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FLEXIBILITY MONITORING EVALUATION STUDY

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REFERENCES

1. Rubin, S., "Ambient Vibration Survey of Offshore Platform", Journal of the Engineering Mechanics Division, ASCE, Vol. 106, No. EM3, Proc. Paper 15458, June 1980, pp. 425-441.

2. Rubin, S., Coppolino, R. N. and Conley, J. A., "Scale Model Nondestructive Examination (NDE) Round Robin Test", Report No. ATR-82(2830)-IND, The Aerospace Corporation, El Segundo, California (Dec. 1981).

3. MacNeal, R. H., editor, "The NASTRAN Theoretical Manual," NASA SP-221(01), December 1972.

4. Bathe, K. J. and Wilson, E. L., "Solution Methods for Eigenvalue Problems in Structural Mechanics," International Journal for Numerical Methods in Engineering, Vol. 6, 1973, pp. 213-226.

#. Guyan, R., "Reduction of Stiffness and Mass Matrices", AIAA Journal, V. 3, No. 2, February 1965, p. 380.

6. Rubin, S. and Coppolino, R. N., "OCS Instrumentation Monitoring Evaluation," Report No. ATR-79(7787)-1, The Aerospace Corporation, El Segundo, California (June 1979).

7 Rubin, S. and Coppolino, R. N., "Detectability of Structures Failures in Offshore Platforms by Ambient Vibration Monitoring", Paper OTC 3865, Offshore Technology Conference [1980], 101-110.

8. Rubin, S. and Coppolino, R. N., "Flexibility Monitoring of Offshore Jacket Platforms", Paper OTC 4535, Offshore Technology Conference [1983], 201-208.

9. Marshall, P. W., "Strategy for Monitoring Inspection and Repair for Fixed Offshore Platforms", ASME Publication Structural Integrity Technology [May 1979], 97-109.

10. Bendat, J. S. and Piersol, A. G.: "Engineering Applications of Correlation and Spectral Analysis", John Wiley and Sons, New York [1980], Ch. 5.

11. Dame, R. E. and Warren, H. A. Jr.: "NDE Round Robin Final Report", Mega Engineering Inc., January 1983, p. 18.

12. Ting, S. K. and Sunder, S. S.: "Damage Detection of Steel Jacket Offshore Platforms Using Flexibility Monitoring", Massachusetts Institute of Technology, Research Report R83-19, Order No. 759, May 1983.

FOREWORD

Since 1976, Aerospace has been working with the Minerals Management Service (MMS)[1] on conceptual approaches to assessment of structural integrity of fixed offshore platforms. A promising concept, Flexibility Monitoring evolved during these studies. As a result, the Aerospace Corporation initiated effort under an Interagency Agreement between the MMS and the U.S. Air Force Space Division in April of 1981 to evaluate the operation of specialized hardware and its ability to acquire data of sufficient quality to support the Flexibility Monitoring technique. Extended testing on a 1:13.8 scale model structure (Phase I) was designed to check out the hardware and test procedures prior to generating detailed plans for testing the technique on offshore platforms (Cognac-Phase II and Garden Banks-Phase III). A shaker was used on the scale model whereas the ambient excitation of wind and waves was employed in the testing of the offshore oil platforms.

The two field tests provided compelling evidence that good signal quality is achievable when employing both the type of equipment outlined in this report and experienced personnel to exercise stringent quality control procedures. It has also been confirmed that Flexibility Monitoring has the necessary discriminatory attributes for jacket damage detection in that it can localize damage to the bay and possibly even to the face and not be misled by foundation and deck mass changes.

This report has been prepared for the Minerals Management Service, U.S. Department of the Interior under Interagency Agreement Numbers 1-6009-05813(64), 2-6009-05813(64) and 3-6035-25213. The Technical Officer for these agreements was Mr. Charles Smith, Technology Assessment and Research Branch, Minerals Management Service.

[1]Minerals Management Service (MMS), as used in this report, refers to both the present MMS organization and the Conservation Division of the U.S. Geological Survey which was incorporated as part of the MMS in March of 1982.

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Appreciation is extended to Shell and Chevron for providing the opportunity and technical support which enabled the two offshore measurement programs.

Art Conley of Aerospace served as Project Engineer and was a participant in the Cognac field test. Planning, direction, and real time data analyses for all laboratory and field tests were performed by Shel Rubin. Mathematical model analyses were conducted by Bob Coppolino.

EXECUTIVE SUMMARY

Progressively larger and costlier structures, deeper waters and more severe weather conditions have prompted a growing concern for the structural integrity of fixed offshore platforms and the resultant safety for personnel. Historically, divers and remotely controlled submersibles have been employed for this task, however, even in shallow waters these techniques are time consuming and costly. Various platform monitoring techniques are being investigated for the purpose of reducing inspection time and costs and to provide a reliable structural integrity indicator in lieu of detailed visual inspections. Evaluations of a promising technique, called Flexibility Monitoring, are presented in this report.

The Flexibility Monitoring Method and Its Applicability

Flexibility Monitoring has been conceived, analyzed and experimentally tested as to its effectiveness for identifying significant loss of strength to a jacket platform. Inasmuch as strength loss is generally evidenced by corresponding increases in shear flexibilities of the jacket bay involved, the method is based upon measurement of specially defined flexibility parameters. These parameters are defined as the ratio of shear deflections across each jacket bay, divided by the corresponding shear deflection between the decks, as they occur in the three fundamental modes of vibration (two sway and torsion). They can be measured accurately from the random responses of the jacket to ambient sea and wind excitation without regard to weather and sea state (for other than extremely severe events) and with little regard to the operational status of the platform. The key requirement is the absence of a significant degree of atypical mechanical or electrical noise. The Garden Banks tests showed that high quality results can be attained in a calm sea, near the bottom of the structure (where the amplitudes are the lowest of anywhere on the structure), and in the presence of drilling operations--and further, that the results can be accurately repeated.

It is judged that 5% accuracy or better can be achieved for measurement of flexibility parameters in an operational Flexibility Monitoring application having optimized equipment and procedures. The degree of repeatability in measuring flexibility parameters for a lower bay of the Garden Banks platform ($\leq$ 3.4%) lends support to this judgment. This degree of accuracy requires the following:

a. Force-balance instruments of the quality currently being used by industry (reported herein).

b. Means for accurate, and highly repeatable, positioning and angular orientation of instrument packages at the jacket bay levels. Instrument chutes of the type currently installed on some recent platforms can be ideal for this type of monitoring if carefully oriented and rigidly supported.

c. Quality signal conditioning and digital data processing systems tailored to the demanding requirements of this application, (including software) operated in real time by trained personnel following established procedures.

d. Precise relative system calibrations using ambient excitation onboard the platform.

Baseline data can be obtained at any time in the life of a platform to serve as a reference for subsequent monitoring tests.

Evidence of significant flexibility changes within a jacket bay can be unambiguously identified and localized to the bay and sway direction affected. The following effects will, at most, produce smooth changes in flexibility parameter distributions and will, therefore, not lead to confusion about local damage of the jacket:

a. distributed flexibility change of the foundation

b. mass changes on the decks, member flooding and marine growth (The latter two were evaluated in Ref. 2 and Ref. 12)

c. magnitude of platform dynamic response (that is, variable sea state) introducing mildly nonlinear effects in terms of soil behavior, vibration damping and degree and intermittency of intercontact by ungrouted piles and conductors with the jacket. (These have not been studied specifically, but are reasonable expectations.)

The Flexibility Monitoring method can also identify changes in flexibility of the foundation. And, in more general terms, Flexibility Monitoring can play a valuable role in the experimental identification of the system dynamic flexibility parameters.

Effective operation of Flexibility Monitoring can be conducted using specially developed portable equipment and experienced personnel using careful quality controls to assure accuracy of the measurements.

Scale Model Testing

The testing of a simplified subscale model (1:13.8) of a 4-leg offshore platform entailed precise calibration of the instrumentation followed by the acquisition and real time analysis of data from a series of actual damage tests. The prime purpose of these tests was to evaluate the specific implementation of the Flexibility Monitoring Technique proposed for field testing of operating offshore platforms; i.e., accelerometer placement, real time generation and analysis of flexibility parameters using portable equipment. The second purpose was to experimentally explore some basic sensitivity characteristics of the technique.

Field Testing

In April 1981 mutual interest was established for cooperative testing programs with Chevron, Shell and Union Oil. The Union platform, Cerveza, installed in August 1981 was selected for initial field test evaluation. It was considered to be a highly desirable candidate because of its height and because it offered an opportunity to test under a low deck mass condition shortly after installation. A future retest opportunity with greatly increased deck mass would then provide an ideal demonstration of the insensitivity of flexibility parameters to deck mass. However, a Union decision to delay the schedule for development of the instrumentation packages precluded this possibility.

It was then judged that the Chevron U.S.A. Inc. Garden Banks platform and instrumentation package development schedule best fit the initial evaluation. During the months of June, July and August 1981, meetings were held at the La Habra, California facility of the Chevron Oil Field Research Company to discuss instrumentation, data acquisition and test procedures. A trip was made to Chevron's platform Grace in the Santa Barbara Channel, California, to check out prototype instrumentation. In September Aerospace received the Garden Banks mathematical model and structural details from Chevron and initiated effort to install the model on the Aerospace computer system.

Aerospace maintained constant contact with both Chevron and Shell as it became increasingly apparent that both companies were at approximately the same stage of development with their instrumentation packages and data acquisition systems. Consequently, coordination meetings were held with both groups regarding package development, calibration, data acquisition and test procedures. During the month of November 1981, Aerospace received the mathematical model and drawings of the Shell Cognac platform, as well as the working agreements from both industry groups.

By February 1982 the prototype instrumentation packages had been tested, the operational packages fabricated and placed on both platforms for preliminary test. Negotiations between Aerospace and Shell quickly resulted in an equitable working agreement document and so the Shell Cognac platform became the designated subject for the initial field test. Efforts on the Garden Banks platform mathematical model were discontinued at that time and the installation of the Cognac platform mathematical model on the Aerospace computer system was initiated.

Field testing on the Cognac platform was conducted during the month of April 1982.

The physical layout for the relative calibration of the instrument packages was very satisfactory. Coherence results of 0.998 or above were obtained at frequencies of the fundamental modes. Thus, high statistical confidence in the calibrations was clearly achievable.

The planned real-time determination of flexibility parameters was not achievable because of the unanticipated misalignment of the instrumentation chutes on two of the four corners. Before this condition was identified, the analog summing unit and dual-channel analyzer were utilized as planned and the equipment performed well. The resulting flexibility parameters displayed poor coherence because of the misalignments of two of the four underwater packages. In addition, looseness of the two misaligned chutes at the 12-foot level produced spikes in the accelerometer signals from those packages further deteriorating coherence. Checks of coherence of accelerometers in the other two chutes showed values near unity when related to a corresponding lateral acceleration at the deck. It was thus apparent that with known orientation and well supported chutes, good quality data can be obtained.

As a first field experiment, the Cognac test was a useful learning experience. Test design for the second field test benefited considerably from this prior evaluation.

Field Testing on the Garden Banks platform was conducted during the month of December, 1982.

The physical layout for the relative calibration of the instrument packages was different from the layout on the Cognac platform because of the unique orientation of the accelerometers within the packages. The resident deck accelerometers were permanently affixed to a leg and the packages were placed in orientation stands on deck plating about one meter distant. The relative calibrations were somewhat less satisfactory than expected. It is believed that this difference was primarily the result of slight differences between vibration as sensed on the deck plate versus on the nearby leg--with differences occurring sporadically.

The real-time determination of flexibility parameters was achieved with a high statistical confidence. In addition, testing was repeated at both the lowest bay and the highest level, including repositioning of the packages, to check on the short term (13-22 hours) repeatability of the technique. Results were very favorable with flexibility parameters differing by less than 5 percent--testimony to the considerable capability of the instrumentation and data acquisition and processing systems.

Further sophistication of the analog summing unit is being considered, i.e.,

- a capability for phase compensation
- a capability to compensate for unique orientations of the instrumentation packages.

Sensitivity

An evaluation was made to assess the relative payoff of mathematical modeling studies on the specific field structures versus a study on generic models using a generalization of the approach taken in Ref. 7. It was deemed that information of greater overall value, given the practical constraints on the effort, would be obtained by generic model studies, therefore, modeling of the actual platforms were not carried out.

The sensitivity of the Flexibility Monitoring method for damage detection was explored in two ways. First, an experimental study was conducted on a simple 4-leg laboratory model and then an analytical study was made on generic mathematical models spanning a wide range of geometric complexity: 4-leg, 4 bay; 8-leg, 6 bay; and 12-leg, 11 bay. The details of these two studies appear in Sections 2 and 5, respectively. Essential trends which make Flexibility Monitoring attractive were observed.

a. Vertical diagonal member failures produced changes in flexibility parameters only for the bay and in the direction or directions involved (that is, lateral and possibly torsion). Elsewhere the changes were negligible.

b. Foundation flexibility or deck mass changes produced a smoothly varying shift in the overall flexibility parameter shape. The major effect was due to the rotational flexibility (allows platform rigid-body rocking).

c. Torsion/lateral coupling, when sufficiently strong, permitted identification of the face of the damage.

It has, therefore, been confirmed that Flexibility Monitoring has the necessary discriminatory attributes for feasibility of vertical diagonal severance detection in that it can localize the damage to the bay and direction involved (and possibly even to the face) and it will not be misled by foundation and deck mass changes.

In ascending order of significance, the degree of shift of flexibility parameters due to vertical diagonal severance increased with the following factors:

a. The depth of the bay.

b. The degree of lateral/torsion coupling produced by the severance

c. The lack of significant rocking flexibility of the foundation

d. The lack of redundancy of vertical diagonal braces within a bay

The lack of redundancy, of course, gave rise to a decrease in damage strength rating due to severance. Figure 5.5 clearly shows the trend of increasing magnitude of flexibility parameter change with reduced damage strength rating. The relatively little redundancy of a 4-leg platform (with single diagonal brace) led to flexibility parameter changes which were from 100 to 300 percent in at least one of the affected modes. It is expected that crossed bracing would reduce the sensitivity to severance of one vertical diagonal to no more than 50 to 150 percent. For results of a study of a particular X-braced, four leg platform, see Ref. 12. For the 8-leg platform, the sensitivity to loss of diagonal stiffness depended a great deal on the face involved. On the exterior end-on faces, the flexibility parameter change was a relatively high 50 to 90 percent, with the torsion mode being a far stronger indicator for the soft foundation. For the interior end-on and the broadside faces, the lateral mode was the most responsive and the change was as low as 12 percent. The flexible foundation was not significant relative to the platform flexibility for the 12-leg platform and the changes for failure on any face did not fall below the least sensitive 8-leg platform failure case with a flexible foundation, namely 12 percent. For all platforms the percentage change increased with the depth of the damaged bay with only one exception (the torsion mode for case 5; see Table B.3.

The reader is cautioned that the trends observed in the sensitivity studies are the most reliable aspect and that the numerical values of sensitivity are only indicators of order of sensitivities expected for actual platforms.

Based upon the analytical studies and extrapolating therefrom, the following judgments are made on the premise that at least a 15 to 20% local increase in a bay or foundation flexibility parameter will be necessary for reliable failure identification.

a. There is little question of the adequacy of the sensitivity of Flexibility Monitoring, for a 4-leg platform, to identify severance of a single vertical diagonal brace even if cross braced.

b. For an 8-leg platform, such identification was possible for a relatively stiff foundation in rocking, especially in the absence of cross bracing. Cross bracing and significant rocking made problematic the identification of individual vertical diagonal severances, especially for interior and broadside face members.

c. Identification of single severance of most vertical diagonals in a 12-leg jacket was problematic. End-on, outer-face vertical diagonals are expected to be identifiable if uncrossed.

Multiple member damage in a given bay, affecting the same lateral direction, produces larger flexibility parameter increases than that for failure of a single diagonal and identification becomes increasingly easier. It appeared that an effect comparable to two diagonal severances will be identifiable in most cases for either the 8-leg platform on a soft foundation or the 12-leg platform. More definitive statements will require analytical predictions of sensitivity for specific structural configurations.

In concept, Flexibility Monitoring is directed towards the detection of shear flexibility change of individual bays of a jacket and of the foundation. As such, it is capable of detecting the severance of vertical diagonal bracing which is the principal contributor to jacket shear flexibility. In general, horizontal members do not contribute significantly to this flexibility (Ref. 6 and Ref. 12), and thus, their failure may not be detectable by this method. To the extent that failure of vertical members or piles induce significant rotation in mode shapes, such failures will show up in flexibility parameters (Ref. 2 and Ref. 12). Specific attention has not been given to such failures in this study.

Recommendation

A repeat field test is recommended on the Garden Banks structure. Several worthwhile objectives are apparent:

a. evaluation of refined calibration and equalization procedures for the accelerometers

b. evaluation of measurement repeatability after more than a year of elapsed time

c. the opportunity to observe effects of a significantly different deck loading and type of operation than for the original test which was carried out during drilling operations.

In addition, a mathematical modeling and evaluation effort on the Garden Banks structure is recommended. Failure sensitivity studies using that model could then be conducted: (1) to test the reasonableness of the present generic model results and (2) to specifically examine the damage detection capability of Flexibility Monitoring for this platform.

It is also recommended that field tests be structured to verify that jacket failure can be identified in a field situation. Practical considerations suggest use of a platform undergoing repair or scrappage, or some platform that is no longer serviceable and has been or can be designated as a test platform. Hopefully, already developed instrumentation could be utilized on a loan or rental basis from industry. Diver installation of the instrument packages would be required since chutes would likely not be present. Clearly a great deal of planning and industry cooperation would be essential to the conduct of a meaningful test at reasonable cost.

Due to the potential utility of instrument chutes (e.g., for oil company design evaluations, as well as possible application of Flexibility Monitoring), an effort evolved during the subject work to explore such considerations. Technical liaison with industry was established via individual representatives from Chevron, Exxon, Shell and Union Oil--all of whom have installed and/or are in the process of installing chutes on platforms for monitoring purposes. A key objective is to standardize the chute interior dimensions to help make commercial development of an instrument package economically feasible. It is recommended that MMS consider support of this work which could result in the development of a guideline document for industry. The document would address the requirements for Flexibility Monitoring, as well as those for monitoring in general. It is hoped that the design and installation of chutes for several upcoming structures off the California coast, for which chutes have been sanctioned, will be favorably influenced by the interchanges and agreements that have and will take place in coordination with industry representatives.

1. INTRODUCTION

The quest for the discovery of new oil and gas deposits has motivated government and industry to expanded exploration of the Outer Continental Shelf (OCS) for new sources of supply. The hostile environments encountered in these explorations have stimulated considerable effort in the formulation of new methods for assessments of the structural integrity of fixed offshore platforms. Progressively larger and costlier structures, deeper waters and more severe weather conditions have prompted a growing concern for the integrity of the platforms and the resultant safety for personnel.

Historically, the structural integrity of fixed offshore platforms has been periodically assessed by the use of divers or remotely controlled unmanned submersibles. These methods have also been used to perform inspections after storms, collisions, or other occurrences which could damage the platform. Even in fairly shallow waters, these techniques must be applied selectively and are time consuming and costly. These problems are magnified in deeper OCS areas where saturation diving is required. As a consequence, platform monitoring techniques are desired which reduce inspection time and costs and provide a reliable structural integrity indicator in lieu of detailed visual inspections. The Minerals Management Service (MMS) considers such platform monitoring techniques as potentially useful in conjunction with their current OCS Platform Verification Program. These techniques can also be used by industry during the life of the platform to ensure personnel and equipment safety and limit environmental damage.

In response to this need, the MMS initiated a study in October 1976 with The Aerospace Corporation under Contract 14-08-0001-15989 to (a) review existing structural inspection approaches in the United States and the North Sea; (b) perform analyses of selected options; and (c) develop alternative instrumentation configurations for possible operational applications. It was determined that the monitoring of the modes of structural vibration, which was being applied commercially in the North Sea, appeared to provide the most promising approach. It was, however, not possible to fully evaluate the North Sea applications in use because of proprietary restrictions. That fact led to tests performed by Aerospace in September 1977 on the Shell Oil Company Platform C located in South Pass OCS Tract 62 in the Gulf of Mexico as a means of addressing matters related to the assessment of the utility of vibration monitoring. The Shell platform is located in 327 ft (100m) of water, and until about 1978, was among the taller structures in the Gulf. A total of 26 hours of ambient vibration data were recorded, which included periods of both calm and stormy sea conditions. Only a quick-look analysis was conducted on this data. This study was completed in October 1977 and is covered in Aerospace Report No. ATR-77(7626-02)-1, "Instrumentation of Fixed OCS Platforms".

An ensuing contract (14-08-0001-17224) was initiated by the MMS with The Aerospace Corporation in September 1978 to: (a) perform a detailed analysis of the vibration data recorded during the previous contract to extract modal frequencies and shape parameters; (b) develop a dynamic model of the subject offshore platform which yielded modes in good agreement with those measured; (c) determine modal changes associated with single structural failures using the dynamic model; and (d) develop a plan for evaluating prototype instrumentation. This study was completed in June, 1979 and the results are documented in Aerospace Report No. ATR 79-(7787)-1, "OCS Instrumentation Monitoring Evaluation."

As a result of the above studies and studies by others of non-destructive evaluation (NDE) techniques (i.e. Internal Friction Monitoring, Random Decrement, Acoustic Emissions, Ultrasonic, and more), the MMS proposed to assess the applicability of the various techniques in a laboratory test program. The "NDE Round Robin" program was formulated to focus, evaluate and document the NDE procedures and techniques of a number of advocates, as well as to compare these methodologies and others which appeared to be applicable to underwater inspection and monitoring. The "NDE Round Robin" program, which consisted of baseline and "blind" testing of subscale models, was sponsored jointly by the Office of Naval Research and the Minerals Management Service. The organization of the participants in the "NDE Round Robin" program is shown in Figure 1.1.

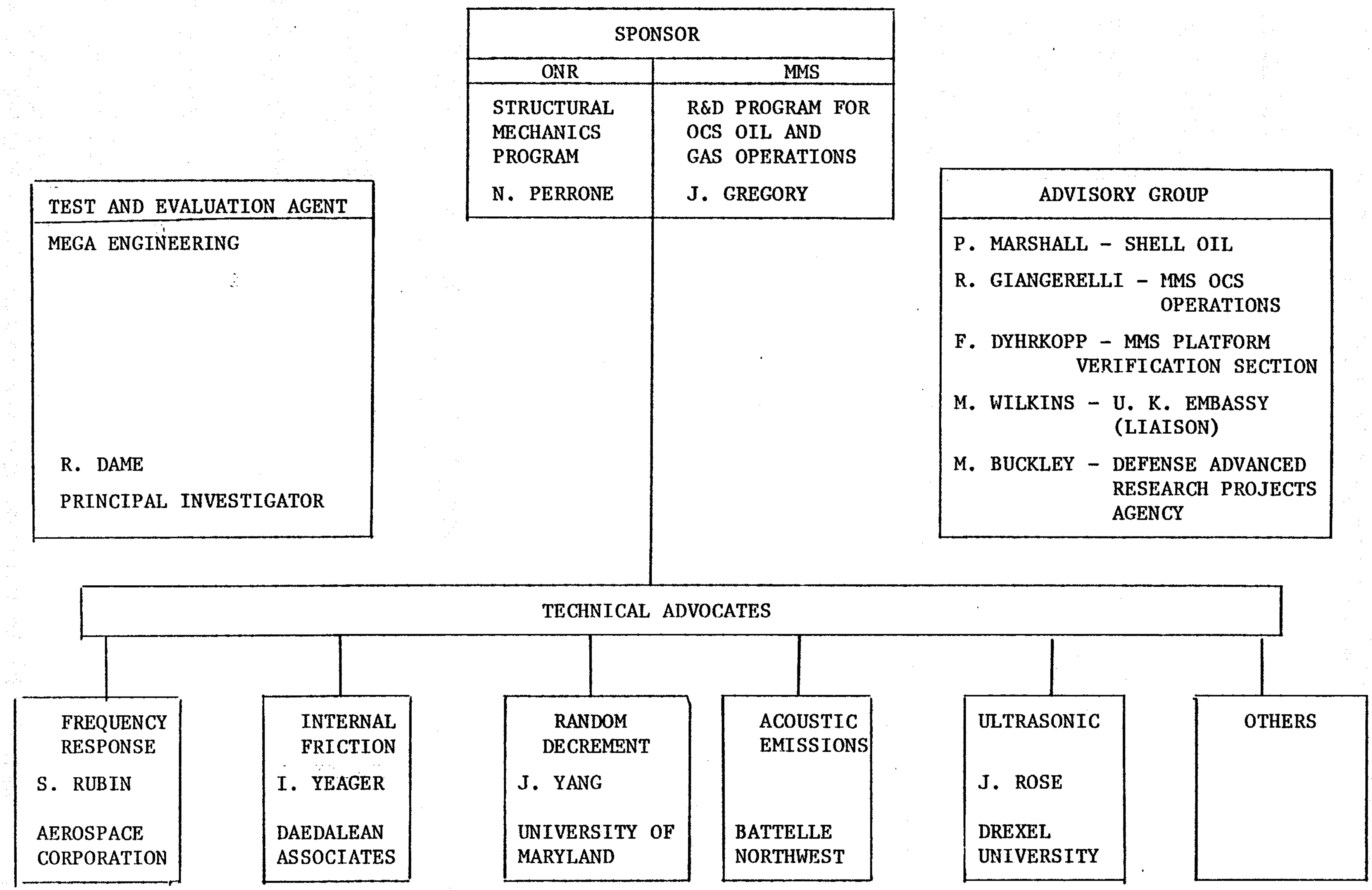


Figure 1.1 NDE Round Robin Organization

1. Fundamental Modes, Abovewater Equipment Placement

This approach involved data that could be obtained accurately from ambient excitation and with abovewater located accelerometers (Reference 1). This is basically the application of classical Global Mode Monitoring to this model. In field use, modes from the second and third modal groups, when identifiable, would also be employed for diagnosis of failures. Such modes, however, were not included for the model since they occurred at an unrealistically high frequency (compared to actual platforms) relative to the group of three fundamental modes (2 lateral and torsion).

