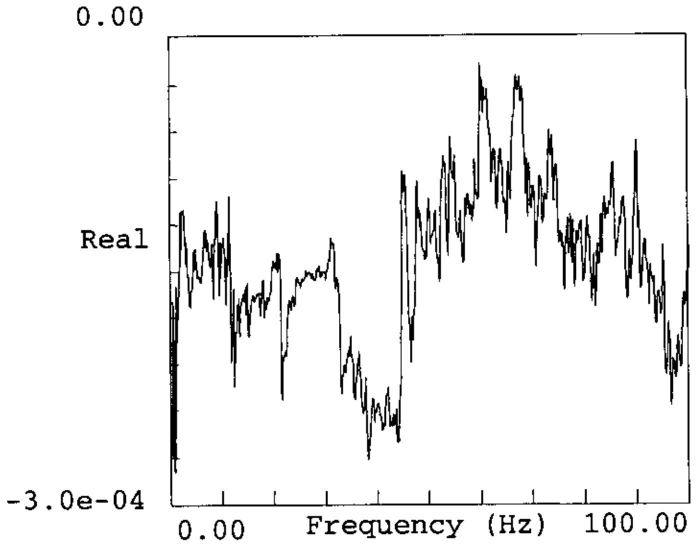

Figure 10
Typical FRF measurement

Table 7
Modal analysis results for the explosion test rig

Mode number	Frequency (Hz)	Damping (%)	Comments
1	6.47	10.82	Sway mode - Y direction
2	10.81	5.27	Rotation about Z axis
3	11.85	5.49	Rotation about Z axis
4	32.76	3.24	2nd Order sway

Figure 11 to Figure 14 give graphical representations of the mode shapes.

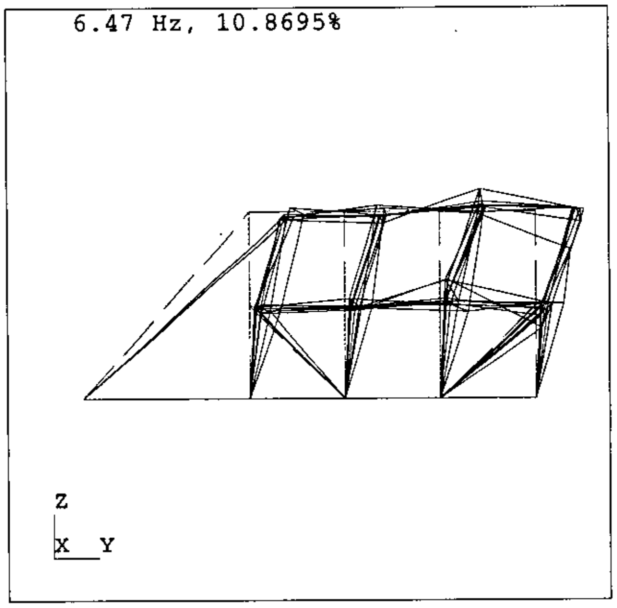

Figure 11
Explosion test rig - mode shape 1

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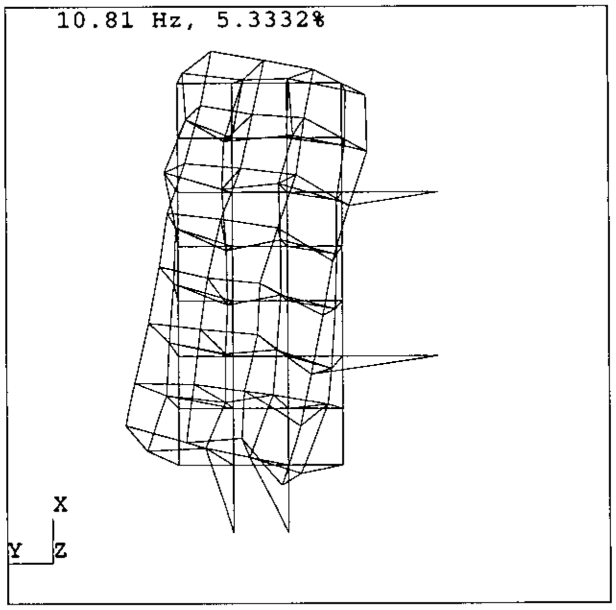

