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# MEASURED VIBRATIONAL BEHAVIOR OF A GULF OF MEXICO PLATFORM

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## ABSTRACT

This paper presents results from recently completed joint-industry research projects which investigated the feasibility and utility of using surface ambient vibrational measurements to evaluate the structural integrity of steel template platforms in the Gulf of Mexico. Demonstration of the success of this technique would allow offshore operators to use relatively inexpensive methods of vibrational monitoring to increase the effectiveness and decrease the frequency of conventional inspection by divers, thereby increasing operational safety while reducing overall inspection costs. The research projects have been described previously in OTC 3864 (1980). The conclusions presented in that paper were based mainly on the behavior of one of the three platforms that were monitored; Shell's Ship Shoal 274A (SS274A). This paper describes further work intended to improve the basis for extrapolation of those conclusions.

OTC 3864 presented the conclusion that surface ambient vibrational monitoring failed to detect the removal of bracing members on SS274A. This paper presents the results of detailed analysis of the vibrational data recorded on another platform, Conoco's Main Pass 296A (MP296A). Preliminary analysis indicated that, of the three platforms, MP296A was the most suitable platform for integrity monitoring. The lack of low frequency machinery noise, the use of grouted piles, the absence of significant deck mass variations, and the apparent stability of peaks in the response spectra all supported this view. The detailed analysis of MP296A data was undertaken to investigate the utility of integrity monitoring on such a favorable structure.

The results of the MP296A data analysis demonstrated excellent frequency and mode shape stability of the first and second order modes of vibration as measured over a six month period. The frequencies and mode shapes of the third order modes were not observed to be sufficiently stable for use in integrity monitoring. The number of peaks in the platform response spectra exceeded the number of identified modes. Several groups of peaks were classified as corresponding to single mode shapes. This "split peak" effect was observed consistently for two of the fundamental modes and for the third order modes. The exact cause of the behavior was not identified, but several possible causes were postulated.

The general conclusion of the work described in this paper is that, although it is possible to observe stable vibrational behavior up to at least the second order modes on certain Gulf of Mexico platforms, it is unlikely that surface ambient vibrational integrity monitoring would be a viable prospect even on these favorable structures.

## INTRODUCTION

The concept of using vibrational monitoring to assess the structural integrity of offshore platforms has been the subject of considerable interest over the past several years. This concept is based on the premise that the loss of, or major damage to, one or more structural members causes measurable changes in the vibrational behavior of a platform which are distinguishable from any changes that normally occur due to variations in operating and environmental conditions. If vibrational monitoring can be shown to be a reliable technique, then significant savings may be achieved by reducing the frequency and extent of conventional underwater inspections. This is particularly true in OCS areas with deep water or perennially rough seas. Further, if ambient vibrational monitoring from the surface provides adequate data, then the cost of instrumentation can be greatly reduced. For the technique to be successful, it is necessary to be able to predict vibrational behavior by structural analysis in order to interpret the meaning of changes in the measured vibrational response. The scope and results of two joint-industry research projects which investigated the technique were presented in Reference 1. This paper summarizes further work which was intended to improve the basis for extrapolation of the conclusions of the two research projects.

References and illustrations at end of paper

The projects described in Reference 1 consisted of a data gathering and preliminary data analysis effort, followed by detailed data analysis and structural analysis. The data gathering effort involved the measurement of the vibrational behavior of three typical Gulf of Mexico steel template platforms over a 6-month period. On one platform, Shell's Ship Shoal 274A (SS274A), three bracing members were removed and replaced during the monitoring period. The second project comprised detailed analysis of the vibrational behavior of SS274A prior to, during and following the removal of the members and their subsequent replacement. The principal conclusion of the two projects was that it was not possible to detect the removal of bracing members on SS274A using surface ambient vibrational monitoring techniques. For the techniques to have been successful, it would have been necessary to have clearly identified second and higher order modes with stable peak frequencies. The identification of second order modes on SS274A was uncertain, and no higher order modes were clearly distinguishable.

In order to improve the basis for extrapolating this conclusion, a detailed analysis of a limited amount of the data recorded on a second platform, Conoco's Main Pass 296A (MP296A), was subsequently performed. In many respects, MP296A appeared to be a much better structure for vibrational monitoring than SS274A, even though the platforms have similar framing configurations and are located in comparable water depths. All the piles on MP296A were grouted into the jacket legs. Operational noise on this platform was the least of the three platforms monitored and tended to fall within narrow frequency bands. In addition, deck mass was constant throughout the period of monitoring. The preliminary data analysis conducted during the first of the joint-industry projects noted 19 stable "structural" peaks below 5 Hz. It was concluded that, if vibrational monitoring was going to be successful on typical Gulf of Mexico platforms, it would probably be successful on MP296A.

This paper describes the results of the MP296A study, the objectives of which were to identify as many structural modes as possible between 0 and 15 Hz in the recorded data and to track the stability of each in terms of peak frequency and mode shape. No structural analysis of MP296A was performed.

## PLATFORM DESCRIPTION

Platform MP296A is sited in 212 ft. of water and was eight years old at the time of the recordings. As shown in Figure 1, this platform is a jacket configuration with eight 42 in. diameter legs, three tiers of bracing ranging from 17 in. diameter to 30 in. diameter, and sixteen conductors (fourteen 24 in. diameter and two 30 in. diameter). The mudline footprint of this structure is 103 ft. by 162 ft. reducing to 50 ft. by 105 ft. at the jacket top (+13 ft.). There are no skirt piles and primary piles are grouted into the jacket legs. Soil properties are reported to vary from soft to very stiff gray clay with occasional sand strata. Pile penetrations are approximately 230 ft. All conductors are restrained in guides at elevations +10, -50, -130 and at the mudline, -212 ft.