2. Fundamental Modes, Abovewater and Underwater Equipment Placement

This is an extension to approach #1 involving accelerometers on the legs at various underwater levels in addition to abovewater locations (Reference 2). Underwater placement of accelerometers can readily be made in the field without use of divers if the platform is equipped with instrument chutes. Such a chute is typically a square tube, welded to the side of a leg, that enables entry of an instrument package from abovewater and clamping of that package at any depth (limited only by the length of the chute). This approach facilitates the application of the new concept, "Flexibility Monitoring" which exhibits improved sensitivity and localizing capability for failure detection. The ambient responses of the fundamental modes are utilized.

The "Flexibility Monitoring" concept utilizes the basic behavior of a fixed offshore structure as a shear beam to detect the shear flexibility across individual bays of the jacket, as well as gross flexibilities of the foundation. The term "flexibility" is used to imply deflection per unit force. The inertial forces acting on the top of the jacket can be inferred to be proportional to the measured relative deflections of the above-water structure between the deck and jacket top (boat deck). An estimate of gross shear flexibility of a bay is then proportional to the corresponding relative deflection across the bay, divided by the above water relative deflection. Similarly, by appropriate relative deflection measurements at the foundation, normalized by the same abovewater force measure, various foundation flexibilities are estimated. Each level of the platform is assumed to deflect as a rigid body (i.e., no warping of the level in plan view).

The attractive characteristics of the "Flexibility Monitoring" approach for field application are:

1. Total reliance is placed upon detection of the fundamental modes, thus completely avoiding higher mode identification difficulties.

2. There is relatively low sensitivity to deck mass changes, to marine growth, to flooding of structural members, and to conductor/guide contact uncertainty.

3. Sensitivity to damage and the ability to detect the location of damage is enhanced relative to the usual Global Mode Monitoring because flexibility changes are detected on a per structural bay basis and separately for the base/foundation portion. Thus, sensitivity is not reduced for tall structures having numerous bays, as is the case for Global Mode Monitoring. For example, the model structure in the Round Robin program was analyzed to determine indicated flexibility changes for a series of damage and nondamage possibilities. The results for a series of four distinct diagonal severance cases, in the affected first lateral mode, are shown in Figure 1.2. The failed diagonals are numbered 1 to 4 at the left of the figure and the corresponding flexibility parameters for each failure case are shown at the right. The percent frequency reduction in the mode for each failure case is shown by the percent frequency change values. Note that the flexibility increases for the damaged bays vary from about 80 to 180 percent,

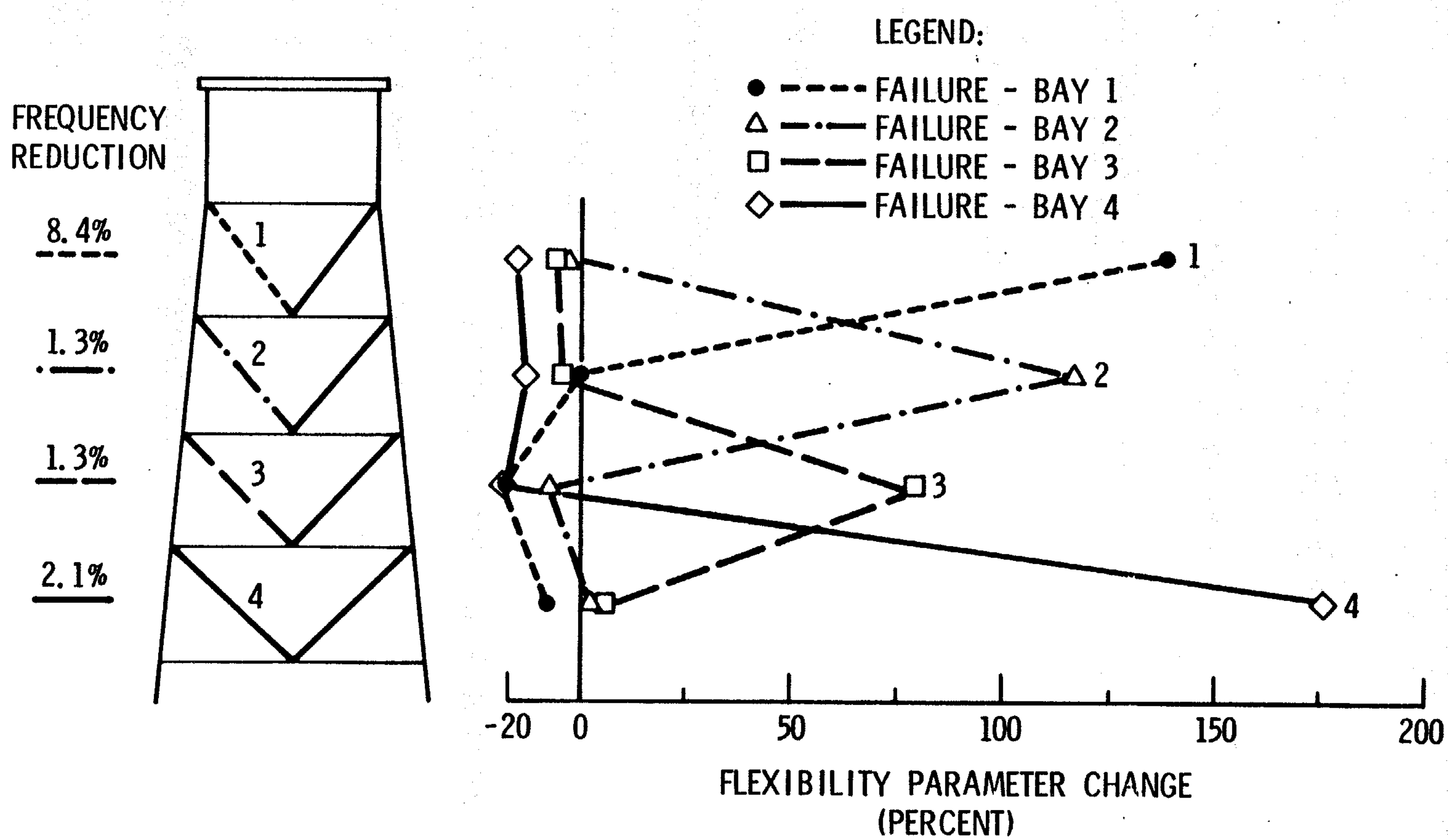


Figure 1.2 Indicated Flexibility Consequences in the Fundamental Lateral Mode for Diagonal Failure

while much smaller changes (from a 20 percent reduction to a 4 percent increase) are indicated for the nondamaged bays due to minor deviations from the idealized behavior assumed. The face on which the damage exists is indicated clearly by the much larger deflection across that face relative to the opposite undamaged face. Computed results for major deck mass and marine growth changes show negligible influence on the flexibility indications.

Two complications of the new concept are the need for accuracy in the underwater placement of sensors and the measurement of relative amplitudes. Underwater placement, a major operational and cost issue, is mitigated by the fact that accelerometer positions on main legs only, are required. Amplitude accuracy is believed to be the key measurement issue for Flexibility Monitoring. Of note was the fact that several newer large structures have had instrumentation chutes installed during construction for design evaluation purposes. These chutes lend themselves well to convenient trial and evaluation of Flexibility Monitoring.

Meetings were held with several owner/operator companies to present the concept and discuss its advantages, and as a result, key technical and management personnel of these organizations agreed to cooperative testing efforts on their structures.

Subsequently, a multi-phase effort was designed to assess the feasibility of Flexibility Monitoring for operational application. The initial phase involved additional testing on the NDE Round Robin model to refine the practical application of Flexibility Monitoring prior to field testing. For the second and third phases of this study, field tests on operating offshore platforms were proposed. The platforms tested were:

- Cognac (Shell Oil Company)--located in 1025 feet of water in the Gulf of Mexico. Dry instrumentation chutes were installed on four corner legs extending to a depth of about 260 feet staying within the top section of the jacket which is an 8-leg configuration.

- Garden Banks (Chevron U.S.A., Inc.)--located in 685 feet of water in the Gulf of Mexico. Dry instrumentation chutes were installed on three corner legs extending down to below the top of the skirt piles at 585 feet.

During field tests, accelerometers placed above the water line were employed to provide a measure of the net forces applied by the deck to the structural jacket in the three fundamental modes of vibration. Underwater accelerometers placed at the extremities (top and bottom) of each bay (at the corner legs) were used to measure shear deflections across the bays and at the top of the base/foundation. The availability of instrumentation chutes (minimum of 2 on diagonally opposite corners, 4 being preferable) for accelerometer packages on the above operating offshore structures permitted the placement of the necessary sensors without the use of divers.

The instrumentation and deployment systems utilized by the oil firms were developed for environmental data gathering and for mathematic model verification purposes; the development on Cognac was by the Shell Development Company and on Garden Banks by the Chevron Oil Field Research Company. Basic ingredients for practical Flexibility Monitoring studies were present: (1) instrument chutes on corner legs, (2) accelerometer packages deployable at any position down the chutes, (3) accelerometers properly placed on the deck, and (4) a data acquisition capability. All accelerometers were of the force-balance type (also known as servo-rebalance), which is the most suitable for the necessary precise measurements. Special test equipment furnished by The Aerospace Corporation for the real-time Flexibility Monitoring investigations included the same analog summing unit and FFT signal analyzer previously utilized in the follow-on testing of the Round Robin model.

1.1 Summary

This technical report presents the results of a series of evaluations of the Flexibility Monitoring technique.

Phase I of the evaluation entailed a series of instrument calibration and damage tests (Appendix C) using a simplified subscale model (1:13.8) of a 4-leg offshore platform tested at the NASA Goddard Space Flight Center. The first purpose of the scale model platform testing was to evaluate the specific implementation of the Flexibility Monitoring technique proposed for field testing of operating offshore platforms. The second purpose was to experimentally explore some basic sensitivity characteristics of the technique.

Phase II of the evaluation study entailed a field test (Appendix D) of an operating (production) offshore platform, Cognac, wherein the relative calibration of instrumentation packages (designed by the Shell Development Company of Houston, Texas), the acquisition and recording of vibration data and real-time data analysis were accomplished.

Phase III of the evaluation study entailed a field test (Appendix E) of an operating (drilling) offshore platform, Garden Banks, wherein the relative calibration of instrument packages (designed by The Chevron Oil Field Research Company of La Habra, California), the acquisition and recording of vibration data and real-time analysis were accomplished.

In addition, a numerical study of the technique was conducted on mathematical models of generic platform configurations to assess trends in sensitivity for various degrees of platform redundancy and foundation flexibility.

1.2 Objectives

The principal objective of this evaluation study was to assess the overall accuracy and the practicality of the measurement of flexibility parameters on representative offshore structures. This involved (1) the accuracy of relative calibration of the accelerometer channels, (2) the quality of ambient fundamental-mode vibration data as a function of elevation on the structures, (3) the effectiveness of a real-time technique developed by Aerospace for direct determination of flexibility parameters, (4) the ease of positioning accelerometer packages at the selected underwater elevations, and 5) as an adjunct to tests, the sensitivity of the approach on actual structures.

1.3 Scope

Phase I - Evaluation of Flexibility Monitoring Using Round Robin Model

This phase made use of the subscale model of a four-leg platform (Figure 1.3) utilized for the initial NDE Round Robin Program. All members previously cut in that program had been restored by welding. For the extended testing program (Phase I), the model platform was randomly excited at the deck by an electrodynamic shaker to enable response measurements and data analysis to yield flexibility parameters. The specific goals were (1) to evaluate the real-time determination of the flexibility parameters as a precursor to field testing and (2) to investigate experimentally the major sensitivity issues regarding the Flexibility Monitoring concept. The model changes made for the sensitivity studies included a severed diagonal, a large deck mass addition, and a greatly increased flexibility of the foundation.

As in the Round Robin program, the testing was conducted in a laboratory at the NASA Goddard Space Flight Center (Greenbelt, Maryland) with Mega Engineering handling the administrative arrangements. Aerospace operated the portable real-time equipment and prepared the test plan in consultation with Goddard.

Phase II - Field Test of Cognac Platform

The first field structure available for testing was the Shell Cognac platform. Instrumentation packages and their deployment down the installed instrumentation chutes had been checked out by Shell personnel with satisfactory results. Following that, a cooperative test agreement was established and the testing conducted during 13-17 April 1982.

The Cognac platform is installed in the Gulf of Mexico in over one thousand feet of water (Figure 1.4). The top section of this three-section platform is an eight leg jacket to which instrumentation chutes are installed on the four corner legs designated as shown. The chutes are square steel tubes

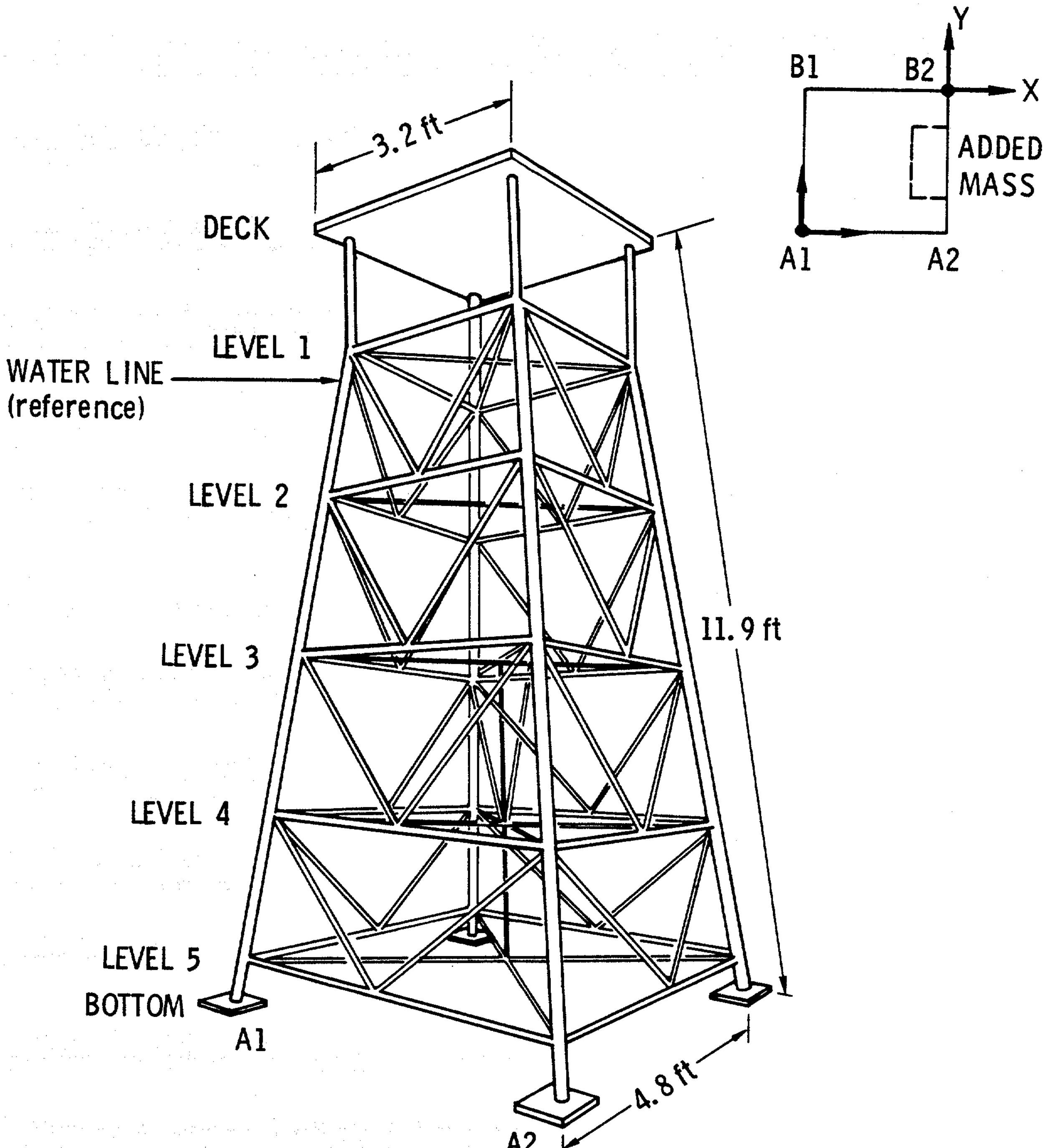


Figure 1.3 Scale Model Structure

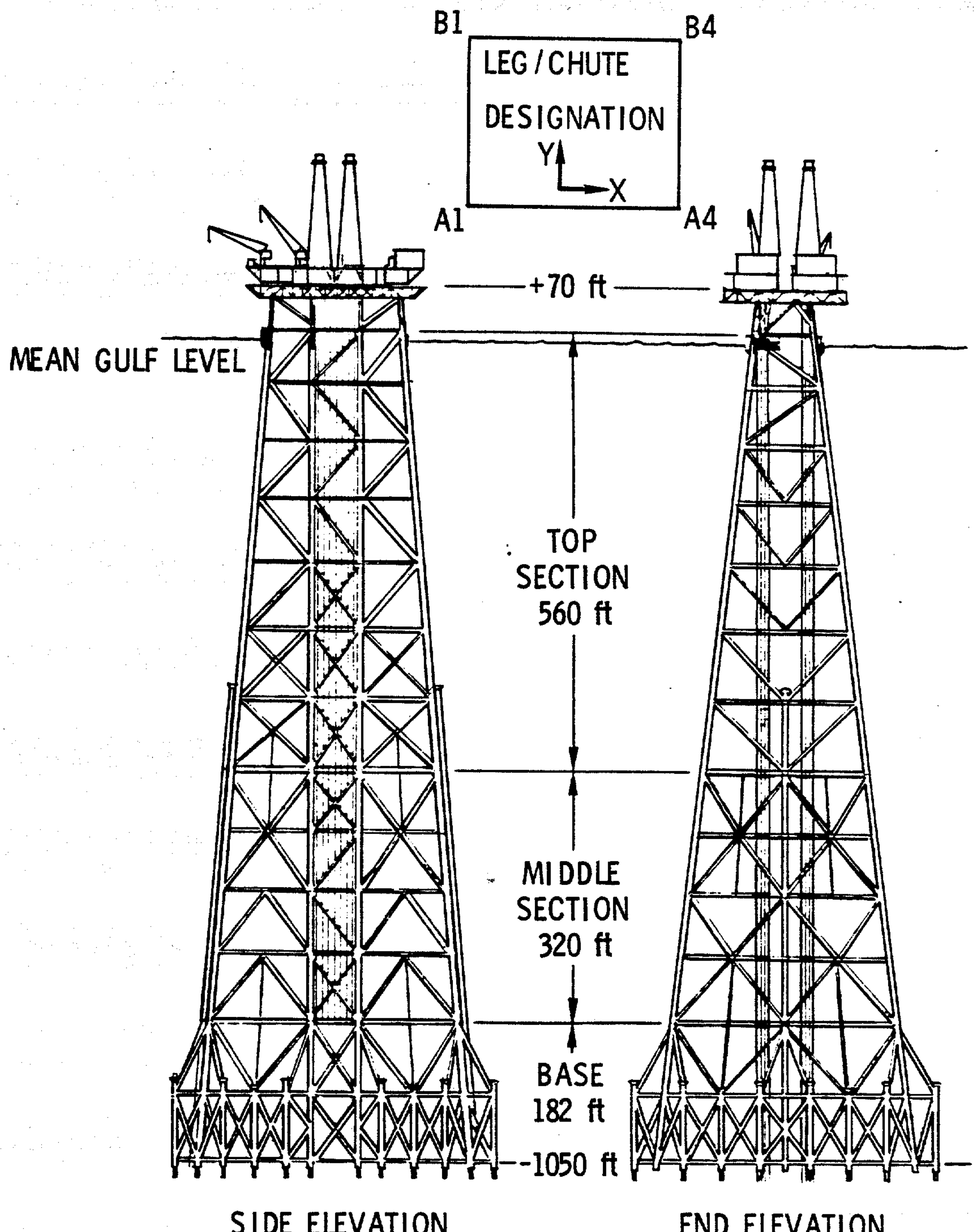


Figure 1.4 Cognac Structure

(dry interior) that parallel the non-vertical (battered) legs from just above the grating at the + 12-foot boat deck to approximately 260 feet below the sea surface. A portable instrumentation system, developed by Shell was comprised of four instrumentation packages and associated signal conditioning and recording equipment. A package can be located at any desired depth within a chute, with the restriction that only one package can be resident in each chute. Permanently installed biaxial accelerometers were oriented along the platform lateral axes on the A-1 and B-4 legs about midway between the upper decks. Triaxial accelerometers within the instrumentation package were oriented parallel to the local battered axes of the chute, with the near horizontal axes lying within the broadside and end-on faces. All accelerometers were the force-balance type.

As discussed subsequently, misalignments of two of the chutes, which were unknown during the measurements, made it impossible to utilize the Aerospace signal-processing apparatus to determine flexibility parameters in real time as planned. The results were, therefore, limited to post-test evaluation of the data as recorded on the analog tape recorder.

<u>Phase III</u> - Field Test of Garden Banks Platform

The second field test was performed on the Chevron U.S.A. Inc. Garden Banks platform in The Gulf of Mexico during 13-17 December 1982 (Figure 1.5). Dry instrumentation chutes, similar in character to those on Cognac, were attached to three of the four corner legs. The chutes extended from above the middle deck level at +65 feet to just below the top of the skirt piles at about -587 feet. Biaxial accelerometers within an instrumentation package deployed down a chute were oriented parallel to the platform lateral axes. With the capability to deploy two packages within a single chute it was decided to utilize only the two diagonally opposite corner chutes for real-time Flexibility Monitoring. Also involved were the permanently installed biaxial accelerometers above the +65 foot deck.