Figure 12
Explosion test rig - mode shape 2

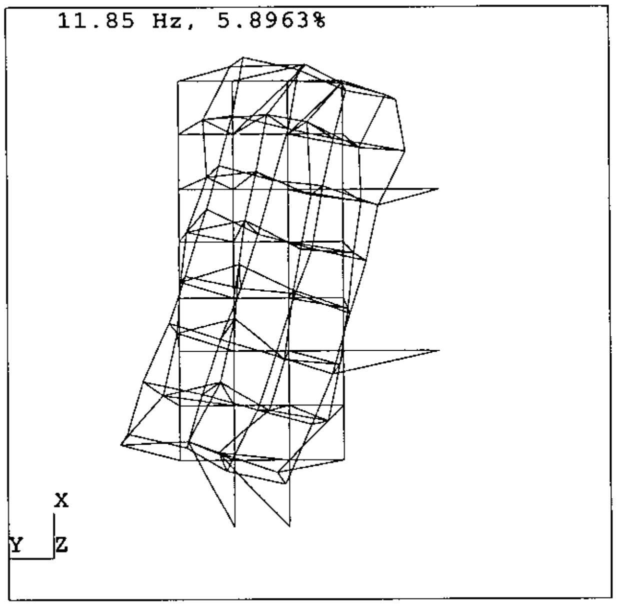

Figure 13
Explosion test rig - mode shape 3

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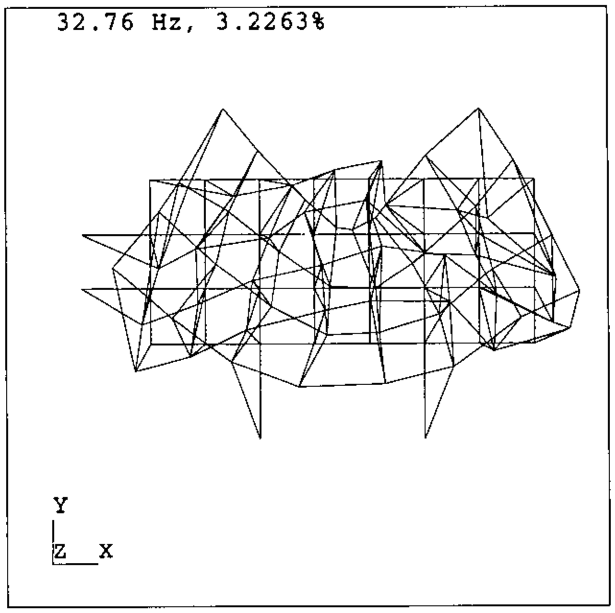

Figure 14
Explosion test rig - mode shape 4

4.2. WALL PANEL

Again, the measurement grid was converted to a stick model on which to represent the mode shapes. The undeformed model can be seen in Figure 15, along with the measurement numbers. The accelerometers were magnetically attached to the panel at locations 21, 29 and 40.

A view of one of the wall panels can be seen in Figure 16.

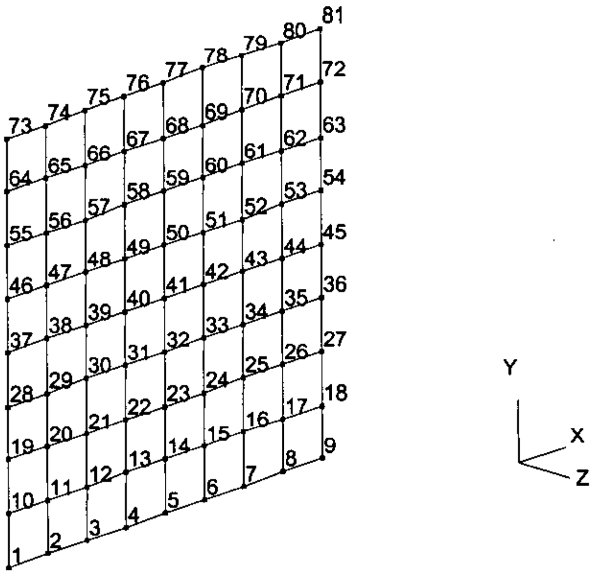

Figure 15
Wall panel - undeformed model

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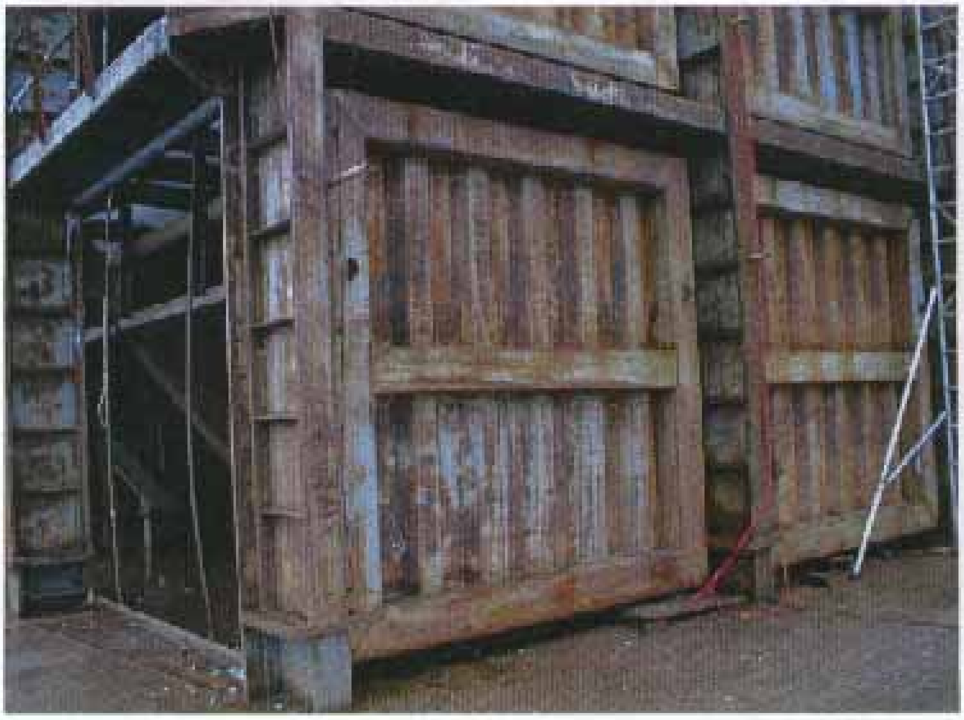

Figure 16
Confining wall panel

A large number of modes were identified from the FRF measurements. As with the explosion test rig, many of these modes were localised, and may originate from excitations of the flat internal plate, (which was only pinned by plug welds to the outer corrugations), and not the whole panel.

The global modes identified can be seen in the Table 8.

Table 8
Modal results for wall panel

Mode number	Frequency (Hz)	Damping (%)	Comment
1	35.8	1.82	Fundamental mode
2	75.28	1.12	
3	86.51	0.91	

The mode shapes can be seen in the Figure 17 to Figure 19.