The platform is in a fully automated production mode and does not contain any drilling equipment (derricks, mud pumps, etc.). The two principal platform working surfaces are the main deck at +62.5 ft. and the cellar deck at +46.5 ft.

All production equipment, except for two diesel driven gas compressors and two gas turbine generator sets, is housed on the cellar deck.

Both the cellar and the main deck have external dimensions of approximately 125 ft. by 70 ft. General living quarters, sufficient to house twelve personnel, are located on the main deck.

## DATA GATHERING

The data gathering equipment consisted of accelerometers attached primarily to the top of the jacket legs and connected to an 8-track tape recorder. The platform vibrational behavior was recorded using four different accelerometer configurations, each of which utilized seven accelerometers. One configuration (A) included two accelerometers at the cellar deck level, as shown in Figure 2.

Data was recorded during visits in February, June, and July. Recordings in the 0 to 5 Hz range were taken during all visits. 0 to 15 Hz recordings were taken only during the second and third visits.

In order to obtain a representative sample of data, twelve 0 to 5 Hz tests and four 0 to 15 Hz tests were selected for analysis. The 0 to 5 Hz tests represent each configuration and each visit; the 0 to 15 Hz tests represent each configuration, with two tests from visit 2 and two from visit 3.

## DATA ANALYSIS

The details of the techniques of data analysis are discussed in References 1 and 2. This paper is limited to a discussion of the objectives and results of the analysis.

## MODAL IDENTIFICATION

For integrity monitoring to be a reliable tool, it is necessary to establish a recognizable baseline behavior or "signature" of the platform such that changes in the behavior can be interpreted. In this manner, variations caused by operational or environmental changes can be distinguished from variations due to structural distress. In order to have confidence in the conclusions drawn from observed changes in behavior, it is necessary to identify the peak frequency and response shapes of as many modes of vibration as possible. This identification of the structural modes of MP296A was achieved by manipulating auto and cross-spectral density functions of the recorded data.

Autospectral density functions were computed and plotted for each record (seven records each from sixteen tests) and cross-spectral density functions were computed for all pairs of records within a test. The response shape vector method (References 1 and 2) was then used to consolidate the results of all seven channels on each test to provide response norms and vectors at each frequency increment. The frequency range of each response shape was investigated by computing the dot product of a vector at a given frequency with vectors at neighboring frequencies. The stability of response shape from one test to another (with an identical accelerometer configuration) was evaluated by computing the dot product of vectors of the two tests at equal or proximate frequencies.

Plots of response norms and error terms for all sixteen tests were evaluated in addition to response fraction and response correlation terms. Figure 3 shows the response norm for 1C34A, which represents the consolidation of the auto and cross-spectral density functions for that test. Table 1 is a listing of peaks in the response norms of all the tests. Peaks corresponding to peaks in the wave energy forcing function are omitted. The letter following the test number (e.g. 1C34A) refers to the accelerometer configuration. It should be noted that, in preparing Table 1, no attempt was made to identify the modes associated with each peak. There is very good stability of peaks from one test to another. The identification of the response shapes associated with these peaks was the next step in the interpretation of the data.

The fundamental modes were identified by plotting the response shapes of the boat and cellar decks at each of the peak frequencies noted in Table 1. The end-on (X-sway) mode had the lowest frequency, followed by the broadside (Y-sway) mode and the torsional mode. The X-sway mode is associated with more than one peak in the response norm and autospectral density functions. This also is true for the torsional mode. This multiple peak behavior is discussed further in a later section.

The identification of higher modes was not readily available from the plots of response shapes. The phase and coherence relationships between selected channels (Figures 4, 5, 6, 7, for example), the computer listings of response vectors, and the dot products were all evaluated in order to extract as much modal information from the data as possible.

Second order mode activity was identified by a 180° phase relationship between cellar deck and boat deck motion. By tracking the variation of acceleration levels of different sensor locations with frequency, X-sway and Y-sway modes were identified. The second order modes were characterized by low acceleration levels at the boat deck and higher levels at the cellar deck. The modes were therefore only clearly identified in tests using the "A" accelerometer configuration. The second order torsional mode was not exhibited clearly in the data because of the very limited cellar deck accelerometer locations used and because of the small accelerations recorded at the boat deck.

The third order modes were characterized by large amplitude motion at the boat deck and smaller amplitude (but still out of phase) motion at the cellar deck. As a result, the third order peaks were prominent in all the test configurations with horizontal sensors at the boat deck. It should be noted that the distinction between second and third order modes was based solely on the difference in the relative motion of the decks. Although it is reasonable to expect that the differentiation is accurate, this could only be confirmed by subsea sensors. Moreover, positive identification of higher modes was not possible using the limited data available. Using surface monitoring, it is only possible to identify peaks as being associated with particular forms of deck motion (e.g. torsion) for modes higher than third order.

By detailed interpretation of the type described above, it was possible to generate the information shown in Table 2. The peaks and ranges listed in Table 2 were taken from 1C34A, 2C02A, and 3C51D, but the modal identification was confirmed by interpreting the data from all sixteen tests.

The third order torsional mode is stated in Table 2 to have peaks at frequencies varying from 3.22 Hz to 4.75 Hz. It is unlikely that the mode is spread over such a broad band, but the response shape over that frequency range is remarkably stable. It is possible that the true third order mode exists at the lower end of the range, and that the peaks at the higher end are associated with the vertical mode at approximately 5.0 Hz.

The vertical mode was identified primarily using data from 3C51D, the only 0 to 15 Hz configuration D test which was evaluated. The peak exists on the 0 to 5 Hz configuration D tests, but because of the 5 Hz cutoff, it is not possible to be certain that the peak is not greater than 5 Hz without the use of the 0 to 15 Hz test results.