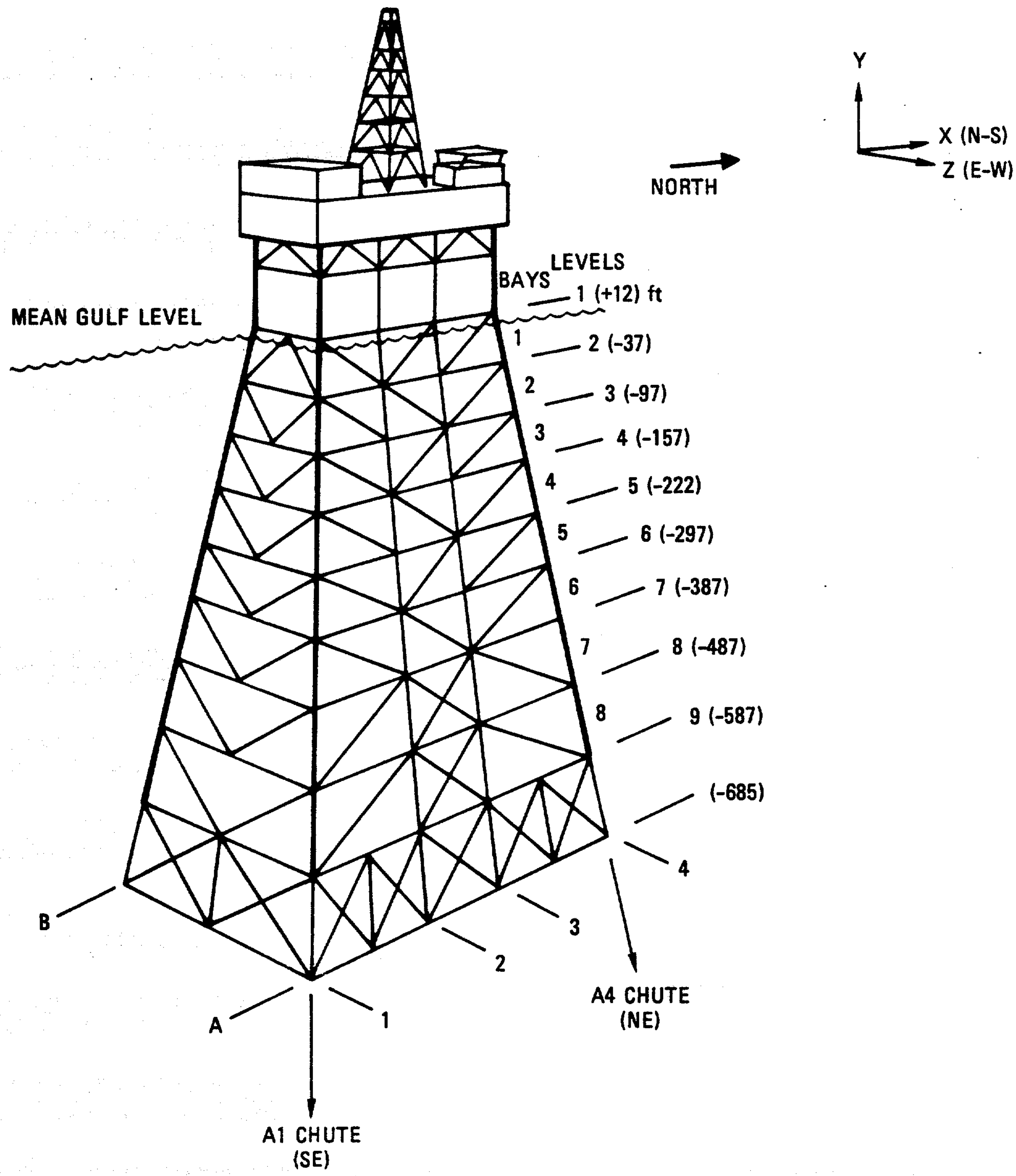


Figure 1.5 Garden Banks Structure

Flexibility parameters were measured during the test period using the Aerospace real-time apparatus.

Sensitivity Studies on Generic Configurations

As an adjunct to the tests, computer models of simplified configurations of structures with 4, 8 and 12 legs were analyzed for the sensitivity of flexibility parameters to failures of individual diagonal members. The models included an offset deck center of gravity and distributed jacket mass for both rigid and flexible foundations. The goal was to establish ranges and trends of the flexibility parameters. This information was useful for assessing the potential of Flexibility Monitoring and, in particular, for establishing accuracy requirements for data acquisition and processing.

1.4 Ground Rules and Assumptions for Field Test Evaluations

It was necessary to assume certain facts or conditions as a prerequisite to the development of the field experiments. The following is a list of these ground rules and assumptions:

- The evaluation of both Flexibility Monitoring and Global Mode Monitoring for structural assessment was based on ambient excitation with accelerometer groupings located at positions above water and in instrumentation chutes attached to the main legs.

- Aerospace and industry representatives cooperated and coordinated their test requirements. A test plan was developed for the structure wherein all accelerometers, cabling, signal conditioning, positioning requirements, recording and test procedures were specified. Special data processing and/or instrumentation requirements which were beyond the scope of the intended industry testing, were the responsibility of Aerospace.

- Testing was performed on two existing fixed offshore platforms which are owned and operated by Shell and Chevron U.S.A. Inc. Actual test execution was provided by industry as were most of the field personnel, instrumentation, and ancillary equipment. Aerospace supplied the personnel and equipment necessary to satisfy requirements unique to their testing procedures and participated directly in all tests. The interpretation of the test results in terms of flexibility and mode identification was Aerospace's responsibility. Aerospace provided real time data quality monitoring and analysis. Suitable recordings of data were supplied by industry to Aerospace for post-test studies.

1.5 Approach

The major steps employed in the execution of the above tasks were as follows:

Phase I. Evaluation of Flexibility Monitoring Using Round Robin Test Model

- Modified the Round Robin test setup: (1) introduced foundation flexibility, (2) positioned accelerometers in an optimum fashion and (3) specified software for calculation of flexibility parameters.

- Performed comparative calibration testing of the accelerometers to attain a more precise determination of flexibility parameters.

- Measured the flexibility parameters of the test model stimulated by forced random excitation for baseline and damage/change configurations of the model.

- Independently evaluated the accuracy of portable test equipment for real-time flexibility parameter determination in the field by direct comparison of results with those obtained by the test laboratory

- Established guideline criteria for offshore tests in Phase II and III.

Phase II & III. Field Tests of Offshore Structures

- Coordinated test plans with industry technical representatives to evaluate Flexibility Monitoring approach within the existing physical and operational constraints.

- Performed real time evaluation of data using special data processing equipment.

- Assisted in the execution of the testing.

- Performed post test evaluation of data using tape recordings provided by industry.

Sensitivity Studies

- Formulated mathematical models of simplified configurations of 4, 8, and 12 leg platforms.

- Prepared software for determination of the fundamental normal modes and their conversion to flexibility parameters. Included was the ability to remove the stiffening influence of any of the diagonal members.

- Analyzed the 4, 8, and 12 leg mathematical model platform configurations for both rigid and flexible foundations, for selected failed members within a bay, and for failures in various bays of the platform.

2. PHASE I EVALUATION PROGRAM

A plan for the extended testing on the Round Robin scale model platform was finalized during the month of April 1981 (Appendix C). The design, assembly and checkout of the specialized instrumentation equipment (analog summing unit) and the acquisition of a dual-channel spectrum analyzer, both of which were used for real time data evaluations, were accomplished during the months of May and June 1981. The extended testing started on 27 July 1981 to be completed some four weeks later. After two weeks of testing, however, the program was interrupted by NASA priority activities. The testing was resumed in February 1982 and completed in March 1982. Data were fowarded to The Aerospace Corporation on 27 April 1982.

2.1 Model Structure and Test Configuration

The four-leg platform model was the same one utilized for the earlier Round Robin program (Ref. 2, 11). No piles or soil interactions were modeled. The model stood 11.9' high and was 4.8' square at the base and 3.2' square at the top (Figure 1.3). The legs were 2-inch (O.D.) steel pipe with a 0.109-inch wall and all the brace members were 3/4-inch (O.D.) steel pipe with a 0.065-inch wall. The model was all welded, except for a 1.5-inch thick stiffening aluminum honeycomb plate adhesively bonded onto the 0.112-inch thick steel deck plate. Stiffening of the deck was done at Aerospace request to prevent an unrealistically low fundamental plate mode of the model deck.

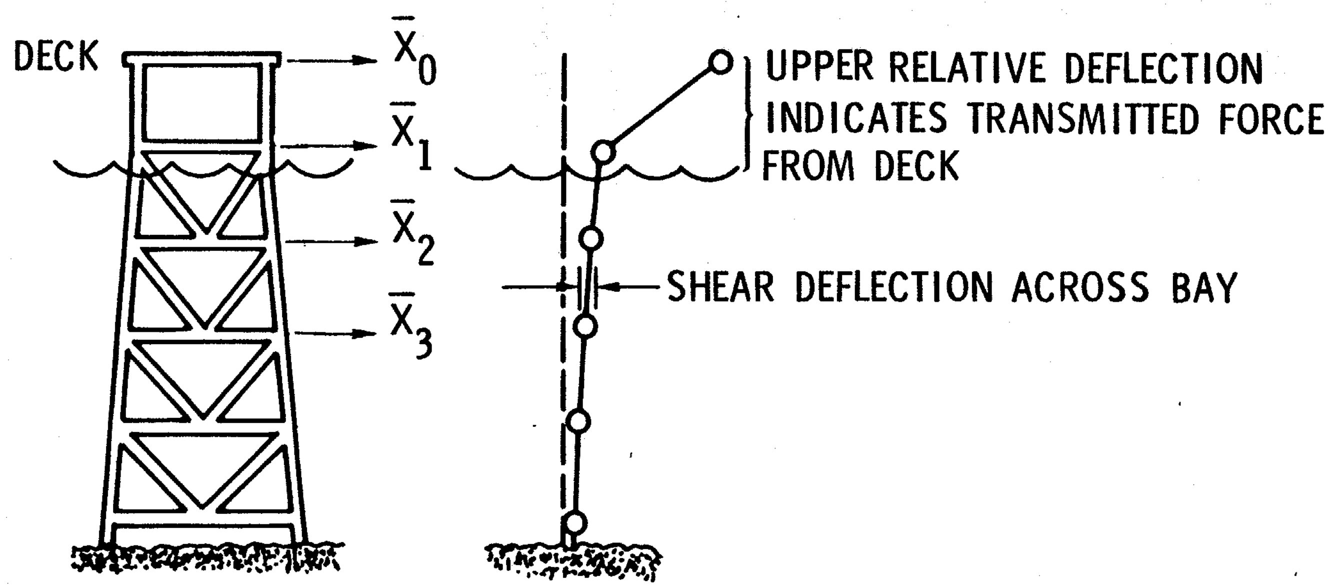
The model was set up in the following sequence of configurations for determination of flexibility parameters as defined in Figure 2.1.

- Baseline structure with soft foundation (rubber pads at leg bottoms as described in Appendix C).
- Large mass addition at the center of one edge of the deck with the soft foundation.
- Cut through single diagonal between levels 3 and 4 with soft foundation.
- Same cut diagonal with hard foundation (rubber pads removed and leg bottoms bolted directly to large seismic block).
- Cut diagonal welded to return to baseline configuration with hard foundation (same as baseline for Round Robin Program).

Excitation of the model at the deck was provided by a horizontally acting electrodynamic shaker oriented at 45^{o} to the lateral axes. The excitation was broadband random to simultaneously excite the three fundamental modes.

LEGEND:

$\bar{X}_i$ - AVERAGE DEFLECTION OF i^{TH} LEVEL



FLEXIBILITY = DEFLECTION/FORCE

$$\text{FLEXIBILITY PARAMETER} = \frac{\text{BAY DEFLECTION}}{\text{UPPER RELATIVE DEFLECTION}}$$

Figure 2.1 Conceptual Basis for Flexibility Monitoring

2.2 Instrumentation

Piezoelectric accelerometers were placed along diagonally opposite legs (A1 and B2, Fig 1.3) of the model platform for determination of flexibility parameters of each bay. Aluminum cubes, 3/4-inch on a side, were bonded at each level to permit accelerometer attachment for both the x and y directions of motion. Eight accelerometers were employed for the analysis of one bay and one direction (x or y). The upper four accelerometers were at the deck and level 1 to measure average relative deflection of the upper section of the platform. The lower four accelerometers were at the upper and lower levels, (at diagonal corners) of the selected bay to measure its relative deflection. A piezoelectric force transducer was utilized to measure the random force applied by the shaker to the deck plate of the model platform. A GenRad data acquisition system was employed to gather the resultant data.

Aerospace supplied the real-time data analysis system consisting of an analog summing unit and a two channel Fast Fourier Transform Analyzer (Model SD 375 Dynamic Analyzer II).

2.3 Calibration

Relative system calibrations of seven accelerometers with respect to the eighth were performed by subjecting the accelerometers to identical sinusoidal motion on an electromagnetic shaker. The relative calibration factors (amplitude and phase) were entered into the software program to permit equalization of the accelerometer channels prior to numerical summing and differencing of the signals necessary for the real time determination of flexibility parameters.

Special instrument calibration tests were conducted with the intent to define the axis of minimum cross-axis sensitivity for each accelerometer. The idea was to then orient each accelerometer on the test model so that cross-axis outputs would be minimized. This approach was found not to be feasible because the cross-axis sensitivities, determined as a function of angular orientation, did not reveal a clear direction of minimum sensitivity for these particular accelerometers.

2.4 Data Processing

The laboratory data processing utilized a six-channel GenRad system to generate frequency responses by Fast Fourier Transform (FFT) processing. The acceleration and force signals were sampled by a 12-bit A/D converter at a 102.4 sample/second rate. An FFT transform was applied to 1K blocks of data using a Hanning window. Results from fifty blocks were averaged to produce frequency response data at 0.1 Hz intervals of frequency. Selected acceleration/force frequency responses were determined to identify the three fundamental resonant frequencies. Acceleration/acceleration frequency responses were computed to determine the flexibility parameters. See Appendix C for details.

The portable data acquisition system developed by Aerospace in anticipation of field testing was utilized to process in real time, the accelerometer signals in parallel with the laboratory data processing system. This was done for the initial testing to enable validation of accuracy. Figure 2.2 shows the essentials of the setup schematically. Shown are four acceleration signals, each selected for sign and adjusted in gain so that all channels have identical sensitivity, then summed to provide an input signal to a two-channel FFT analyzer. The analyzer (a model SD 375 Dynamic Analyzer II by the Scientific Atlanta, Spectral Dynamics Division) was utilized to digitally process the A and B input random signals to produce a complex B/A frequency response and associated coherence function by FFT averaging with a Hanning window. An analog summing unit, built at Aerospace, contained four groups of four-channel summing networks and associated gain adjustment amplifiers and sign selector switches. Two such groups were utilized to provide the numerator and denominator signals for determination of a lateral flexibility parameter, and the other two groups to do likewise for a torsional flexibility parameter.

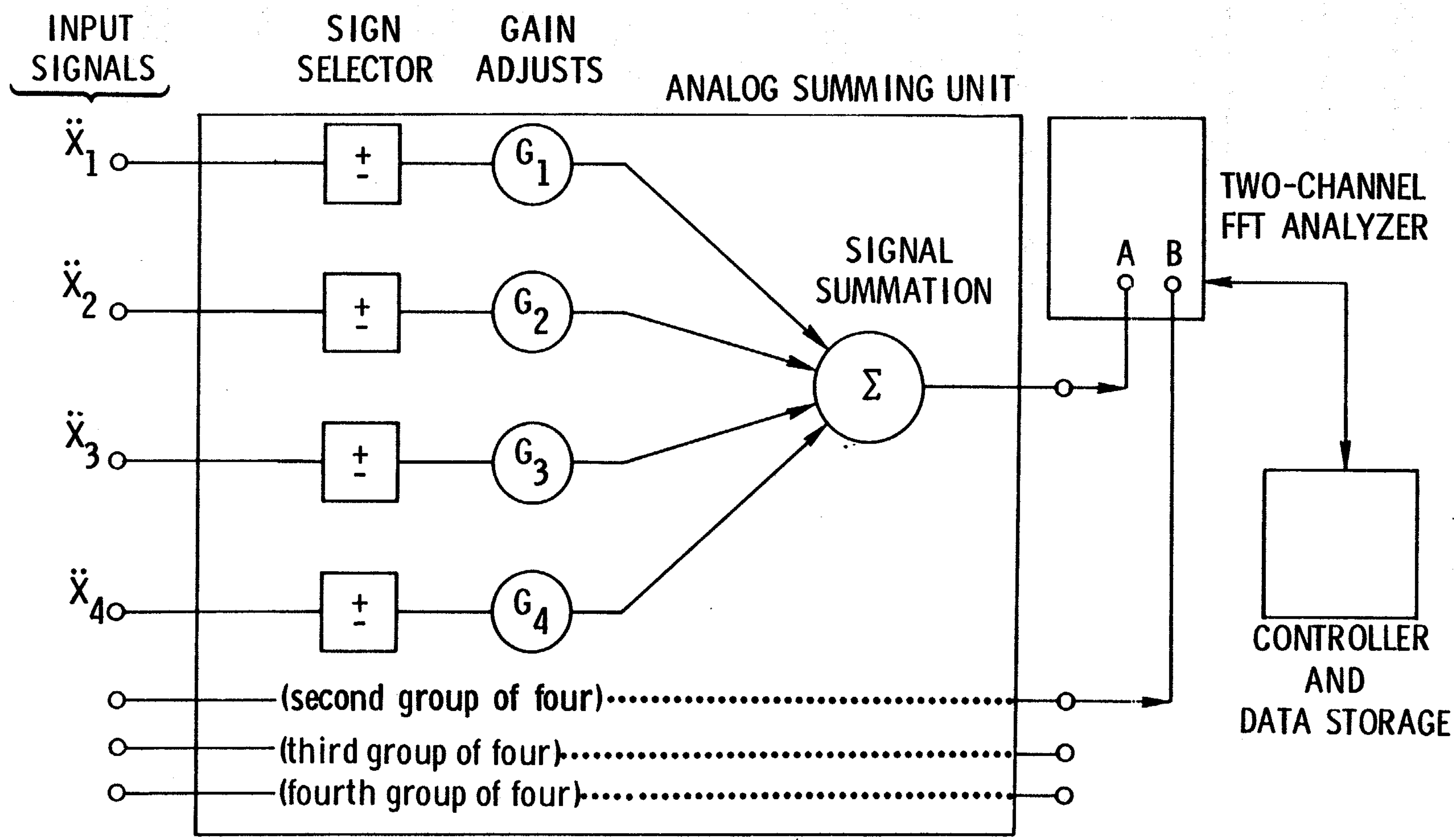


Figure 2.2 Schematic of Aerospace Portable Data Acquisition System

2.5 Experimental Results

The natural frequencies for the five model configurations identified in Section 2.1 are shown in Table 2.1. The softness added to the foundation and the mass added to the deck were qualitative changes designed to provide major frequency shifts. The lower portion of the table contains a series of significant comparisons. Figure 2.3 displays the average level deflections normalized to the corresponding average deck deflection for X-sway and torsion. (Y-sway results are similar to X-sway and are omitted to avoid clutter.) In all cases, the diagonal severance below level 3 essentially shifted the shapes to the right at level 3 and above. Also, the soft foundation produced a relatively large translation and rotation of the shape. Finally, the added deck mass, even though it provided the biggest shifts in natural frequencies (see Table 2.1), produced only a relatively small shift of mode shape to the left. Figure 2.4 displays results for the non dimensional flexibility parameters (as defined in Figure 2.1), which emphasize slopes of deflection shapes. Note that the flexibility parameters for each bay are plotted at the mid level for that bay. Omitted for clarity were results for Y-sway and added mass which, except for scatter, overlay the baseline X-sway curves.

For another comparison, Figure 2.5 presents the difference in flexibility parameters for the three configuration comparisons identified in Table 2.1. The horizontal bars for sway show the spread between the soft and hard foundation or between the X and Y directions, as labeled. The key observations from Figure 2.5 are as follows:

1. Diagonal severance produced a strong shift for the bay involved only in the affected sway direction and in torsion (see short dotted lines in Figure 2.5). Relatively little shift occurred for the other bays. Moreover, the magnitude of the shift due to severance was practically independent of the degree of softness of the foundation (barring foundation change at the same time). This was not observable for torsion, only because the data were unavailable for the hard foundation case with severance.

2. Major increases in foundation softness (8 to 9% reduction in sway frequencies) produced a strong shift for all bays in both sway directions (see solid line in Figure 2.5), which is clearly distinguishable from the shift pattern due to severance. The shift for torsion in this case was generally small; this is believed to be due to the relatively slight foundation change for torsion (as evidenced by the relatively small change in frequency, see Table 2.1).

3. An increase in deck mass (14 to 15% reduction in sway frequencies and 9% in torsion frequency) yielded much smaller shifts in the sway modes than did the foundation alteration, even though the frequency shifts were considerably larger for the mass increase (see long dotted lines in Figure 2.5).