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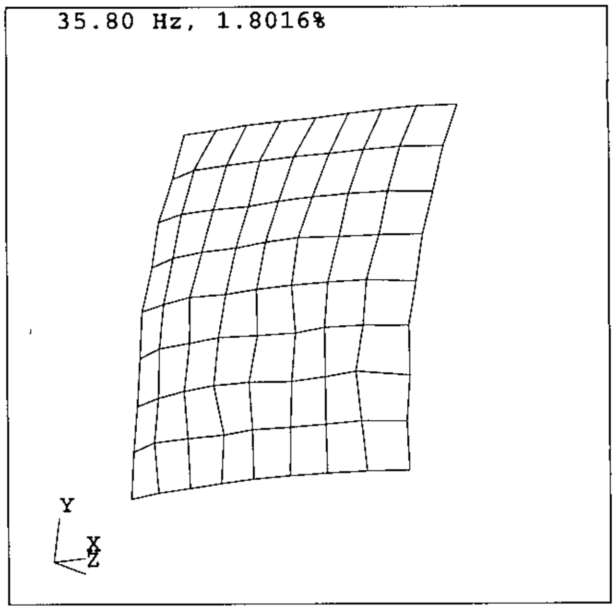

Figure 17
Wall Panel - mode shape 1

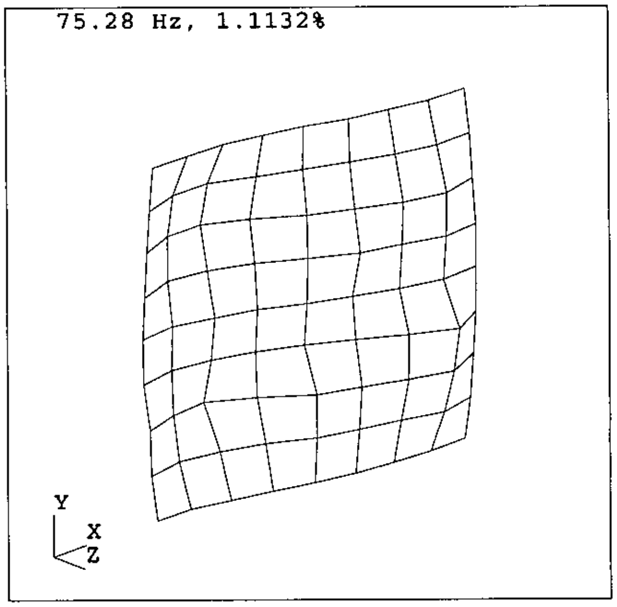

Figure 18
Wall panel - mode shape 2

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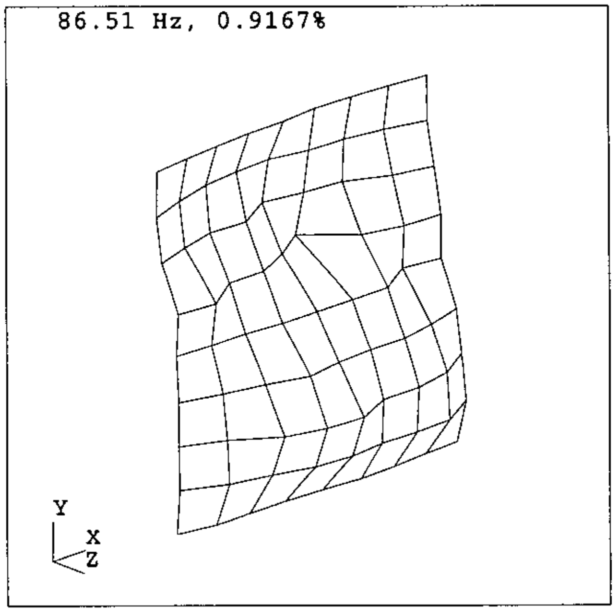

Figure 19
Wall panel - mode shape 3

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5. EXPLOSION TESTS RESULTS

Data was recorded during all six of the tests conducted. The data is included with this report in electronic format on CD-ROM.

Additional files are provided in which the recorded data has been filtered to remove high frequency components above 50Hz. Appendix A of this report describes the method and characteristics of the electronic filter used.

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6. ACCELEROMETER DATA ANALYSIS

The movement of the test rig due to blast loading has been examined using the accelerometer data measured during Test PF 5. Test PF 5 was used as the basis for analysis, since this test recorded the highest overpressures, and also greatest accelerations. Some interpretation has also been given to linear displacement transducers.

6.1. ACCELEROMETER INTEGRATION

Two approaches have been tested to obtain accurate displacement measurements. Both techniques assume that any movement of the test rig is about a fixed point.

To obtain displacement measurements from accelerometer data, the accelerometer signal must be double integrated. Whilst this process is relatively straight forward; determining the integration constants can prove to be more complicated. The integration constant can be thought of as the offset, or drift to the integrated signal, and two methods have been used to remove it from the signal;

- The first method uses a high pass filter to remove the low frequency component of the signal, (essentially the D.C component). The signal is passed through the filter after each integration. The advantage of this method is that it is very fast, and the entire time history is retained. The disadvantage of this method is that there may be some signal attenuation of low frequency components just above the high pass frequency cut off limit.
- The second method is a construct a rolling average file of the displacement data after double integrating of the accelerometer signal. A large window, based on the period of vibration (approximately 200 msec for each of these signals), is moved across the data one point at a time. This effectively records the offset of the data. The advantage of this method is that there is little attenuation of the displacement signal. The disadvantage is that half a window of data is lost at each end of the recorded data, and that it takes a lot of processing time.