The region 5 to 15 Hz contains more machine-associated vibration than that below 5 Hz. Nevertheless, it is possible to describe some response shapes associated with assumed structural peaks. Sway modes exist at 5.5 and 5.9 Hz. At higher frequencies, the response shapes involve deformation of the decks in plan and cannot be adequately described from the available data.

## MODAL STABILITY

Table 3 lists the peak frequencies of each mode identified in each of the twelve 0 to 15 Hz tests. Note that frequencies have only been listed if the mode could be identified within the individual test. Thus, although peaks appear at 1.2 and 1.45 Hz for the configuration D tests, there is insufficient information within these tests to identify those peaks as corresponding to torsional behavior.

The fundamental sway peaks are seen to be stable within .02 Hz; the torsional peaks are stable to within .04 Hz. The second order peaks are stable to within .03 Hz. The stability of the third order peaks is clouded by the appearance or nonappearance of different peaks corresponding to the same response shape. Under these circumstances, it is more useful to study the stability of response shapes, rather than that of frequency peaks.

Table 4 gives a measure of the response shape stability between 1C34A and 2C13A, and 1C34A and

3C05A. The table shows the value of normalized vector dot product between 1C34A and 2C13A, and 1C34A and 3C05A, for the frequencies which correspond to identified structural modes in 1C34A. A normalized dot product of 1.0 would indicate identical response shapes. The table demonstrates very good modal stability of the fundamental and second order mode shapes. The stability of the third order modes is good to poor, with the exception of the region 3.11 Hz to 3.55 Hz, which is very good.

In summary, the fundamental modes are stable to within 3% in terms of frequency and 8% in terms of mode shape. By any standards, this stability over a period of six months is as good as could be reasonably expected. The second order modes could be distinguished clearly in only three of the 0 to 5 Hz tests, and the identification was limited by the smaller number of sensors at the cellar deck level. Nevertheless, frequency stability was within 2% and modal stability within 6%. The third order modes, although characterized by repeatable peaks, could not be considered completely stable due to the changes in relative magnitude of the peaks from test to test, and marginal response shape stability.

## MULTIPLE PEAKS

As noted above, several modes of vibration had peak amplitudes which occurred at more than one distinct frequency. Modes which exhibited this behavior included the fundamental X-sway and torsion and the third order Y-sway and torsion. Several possible explanations for this behavior have been proposed, including:

1. Liquid sloshing in tanks with a frequency close to the structural frequencies.
2. Nonlinearities in the system which cause a variation in structural stiffness with displacement. For example, conductor tubes rattling in guides or piles taking up "slop" in foundations.
3. Appendages to the structure such as catwalks, equipment supports, and cranes which vibrate at relatively large amplitudes with a natural frequency close to the structural frequencies.

Taking each possibility separately, there are no sizable tanks on MP296A, so the first cause can be dismissed. If the multiple peaks were caused by system nonlinearities, then their occurrence would be expected to be linked to vibration amplitude. This was not the case. All the peaks were exhibited in all the tests. On the other hand, it is possible that there are appendages to the platform which vibrate at frequencies close enough to the structural frequencies to affect the overall response of the platform and to create, in effect, "split peaks". Split peaks caused by this phenomenon should not impair the ability to compare the results derived in the previous study of SS274A to those derived for MP296A.

## DISCUSSION OF RESULTS

The work reported in Reference 1 concluded that surface ambient vibrational integrity monitoring failed to detect the removal of bracing members from SS274A. It was further concluded that for monitoring to detect bracing member removals, it would be necessary to achieve positive identification of the second, third, and preferably certain higher order modes, and for those modes to be stable under varying environmental and operating conditions.

The data from MP296A was far superior to the data from either of the other two platforms monitored. It could therefore be expected that this platform would be a good candidate for testing the utility of surface ambient vibrational integrity monitoring. This section contains a discussion of the extent to which the data from MP296A satisfied, or did not satisfy, the criteria for successful detection of bracing member removal established by the earlier work.

The fundamental modes of MP296A are stable. Structural analysis previously demonstrated, however, that the frequency and mode shape changes of the fundamental modes caused by removal of typical bracing on SS274A were so small as not to be detectable by standard measurement techniques (Reference 1). There is no reason to believe that MP296A would be any more sensitive to bracing member removal than SS274A.

The second order modes of MP296A are stable within 0.03 Hz, in terms of frequency. The member removal analyses performed earlier predicted frequency shifts of between 0.01 Hz and 0.07 Hz in the second order modes of SS274A, depending on the location of the removed member. It could possibly be concluded, therefore, that the removal of certain bracing members would be detectable by surface monitoring on MP296A. There are, however, a number of factors which call this conclusion into doubt.

1. The lack of sensors at the cellar deck limits the confidence with which second order modes can be identified. This could have been corrected by more extensive sensor locations.
2. The close proximity of the second order X and Y sway modes may make it difficult to distinguish the modes when one is affected more than the other by member removal or damage. It is possible that the apparent close proximity would be clarified with further cellar deck sensors, but given the available data, there is room for uncertainty.

The structural analysis of SS274A indicated frequency shifts of between 0.01 Hz and 0.04 Hz for the third order modes when bracing members were removed. The observed frequency variations on

MP296A are of the same order. It is therefore unlikely that the third order modes of MP296A could be used for vibrational monitoring.

The structural analysis of SS274A demonstrated that certain modes exhibited very large "jumps" due to member removal. Such behavior is possibly platform-specific. No conclusions can be drawn regarding the possibility of similarly large frequency shifts on MP296A without performing a structural analysis.

In summary, although there is a possibility that bracing member removal on MP296A would be detected by frequency shifts of the second order modes, these modes have not been defined sufficiently in the data to have total confidence in member removal detection. Additional sensors at the cellar deck level might have increased the probability of detecting member removal.

## CONCLUSIONS

1. The fundamental modes of MP296A were easily identified. The fundamental X-sway spanned three peaks, the Y-sway one, and the fundamental torsion two. The peak frequencies were stable within .04 Hz and the mode shapes were stable within 8% over a six month period.