Table 2.1. Configurations and Natural Frequencies For Model Platform

Configuration	Natural Frequency (Hz)		
	X-Sway	Y-Sway	Torsion
A. Hard foundation	19.8	19.1	31.6
B. Hard foundation + severed diagonal	19.7	19.1	31.4
C. Soft foundation	18.1	17.5	31.2
D. Soft foundation + severed diagonal	17.9	17.5	30.9
E. Soft foundation + added deck mass	15.6	14.8	28.4

Comparisons	Percentage Changes		
From baseline to severed diagonal			
Hard foundation (A B)	- 1	0	-1
Soft foundation (C D)	- 1	0	-1
From hard to soft foundation (A C)	- 9	- 8	-1
From original to added deck mass (with soft foundation; C E)	-14	-15	-9

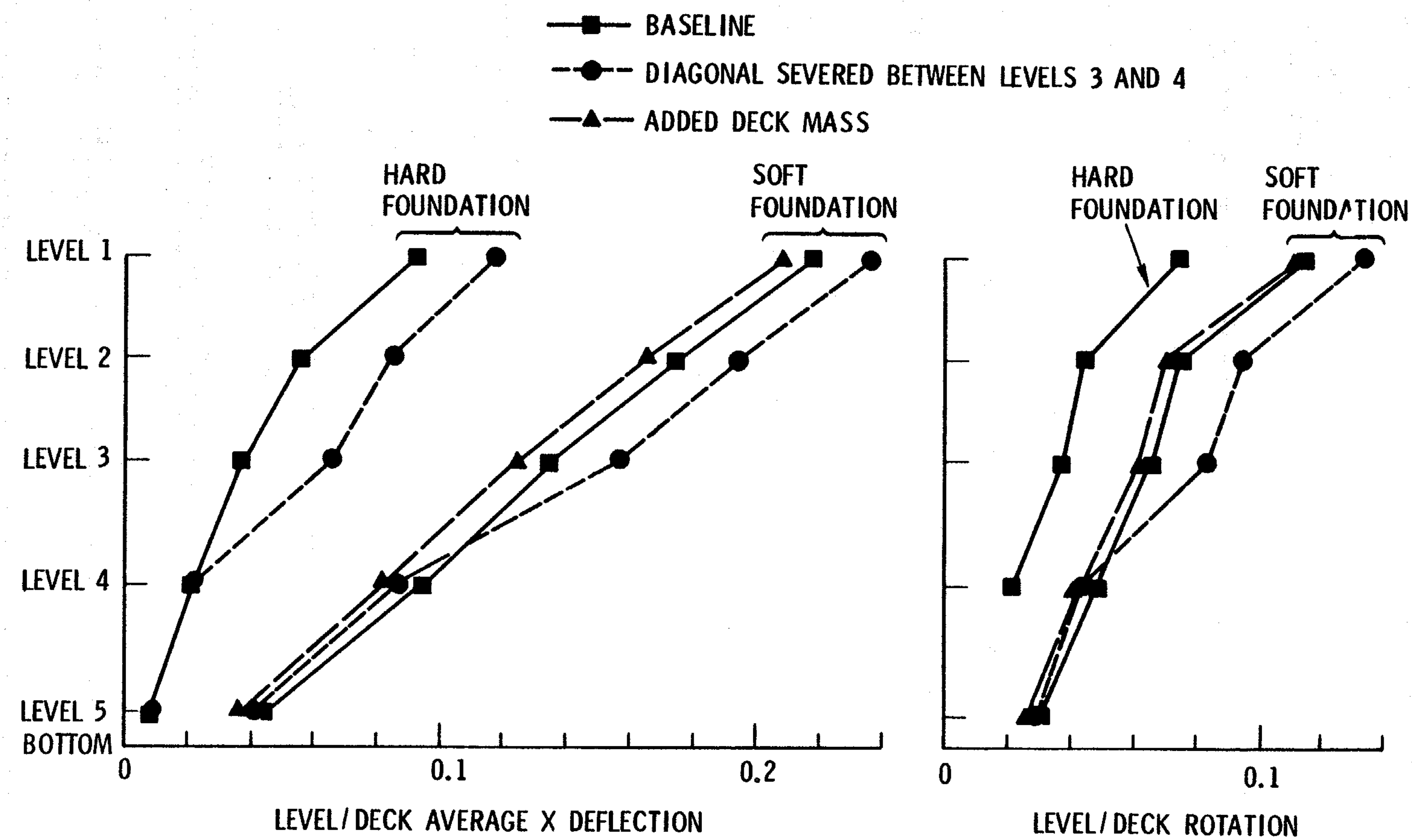


Figure 2.3 Normalized Mode Shapes for X-Sway and Torsion Modes of Model Platform

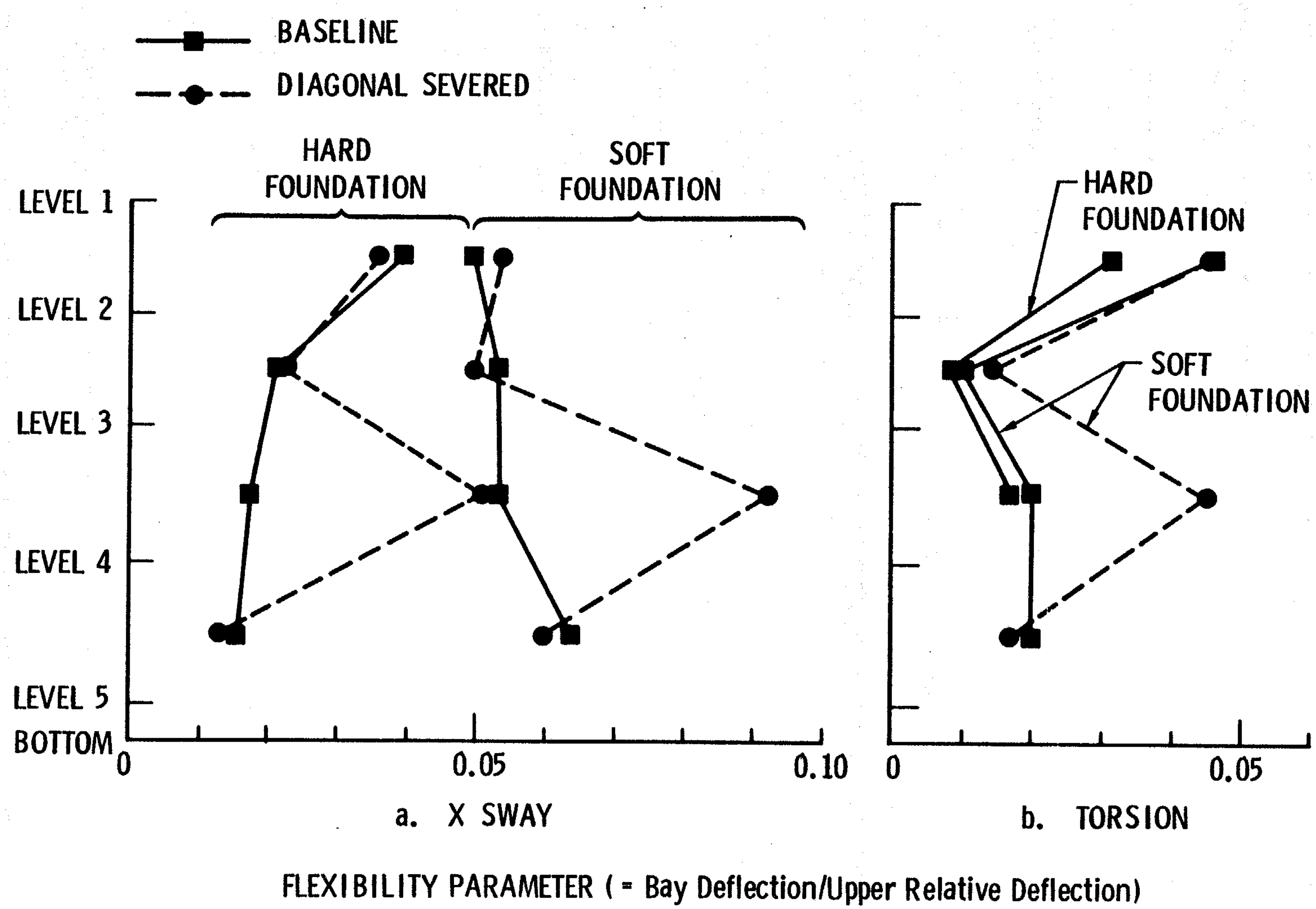


Figure 2.4 Flexibility Parameters for Model Platform

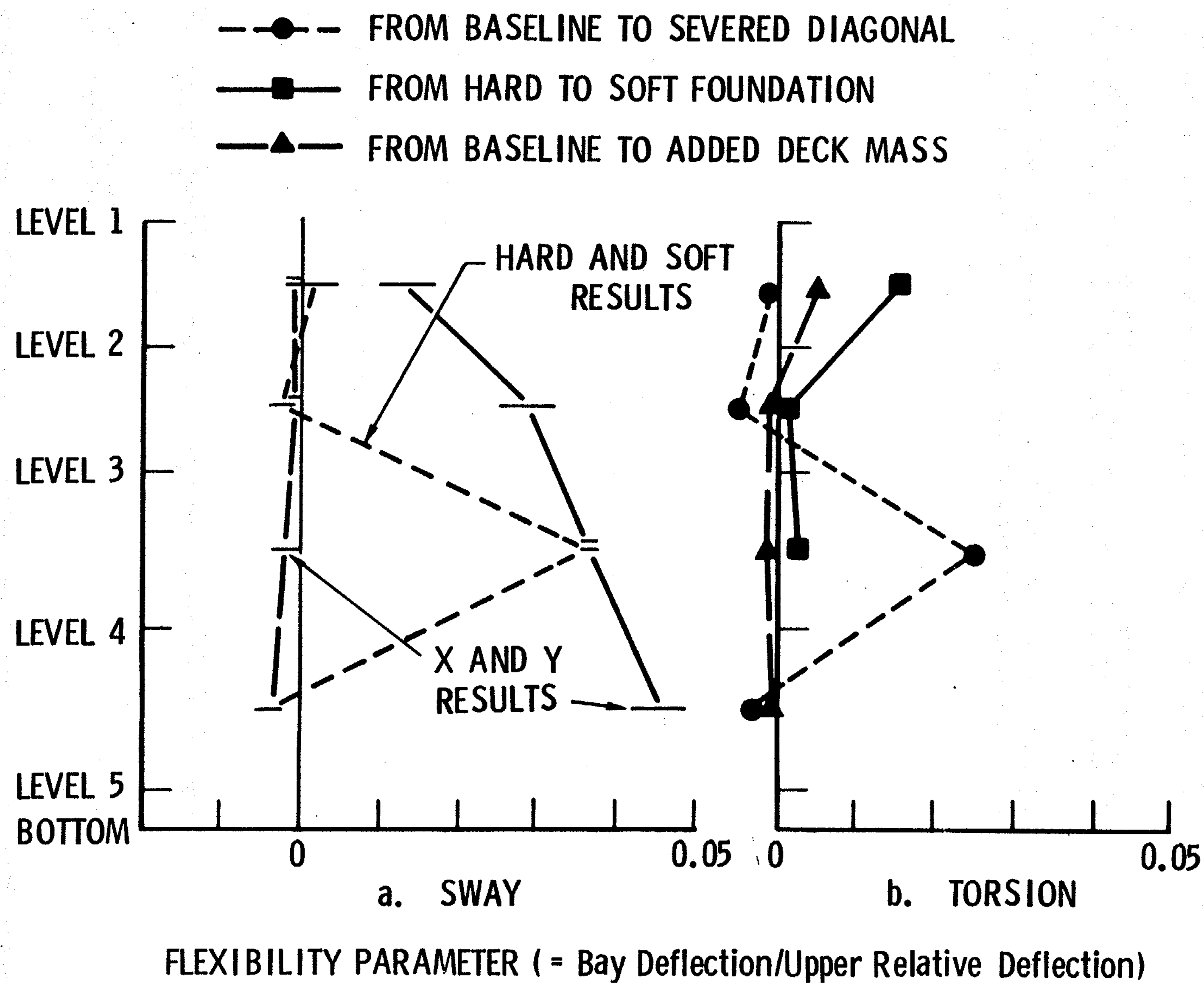


Figure 2.5 Differences in Flexibility Parameter for Model Platform

2.6 Analytical Simulation of Observed Sensitivity Trends

The very simplified mathematical model shown in Figure 2.6 simulated the basic sensitivity behavior observed in the model testing. In this planar model, the foundation flexibility is idealized as separate shear flexibility A_f and rotational flexibility A_θ. The effective mass M is assumed to be concentrated at the top, a distance H from the foundation, and the i^{th} bay has shear flexibility A_i. The result, for m bays, is a single degree of freedom dynamic model having the overall stiffness

$$K = (A_0 + A_1 + A_2 + \ldots + A_m + A_f + H^2 A_\theta)^{-1} \qquad (1)$$

The natural frequency is

$$\omega_n = (K/M)^{1/2} \qquad (2)$$

and the associated mode shape normalized to unity at the top, is

$$\phi_i = X_i / X_0 = (A_i + \ldots + A_m + A_f + h_i H A_\theta) K \qquad (3)$$

where h_i is the height of level i above the foundation. Note that the mode shape is independent of mass.

The flexibility parameter for the i^{th} bay is given by

$$C_i = \frac{X_i - X_{i+1}}{X_0 - X_1} = \frac{A_i + \alpha_i H^2 A_\theta}{A_0 + \alpha_0 H^2 A_\theta} \qquad (4)$$

where α_i and α_0 are the fractions of the total height H occupied by bays i and 0, respectively.

For the model tested, it was found that the following parameters yielded a rough match of the observed X-sway mode shape: $m = 4$, all $\alpha_i = 1/5$, $A_2 = A_3 = A_4 = A$, $A_1 = 2A$, $A_0 = 45A$; for the hard foundation, $A_f = A_\theta = 0$ and for the soft one, $A_f = 3A$ and $H^2 A_\theta = 6A$. When a diagonal is severed in the physical model, it is assumed that the entire shear stiffness of the involved bay face is lost and that the average bay shear flexibility becomes double the intact flexibility. Therefore, the severance of a diagonal in a face of bay 3 is represented by an increased flexibility in the mathematical model of $A_3 = 2A$. The mode shapes for the hard and soft foundation, with and without diagonal severance, are shown in Figure 2.7. These shapes are similar to the corresponding measured average X-sway shapes seen in Figure 2.3. Moreover, the natural frequency shifts match those for X-sway in Table 2.1: a 1% reduction for the severed diagonal for both the hard and soft foundation and an 8% reduction from the hard to soft foundation. The flexibility parameters are illustrated in Figure 2.8 for comparison to the measured ones shown in Figure 2.4. It is quite clear that the primitive mathematical model in Figure 2.6 roughly simulated the experimentally observed sensitivity trends.

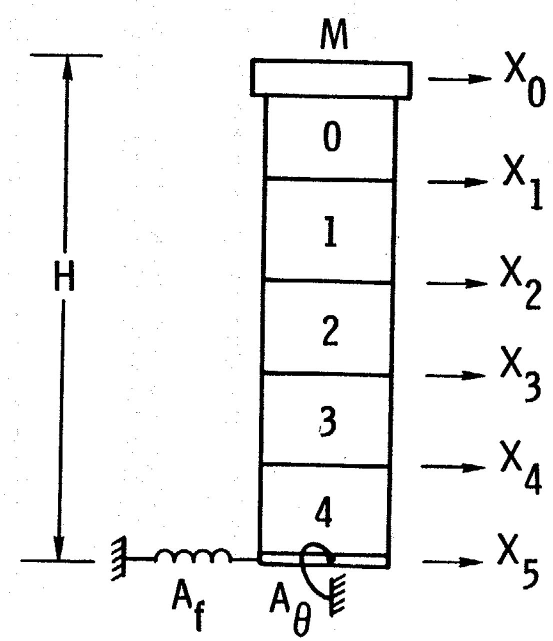


Figure 2.6 Simplified Mathematical Model

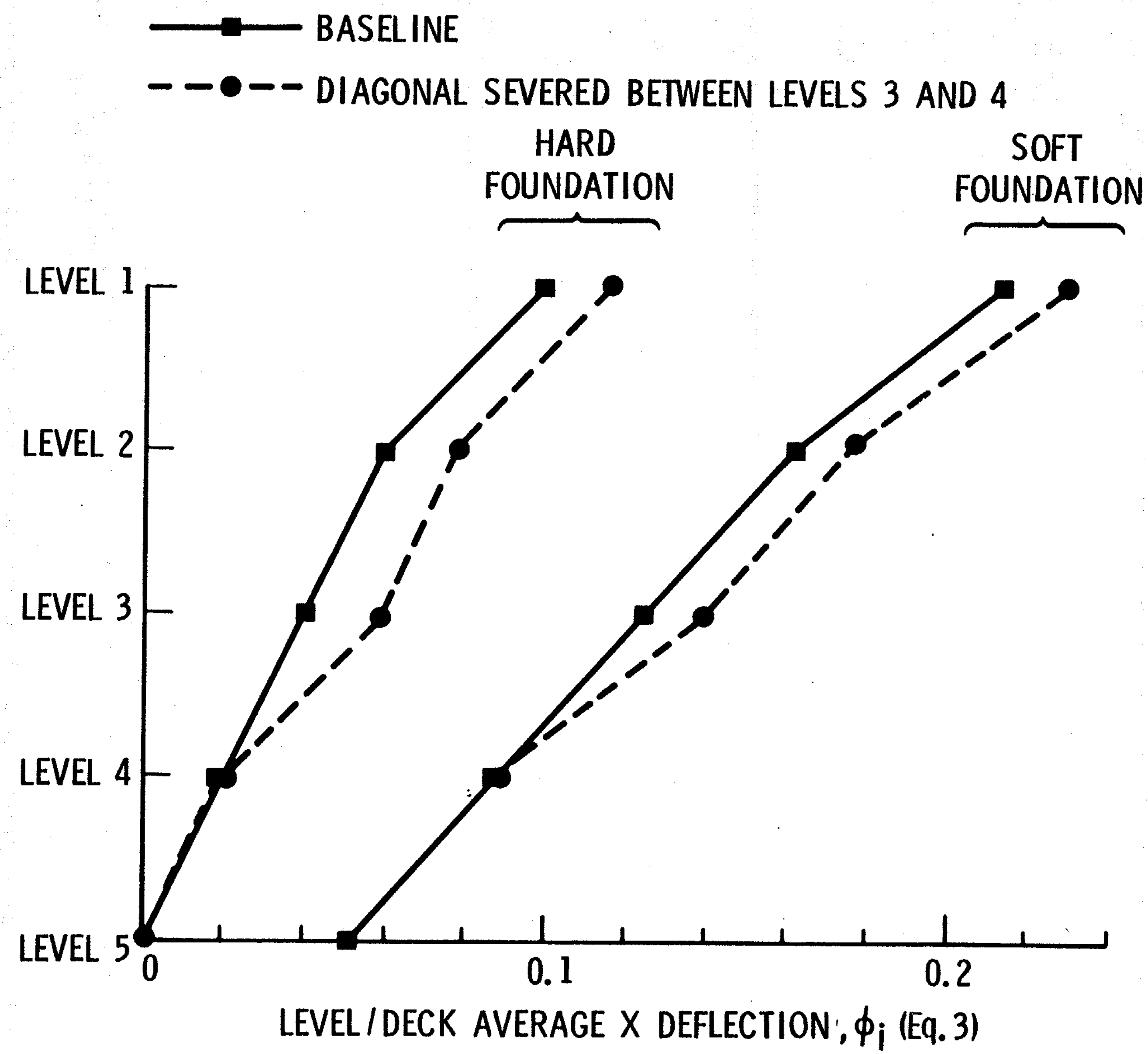


Figure 2.7 Analytical Mode Shapes

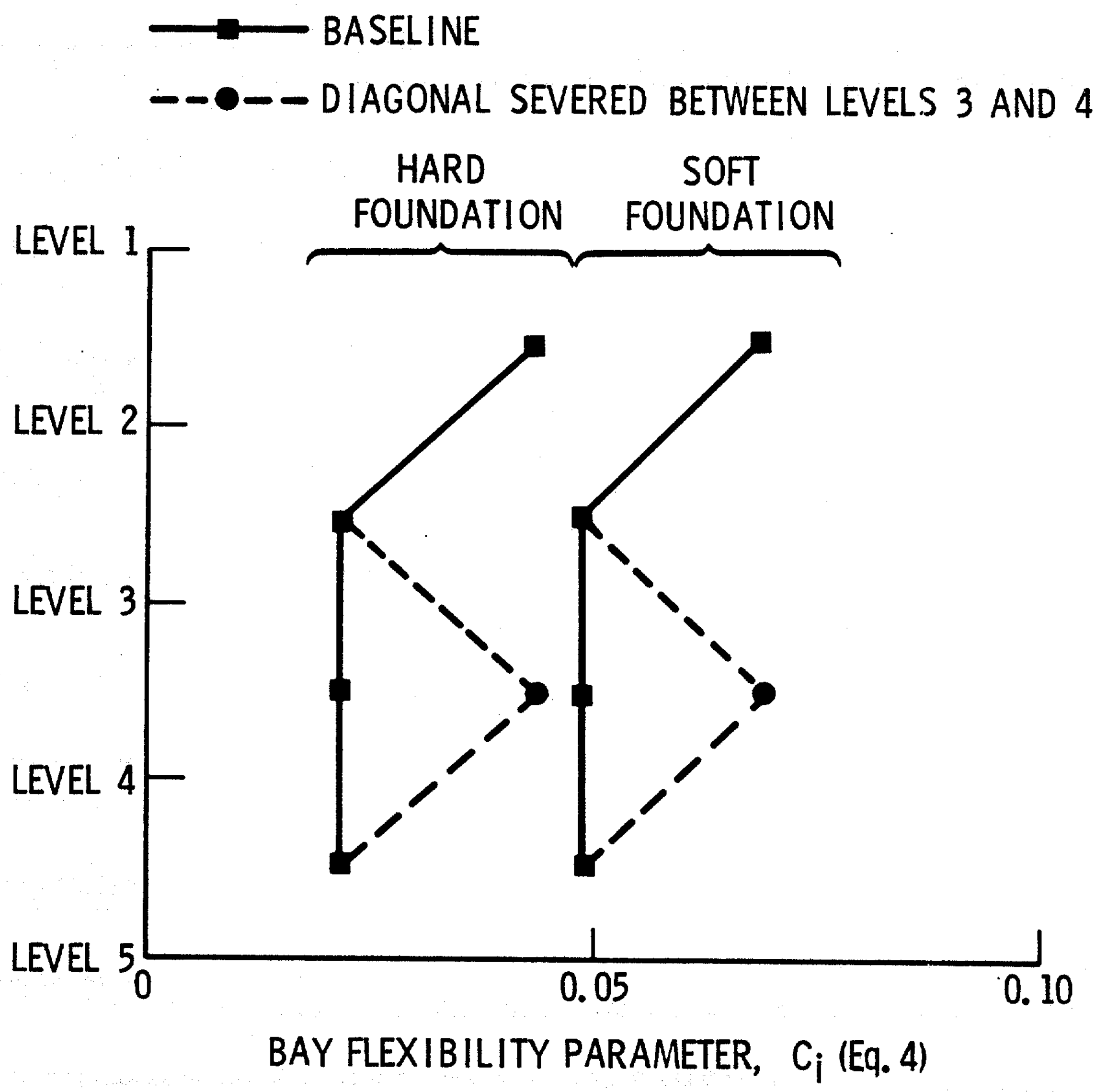


Figure 2.S Analytical Flexibility Parameters

2.7 Findings

The purpose of the extended scale model platform testing was to evaluate the implementation of the Flexibility Monitoring Technique proposed for field testing on operating offshore platforms. This evaluation included performing comparative calibration testing of the accelerometers to attain a more precise determination of flexibility parameters, evaluating the accuracy of portable test equipment for real time flexibility parameter determination in the field, exploring several basic sensitivity characteristics of the Flexibility Monitoring Technique and establishing guideline criteria for offshore tests. All of the objectives were satisfactorily achieved.

3. PHASE II EVALUATION PROGRAM

The Flexibility Monitoring evaluation tests were conducted on the Cognac platform from April 12-18, 1982. Real time and playback monitoring and analyses were conducted during the testing period. All data were recorded on magnetic tape for additional analysis. These tapes were reformatted by Shell Development Company and forwarded to Aerospace in late May 1982 where the data were assessed for quality and validity for the Flexibility Monitoring concept. A misalignment of the two instrumentation chutes (B1 and B4, Figure 1.4) was determined during the test. Accurate measurement of the instrumentation chute misalignment was later accomplished by Shell Development and data were sent to Aerospace in September 1982.

3.1 Cognac Structure

The Cognac platform shown in Figure 1.4 is an eight-leg structure which was constructed in three sections. The base section, 182 feet high, provides guide sleeves for 24 skirt piles which were driven 450 feet into the Gulf floor anchoring the platform. The two long sides of the platform were designated the "A" and "B" rows. The four rows of leg members viewed in the orthogonal direction were given numbers from one to four so that each leg was identifiable by a letter and number combination, i.e., A1, B1, A2, etc. The middle section, 320 feet high and the top section, 560 feet high bring the total jacket structure to a nominal elevation of 12 feet above mean Gulf water level (MGL). Upper deck supports extend the platform structure to 70 feet above MGL with a lower deck installed at 55 feet. Eight 72-inch diameter connector pins were inserted into the legs reaching from the mudline through the mid-section and into the top section about 170 feet. With the pins grouted in place, the overall structure became an integral unit in which the 56 well conductors were installed.

The tests were performed during producing operations with a small, well workover rig being assembled on deck.

3.2 Instrumentation and Chutes

The instrumentation system was developed by Shell Development Company for environmental data gathering and for mathematical model verification purposes. Instrumentation included five portable chute packages and cabling, a data acquisition module and resident biaxial accelerometers permanently attached to legs A1 and B4 just above the 55-foot deck level.

The chute packages were four inches square and eighteen inches long. Each one contained three Sundstrand Q-flex 1200A accelerometers, a buffer line driver, a power supply regulator and two 1" air cylinders with extending shafts to clamp the package in position within the chute. Attached to the top of the package were a lowering line, flexible pneumatic tubing and electrical cabling to carry signals back to the data acquisition module on the 55' deck. The lowering line was marked for length to assist in positioning the package at the required levels. One package was used in each of the four corner chutes leaving one unit as a spare.

The data acquisition module had the capability of accepting sixteen signal channels. Each channel was conditioned through a differential buffer receiver amplifier, a low-pass filter, a high-pass filter, a differential buffer driver, and then routed to a tape recorder. The recorder was a Racal/Lockheed Store 14 model, with a 14-track capability, each track having FM record and reproduce electronics, thereby allowing playback capability. Maximum FM bandwidth was 20KHz at 60 in./second. Tape reels were one-half by eight and three-quarter inches and recording speeds ranged from fifteen-sixteenths to sixty in./second. Attenuation was selectable. The low-pass filters were employed to limit the information content of the signals to 2 Hz.

Complementing the data acquisition system was equipment supplied by the Aerospace Corporation to monitor signal quality and perform real time and playback analysis: an analog summing unit (see Fig. 2.2), a dual-channel spectrum analyzer (SD 375) and a video plotter for hard-copy retention of analyzer displays.