The later technique gave much better results in terms of signal drift and attenuation due to the low frequency content of the accelerometer signal.

The full processing technique adopted is laid out below and referenced to Figure 20 to Figure 23:

a. Extract accelerometer trace from the data file.
b. Minimise the integration offset by normalising the extracted section to a zero mean Figure 20.
c. Double integrate the signal from acceleration to displacement (Figure 21 shows a first integration i.e. acceleration to velocity, Figure 22 shows a second integration from velocity to displacement and indicates a drift on the signal resulting in a linearly varying offset in the displacement with time).
d. Construct a "mean" signal using a data point window based on the period of vibration (in Figure 22 this equates to 6000 points, which is approximately 210 msec), with 1 point increment in window position
e. Subtract the mean signal from the displacement signal (Figure 23 shows the resulting processed signal).

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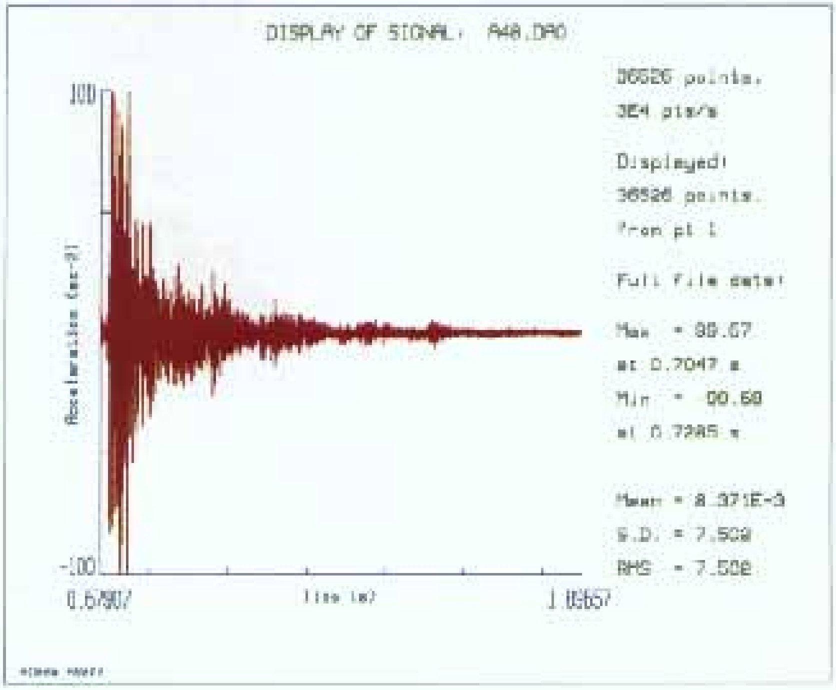