2. The second order modes were characterized by high amplitude motion of the cellar (upper) deck, and lower amplitude, opposite phase motion of the boat deck. The fact that only one leg was instrumented on the cellar deck and that it was only instrumented in one of the four configurations, severely limited the extent to which the second order modes could be identified. Nevertheless, these modes were observed to be stable within .03 Hz with respect to frequency and within 6% with respect to mode shape.

3. The third order modes were characterized by high amplitude motion of the boat deck and lower amplitude, out of phase motion of the cellar deck. Multiple peaks were observed. Frequency stability could not be established because of the changes in relative amplitude of several peaks. Mode shape stability was marginal.

4. Multiple frequency peaks, or "split peaks", were thought to be caused by structural appendages such as catwalks, cranes or equipment supports, vibrating at natural frequencies close to the platform frequencies.

5. Although it is possible that the removal of certain bracing members on MP296A would be detectable by frequency shifts of the second order modes, the close proximity of the two sway modes might prevent the shifts from being observed. In order to draw any conclusions from a shift in second order frequencies, more sensors at the cellar deck level would be required. Bracing member removal would probably not be detectable by observing the fundamental modes, or the third or higher order modes.

6. This work demonstrated that it is possible to observe stable vibrational behavior up to at least the second order mode group on certain Gulf of Mexico platforms. It is unlikely, however, that surface ambient vibrational monitoring will be a viable technique for evaluating structural integrity even on apparently favorable platforms.

## ACKNOWLEDGMENTS

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## REFERENCES

1. Duggan, D.M., Wallace, E.R. and Caldwell, S.R.; "Measured and Predicted Vibrational Behavior of Gulf of Mexico Platforms", OTC Paper 3864, presented at the Twelfth Annual Offshore Technology Conference, May 5-8, 1980, Houston, Texas.

2. Burke, B.G., Sundararajan, C. and Safaie, F.; "Characterization of Ambient Vibration Data by Response Shape Vectors", OTC Paper 3862, presented at the Twelfth Annual Offshore Technology Conference, May 5-8, 1980, Houston, Texas.

## TABLE 1

| TEST NO. | FREQUENCIES OF PEAKS IN RESPONSE NORMS | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1C15B | 0.72 | 0.80 | 0.89 | 0.99 | 1.20 | 1.41 | 1.58 | 1.86 | 2.00 | 2.28 | 2.53 | 2.59 | 2.75 | -- | 3.25 | -- | 3.67 | -- | -- | -- | -- | -- | 4.45 | 4.72 | -- |
| 1C23C | 0.72 | 0.81 | 0.90 | -- | 1.20 | 1.43 | 1.52 | 1.90 | 2.00 | 2.30 | 2.56 | 2.60 | 2.75 | 2.91 | 3.25 | 3.45 | 3.72 | 3.90 | -- | -- | -- | 4.30 | 4.48 | 4.75 | -- |
| 1C27D | 0.72 | 0.81 | 0.90 | 0.99 | 1.20 | 1.45 | 1.59 | 1.88 | 2.00 | 2.32 | 2.54 | 2.60 | 2.76 | 3.08 | 3.22 | -- | 3.61 | 3.88 | 3.97 | -- | 4.22 | 4.30 | 4.50 | 4.76 | 4.97 |
| 1C34A | 0.72 | 0.81 | 0.90 | 0.99 | 1.17 | 1.44 | -- | 1.86 | 2.03 | 2.30 | 2.53 | 2.60 | 2.74 | -- | 3.22 | -- | 3.60 | 3.87 | -- | -- | 4.20 | -- | 4.45 | 4.75 | -- |
| 2C07C | 0.72 | 0.81 | 0.90 | 1.00 | 1.20 | 1.46 | -- | 1.87 | 2.04 | 2.28 | -- | 2.59 | 2.75 | -- | 3.25 | -- | 3.66 | 3.90 | -- | -- | -- | -- | 4.41 | 4.72 | -- |
| 2C01D | 0.72 | 0.80 | 0.90 | 1.00 | 1.20 | 1.44 | -- | 1.88 | 2.06 | 2.28 | 2.50 | 2.59 | 2.75 | -- | 3.25 | 3.43 | 3.69 | 3.89 | 4.00 | -- | 4.20 | 4.28 | 4.40 | 4.75 | 4.95 |
| 2C13A | 0.72 | 0.81 | 0.90 | 1.00 | 1.19 | 1.44 | -- | 1.88 | 2.07 | 2.30 | -- | 2.59 | 2.74 | 2.90 | 3.26 | -- | 3.67 | 3.84 | -- | 4.15 | -- | -- | 4.40 | 4.75 | -- |
| 2C28B | 0.72 | 0.81 | 0.90 | 1.00 | 1.19 | 1.44 | 1.65 | -- | 2.07 | 2.28 | -- | -- | 2.75 | -- | 3.25 | 3.43 | 3.67 | -- | 4.01 | 4.10 | 4.25 | -- | 4.43 | 4.74 | -- |
| 3C05A | 0.72 | 0.81 | 0.91 | 1.01 | 1.21 | 1.44 | -- | 1.88 | 2.05 | 2.30 | -- | -- | 2.75 | 2.90 | 3.24 | 3.43 | 3.68 | 3.86 | 4.02 | -- | 4.19 | -- | 4.42 | 4.72 | -- |
| 3C11C | 0.72 | 0.82 | 0.90 | 1.00 | 1.20 | 1.46 | -- | 1.86 | 2.05 | 2.29 | -- | 2.59 | 2.75 | -- | 3.25 | -- | 3.67 | 3.90 | 4.00 | 4.10 | -- | 4.30 | 4.40 | 4.73 | -- |
| 3C14D | 0.72 | 0.82 | 0.91 | 1.01 | 1.21 | 1.44 | 1.60 | 1.86 | 2.05 | 2.29 | 2.40 | 2.60 | 2.76 | 3.02 | 3.25 | 3.43 | 3.68 | 3.88 | 3.96 | 4.09 | 4.20 | 4.28 | 4.42 | -- | -- |
| 3C41B | 0.72 | 0.81 | 0.90 | 1.01 | 1.18 | 1.45 | -- | 1.86 | 2.05 | 2.30 | 2.49 | -- | 2.75 | 2.90 | 3.25 | -- | 3.68 | 3.90 | 4.03 | -- | 4.20 | -- | 4.47 | -- | 4.97 |
| 2C05B* | 0.7 | 0.8 | 0.9 | 1.0 | 1.2 | 1.4 | -- | -- | -- | 2.4 | 2.5 | 2.6 | 2.8 | 2.9 | 3.3 | -- | 3.7 | -- | 4.0 | -- | -- | -- | 4.4 | 4.8 | -- |
| 3C30C* | 0.7 | 0.8 | 0.9 | 1.0 | 1.2 | 1.4 | -- | 1.8 | 2.1 | 2.3 | -- | -- | 2.7 | -- | 3.3 | 3.4 | 3.7 | 3.9 | -- | -- | 4.2 | -- | 4.4 | 4.8 | 5.0 |
| 3C51D* | 0.7 | 0.8 | 0.9 | 1.0 | 1.2 | 1.4 | -- | -- | 2.2 | 2.4 | 2.5 | -- | 2.7 | -- | 3.2 | -- | 3.7 | 3.9 | -- | -- | -- | 4.3 | 4.5 | -- | 5.0 |
| 2C02A* | 0.7 | -- | 0.9 | 1.0 | 1.2 | 1.4 | -- | 1.8 | 2.0 | 2.3 | 2.5 | -- | 2.7 | 2.8 | 3.3 | -- | -- | 3.8 | -- | -- | -- | 4.3 | 4.4 | 4.7 | -- |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2C05B* | -- | 5.5 | -- | -- | -- | -- | -- | -- | 8.6 | -- | 9.8 | -- | -- | 11.9 | -- | 13.4 | -- |
| 3C30C* | -- | 5.5 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | 10.6 | 12.0 | -- | -- | -- |
| 3C51D* | 5.3 | 5.6 | 5.9 | 6.2 | 6.4 | 6.6 | 7.0 | -- | 8.6 | 8.9 | 9.4 | 10.2 | 10.6 | 12.0 | 12.6 | 13.3 | -- |
| 2C02A* | -- | 5.5 | 5.9 | 6.2 | -- | 6.6 | 7.1 | 8.2 | 8.6 | -- | 9.4 | 10.2 | -- | 12.0 | 12.8 | 13.5 | 14.0 |