A dry chute was present on each of the four corners, extending to a water depth of 247 feet (approximately 1/4 of the total depth) with access from the + 12-foot walkway. Deployment was limited to one package per chute. The deployed triaxial accelerometers were inclined to the platform axes as dictated by the orientation of the chute. On the A1 and A4 corners the near lateral accelerometers were aligned within the planes of the platform faces as planned. On the B1 and B4 corners, however, it was learned late in the testing that the chutes were misoriented by approximately 15° in rotation about the leg axis. The A1 and A4 chutes had been used by Shell on three previous occasions but this was the first use of the B1 and B4 chutes.

It was recognized in the pretest planning that real-time determination of flexibility parameters would be imperfect for two reasons. First, acceleration signals along the lateral axes of the platform were not directly available and the analog summing unit had insufficient capacity to correct for this by suitably combining near horizontal and near vertical signals. Given that this testing was foremost a method evaluation effort, rather than one to measure accurate flexibility parameters, it was decided to accept the resulting modest errors and use the near horizontal signals as if they were truly horizontal. Second, there was insufficient instrumentation available to measure near the +12-foot level simultaneously with measurement at two underwater levels across a bay. It was decided to accommodate this limitation by normalizing a bay relative acceleration in real time by deck acceleration. The abovewater relative acceleration (deck to +12-foot level) was also obtained with this same normalization. A simple division of the two results yielded the desired bay relative acceleration normalized by the abovewater relative acceleration, which is by definition a flexibility parameter. This same normalization process was also utilized for the Garden Banks platform. Hereafter, reference will be made to "real-time" determination of flexibility parameters even though the determination is carried out in two steps.

3.3 Calibrations

The instrument packages were calibrated statically in the laboratory at the Shell Development Company prior to their transport to the Cognac platform.

After installation on the Cognac platform, the data acquisition module operation was checked out. Tape calibration signals were recorded directly on tape (all data tracks).

Relative system calibrations were accomplished by strapping two instrument packages together, positioning them in the recess of vertical I beams at legs A1 and B4, activating the pneumatic plungers and recording the data on tape while performing real-time frequency response analyses. Alternate pairs were calibrated at both A1 and B4 positions to cover all combinations. Signals from the resident accelerometers at A1 and B4 were also employed. The net gains of channels in the analog summing unit were equalized using the relative calibration results.

3.4 Data Acquisition

Upon completion of the system calibrations, four packages were taken to the +12 foot level (boat deck) where one package was inserted in each chute on the four corner legs. Packages 3 and 4 were positioned just below the +12 foot level on legs A4 and B1, packages 1 and 2 were positioned at the -32 foot level on legs B4 and A1 respectively and one hour and 48 minutes of data were recorded. Due to a power loss at midnight, during the test, a rerun of 1 hour and 42 minutes was recorded the next morning using the same package deployment configuration.

The tape recorder used accommodated a total of 14 channels of information, two of which were reserved for reference frequencies for tape recorder speed compensation. The four packages generated 12 parameters (x, y, z times 4), the two resident accelerometer installations generated 4 parameters (x, y times 2), and the analog summing unit (Figure 2.2) generated 4 parameters for a grand total of twenty. The tape recorder was limited to twelve, therefore, two tests were conducted at the Bay #1 and Bay #4 levels to allow recording of all the required data parameters for a complete evaluation of both x and y flexibility. Tests on the other bays recorded only selected parameters (x or y).

Bay #2 was tested by lowering packages 3 and 4 from the +12 foot level to the -92 foot level and recording one hour and 30 minutes of selected data. In turn, packages 1 and 2 were lowered from the -32 foot level to the -167 foot level to test Bay #3 where one hour and twenty minutes of data were recorded. Next, to test Bay #4, packages 3 and 4 were lowered from the -92 foot level to the -247 foot level where one hour and thirty-four minutes of data were recorded. A second test run of one hour for Bay #4 was followed by half hour test runs in Bays 3, 2 and 1, positioning the packages as described above, before removing all four packages from the chutes.

Real time monitoring of data using the Aerospace analog summing unit and dual-channel analyzer was accomplished during each test run using selected data channel combinations, as well as individual data channels. Additional analyses were performed as desired using the playback capability of the tape recorder.

3.5 Findings

The procedure for relative calibrations of the packages was satisfactory. The physical setup worked out well and very high coherence results (0.998 or above) were obtained at frequencies of the fundamental modes. Thus, high statistical confidence in the calibrations was clearly achievable.

The planned real-time determination of flexibility parameters, however, were not achievable because of the unanticipated alignments of the chutes on the B1 and B4 corners. Before this was identified, the analog summing unit and analyzer were utilized as planned and the equipment performed well. The resulting flexibility parameters, however, displayed very poor coherence. In retrospect, this was caused by the misalignments of the B1 and B4 chutes which introduced a mixture of x and y accelerations in the bay shears resulting in only partial correlation with either the x- or the y-directed deck accelerometers.

Another difficulty with signals coming from the B1 and B4 chutes was the presence of noise spikes in the data which were especially strong when a package was positioned in the chute at the 12-foot level. Based upon observed looseness of these chutes at that level, it was postulated that some rattling of these chutes, probably only at their upper ends, was the source of high frequency signals which momentarily overloaded the data channels. Such noise deteriorates coherence and consequently the accuracy of flexibility parameter determinations.

Checks of coherence of near lateral accelerometers in the A1 and A4 chutes showed values near unity when related to a corresponding lateral acceleration on the deck. It was thus apparent that, with proper orientation and well supported chutes, good quality data could be obtained.

The Cognac test was a valuable learning experience for field application of Flexibility Monitoring. The underwater positioning of instrument packages worked very well, the attainability of high coherence data was demonstrated, and chute problems to guard against in the future were identified. The test did not achieve all that was desired because real-time determination of flexibility parameters was unsuccessful. Although possible, no attempt was made post test to extract flexibility parameters from the recorded data by accounting for the known misalignments. It was believed that such results would be so questionable quantitatively that the necessary data reduction effort was not justified. Modification of the data acquisition equipment is required for accurate real time flexibility parameter determination for the Cognac platform.

The Cognac test, as a first field experiment, contributed significantly toward possible practical implementation of the Flexibility Monitoring approach. Test design for the second field test, described next, certainly benefited considerably from this prior experience.

4. PHASE III EVALUATION PROGRAM

The Flexibility Monitoring evaluation tests were conducted on the Garden Banks platform from December 13-16, 1982. Real time monitoring and analysis were successfully accomplished during the testing period. All data were recorded on magnetic tape to enable additional analysis. Two identical tapes were recorded, one of which was given to Aerospace. The data were additionally assessed onshore in greater detail relative to its quality and validity for the Flexibility Monitoring concept.

4.1 Garden Banks Structure

The Garden Banks platform shown in Figure 1.5 was an eight leg structure, constructed as a single unit. The jacket section was 705 feet high whose top extended 15 feet above Mean Gulf Level (MGL). The eight main legs of the structure were 52-1/2 inches in diameter at the top, increasing to 53-1/2 inches at the mudline through which piles were driven deep into the ocean floor. Eight guide sleeves, 78 inches in diameter were added to the base of the jacket, four on each long side (face) of the structure to accommodate eight additional piles. The upper deck supports extended the jacket structure to the production deck which was 66 feet above MGL. It is installed in the Gulf of Mexico about 150 miles south of Cameron, Louisiana in approximately 685 feet of water.

The field test evaluation was conducted during drilling operations with relatively calm weather conditions.

4.2 Instrumentation and Chutes

The instrumentation employed in the Flexibility Monitoring evaluation included four portable chute packages and cabling, a data acquisition station, resident triaxial accelerometer packages permanently attached to corner legs A1 (SE) and B4 (NW) at the 66 foot deck level (all developed by Chevron Oil Field Research Company) and real-time data monitoring and analysis equipment. Dry instrumentation chutes were mounted on three corner legs of the structure: A1 at the southeast corner, A4 at the northeast and B4 at the northwest. The chutes were positioned one foot off the leg outboard of the structure and rigidly supported, typically at five foot intervals. The chutes extended to below the top of the skirt piles at a depth of 585 feet.

The portable chute packages each contained two Sundstrand Q-flex 1200 accelerometers, associated electronics, and two electrically actuated mechanisms to position the package within the chute. The accelerometers were oriented within the packages to compensate for chute batter (off vertical) so that they sense in the x and y principal directions of the platform. The packages were so designed that up to three units could be placed at different levels within one chute with the electrical cable for a lower unit passing through a conduit on each unit above. The units were mechanically interconnected by a wire rope adjusted to the desired spacing. The lowering wire rope was attached to the upper unit, ran through a pulley mounted six to seven feet above the open end of the chute to a hand operated supply winch. A footage counter was inserted between the pulley and winch for measurement to position the package at the desired level. Two packages were used in each of two diagonal opposite chutes (A1, B4) for the Flexibility Monitoring evaluation.

The acquisition station, located on the 66-foot deck near the northwest corner, contained three tape recorders. Output connectors were provided to allow other equipment to be connected to the amplified signals. The recorders were Geotech model 19429, 14 track on 1 inch tape, with FM record electronics. Only one set of reproduce electronics were supplied (1 track, switchable) which limited playback operation. The recorders were operated at a speed of 0.03 inches per second which effectively limited information content to below 5 Hz.

Complementing the acquisition station hardware were an HP 7225 plotter and a set of four-pole Butterworth low-pass filters supplied by Chevron at Aerospace request. Aerospace supplied a dual-channel spectrum analyzer (SD 375), analog summing unit, and an HP 85 microcomputer. The HP 7225 plotted the output of the spectrum analyzer. The set of low-pass filters was employed to limit the information content of the signals at 2 Hz. The spectrum analyzer generated frequency response functions and the HP 85 retrieved and stored the results of these analyses on a magnetic tape cartridge for post-test studies.

The acquisition station on the Garden Banks platform was a permanent installation used to gather data on a daily basis. Therefore, no checkout of the basic station was necessary. The equipment brought on board for the Flexibility Monitoring evaluation did require special hookup to the basic station hardware and subsequent checkout.

4.3 Calibration

The instrument packages were calibrated statically at the Chevron Oil Field Research Company prior to being transported to the Garden Banks platform. They were checked for zero output and appropriate gains in the normal and reverse positions.

Relative system dynamic calibrations were performed on the platform by positioning accelerometers so that they sensed identical motions in the fundamental modes. Relative amplitude and phase were obtained by real-time measurement of frequency response functions at the fundamental sway frequencies. Because the accelerometers were oriented within the package to compensate for leg batter, special wood stands, to hold the packages individually in that orientation were employed. The deck accelerometers were permanently affixed to a leg and the packages were placed in the calibration stands on deck plating about one meter away.

The relative calibrations, using accelerometer 1 as a reference, were conducted both prior to and after the series of tests. The precalibrations were made between 5 and 10 p.m. on Tuesday, December 14 and the post calibrations were made two days later between 5 and 10 p.m. on Thursday, December 16. Table 4.1 contains the amplitude, phase, and coherence results. Conditions existed on the platform that caused an atypical banging impulse to be imparted to the structure periodically, resulting in momentary overloading of the data channels. Drilling was not a fully continuous operation. These two conditions are noted in Table 4.1. When no drilling and/or banging were present, most accelerometers showed changes that are smaller than the acceptable 1% change between pretest and post test calibrations. There were two exceptions, those being deck accelerometer no. 5 and package accelerometer no. 2 (Table 4.1). It was believed that this lack of repeatability was primarily the result of slight differences between the vibration as sensed on the deck plate versus on the nearby leg--with differences occurring sporadically. This was most noticeable when drilling, especially with banging, was taking place. This would also explain why the leg-mounted permanent accelerometers as a group did not fare well with respect to the deck-plate mounted accelerometer no. 1. The poor repetition evidenced by accelerometer 2 also fits this explanation: since accelerometer 2 is located within the same package as the reference accelerometer 1, its calibration had to be through an intermediary accelerometer--and the intermediary used was the leg-mounted accelerometer 6 (i.e., calibration 2/1 was obtained from 2/6 times 6/1).

Table 4.1. Pre and Post Calibration Comparisons*

	ACCELEROMETER** (relative to 1)		PRE CAL (Dec 14, 5-11pm)	POST CAL(A) (Dec 16, 5-10pm)	AMPLITUDE CHANGE (%)
	2	(C)	0.996,0.2°(1.000)	1.014,1.4°(0.996)	+ 1.8
	3	(C)	0.992,-0.2°(0.998)	0.991,0.0°(0.999)	- 0.1
Portable	4	(C)	0.997,0.2°(1.000)	1.00,-0.9°(1.000)	+ 0.3
Package	8	(B)	0.982,0.5°(0.968)	0.987,0.7°(1.000)	+ 0.5
Accelerometers	9	(B)	0.990,0.2°(0.990)	0.998,0.9°(1.000)	+ 0.8
	10	(B)	0.984,0.0°(0.949)	0.990,-0.5°(1.000)	+ 0.6
	11	(B)	0.950,6.3°(0.986)	0.959,6.5°(1.000)	+ 0.9
Deck	5	(C)	1.01,0.2°(1.000)	0.978,0.0°,(1.000)	- 3.2
Permanent	6	(C)	1.00,0.0°(1.000)	0.994,0.2°,(0.992)	- 0.6
Accelerometers	12	(B)	1.07,6.4°(0.983)	1.028,4.7°(0.994)	- 3.9
	13	(B)	1.04,-1.8°(0.971)	0.973,0.2°(0.995)	- 6.4

*Values are amplitude, phase (coherence)

**#7 and #14 do not contribute to this analysis (oriented vertically)

(A) Drilling, no banging during all post calibrations

(B) Drilling, with banging

(C) No drilling, no banging

Because of the anomalies noted, it was evident that relative system calibrations should not be performed when the data channels exhibit electronic overload conditions. All sensors being calibrated should be collocated on a primary structural member.

Gain adjustments were made in the analog summing unit, on the basis of the pretest calibration, so that the net gain of all signal channels was identical. Table 4.1 shows phase differences as high as 6.5^{o} for accelerometers 11 and 12, all the others do not exceed 1.8^{o}. The instrumentation used for the field test evaluation had no capability to achieve phase compensation. It is believed necessary to achieve phase compensation to realize the full potential accuracy of the method.

4.4. Data Acquisition

The instrumentation positioning for Flexibility Monitoring of a bay involved two packages at diagonally opposite corners at the upper level of the bay, and two at the same corners at the lower level of the bay. The x and y average shear deflections were formed in the analog summing unit, as were the x and y average deck deflections. The ratios of bay shear to deck acceleration were measured in real time using the two-channel analyzer, first for the x direction and then for the y direction. The relation of the below-deck average shear deflections to deck average deflections was measured first to permit determination of the flexibility parameters in the form of bay shear divided by below-deck shear. The real-time measurements were restricted to the two fundamental sway directions (at about 1/3 Hz) for the first and second bay below the +12 foot level, and again for the two lowest bays of the structure. In addition, average sway motions at some intermediate levels were also measured. The FFT resolution was 0.025 Hz, with a Hanning window and 30 overlapped (by 50%) averages, requiring 10-1/3 minutes of data. These FFT parameters were established during an evaluation of several alternative bandwidths for the relative calibrations. The criterion was high coherence ($>$ 0.99) using as wide a bandwidth as possible, to permit data collection in a relatively short time.

4.5 Findings

Real-time determinations of the bay shears relative to deck average accelerations in the two fundamental lateral modes were made for bays 2, 7 and 8 (see Figure 1.5) in the end-on and broadside directions. The approximate natural frequency of the end-on (x) mode was 0.40 Hz and for the broadside (z) mode was 0.35 Hz, determined with 0.05 Hz resolution. Precise measure of these frequencies is not a requirement of Flexibility Monitoring. The ratio of level 1 average to deck average acceleration was also made to complete the information needed to determine the flexibility parameters. It was decided in advance not to measure the deck to level 1 shear simultaneously with bay shear to avoid greatly complicating the accelerometer installation requirements for Chevron. This two-step process to measure flexibility parameters was expected to introduce some minor degradation in accuracy.

As a check on the short-term repeatability of the data, the level 1 and bay 7 measurements were repeated, including the repositioning of the packages. The results appear in Table 4.2. The approximate time interval between measurements for level 1 was 22 hours, and 13 hours for bay 7. As shown, the greatest percentage changes are 4.9 percent for level 1 and 3.4 percent for bay 7 shear.

In addition to the above, levels 4, 5, 6 and bays 2, 8 were measured. All available information was used to construct the partial lateral mode shapes shown in Figure 4.1. Some judgment was required for the bay 2 and bay 7, 8 portions since insufficient information was available. Although not required for Flexibility Monitoring, the shapes were interesting from the standpoint of motion amplitudes as a function of depth. In particular, the average amplitude at the top of the skirt piles (level 9) was only about 4 percent of that of the deck. More to the point from the Flexibility Monitoring standpoint was that the bay average shears for the lowest bays were about 6 to 7 percent of the deck average amplitude. If 1 mg rms is roughly the acceleration amplitude of the deck in a lateral mode under calm conditions, an array of four accelerometers must sense a net shear acceleration of 60-70 μg rms. The fact that the repeated measurements on bay 7 were different by no more than 3.4 percent under calm conditions, employing only 10-1/3 minutes of data (see Table 4.2) is testimony to the high capability of the instrumentation and data acquisition and processing systems.

The physical positioning of the instrument packages to obtain relative calibrations was less ideal than the procedure employed on Cognac. It proved that instrument packages being calibrated should be collocated on a primary structural member and calibration should not be performed when the data channels exhibit electronic overload conditions. Real time determination of flexibility parameters was very satisfactory on the Garden Banks platform, showing that quality data necessary to the technique can be acquired under calm ambient conditions even during drilling operation.

Table 4.2. Comparison of Repeated Measurements

	Level 1X	Level 1Z	Bay 7X	Bay 7Z
Dec 15, 3-4 PM	1.43* (0.996)	1.44 (0.997)		
Dec 15, 9-10 PM			0.117 (0.979)	0.171 (0.992)
Dec 16, 10-11 AM			0.121 (0.992)	0.171 (0.969)
Dec 16, 1-2 PM	1.50 (0.995)	1.45 (0.996)		
% Difference	4.9	0.7	3.4	0

*Magnitude (coherence); magnitude is twice the level or bay shear average divided by the deck average.

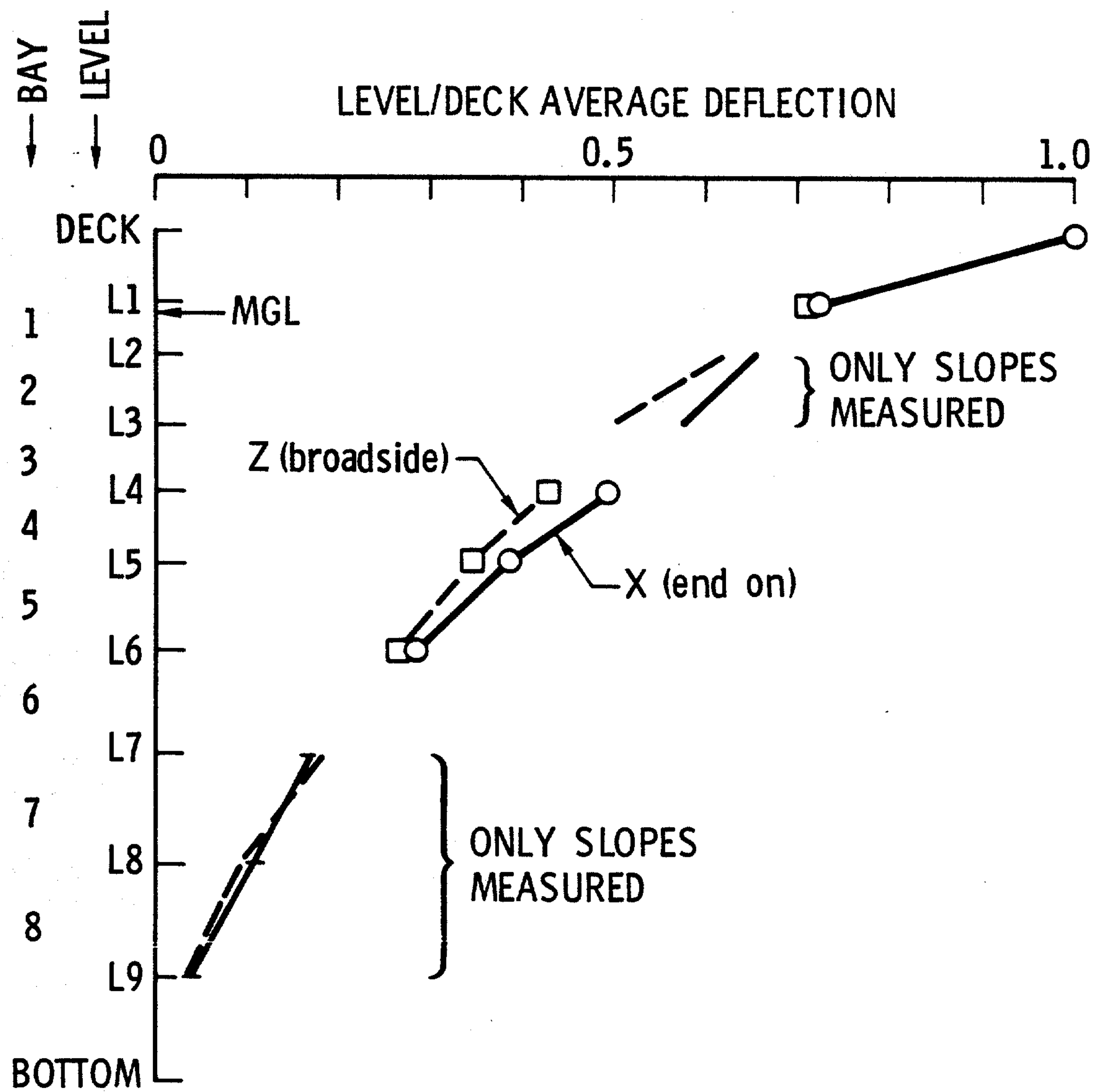


Figure 4.1 Lateral Mode Shapes

5. MODELING AND MODAL SENSITIVITY ANALYSIS

5.1 Description of the Simplified Generic Platform Model

In previous studies (Ref. 7,8) the generic behavior of fixed offshore platforms has been utilized to describe the dynamic characteristics of such structures and to gain perspectives on sensitivity to local structural failures. The present investigation was aimed at extending the generic shear beam model to include (1) out-of-plane coupling due to eccentric deck mass and member failures, (2) effects of distributed jacket structural mass and submerged member apparent fluid mass and (3) effects of foundation flexibility. Sensitivity of the fundamental lateral and torsional modes to member severance in the presence of the above effects was evaluated. The purpose of this analytical investigation was to establish trends in behavior rather than authentic simulations.

The present generic model configuration is schematically illustrated in Figure 5.1. A displacement coordinate system referenced along the geometric center of each level is noted in that figure. The configuration geometry has the cross-sectional dimensions "a" and "b", taken as uniform over the entire structural height. Individual bays, including the abovewater section are all of height h. The deck is configured as a rigid plate of mass M_D, which is uniformly distributed over the surface area. An eccentric concentrated mass M_0, located at coordinates a_0, b_0 with respect to the geometric center of the deck, was added to the distributed mass.