Figure 20
Acceleration trace

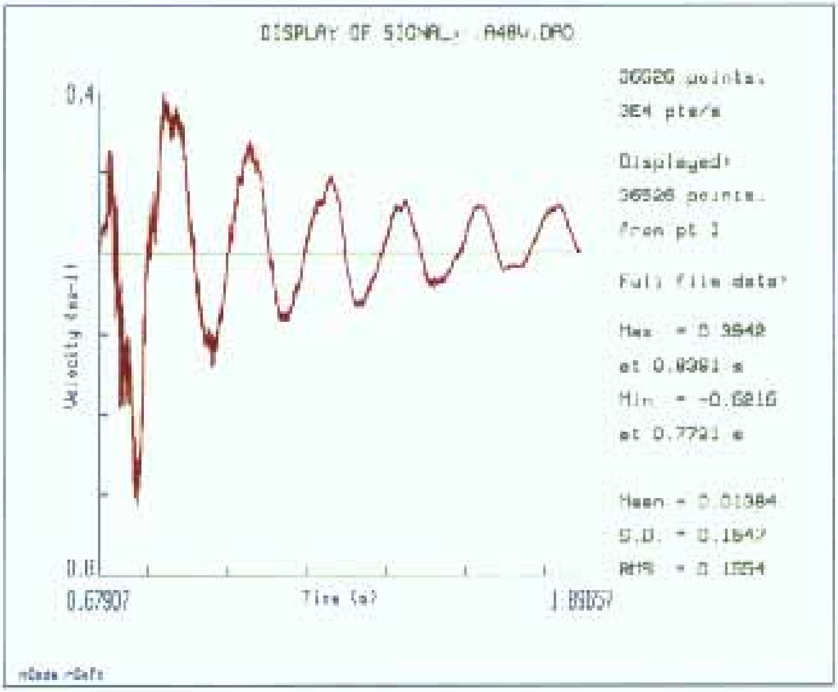

Figure 21
Velocity trace

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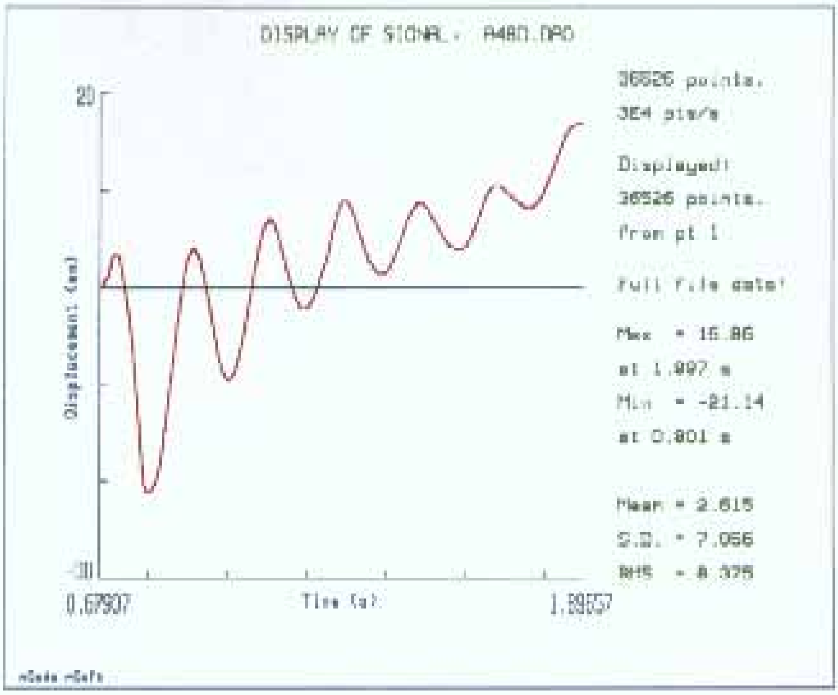

Figure 22
Initial displacement trace

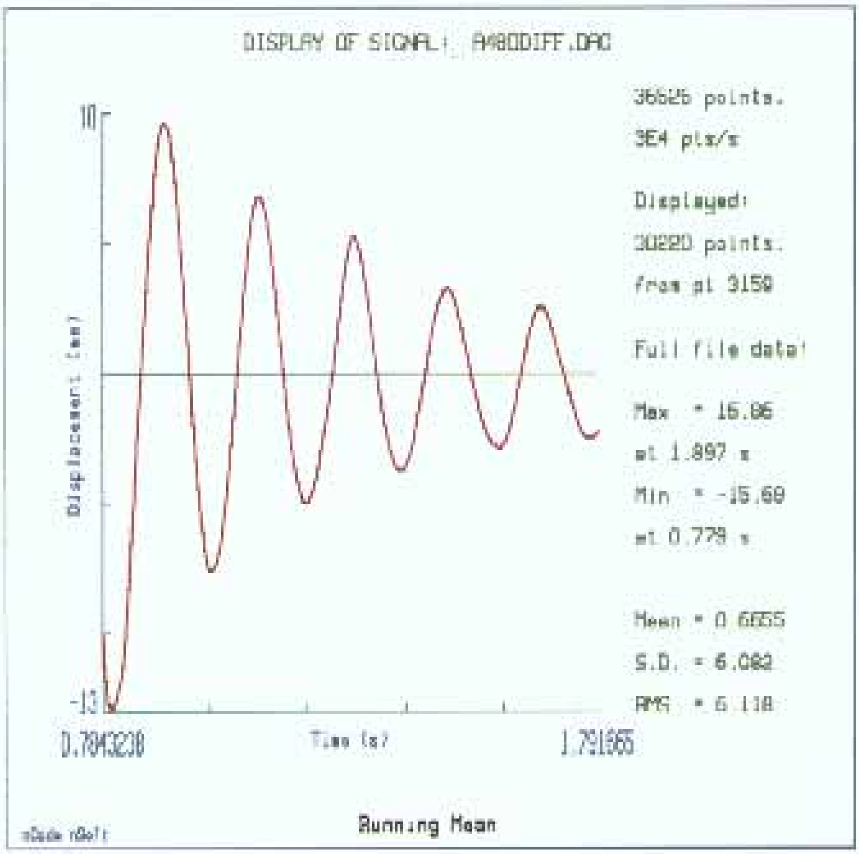

Figure 23
Corrected displacement trace

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6.2. ACCELEROMETER / DISPLACEMENT INTERPRETATION

From the resulting displacement measurements, maximum and minimum displacement, frequency, and damping parameters can be determined.

The results obtained from the accelerometer measurements are displayed in Table 9 below:

Table 9
Accelerometer signal processing results

Accelerometer number	Signal duration (s)		Minimum displacement		Maximum displacement		Frequency Hz	Damping %
	Start	End	Value (mm)	Time (s)	Value (mm)	Time (s)		
A39	Signal too small to analyse							
A40	0.597	1.898	-11.71	0.802	11.51	0.731	5.3	5.8%
A41	Signal too small to analyse							
A42	0.703	1.900	-12.28	0.821	11.41	0.904	5.2	7.6%
A48	0.780	1.795	-12.83	0.800	9.59	0.907	5.2	5.4%

Accelerometers A39 and A41 were orientated in the X - direction, and did not record appreciable signals. This is not unsurprising given the test rig geometry. Both the east and west wall of the test rig were open, and therefore there were no significant areas on which the explosion load could be applied.

Close agreement is seen between peak displacements, frequency and damping. To gain an idea of the mode shape that this frequency corresponds to, A40, A42 and A48 have been overlaid.

The displacements of the three available corner accelerometers are in phase, and rig movement is therefore likely to be a North to South sway mode.