NOTES:

1. * 0-15 Hz Test
2. The peak at 3.67-3.69 Hz corresponds to the pipeline pump, fundamental frequency.

# TABLE 2

## FREQUENCY RANGES OF IDENTIFIED MODES

| MODE SHAPE | PEAK FREQUENCY (Hz) | RANGE (Hz) |
|---|---|---|
| X-sway | 0.72, 0.81, 0.90 | 0.47-0.90 |
| Y-sway | 0.99 | 0.98-1.04 |
| Torsion | 1.17, 1.44 | 1.14-1.53 |
| 2nd Order Y-sway | 1.84 | 1.72-1.91 |
| 2nd Order X-sway | 1.88 | |
| 2nd Order Torsion | 2.03 | 1.95-2.08 |
| 3rd Order Y-sway | 2.53, 2.60 | Alternating Bands<br>2.31-2.40, 2.63-2.76<br>2.42, 2.56<br>2.57-2.62, 2.77-2.83 |
| 3rd Order X-sway | 2.74 | |
| 3rd Order Torsion | 3.22, 3.87, 4.20<br>4.55, 4.75 | 3.12-3.55, 3.86-3.96<br>4.20-4.96 |
| Vertical Mode | 5.0 | undefined |
| Higher Order Sways | 5.5, 5.9 | 5.18-5.80, 5.83-6.30 |
| Complex Modes | >6.0 | |

NOTES:

1. Frequency ranges of modal behavior are taken from 1C34A to 2C02A data. Ranges on other tests vary slightly.

2. First and second order modes are differentiated by the relationships between boat deck and cellar deck motion. Second, third and higher order modes cannot be differentiated by any means other than estimation.