Consistent with observed behavior of detailed finite-element platform models and supported by field data comparisons, the jacket structure was assumed to deform as a shear beam. For simplicity a number of assumptions consistent with such behavior were made: (1) main legs were axially rigid; (2) horizontal braces were axially rigid; (3) lateral elastic structural stiffness of all bays at and below the water line was completely due to axial stiffness of the diagonal braces (i.e., bending stiffness of the main legs was negligible in comparison); and (4) lateral elastic structural

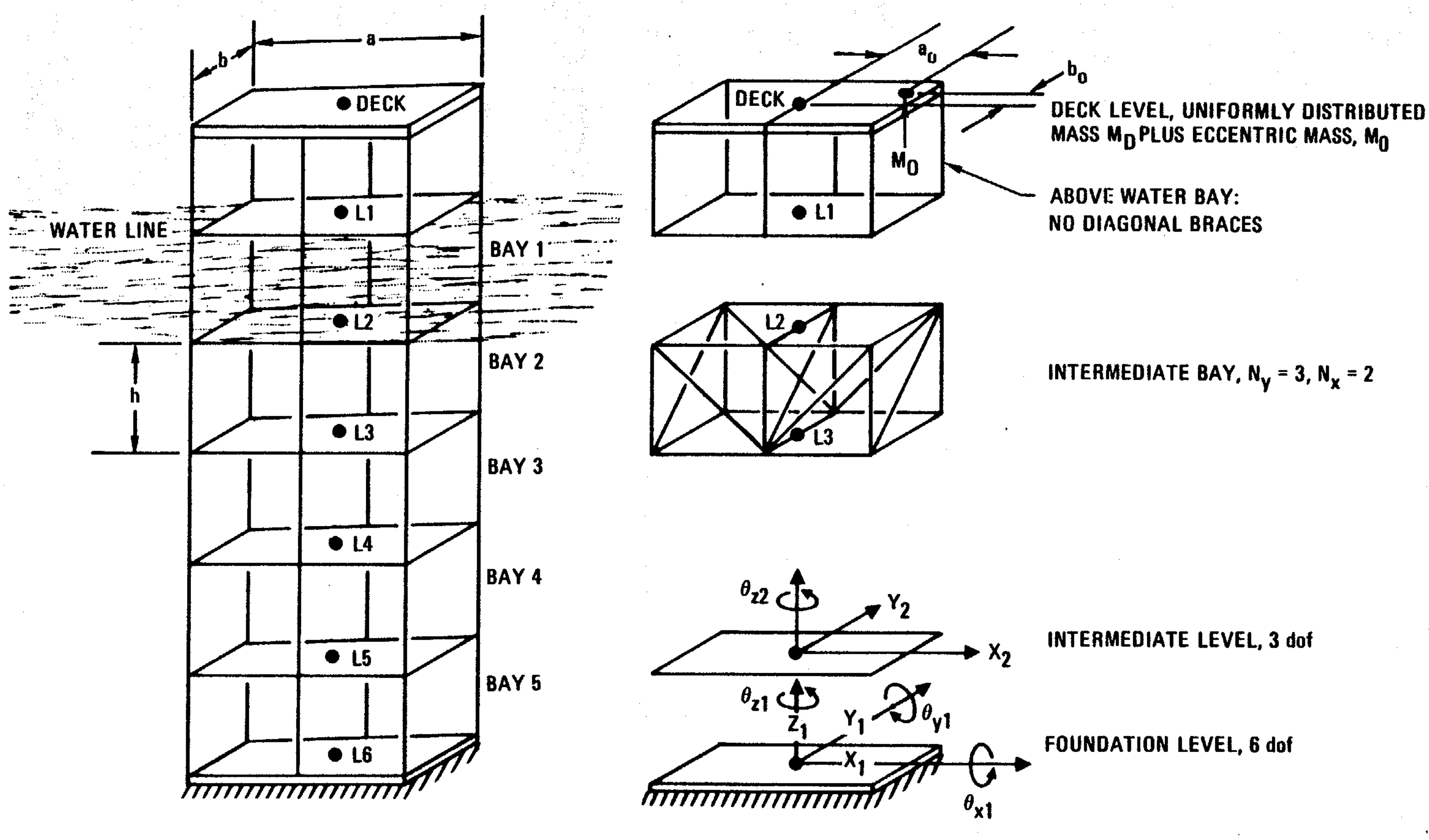


Figure 5.1 Five Bay Generic Model Schematic

stiffness of the abovewater bay was due to bending stiffness of the main legs. An additional simplifying assumption employed in simulation of foundation flexibility was that the foundation level deformed as a rigid plate. Thus, foundation stiffness was described in terms of uncoupled stiffness coefficients associated with the six displacements, x_1, y_1, z_1, θ_{x1}, θ_{y1}, θ_{z1}. As a result of the jacket structure assumption, the vertical motions, z_i, and rotational motions, θ_{xi} and θ_{yi}, of all levels above the foundation level were equal to the respective foundation displacements z_1, θ_{x1}, and θ_{y1}. The displacements required to describe the independent motion of any level above that of the foundation were thus x_i, y_i and θ_{zi}. In the case of the five-bay configuration illustrated in Figure 5.1, the number of the structural degrees of freedom were therefore 6 for the foundation, plus 6 levels at 3 degrees of freedom each, totalling 24. In the case of a rigid foundation there were a total of 18 dof.

The jacket structure mass and apparent fluid mass associated with submerged structure were accounted for by concentrating them along the main legs. Structural mass of the set of main legs was designated M_s for a length h (equivalent to one bay). The structural mass, equally allocated to the nodal degrees of freedom, acts in the three displacement directions, x_i, y_i, θ_{zi}. Moreover, due to the kinematic assumptions, moments of inertia associated with structural mass of the distributed legs act in the θ_{xi}, θ_{yi}, θ_{zi} degrees of freedom. Apparent fluid mass was estimated based upon the cross-sectional dimensions of the individual legs. According to inviscid potential fluid flow theory, the mass of fluid per unit length surrounding a cylinder of outer radius R_o, which moves with the cylinder in a lateral direction is equal to the mass of fluid displaced by the cylinder $\rho_w \pi R_o^2$, where ρ_w is the density of the fluid. This added mass acts only perpendicular to the axis of the cylinder. In addition, since the main legs are typically flooded, the mass of entrained fluid per unit length, $\rho_w \pi R_i^2$, acts laterally.

The total apparent fluid mass, M_f for length h, is equally allocated to the submerged fluid degrees of freedom and acts in the two lateral displacement directions, x_i, y_i. A net torsional moment of inertia also acts in the θ_{zi} direction due to geometric positioning of the individual legs.

5.2 Representative Platform Configurations

Three generic configurations with contrasting levels of complexity were chosen for damage sensitivity study. They consisted of a 4-leg, 4-bay structure much like the one employed in Ref. 8, an 8-leg, 6-bay structure of similar complexity to SP-62C studied in Ref. 7, and a 12-leg, 11-bay structure with bay complexity resembling that of the lower sections of the Shell Cognac platform (see Fig. 1.4). The jacket, deck and foundation properties of each configuration are presented in Table 5.1.

Fundamental lateral and torsional mode characteristics of the three representative configurations with all members intact are summarized in Figure 5.2; the x-sway mode is illustrated for rigid and flexible foundation conditions for each structure. Along with each illustration is the fractional contribution of the deck to total modal kinetic energy and fractional contribution of foundation potential energy to the total modal potential energy. When comparing the configuration extremes (4-leg and 12-leg), clearly for the 4-leg configuration, jacket structural mass and apparent fluid mass played a minor role in determination of modal frequency. Moreover, the relatively uniform slope of submerged jacket modal displacements for the 4-leg configuration indicated that the fundamental lateral modes were governed by quasi-static behavior of the jacket. In contrast, the 12-leg configuration behaved more like a shear beam with uniform mass and stiffness distribution as indicated by the relatively low contribution of deck mass to modal kinetic energy and by the near quarter-wave character of the lateral mode shape.

Table 5.1 Generic Platform Configuration Data

	PARAMETER	GENERIC CLASSIFICATION: 4 LEGS	8 LEGS	12 LEGS
JACKET CONFIGURATION	a (in.)	672	2000	3600
	b (in.)	672	1000	2400
	h (in.)	420	650	1200
	N_x	2	2	3
	N_y	2	4	4
	N	5	7	12
	α	0.05	0.5	0.5
	K_s (lb/in.)	1.40×10^6	1.25×10^6	4.64×10^6
	M_s (lb-sec^2/in.)	172	1040	8000
	M_f (lb-sec^2/in.)	200	2480	20000
DECK	M_D (lb-sec^2/in.)	550	7520	35000
	M_0 (lb-sec^2/in.)	50	3340	10000
	a_0 (in.)	300	300	1000
	b_0 (in.)	0	0	0
	$2x_{cg}/a$	0.074	0.185	0.123
FOUNDATION	RIGID	—	—	—
	K_{fx} (lb/in.)	2.0×10^6	8.0×10^6	1.2×10^7
	K_{fy} (lb/in.)	2.0×10^6	8.0×10^6	1.2×10^7
	K_{fz} (lb/in.)	4.0×10^6	1.2×10^7	2.4×10^7
	$K_{f\theta_x}$ (in.-lb/rad)	4.5×10^{11}	3.0×10^{12}	2.3×10^{13}
	$K_{f\theta_y}$ (in.-lb/rad)	4.5×10^{11}	6.7×10^{12}	4.0×10^{13}
	$K_{f\theta_z}$ (in.-lb/rad)	4.5×10^{11}	6.5×10^{12}	3.2×10^{13}
OVERALL	$(M_D + M_0)$	600	10860	45000
	NM_s	860	7280	96000
	$(N-1)M_f$	800	14880	220000
	MASS RATIO*	0.520	0.595	0.299
	Nh (ft)	175	379	1200

*$(M_D + M_0) / \{1/3\ [NM_s + (N-1)\ M_f] + M_D + M_0\}$

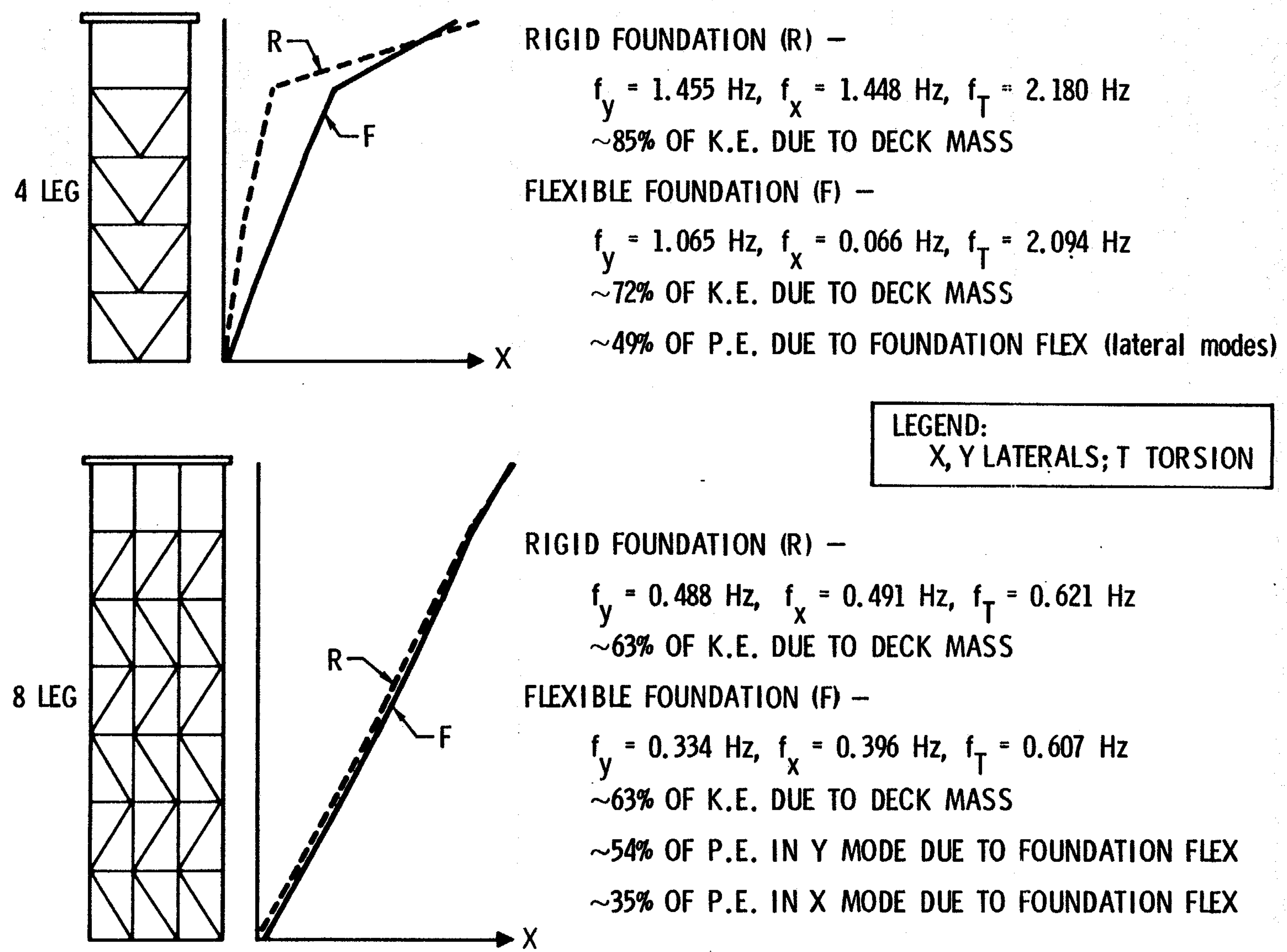
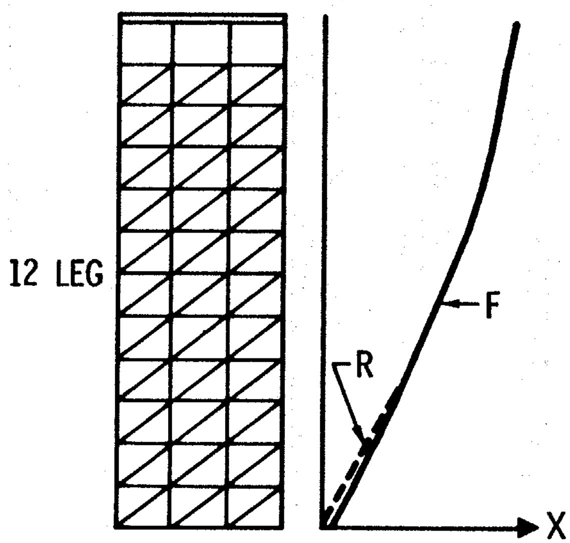


Figure 5.2 Modal Characteristics of Intact Platforms



RIGID FOUNDATION (R) —

f_y = 0.247 Hz, f_x = 0.248 Hz, f_T = 0.266 Hz

~26% OF K.E. DUE TO DECK MASS

FLEXIBLE FOUNDATION (F) —

f_y = 0.237 Hz, f_x = 0.239 Hz, f_T = 0.257 Hz

~25% OF K.E. DUE TO DECK MASS

~ 8% OF P.E. IN Y MODE DUE TO FOUNDATION FLEX

~ 7% OF P.E. IN X MODE DUE TO FOUNDATION FLEX

Figure 5.2 Modal Characteristics of Intact Platforms (Continued)

5.3 General Sensitivity to Member Severance

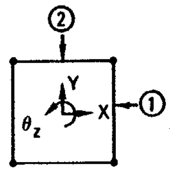
The three representative platform models were subjected to single member severances on various faces and bay levels to assess sensitivity of fundamental lateral mode parameters. While it was established in Ref. 8 that the most sensitive indicators of member failure were flexibility parameters, it is also of interest to note modal frequency sensitivity of the subject structures. A summary of frequency shifts due to member severance is presented in Table 5.2. The range of percentage frequency reduction due to member failure on a particular face indicates variation with damaged bay level. In all cases it was found that the highest frequency sensitivity occurred for damage in the lowest bay (i.e., closest to foundation) with sensitivity monotonically decreasing with distance above the foundation. This sensitivity characteristic arises as a result of the contribution of jacket structural mass and apparent fluid mass; that is, the highest fraction of system mass is affected by damage at the lowest bay level. As noted in prior work (Ref. 7) the general trends indicated that frequency sensitivity decreases with increasing bay configuration redundancy and effective number of bays. The effective number of bays increases with increasing foundation flexibility and above water bay flexibility. In all cases considered, frequency sensitivity appeared to be a generally unreliable indicator of structural failure, especially in view of the potential for foundation and deck mass changes which produced greater frequency changes than those associated with member severance.

The parameter which is most sensitive to member failures, namely, the bay flexibility parameter has been discussed previously (Ref. 8). The bay flexibility parameter, C, is defined as the ratio of relative average lateral or torsional deflection across that bay to the corresponding lateral or torsional deflection for the abovewater bay. Namely, for the x direction

$$C_{xi} = \frac{\bar{x}_{i+1} - \bar{x}_i}{\bar{x}_D - \bar{x}_1} \qquad (5)$$

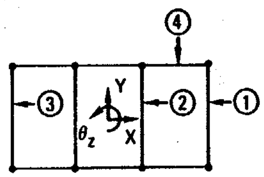
Table 5.2 Summary of Frequency Shifts Due to Member Severance

4 LEG



RIGID FOUNDATION	NOMINAL	PERCENT FREQUENCY REDUCTION* ①	②
f_y	1.445	4.9-7.5	--
f_x	1.448	--	4.6-7.0
f_{θ_z}	2.180	1.7-4.8	2.2-9.4
FLEX FOUNDATION			
f_y	1.065	2.7-5.0	--
f_x	1.066	--	2.5-4.8
f_{θ_z}	2.094	2.1-5.5	2.2-6.4

8 LEG

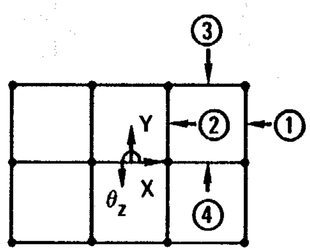


RIGID FOUNDATION	NOMINAL	PERCENT FREQUENCY REDUCTION ①	②	③	④
f_y	0.488	3.1-8.2	1.4-3.7	1.4-4.9	--
f_x	0.491	--	--	--	0.8-2.2
f_{θ_z}	0.621	1.0-4.2	0.0-0.2	1.8-8.2	0.0-0.6
FLEX FOUNDATION					
f_y	0.334	1.0-3.3	0.6-1.8	0.9-2.4	--
f_x	0.396	--	--	--	0.5-1.3
f_{θ_z}	0.607	1.5-6.6	0.0-0.3	1.4-8.2	0.2-0.7

* Ranges for all bays. Greatest change always occurs at lowest bay level severance, decreasing monotonically with increasing bay level.

Table 5.2 Summary of Frequency Shifts Due to Member Severance (Continued)

12 LEG



RIGID FOUNDATION	NOMINAL	PERCENT FREQUENCY REDUCTION ①	②	③	④
f_y	0.247	0.0-2.0	0.0-1.2	--	--
f_x	0.248	--	--	0.0-1.2	0.0-0.8
f_{θ_z}	0.266	0.0-0.8	0.0	0.0-0.4	0.0
FLEX FOUNDATION					
f_y	0.237	0.0-2.1	0.0-1.3	--	--
f_x	0.239	--	--	0.0-1.3	0.0-0.8
f_{θ_z}	0.257	0.0-0.8	0.0	0.0-0.4	0.0

where the overbar denotes the average deflection. Typical flexibility sensitivities for the three representative platforms are presented in Figure 5.3. It is noted, as in Ref. 8, that foundation rotational flexibility produced an overall shift in flexibility parameters due to added rigid-body angular displacement. This effect was most pronounced in the 4-leg platform, but became a negligible effect for the 12-leg platform. Contributions of jacket and fluid mass led to a monitonically decreasing value of the flexibility parameter with distance above the foundation, especially pronounced for the 12-leg configuration. In all platform configurations, the presence of member severance was indicated by an increase in the flexibility parameter of the affected bay in the direction of action of the severed member. As noted in Ref. 8, the absolute increase in the damaged bay flexibility parameter was relatively insensitive to foundation flexibility. On the other hand, the fractional change in the damaged bay flexibility parameter generally decreased with increasing foundation flexibility due to the increased nominal bay flexibility parameter. This effect was most strong for the 4-leg configuration.

A complete list of flexibility parameter sensitivities for all cases and damage scenarios is presented in Appendix B.

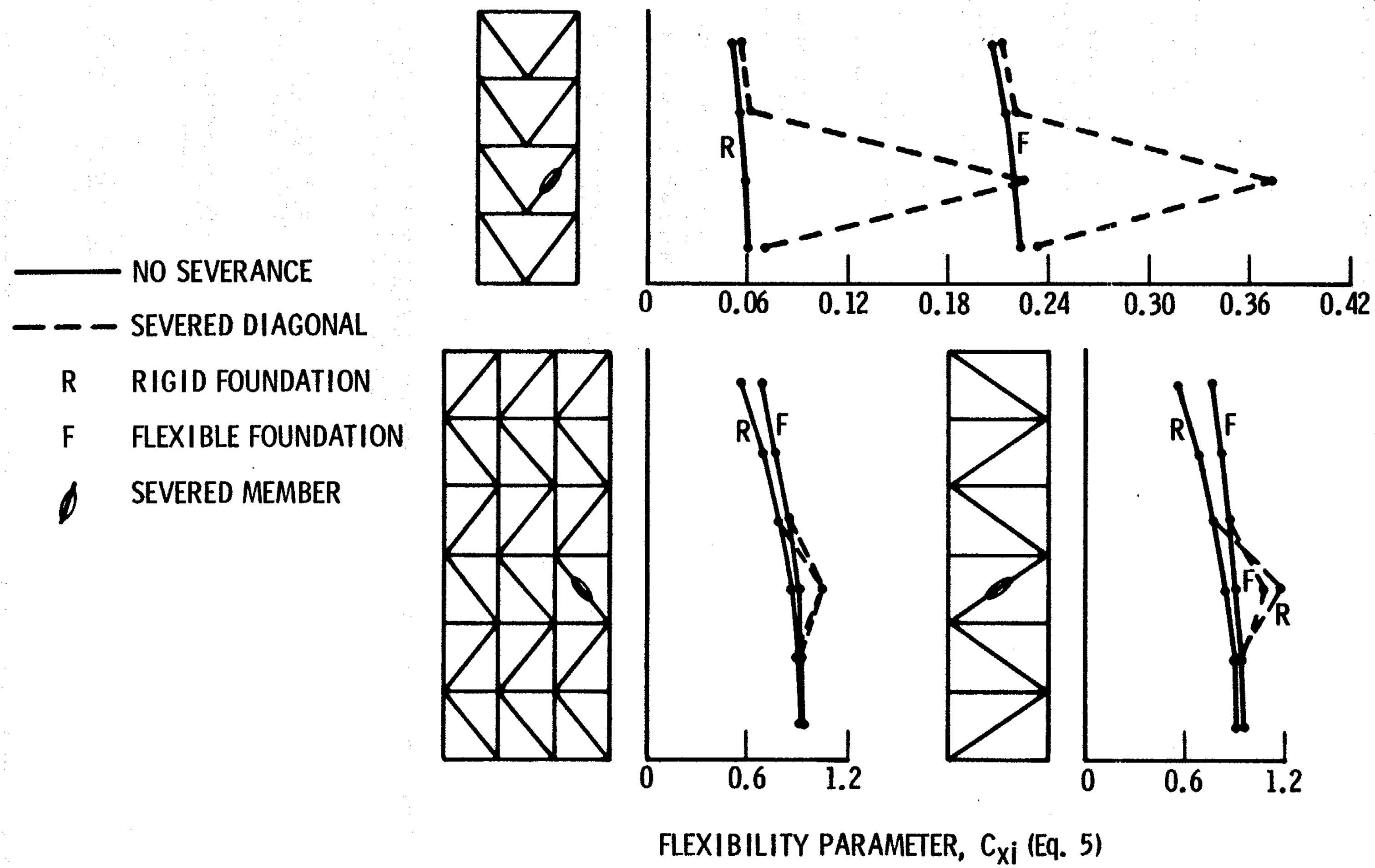


Figure 5.3 Typical Flexibility Sensitivities of Platforms

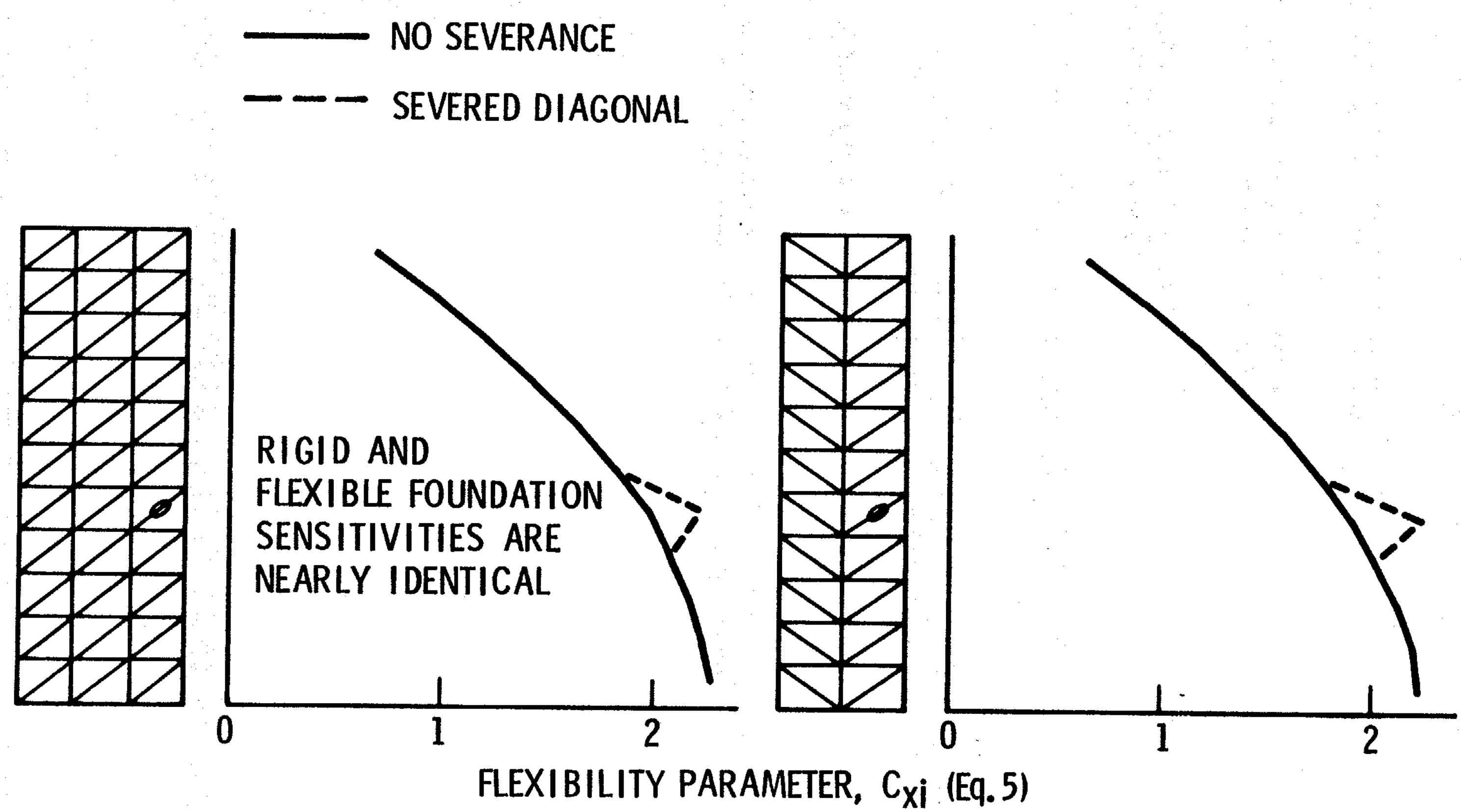


Figure 5.3 Typical Flexibility Sensitivities of Platforms (Continued)