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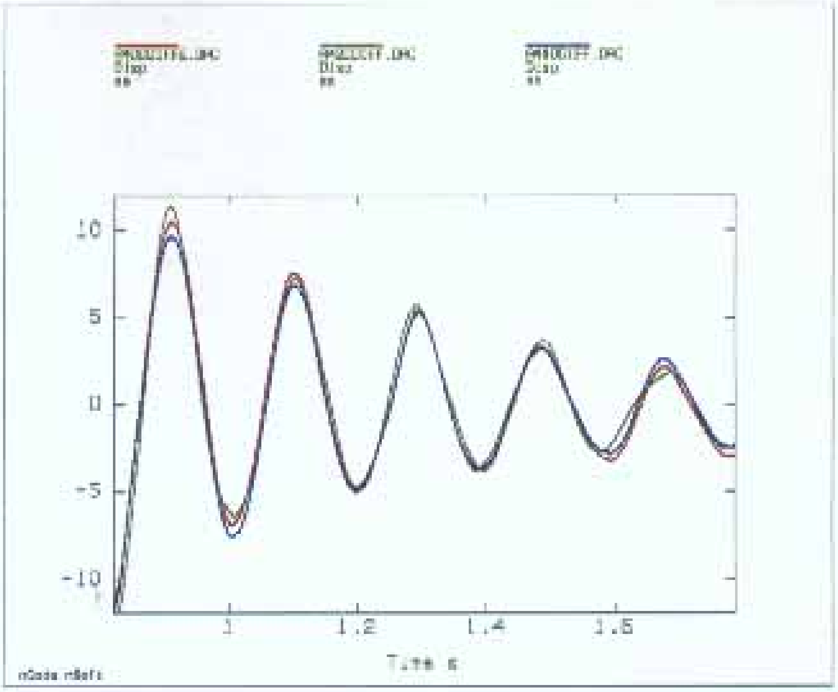

Figure 24
Comparison of Roof Corner Displacements

6.3. LINEAR DISPLACEMENT TRANSDUCERS

Initial examination of the linear displacement transducers (LDT) revealed a bi-modal content to the signal, as shown in the power spectral density plot in Figure 25 below.

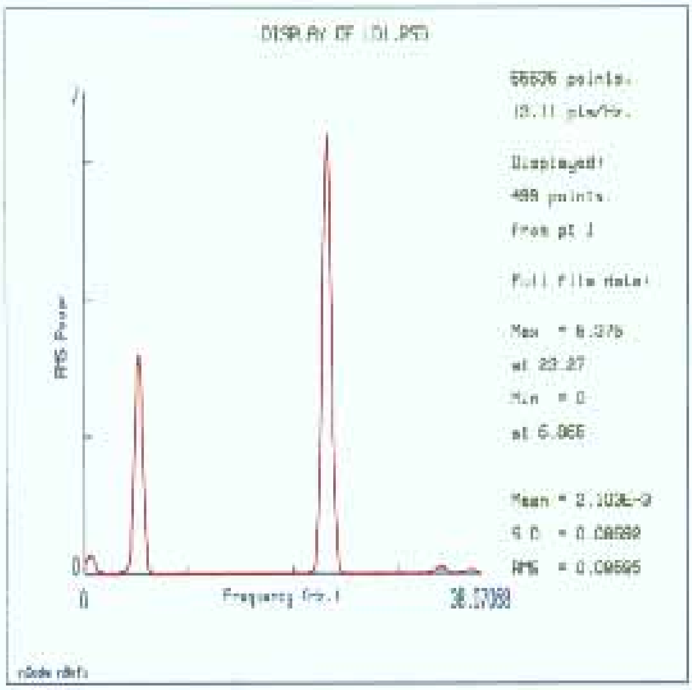

Figure 25
Power spectral density of a LDT

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The first peak is at 5.2 Hz, and corresponds to the movement of the test rig, whereas the second peak is due to the movement of the stand to which the LDT is fixed. To decouple the movement of the LDT from the mounting stand the accelerometer signal was double integrated and the resulting displacement was subtracted from the LDT measurement.

Once the LDT measurements had been processed, a similar analysis to the integrated accelerometers was performed. The results of the analysis are shown below:

Table 10
LDT analysis results

LDT number	Signal Duration		Minimum Displacement		Maximum Displacement		Frequency	Damping Factor
	Start (s)	End (s)	Value (mm)	Time (s)	Value (mm)	Time (s)	(Hz)	(%)
LD1	0.633	1.948	-5.34	0.810	5.11	0.700	5.3	4.3%
LD2	0.631	1.557	-5.21	0.770	7.63	0.719	5.2	3.5%
LD3	0.617	2.081	-4.99	0.807	8.81	0.710	5.2	6.3%
LD4	0.388	2.111	-3.28	0.824	3.40	0.720	5.2	4.0%

From the results above, it can be seen that all the LDT measurements have very similar frequency of vibration and degree of damping.

To confirm that the LDT measurements are all in phase, the processed signals have been overlaid in Figure 26.

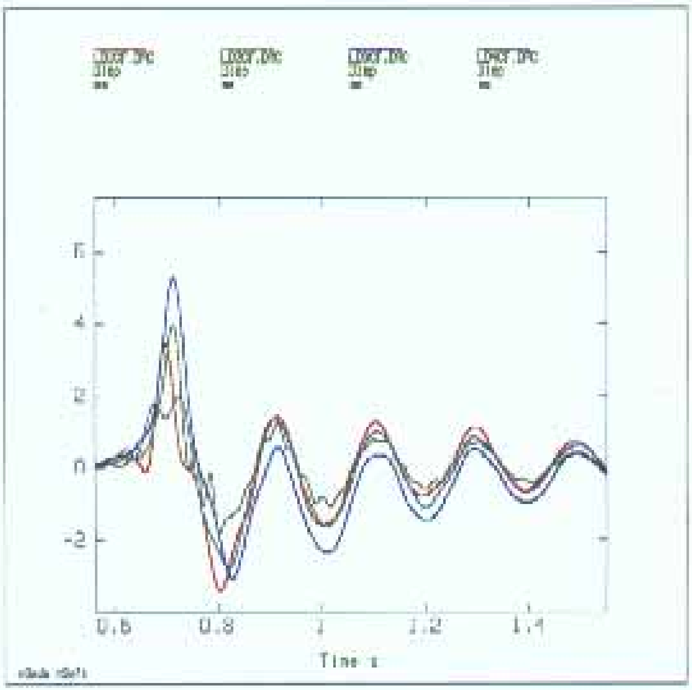

Figure 26
Overlaying of LDT traces

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As can be seen in Figure 26, all four LDT measurements are in phase. By comparing Figure 26 with the overlaid accelerometer traces, (Figure 24), it can be seen that the test rig corners, and the south wall are all moving in phase. This is final confirmation that the rig is moving in a North-South sway mode.