# TABLE 3

## PEAK FREQUENCIES OF IDENTIFIED MODES

| | X-sway | Y-sway | Torsion | 2nd Y | 2nd X | 2nd Torsion | 3rd Y | 3rd X | 3rd Torsion | Vertical |
|---|---|---|---|---|---|---|---|---|---|---|
| 1C15B | .72, .80, .91 | .99 | 1.20, 1.44 | -- | -- | -- | 2.55 | 2.74 | 3.25, 4.45, 4.72 | |
| 1C23C | .72, .81, .90 | .99 | 1.20, 1.45 | -- | -- | -- | 2.55, 2.62 | 2.74 | 3.25, 3.90, 4.30, 4.48, 4.75 | |
| 1C27D | .72, .81, .90 | .99 | -- | -- | -- | -- | 2.53, 2.61 | 2.75 | -- | 4.97 |
| 1C34A | .72, .81, .90 | .99 | 1.17, 1.44 | 1.86 | 1.88 | 2.03 | 2.53, 2.60 | 2.75 | 3.22, 3.87, 4.20, 4.45, 4.75 | |
| 2C07C | .72, .81, .90 | 1.00 | 1.20, 1.46 | -- | -- | -- | 2.59 | 2.75 | 3.25, 3.90, 4.41, 4.72 | |
| 2C10D | .72, .80, .90 | 1.00 | -- | -- | -- | -- | 2.54 | 2.75 | -- | 5.00 |
| 2C13A | .72, .81, .90 | 1.00 | 1.19, 1.44 | 1.88 | 1.88 | 2.06 | 2.59 | 2.75 | 3.26, 3.84, 4.15 4.40, 4.75 | |
| 2C28B | .72, .81, .90 | 1.00 | 1.19, 1.44 | -- | -- | -- | 2.55, 2.60 | 2.73 | 3.25, 4.01, 4.10, 4.25, 4.43, 4.74 | |
| 3C05A | .72, .82, .91 | 1.01 | 1.21, 1.44 | 1.88 | 1.88 | 2.05 | 2.59 | 2.75 | 3.24, 3.86, 4.02, 4.19, 4.42, 4.72 | |
| 3C11C | .72, .82, .90 | 1.00 | 1.21, 1.46 | -- | -- | -- | 2.60 | 2.76 | 4.25, 3.90, 4.00, 4.10, 4.30, 4.40, 4.73 | |
| 3C14D | .72, .82, .91 | 1.01 | -- | -- | -- | -- | 2.52, 2.60 | 2.76 | -- | 5.00 |
| 3C41B | .72, .81, .90 | 1.01 | 1.18, 1.45 | -- | -- | -- | 2.50 | 2.75 | 3.25, 3.90, 4.03, 4.20, 4.47, 4.97 | |
| 3C51D* | | | | | | | | | | 5.00 |

NOTES:

1. Second order modes are observed at the cellar (upper) deck.

2. * 0-15 Hz Test.

# TABLE 4

## CROSS DOT PRODUCT TABULATION

| Response Shape | X-Sway | | | Y-Sway | Torsion | | 2nd Y | 2nd X | 2nd Torsion | 3rd Y | | 3rd X | 3rd Torsion | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Frequency Peak 1C34A | 0.72 | 0.81 | 0.90 | 0.99 | 1.17 | 1.44 | 1.86 | 1.88 | 2.03 | 2.53 | 2.61 | 2.75 | 3.22 | 3.87 | 4.20 | 4.45 | 4.75 |
| Dot Product 1C34A/2C13A | 0.92 | 0.99 | 0.99 | 1.00 | 1.00 | 1.00 | 0.98 | 0.94 | 1.00 | 0.84 | 0.95 | 0.56 | 0.97 | 0.86 | 0.51 | 0.93 | 0.77 |
| 1C34A/3C05A | 0.99 | 0.99 | 0.99 | 1.00 | 1.00 | 1.00 | 0.99 | 0.99 | 1.00 | 0.80 | 0.95 | 0.92 | 1.00 | 0.96 | 0.88 | 0.61 | 0.88 |