5.4 Perspective on Damage Sensitivity

The importance of field detection of any structural damage is directly proportional to the degree of structural integrity degradation associated with it. A relatively straightforward indicator of such degradation is the non-dimensional damaged strength rating (DSR) adopted in Ref. 7 on the basis of an original definition by P. Marshall (Ref. 9):

$$DSR = \frac{\text{damage strength}}{\text{intact strength}} \tag{6}$$

As used here, this rating is based upon the greatest increase in diagonal member loading resulting from a failure, considering constant static lateral shear force to act across the bay containing the failed member(s) and linear elastic structural behavior:

$$DSR = \frac{\text{Member Loading for Undamaged Structure}}{\text{Member Loading for Damaged Structure}} \tag{7}$$

In rough terms the damaged strength rating of a bay which has sustained member failure(s) is estimated by the following logic. Given a bay which carries a transmitted shear force F shared by N diagonals, the individual member loads are proportional to F/N. If M members have failed, the redistributed individual member loads are F/(N-M), neglecting non-uniform distribution of loading due to eccentric positioning of the damage. Thus, a first approximation of the damaged strength ratio is

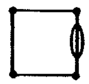
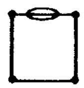
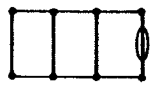
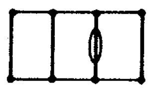
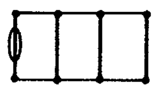
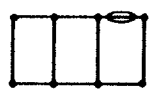
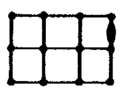
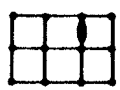
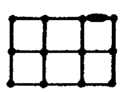
$$DSR \approx \frac{F/N}{F/(N-M)} = \frac{N-M}{N} \tag{8}$$

The more accurate measure of DSR is based upon linear static analysis of a damaged bay, considering redistribution of member loads due to unsymmetric damage (leading to coupled lateral and torsional shear deflection across the bay). It is interesting that in a first-order sense, the net change in bay flexibility, when described as a ratio of undamaged divided by damaged flexibility, is equal to the damaged strength rating. A bay flexibility parameter, which is determined from a lateral mode, differs from the static value due to effects of jacket and fluid mass.

A summary of platform sensitivities associated with the three generic configurations and single member failure damage cases is presented in Table 5.3. For each damage case the number of load carrying members for the intact structure (N) is given, along with the first-order approximation of damaged strength rating and flexibility sensitivity given by (N-1)/N. Next, damaged strength ratings (DSR) and flexibility parameters resulting from static analysis of the affected bay are shown. Finally, flexibility parameters from dynamic analysis (i.e., from the lateral modes) are shown. Included are flexibility parameter sensitivities $C_0/(C_0 + \Delta C)$, the ratio of undamaged and damaged flexibility parameters, for the case of a static force applied to the deck. The like sensitivity for the dynamic case contains the dynamically determined flexibility parameter change ΔC_D, along with the static intact flexibility parameter C_0. The dynamic values of flexibility parameter change, ΔC_D, and flexibility parameter sensitivity, $C_0/(C_0 + \Delta C_D)$, are shown as a range since they vary with bay level. As is the case for frequency sensitivity and flexibility parameters (Figure 5.3), the values of ΔC_D and $C_0/(C_0 + \Delta C_D)$ decrease monotonically with bay distance from the foundation. Damaged strength ratio (DSR) is plotted against flexibility sensitivity $C_0/(C_0 + \Delta C_D)$ in Figure 5.4 in which the static value and dynamic range are shown. In addition, the first-order approximation yielding equality of the two parameters is shown as a dotted line. Two tendencies are seen from Figure 5.4:(1) dynamic flexibility parameter sensitivity $C_0/(C_0 + \Delta C_D)$ is for the most part greater than the equivalent static value (i.e., higher change in flexibility parameter from modal observation than from static analysis), and (2) the damaged strength rating and static flexibility parameter sensitivity are roughly equal, as given by a first-order approximation.

Figure 5.5 displays the percentage increase in flexibility parameter (based upon dynamic analysis) as a function of the damage strength rating. Schematics of the failure cases are shown for easy reference. The form of presentation is the most meaningful for assessing the needed accuracy of detection relative to the significance of failure from the standpoint of retained strength. The notation 1R and 1F denotes case 1 rigid and flexible

Table 5.3 Generic Platform Lateral Sensitivity Summary

CASE	CONFIGURATION	N	$\left(\frac{N-1}{N}\right)$	STATIC ANALYSIS: DSR	STATIC ANALYSIS: C_0	STATIC ANALYSIS: ΔC	STATIC ANALYSIS: $\left(\frac{C_0}{C_0+\Delta C}\right)$	DYNAMIC ANALYSIS: ΔC_D (range)	DYNAMIC ANALYSIS: $\left(\frac{C_0}{C_0+\Delta C_D}\right)$ (range)
1	 *	2	0.50	0.50	0.05	0.10	0.33	0.108-0.200	0.200-0.316
2		2	0.50	0.50	0.05	0.10	0.33	0.104-0.178	0.219-0.324
3		4	0.75	0.69	0.50	0.19	0.72	0.196-0.844	0.372-0.718
4		4	0.75	0.74	0.50	0.17	0.75	0.110-0.380	0.568-0.820
5		4	0.75	0.69	0.50	0.19	0.72	0.157-0.705	0.415-0.761
6		6	0.83	0.78	0.50	0.11	0.82	0.085-0.225	0.690-0.855
7		8	0.83	0.76	0.50	0.075	0.87	0.130-0.534	0.484-0.794
8		8	0.83	0.85	0.50	0.065	0.88	0.089-0.380	0.568-0.849
9		9	0.89	0.83	0.50	0.065	0.88	0.088-0.392	0.561-0.850
10		9	0.89	0.89	0.50	0.065	0.88	0.082-0.321	0.609-0.859

* Severed member.

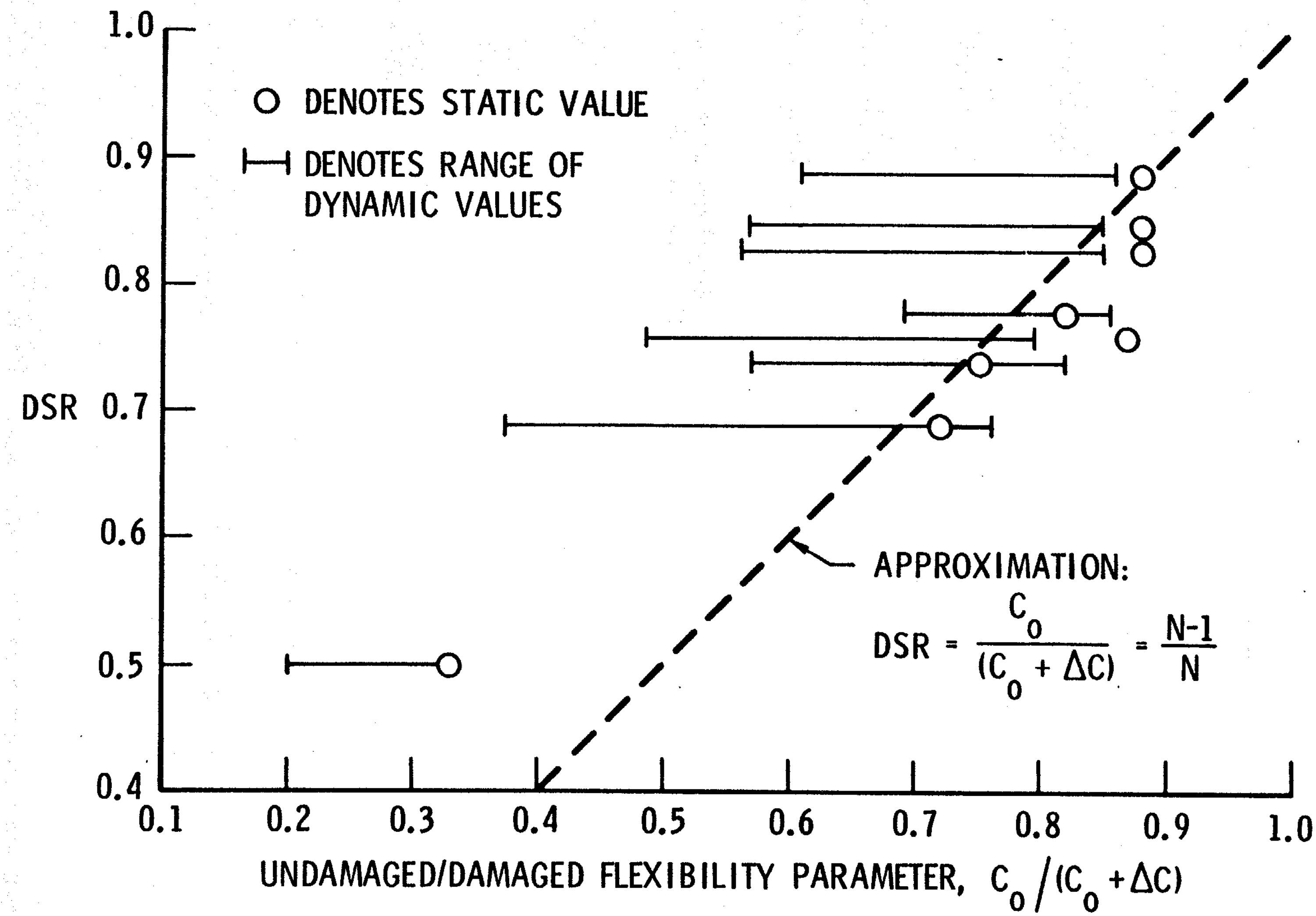


Figure 5.4 Damage Strength Rating vs. Flexibility Degradation

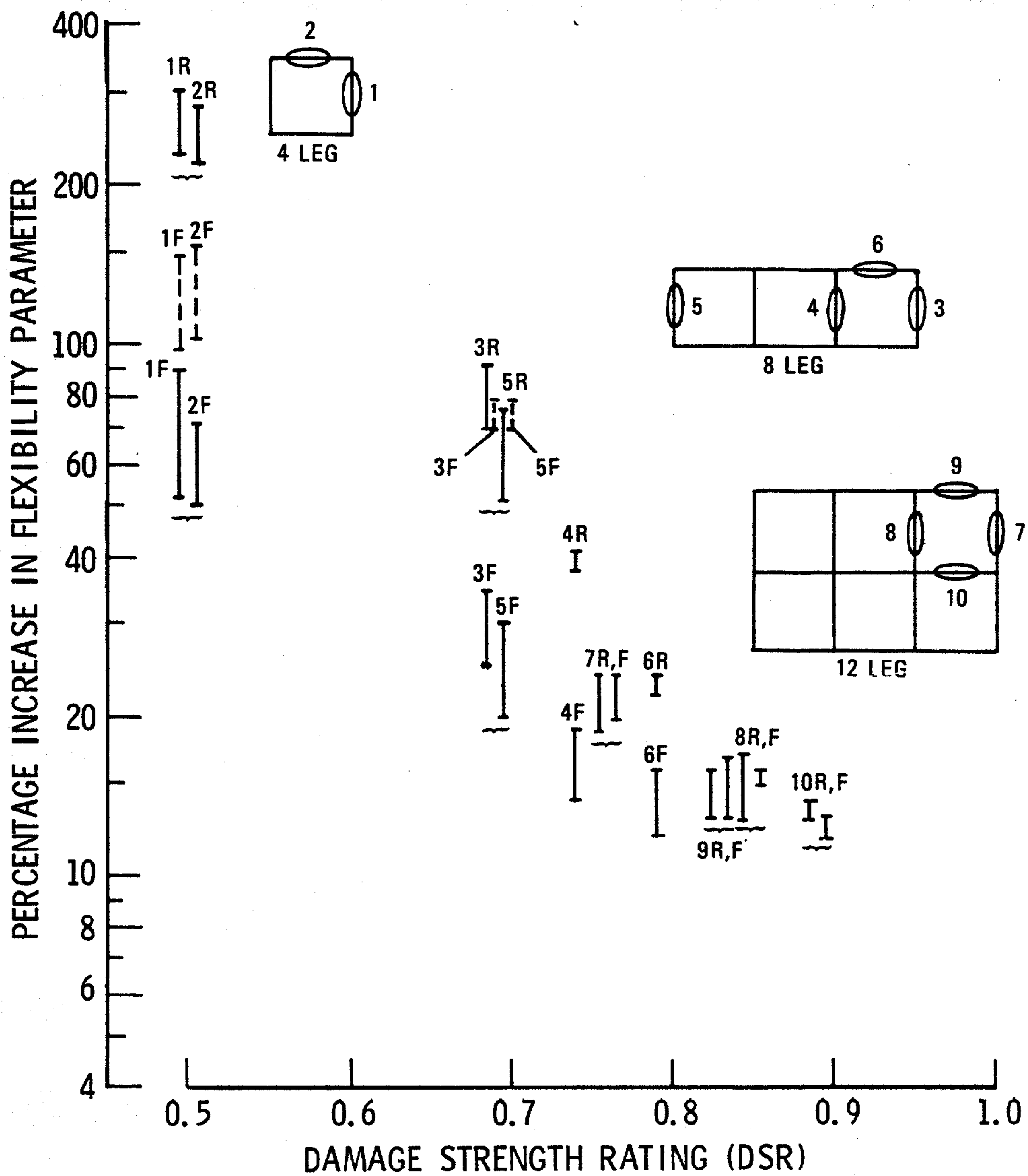
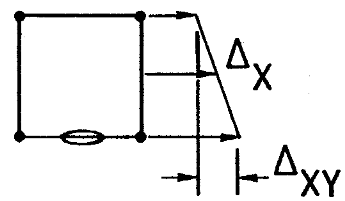


Figure 5.5 Flexibility Parameter Vs. Damage Strength Rating

5.5 Damaged Face Identification

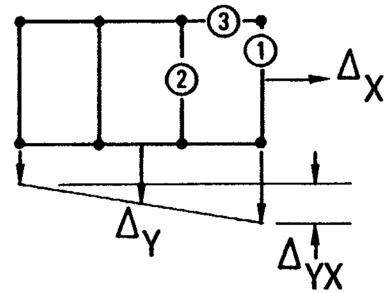
In the prior sections it was established for the three representative structures, that the bay level and member orientation of structural damage were identifiable on the basis of lateral flexibility change. Potential for identification of the face in which damage has occurred is assessed presently by noting the difference in flexibility readings at bay corners rather than the overall lateral flexibility parameter based upon average bay deflections. Typical failure cases for each representative structure, illustrated in Figure 5.6, indicated that localization of damage quadrant is possible when the failed member was a major contributor to bay torsional stiffness.

4-LEG CONFIGURATION (failure in Bay 3)



$$\left|\Delta_{XY}/\Delta_X\right| = \begin{cases} 2.80 \text{ (rigid foundation)} \\ 1.78 \text{ (flex foundation)} \end{cases} \text{ IN "X" MODE}$$

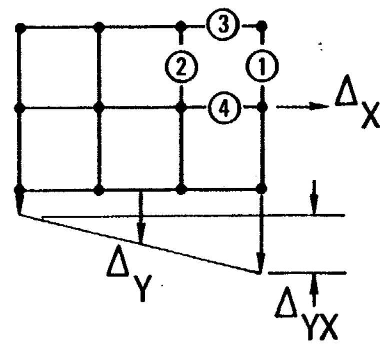
8-LEG CONFIGURATION (failure in Bay 4)



① : $\left|\Delta_{YX}/\Delta_Y\right| = 0.710$ IN "Y" MODE
② : $\left|\Delta_{YX}/\Delta_Y\right| = 0.209$ IN "Y" MODE
③ : $\left|\Delta_{YX}/\Delta_X\right| = 0.880$ IN "X" MODE

FLEX FOUNDATION

12-LEG CONFIGURATION (failure in Bay 7)



① : $\left|\Delta_{YX}/\Delta_Y\right| = 0.991$ IN "Y" MODE
② : $\left|\Delta_{YX}/\Delta_Y\right| = 0.533$ IN "Y" MODE
③ : $\left|\Delta_{YX}/\Delta_X\right| = 0.122$ IN "X" MODE
④ : $\left|\Delta_{YX}/\Delta_X\right| = 0$ IN "X" MODE

FLEX FOUNDATION

Figure 5.6 Employment of Lateral-Torsional Coupling to Locate Member Failure Face

6. RECOMMENDATION

A repeat field test is recommended on the Garden Banks structure. Several worthwhile objectives are apparent:

a. evaluation of refined calibration and equalization procedures for the accelerometers

b. evaluation of measurement repeatability after more than a year of elapsed time

c. the opportunity to observe effects of a significantly different deck loading and type of operation than for the original test which was carried out during drilling operations.

In addition, a mathematical modeling and evaluation effort on the Garden Banks structure is recommended. Failure sensitivity studies using that model could then be conducted: (1) to test the reasonableness of the present generic model results and (2) to specifically examine the damage detection capability of Flexibility Monitoring for this platform.

It is also recommended that field tests be structured to verify that jacket failure can be identified in a field situation. Practical considerations suggest use of a platform undergoing repair or scrappage, or some platform that is no longer serviceable and has been or can be designated as a test platform. Hopefully, already developed instrumentation could be utilized on a loan or rental basis from industry. Diver installation of the instrument packages would be required since chutes would likely not be present. Clearly a great deal of planning and industry cooperation would be essential to the conduct of a meaningful test at reasonable cost.

Due to the potential utility of instrument chutes (e.g., for oil company design evaluations, as well as possible application of Flexibility Monitoring), an effort evolved during the subject work to explore such considerations. Technical liaison with industry was established via individual representatives from Chevron, Exxon, Shell and Union Oil--all of whom have installed and/or are in the process of installing chutes on platforms for monitoring purposes. A key objective is to standardize the chute interior dimensions to help make commercial development of an instrument package economically feasible. It is recommended that MMS consider support of this work which could result in the development of a guideline document for industry. The document would address the requirements for Flexibility Monitoring, as well as those for monitoring in general. It is hoped that the design and installation of chutes for several upcoming structures off the California coast, for which chutes have been sanctioned, will be favorably influenced by the interchanges and agreements that have and will take place in coordination with industry representatives.

APPENDIX A

GENERIC OCS PLATFORM MATHEMATICAL MODEL

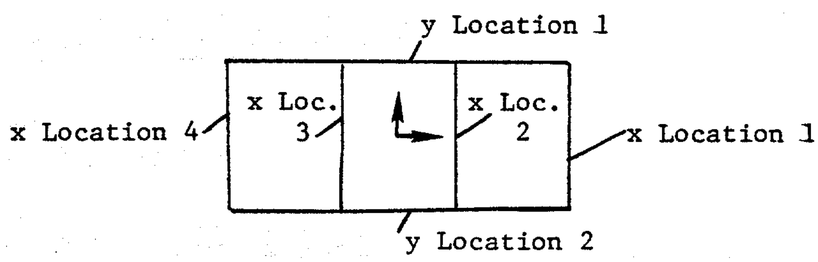
Appendix A - Generic OCS Platform Mathematical Model

The generic platform model discussed in Section 5 and illustrated in Figure 5.1 consists of an assembly of three component types, namely, the deck, structural bays and foundation. The deck is represented by a rigid distributed mass, M_D, and an eccentric concentrated mass, M_O. The structural bays are modeled as shear beam cells which are axially rigid, and mass distribution for the structural bays is lumped at the leg nodes. The foundation is described as a 6-dof stiffness matrix referenced to the base geometric center. Displacement variables for a platform with N bays, including the above water bay connecting the jacket truss to deck, consist of the shear displacements, x_i, y_i, θ_{zi}, for $i = 1$ to $N + 1$. In addition, the base displacements z_1, θ_{x1}, θ_{y1} are included to represent the motion in those directions for all bay levels due to the rigid axial kinematic assumption. Definitions of the system parameters are given in Table A.1.

The assembled intact structure stiffness and mass matrices are presented in Table A.2 and the damaged structure "delta" stiffness matrix is presented in Table A.3. In the course of analysis of the chosen generic structures several anomalies in the matrices were noted which do not affect the integrity of numerical results provided proper interpretations are made. The anomalies are reconciled by the following guidelines:

(1) the base rotations $\bar{\theta}_{x1}$ and $\bar{\theta}_{y1}$ are equal to the negative values of the variables θ_{x1}, θ_{y1} defined by the conventional right-hand rule

(2) The index of a damaged member location follows the convention illustrated in the figure below;



that is, the "x" index increases with decreasing value of the x location coordinate as does the "y" index with decreasing value of the y location coordinate.