6.4. SWAY MODE FREQUENCY

In section 6.1, the natural frequency of the test rig has been clearly identified at 5.2 Hz, and the mode shape is indicative of a North-South sway. A "tap-test" modal analysis has also been carried out on the test rig, (described in section 4), revealed a North-South sway mode at 6.4 Hz.

It is suggested that the difference between these results is due to the way the test rig behaves at different amplitudes of vibration. During a modal test, the amplitude of vibration is extremely small, and the vertical columns in the test rig could be considered as "guided cantilevers". However, when the rig is deflected by a blast load, the roof joints may slip, allowing a degree of rotation at the top of the vertical columns. The difference in these mechanisms can be seen in the resulting stiffness of the columns.

Considering the stiffness of a simple guided cantilever:

$$k_{guided} = 12\ EI/L^3$$

and the stiffness of a simple cantilever is:

$$k_{simple} = 3\ EI/L^3$$

As the frequency of a beam is proportional to the square root of the stiffness, the ratio of the frequencies of the two cantilevers is:

$$f_{guided}/f_{simple} = 2.$$

In reality this is an upper limit to the ratio, since the roof connections will not allow free movement of the columns unless the connections fail. This can be seen by calculating the actual ratio of the measured frequencies quoted at the beginning of this section:

$$f_{modal}/f_{blast} = 1.2$$

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7. SUMMARY

Measurements of the structural response of the large scale explosion rig have been made during six full scale experiments. Measurements of the acceleration, displacement, and strain at a number of locations within the test rig and on an instrumented cylinder were made, combined with additional overpressure measurements. The data has been supplied in electronic format for analysis by CREA consultants for analysis as directed by the HSE.

Accelerometer data measured in the six tests has been analysed to determine rig and linear displacement supports movement.

A series of modal tests of the large scale explosion rig have been made and analysis of the data has been carried out.

Contents

8. REFERENCES

1. *Blast and fire engineering project for topside structures phase 2: Final report on the explosion test programme (work carried out under contract number GRC/2190/105,* D M Johnson, G A Shale, B J Lowesmith; D Campbell, BG Technology Report GRTC R 1579, 1997
2. *Explosions in full scale offshore module geometrics (work carried out under contract to the HSE, MaTSU/8847/3522),* JA Evans; DM Johnson; BJ Lowesmith, BG Technology Report GRTC R 2422 A, 1999

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APPENDIX A DATA FILTERING METHOD

A.1 INTRODUCTION

BG Technology has carried out an experimental programme under Health and Safety Executive (HSE) agreement number D3790, Structural Response Measurements During Gas Explosions in a Test Rig Representing an Offshore Module. As a part of this agreement, BG Technology is required to provide the data in a form that has been processed using an electronic filter.

This Appendix presents the characteristic of the filter used to process the response data recorded.

A.2 DESCRIPTION OF THE FILTER

The filter used was a low pass Butterworth filter set at 50Hz. The frequency setting was made in accordance with requirements specified by CREA, who are contracted by the HSE under a separate agreement to analyse the response data.

A.3 CHARACTERISTIC METHOD

The method of characterising the filter was as follows:

- A 25 kHz white noise signal was generated. This provides a signal that contains a random time based signal.
- The signal was passed through the filter and the output signal was saved.
- The input signal and filtered signal were processed using nSoft v5.1, a proprietary data processing package, to determine the power spectral density of each trace.

A.4 RESULTS

Figures A1 and A2 respectively show the power spectral densities of the unfiltered and filtered white noise trace.

The unfiltered trace shows that the signal contains a uniform power spectrum over the full 25kHz bandwidth.

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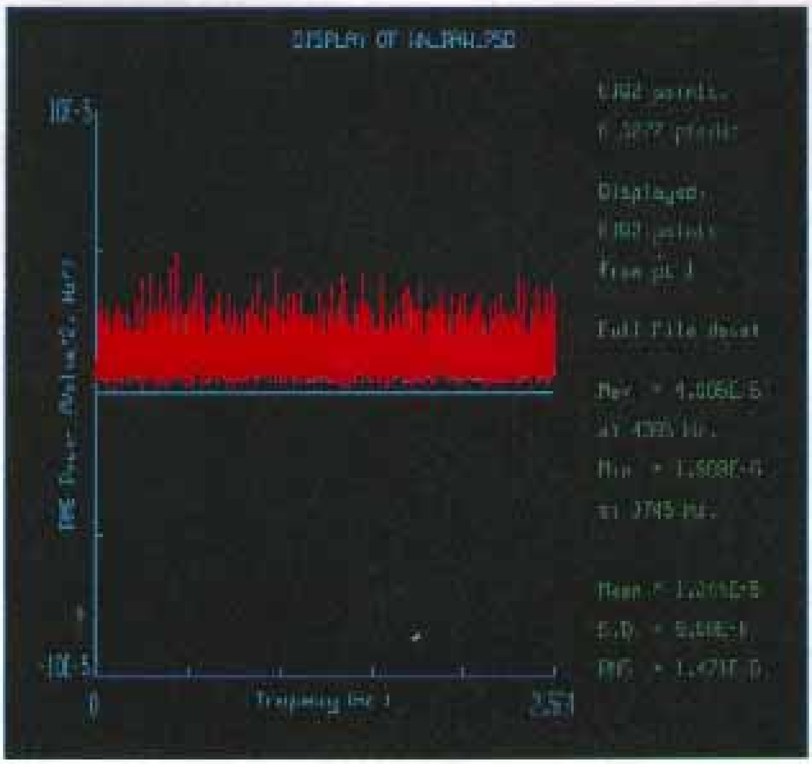