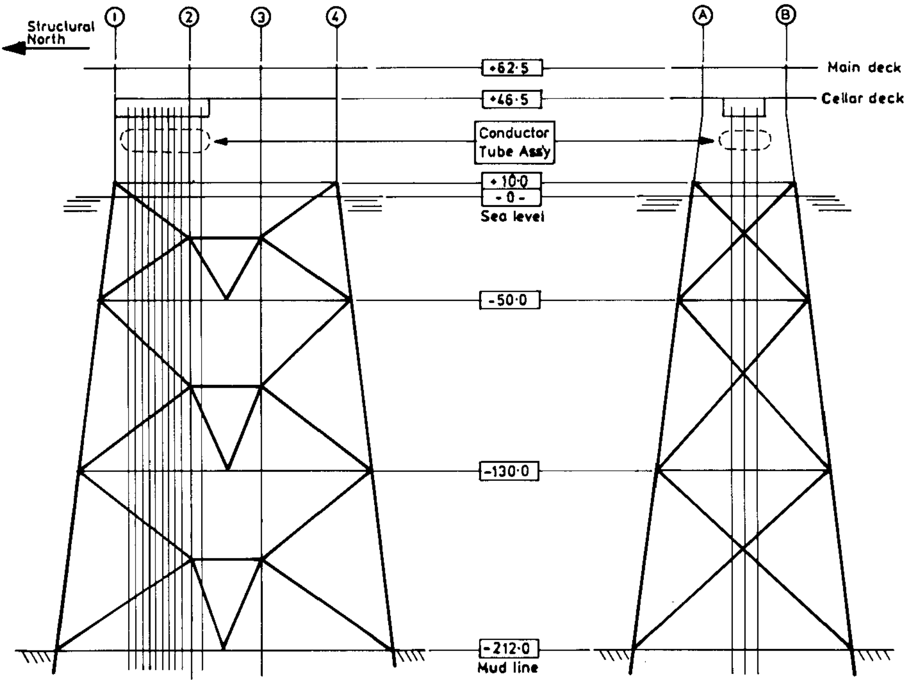


FIGURE 1

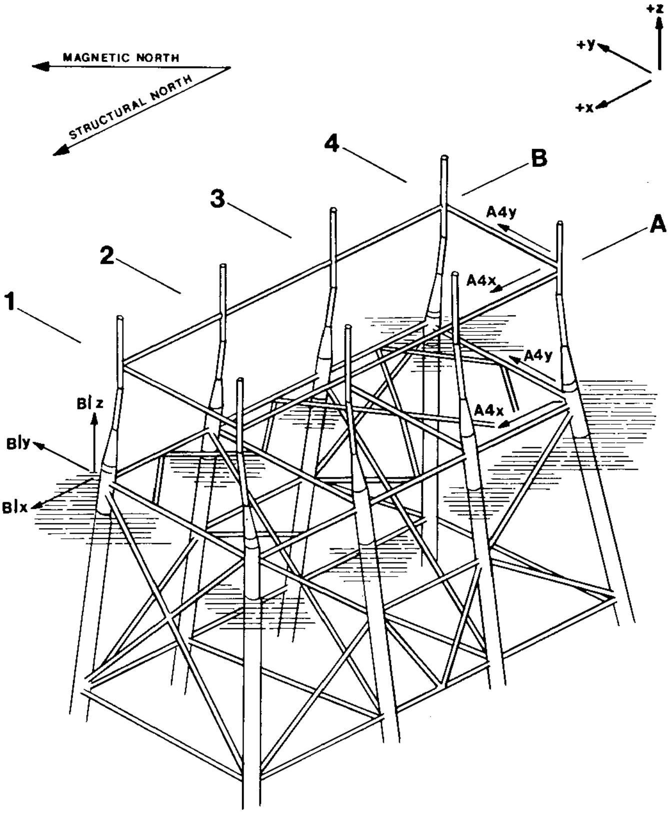
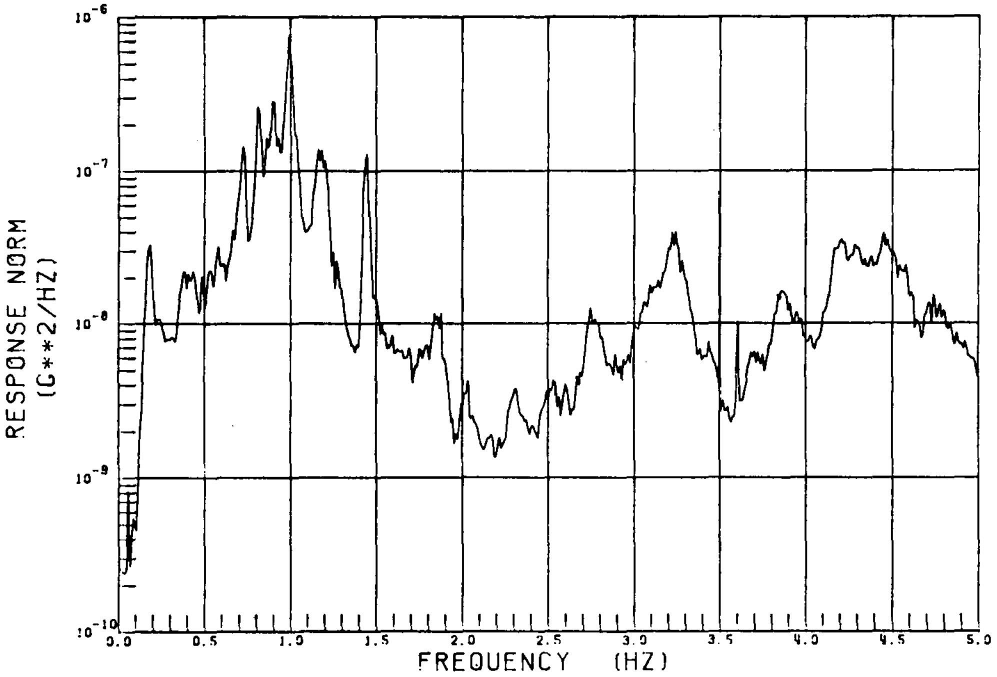


FIGURE 2



RESPONSE NORM FUNCTION
( 1C34A )

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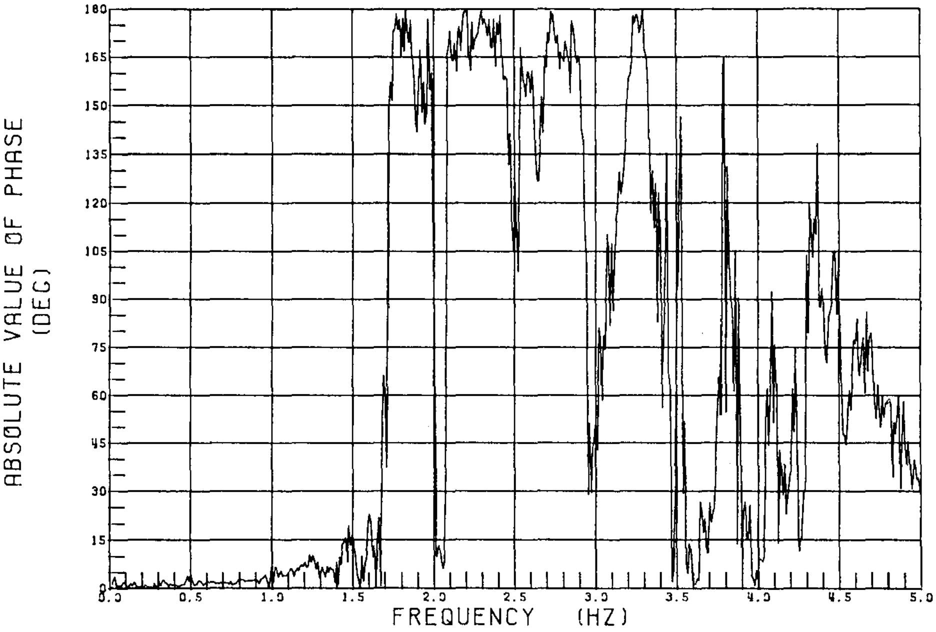
FIGURE 3



PHASE OF THE CROSS SPECTRAL DENSITY FUNCTION
( 1C34A4XL AND 1C34A4XU )

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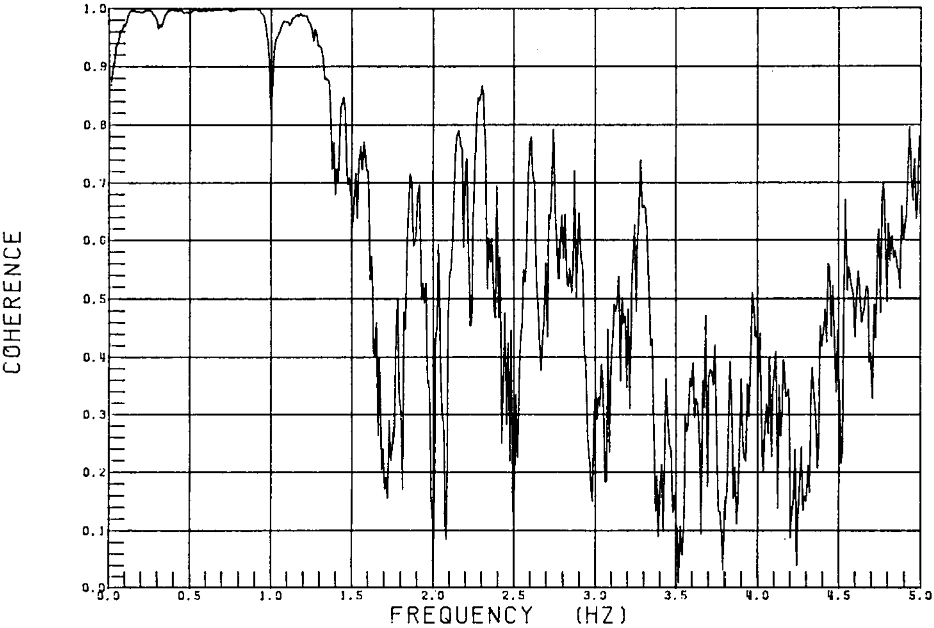
FIGURE 4



COHERENCE FUNCTION
( 1C34A4XL AND 1C34A4XU )

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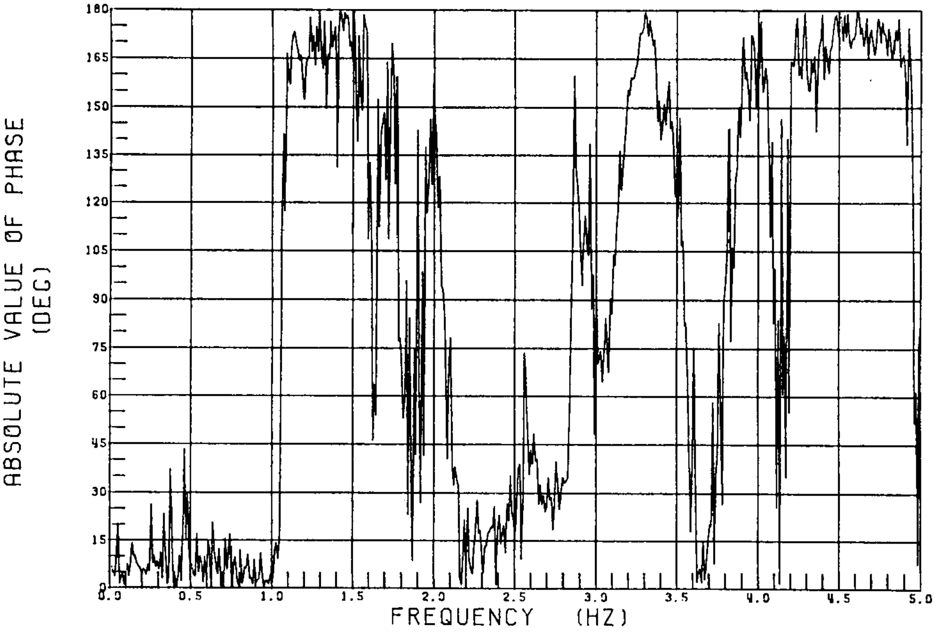
FIGURE 5



PHASE OF THE CROSS SPECTRAL DENSITY FUNCTION
( 1C34B1Y AND 1C34A4YL )

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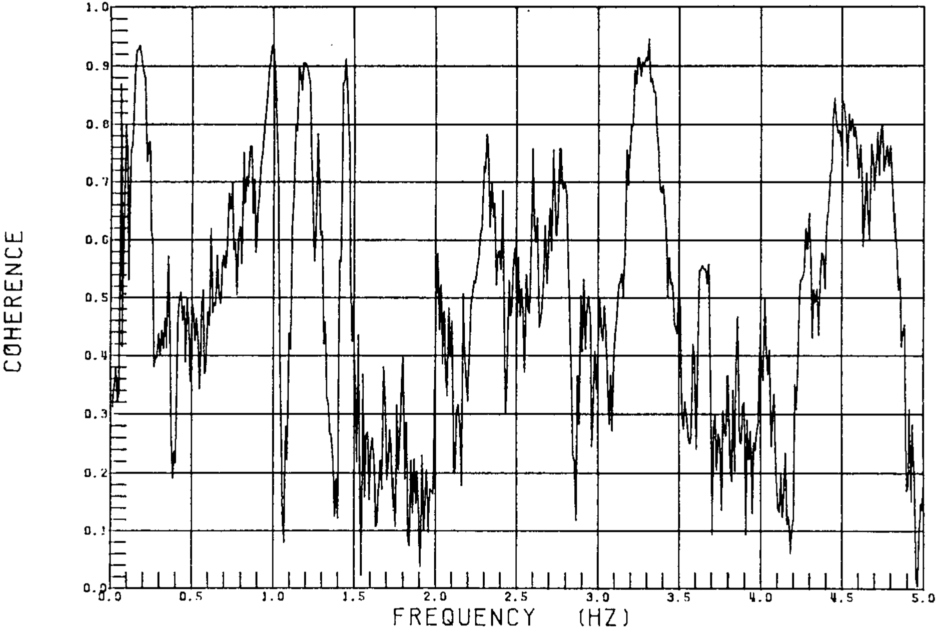
FIGURE 6



COHERENCE FUNCTION
( 1C34B1Y AND 1C34A4YL )

KEITH, FEIBUSCH ASSOCIATES FEBRUARY 1980

FIGURE 7