Figure A1

Unfiltered Trace

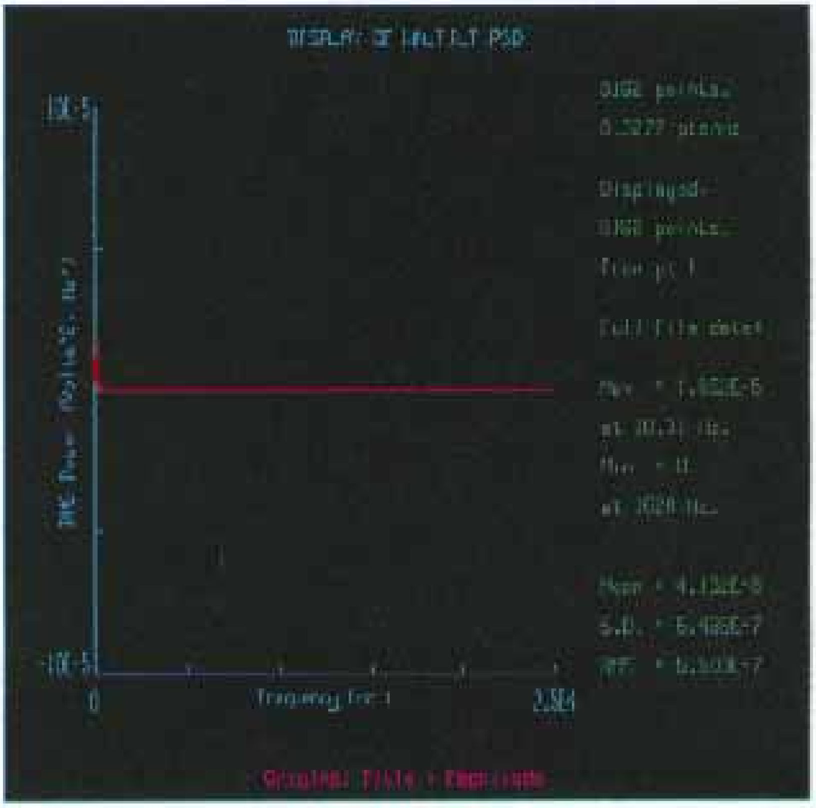

Figure A2

Filtered Trace

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To determine the filter cut-off point, the output trace was divided by the input trace and the result has been plotted on a dB against frequency scale, Figure A3. The cut-off point is defined as the frequency at which the relative power loss is 3dB, corresponding to a frequency of 50Hz.

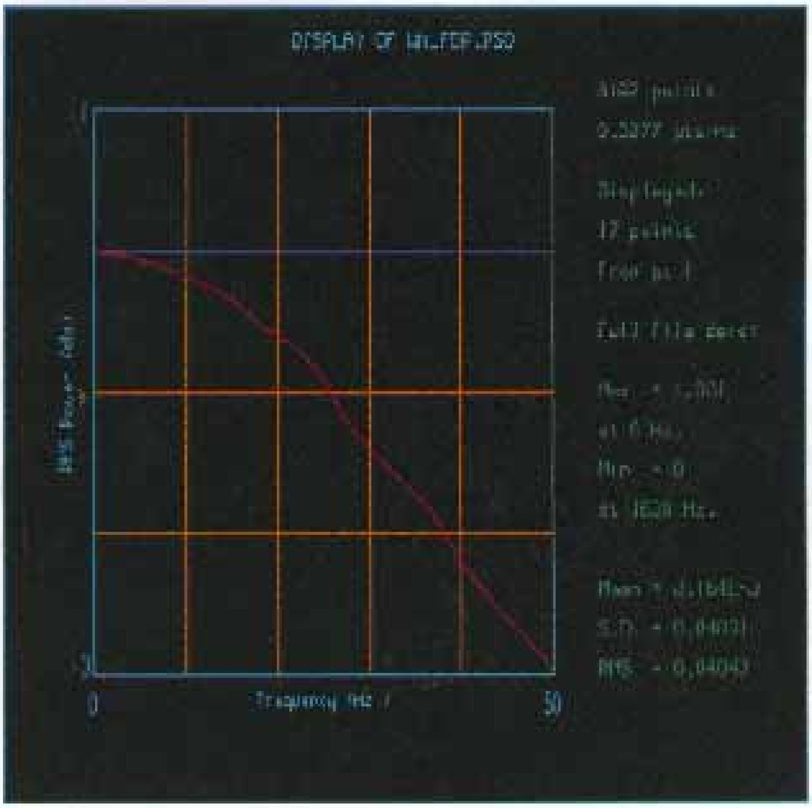

Figure A3

Filtered Trace/Unfiltered Trace

A.5 CONCLUSION

The filter characteristic has been determined using recognised industry processes.

The characteristics of the filter give a low pass 50Hz cut-off.

The data from the response tests has been processed using this filter and the results have been recorded.

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