The modal equations of motion are

$$- \omega_k^2 \; [M] \; \{\phi_k\} \; + \; [(K) - (\Delta K)] \; \{\phi_k\} \; = \; \{0\} \qquad \text{(A.1)}$$

where (ΔK) is null for the intact structure. The measurable flexibility parameters in the two lateral directions and the torsional direction are determined by calculating the appropriate bay difference displacements (e.g., $x_{n+1} - x_n$, $y_{n+1} - y_n$, $\theta_{zn+1} - \theta_{zn}$) in the fundamental lateral and torsional modes. The flexibility parameters are normalized with respect to the appropriate displacement difference for the above water bay.

Table A.1 - Generic Platform Parameter Definitions

GENERAL CONFIGURATION

a, b = x,y dimensions of all bays and deck

h = height of each bay

N = total number of bays

DECK MASS

M_D = uniformly distributed deck mass

M_0 = concentrated deck mass

a_o, b_o = x,y location of concentrated deck mass

I_{xxD} = $M_D a^2/12$

I_{yyD} = $M_D b^2/12$

I_{zzD} = $M_D(a^2+b^2)/12$

BAY STRUCTURAL STIFFNESS

K_s = intact bay lateral stiffness

N_y = number of legs along the x length

N_x = number of legs along the y length

Δa = $a/(N_y-1)$ = leg spacing along x length

Δb = $b/(N_x-1)$ = leg spacing along y length

a_j = $-\frac{a}{2} + (j-1)\Delta a$, $j = 1$ to N_y

b_i = $-\frac{b}{2} + (i-1)\Delta b$, $i = 1$ to N_x

K_T = $\sum_{i=1}^{N_x} b_i^2 \frac{K_s}{N_x} + \sum_{j=1}^{N_y} a_j^2 \frac{K_s}{N_y}$ = intact bay torsional stiffness

α = above water bay stiffness ratio with respect to truss jacket bays ($\alpha < 1$)

BAY MASS

M_s = total structural mass of all legs over length h

M_f = total fluid mass of all legs over the length h acting in the x and y directions only

$$I_s = \frac{M_s}{N_x} \sum_{i=1}^{N_x} b_i^2 + \frac{M_s}{N_y} \sum_{j=1}^{N_y} a_j^2$$ = effective torsional inertia of leg structure

$$I_f = \frac{M_f}{N_x} \sum_{i=1}^{N_y} b_i^2 + \frac{M_f}{N_y} \sum_{j=1}^{N_y} a_j^2$$ = effective torsional inertia of bay fluid

$$I_{sy} = \frac{M_s}{N_y} \sum_{j=1}^{N_y} a_j^2$$ = effective moment of inertia of bay about θ_{y_1}

$$I_{sx} = \frac{M_s}{N_x} \sum_{i=1}^{N_x} b_i^2$$ = effective moment of inertia of bay about θ_{x_1}

FOUNDATION STIFFNESSES

K_{fx}, K_{fy}, K_{fz}, $K_{f\theta_x}$, $K_{f\theta_y}$, $K_{f\theta_z}$ } uncoupled foundation stiffness coefficients

DAMAGED BAY DELTA STIFFNESS

k_x = $K_s/[(N_y-1)N_x]$ = individual x member stiffness

k_y = $K_s/[(N_x-1)N_y]$ = individual y member stiffness

a_{jD} = location of "y" member damage

b_{iD} = location of "x" member damage

m_x = number of "x" damaged members

m_y = number of "y" damaged members

ΔK_x = $m_x k_x$

ΔK_y = $m_y k_y$

Table A.2 - Intact Structure Stiffness and Mass Matrices

The vector of displacements for a platform is written as follows:

$$\{\phi\} = \left\{ z_1 \;\; \bar{\theta}_{x_1} \;\; \bar{\theta}_{y_1} \;\Big|\; x_1 \;\; y_1 \;\; \theta_{z_1} \;\Big|\; x_2 \;\; y_2 \;\; \theta_{z_2} \;\Big|\; \cdots \right.$$

$$\left. \cdots \Big|\; x_n \;\; y_n \;\; \theta_{z_n} \;\Big|\; x_{N+1} \;\; y_{N+1} \;\; \theta_{z_{N+1}} \right\}^T$$

where T denotes the matrix transpose.

The diagonal elements of the system stiffness matrix K (see Equation A.1) for the undamaged structure are:

$$K_{z_1 z_1} = K_{fz}$$

$$K_{\bar{\theta}_{x_1} \bar{\theta}_{x_1}} = K_{f\theta_x} + (N-1+\alpha)h^2 K_s$$

$$K_{\bar{\theta}_{y_1} \bar{\theta}_{y_1}} = K_{f\theta_y} + (N-1+\alpha)h^2 K_s$$

$$K_{x_1 x_1} = K_{fx} + K_s$$

$$K_{y_1 y_1} = K_{fy} + K_s$$

$$K_{\theta_{z_1} \theta_{z_1}} = K_{f\theta_z} + K_T$$

$$K_{x_i x_i} = K_{y_i y_i} = 2K_s \qquad i = 2,3,\ldots N-1$$

$$= (1+\alpha)K_s \qquad i = N$$

$$= \alpha K_s \qquad i = N+1$$

$$K_{\theta_{z_i z_i}} = 2K_T \qquad i = 2,3,\ldots N-1$$

$$= (1+\alpha)K_T \qquad i = N$$

$$= \alpha K_T \qquad i = N+1$$

The non-zero above-diagonal elements of K (a symmetric matrix) are

$$K_{\overline{\theta}_{x_1} y_1} = -K_{\overline{\theta}_{y_1} x_1} = hK_s$$

$$K_{x_i x_{i+1}} = K_{y_i y_{i+1}} = -K_s \qquad i = 1,2,\ldots N\text{-}1$$

$$= -\alpha K_s \qquad i = N$$

$$K_{\theta_{z_i} \theta_{z_{i+1}}} = -K_T \qquad i = 1,2,\ldots N\text{-}1$$

$$= -\alpha K_T \qquad i = N$$

The diagonal elements of the system mass matrix M (see Equation A.1) for the undamaged structure are:

$$M_{z_1 z_1} = M_D + M_0 + NM_s$$

$$M_{\overline{\theta}_{x_1} \overline{\theta}_{x_1}} = I_{xxD} + b_o^2 M_0 + NI_{sx}$$

$$M_{\overline{\theta}_{y_1} \overline{\theta}_{y_1}} = I_{yyD} + a_o^2 M_0 + NI_{sy}$$

$$M_{x_i x_i} = M_{y_i y_i} = \frac{1}{2}(M_s + M_f) \qquad i = 1$$

$$= M_s + M_f \qquad i = 2,3,\ldots N\text{-}1$$

$$= M_s + \frac{1}{2} M_f \qquad i = N$$

$$= M_D + M_0 + \frac{1}{2} M_s \qquad i = N+1$$

$$M_{\theta_{z_i} \theta_{z_i}} = \frac{1}{2}(I_s + I_f) \qquad i = 1$$

$$= I_s + I_f \qquad i = 2,3,\ldots N\text{-}1$$

$$= I_s + \frac{1}{2} I_f \qquad i = N$$

$$= I_{zz_D} + (a_o^2 + b_o^2) M_0 + \frac{1}{2} I_s \qquad i = N+1$$

The non-zero above-diagonal elements of M (a symmetric matrix) are:

$$M_{z_1\overline{\theta}_{x_1}} = b_o M_o$$

$$M_{z_1\overline{\theta}_{y_1}} = - a_o M_o$$

$$M_{\overline{\theta}_{x_1}\overline{\theta}_{y_1}} = - a_o b_o M_o$$

$$M_{x_{N+1}\theta_{z_{N+1}}} = - b_o M_o$$

$$M_{y_{N+1}\theta_{z_{N+1}}} = a_o M_o$$

Table A.3 - Damaged Structure "Delta" Stiffness Matrix

The diagonal elements of the "delta" stiffness matrix, for a failure between level n and n+1, are:

$$K_{\bar{\theta}_{x_1}\bar{\theta}_{x_1}} = h^2 \Delta K_y$$

$$K_{\bar{\theta}_{y_1}\bar{\theta}_{y_1}} = h^2 \Delta K_x$$

$$\left.\begin{aligned} K_{x_i x_i} &= \Delta K_x \\ K_{y_i y_i} &= \Delta K_y \\ K_{\theta_{z_i}\theta_{z_i}} &= b_D \Delta K_x + a_D \Delta K_y \end{aligned}\right\} \quad i = n, n+1$$

where a_D and b_D are the x and y distances, respectively, for the severed member.

Likewise, the non-zero above-diagonal elements of the symmetric "delta" stiffness matrix are:

$$K_{\bar{\theta}_{x_1} y_n} = - K_{\bar{\theta}_{x_1} y_{n+1}} = h \Delta K_y$$

$$K_{\bar{\theta}_{y_1} x_n} = - K_{\bar{\theta}_{y_1} x_{n+1}} = - h \Delta K_x$$

$$K_{\bar{\theta}_{x_1} \theta_{z_n}} = - K_{\bar{\theta}_{x_1} \theta_{z_{n+1}}} = - h a_D \Delta K_y$$

$$K_{\bar{\theta}_{y_1} \theta_{z_n}} = - K_{\bar{\theta}_{y_1} \theta_{z_{n+1}}} = - h b_D \Delta K_x$$

$$K_{x_n x_{n+1}} = -\Delta K_x$$

$$K_{y_n y_{n+1}} = -\Delta K_y$$

$$K_{x_n \theta_{z_n}} = -K_{x_n \theta_{z_{n+1}}} = -K_{\theta_{z_n} x_{n+1}} = K_{x_{n+1} \theta_{z_{n+1}}} = b_D \Delta K_x$$

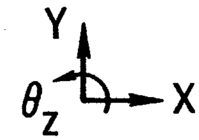
$$K_{y_n \theta_{z_n}} = -K_{y_n \theta_{z_{n+1}}} = -K_{\theta_{z_n} y_{n+1}} = K_{y_{n+1} \theta_{z_{n+1}}} = -a_D \Delta K_y$$

$$K_{\theta_{z_n} \theta_{z_{n+1}}} = -b_D^2 \Delta K_x - a_D^2 \Delta K_y$$

APPENDIX B

TABULATION OF DYNAMIC FLEXIBILITY SENSITIVITIES

Table B.1 4 Leg Flexibility Parameter Sensitivity (Rigid Foundation)



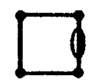
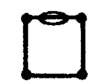
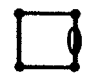
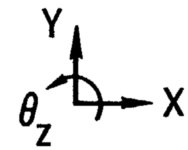
		C_o	 ΔC	$\Delta C/C_o$	 ΔC	$\Delta C/C_o$
Y	1	0.0537	0.123	2.29		
	2	0.0577	0.143	2.48		
	3	0.0603	0.165	2.73		
	4	0.0617	0.184	2.98		
X	1	0.0538			0.117	2.18
	2	0.0577			0.132	2.28
	3	0.0604			0.158	2.62
	4	0.0617			0.178	2.88
θ_Z	1	0.0610	0.051	0.84	0.057	0.94
	2	0.0729	0.071	0.98	0.080	1.10
	3	0.0812	0.098	1.21	0.109	1.34
	4	0.0855	0.129	1.51	0.140	1.64

Table B.2 4 Leg Flexibility Parameter Sensitivity (Flexible Foundation)





		C_o	ΔC	$\Delta C / C_o$	ΔC	$\Delta C / C_o$
Y	1	0.2073	0.108	0.52		
	2	0.2157	0.132	0.61		
	3	0.2216	0.151	0.68		
	4	0.2248	0.200	0.89		
X	1	0.2074			0.104	0.50
	2	0.2159			0.127	0.59
	3	0.2218			0.149	0.67
	4	0.2250			0.162	0.72
θ_z	1	0.0636	0.062	0.98	0.065	1.02
	2	0.0792	0.083	1.05	0.089	1.12
	3	0.0913	0.110	1.21	0.119	1.30
	4	0.0991	0.146	1.47	0.154	1.55

Table B.3 8 Leg Flexibility Parameter Sensitivity (Rigid Foundation)

										
		C_0	ΔC	$\Delta C/C_0$	ΔC	$\Delta C/C_0$	ΔC	$\Delta C/C_0$	ΔC	$\Delta C/C_0$
Y	1	0.5814	0.413	0.71	0.215	0.37	0.297	0.51		
	2	0.6917	0.512	0.74	0.263	0.38	0.374	0.54		
	3	0.7837	0.603	0.77	0.298	0.38	0.462	0.59		
	4	0.8548	0.692	0.81	0.333	0.39	0.556	0.65		
	5	0.9033	0.777	0.86	0.361	0.40	0.632	0.70		
	6	0.9280	0.844	0.91	0.380	0.41	0.705	0.76		
X	1	0.5828							0.128	0.22
	2	0.6951							0.153	0.22
	3	0.7887							0.174	0.22
	4	0.8613							0.198	0.23
	5	0.9107							0.209	0.23
	6	0.9358							0.225	0.24
θ_z	1	0.7201	0.396	0.55	0.022	0.03	0.540	0.75	0.043	0.06
	2	1.029	0.545	0.53	0.031	0.03	0.720	0.70	0.062	0.06
	3	1.294	0.686	0.53	0.039	0.03	0.854	0.66	0.078	0.06
	4	1.503	0.812	0.54	0.045	0.03	0.947	0.63	0.090	0.06
	5	1.647	0.922	0.56	0.049	0.03	1.021	0.62	0.115	0.07
	6	1.721	1.015	0.59	0.052	0.03	1.084	0.63	0.120	0.07

Table B.4 8 Leg Flexibility Parameter Sensitivity
(Flexible Foundation)

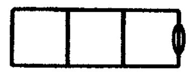
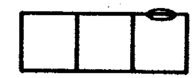
										
		C_0	ΔC	$\Delta C/C_0$	ΔC	$\Delta C/C_0$	ΔC	$\Delta C/C_0$	ΔC	$\Delta C/C_0$
Y	1	0.7847	0.196	0.25	0.110	0.14	0.157	0.20		
	2	0.8423	0.236	0.28	0.135	0.16	0.194	0.23		
	3	0.8895	0.267	0.30	0.151	0.17	0.222	0.25		
	4	0.9256	0.296	0.32	0.167	0.18	0.250	0.27		
	5	0.9503	0.323	0.34	0.171	0.18	0.276	0.29		
	6	0.9631	0.337	0.35	0.183	0.19	0.289	0.30		
X	1	0.7067							0.085	0.12
	2	0.7860							0.102	0.13
	3	0.8515							0.119	0.14
	4	0.9021							0.135	0.15
	5	0.9370							0.141	0.15
	6	0.9555							0.153	0.16
θ_z	1	0.7167	0.502	0.70	0.036	0.05	0.509	0.71	0.050	0.07
	2	1.022	0.650	0.68	0.041	0.04	0.736	0.72	0.072	0.07
	3	1.285	0.874	0.68	0.051	0.04	0.925	0.72	0.090	0.07
	4	1.496	1.047	0.70	0.060	0.04	1.092	0.73	0.105	0.07
	5	1.645	1.201	0.73	0.082	0.05	1.250	0.76	0.115	0.07
	6	1.727	1.347	0.78	0.086	0.05	1.382	0.80	0.121	0.07

Table B.5 12 Leg Flexibility Parameter Sensitivity
(Rigid Foundation)

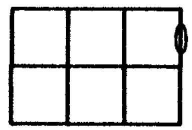
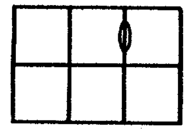
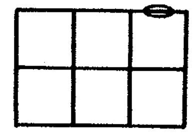
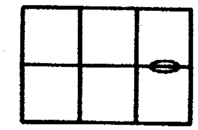
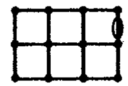
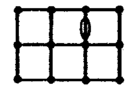
										
		C_0	ΔC	$\Delta C/C_0$	ΔC	$\Delta C/C_0$	ΔC	$\Delta C/C_0$	ΔC	$\Delta C/C_0$
Y	1	0.6862	0.130	0.19	0.089	0.13				
	3	1.160	0.255	0.22	0.186	0.16				
	5	1.585	0.365	0.23	0.254	0.16				
	7	1.917	0.441	0.23	0.307	0.16				
	9	2.138	0.513	0.24	0.363	0.17				
	11	2.236	0.492	0.22	0.380	0.17				
X	1	0.6742					0.088	0.13	0.088	0.13
	3	1.183					0.154	0.13	0.154	0.13
	5	1.622					0.260	0.16	0.211	0.13
	7	1.966					0.295	0.15	0.256	0.13
	9	2.196					0.351	0.16	0.285	0.13
	11	2.296					0.367	0.16	0.321	0.14
θ_Z	1	0.8374	0.126	0.15	0.008	0.01	0.059	0.07	0	0
	3	1.836	0.275	0.15	0.018	0.01	0.129	0.07	0	0
	5	2.712	0.434	0.16	0.027	0.01	0.190	0.07	0	0
	7	3.405	0.545	0.16	0.034	0.01	0.238	0.07	0	0
	9	3.870	0.658	0.17	0.038	0.01	0.271	0.07	0	0
	11	4.076	0.734	0.18	0.041	0.01	0.285	0.07	0	0

Table B.6 12 Leg Flexibility Parameter Sensitivity
(Flexible Foundation)

										
		C_0	ΔC	$\Delta C/C_0$	ΔC	$\Delta C/C_0$	ΔC	$\Delta C/C_0$	ΔC	$\Delta C/C_0$
Y	1	0.6870	0.137	0.20	0.103	0.15				
	3	1.157	0.243	0.21	0.174	0.15				
	5	1.562	0.344	0.22	0.250	0.16				
	7	1.890	0.416	0.22	0.302	0.16				
	9	2.114	0.486	0.23	0.338	0.16				
	11	2.225	0.534	0.24	0.356	0.16				
X	1	0.6850					0.089	0.13	0.082	0.12
	3	1.180					0.153	0.13	0.142	0.12
	5	1.610					0.209	0.13	0.193	0.12
	7	1.953					0.254	0.13	0.254	0.13
	9	2.190					0.285	0.13	0.285	0.13
	11	2.308					0.392	0.17	0.300	0.13
θ_z	1	0.8350	0.134	0.16	0.008	0.01	0.058	0.07	0	0
	3	1.830	0.293	0.16	0.018	0.01	0.128	0.07	0	0
	5	2.710	0.434	0.16	0.027	0.01	0.190	0.07	0	0
	7	3.420	0.581	0.17	0.034	0.01	0.239	0.07	0	0
	9	3.914	0.705	0.18	0.039	0.01	0.274	0.07	0	0
	11	4.163	0.749	0.18	0.042	0.01	0.291	0.07	0	0

APPENDIX C

PHASE I

EXTENDED ROUND ROBIN

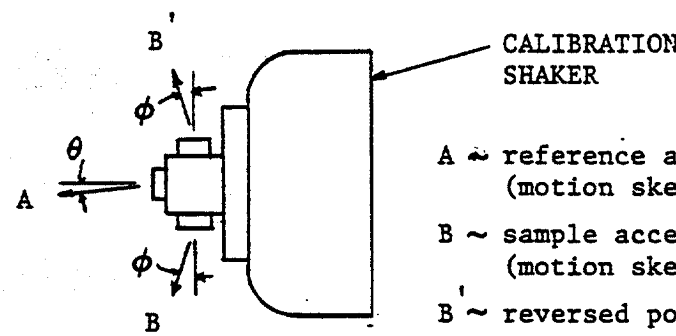
SCALE MODEL TEST PROCEDURES

TASK 1. Accelerometer Cross-Axis Behavior

OBJECTIVE: Measure cross-axis sensitivity of accelerometers and identify axis of minimum sensitivity-for 8 accelerometers.

APPROACH:

1. Establish that the shaker plus a mounting cube is free of cross axis motion by comparing the sign of the outputs of B and B' re A in the setup below:



A ~ reference accelerometer (motion skew angle θ)

B ~ sample accelerometer (motion skew angle ϕ)

B' ~ reversed position of B

Assuming motion in the plane of the page -

$$B/A = |B/A| \sin(\phi+\theta)$$
$$B'/A = |B/A| \sin(\phi-\theta)$$
$$\text{if } \theta = 0,\ \phi \neq 0 : B'/A = B/A$$
$$\text{if } \theta \neq 0,\ \phi = 0 : B'/A = -B/A$$

2. Assuming that the setup is essentially free of cross axis motion (i.e., $\theta = 0$), use it to measure the principal axis sensitivity, as well as sensitivity along at least 4 cross axes separated by 45°, for $10 \leq f \leq 300$ Hz. Plot results vs. frequency f, as well as % sensitivity vs. angular position at one or more frequencies. Mark accelerometer with dot for direction of minimum cross sensitivity. (Reference: B & K description of their method. Copy attached.)

TASK 1. Accelerometer Cross-Axis Behavior (Cont'd)

NOTES: Send plots for first accelerometer tested to Aerospace for review before proceeding with remaining accelerometers. If particular accelerometers are relatively cross sensitive, they may be excluded from use. The decision on the assignment of specific accelerometers to the 8 positions A to H, as well as the orientation of their dots, will be based upon the results of this task.

TASK 2. Accelerometer Relative Calibration

OBJECTIVE: Measure amplitude and phase of accelerometers B-H, including associated antialiasing filters and analyzer channel, relative to accelerometer A.

APPROACH: Establish a relative calibration setup, perhaps using the calibration shaker, for $10 \leq f \leq 40$ Hz for one or more accelerometers in addition to A. Use a 1g and 0.1g amplitude. Channel assignments are:

Channel:	1	2	3	4	5	6
Accelerometers:	A	B	C,G	D,H	E	F

Use GenRad analysis system to obtain required frequency response functions for a 0.08 Hz resolution and a Hann window. Plot results to be read to within 1% on amplitude and coherence, and 2° on phase. All hardware and settings must be identical to that used for platform tests.

CONCERNS: If relative calibrations show amplitude ratios of more than 5% or erratic behavior, the cause will have to be identified and corrected. The final relative calibration should ideally be accomplished within a week of actual testing start. A preliminary relative calibration on a few accelerometers should be done early to assess quality of the processing.

NOTES: Send plots of preliminary relative calibration results to Aerospace for review. Amplitude and phase corrections, derived from this task, will be input to the software program for derivation of flexibility parameters.

TASK 3. Physical Setup of Baseline Model

OBJECTIVE: Create a baseline setup that provides bottom flexibility and damping, and provides for the accelerometer positioning and forcing shown in Figure 1. A capability should exist for easily increasing the bottom flexibility to simulate a foundation change condition.

APPROACH: Use rubber pad material or commercial rubber isolator devices to float the four model leg bottoms to achieve a reduction in fundamental lateral and torsional frequencies of 10 to 15 percent (and, hopefully, a fraction of critical damping of roughly 1 to 2 percent). Vertical flexibility should be within a factor of 2 of the lateral flexibility at each leg bottom. A possible pad design is shown in Figure 2.

To simulate a foundation change, a design that roughly doubles the foundation flexibility should also be established. For example, the pads in the design shown in Figure 2 could be converted to double layer pads with a thin metal plate between them.

Mounting blocks for the accelerometers should be installed at all positions shown in Figure 1, with careful attention to alignment relative to the global X, Y, Z axes. Misalignment should not exceed 2°.

CONCERN: The use of rubber resilient devices will introduce some degree of nonlinear behavior. The degree of nonlinearity, in terms of shifts of natural frequency and changes in damping, will have to be identified. It may be that such nonlinear behavior will be useful in that it will provide an opportunity to investigate the consequent influence on flexibility parameters.

TASK 3. Physical Setup of Baseline Model (Cont'd)

NOTES: After basic setup is created, obtain frequency responses of several deck accelerations per unit force for several levels of forcing to identify natural frequencies, damping, and their variation due to nonlinearity. Use modal software to extract the fundamental modal frequencies and dampings (don't need mode shapes). Supply information to Aerospace in advance of test start for assessment of setup suitability.

Affix label to each accelerometer to denote A to H designation and positive direction of sensitivity. Afix label to each mounting position on the model to denote the level - leg designation and the positive global direction. Each data run should be checked for correspondence to the intended accelerometer configuration.

TASK 4. Software

OBJECTIVE: Prepare software to carry out all data acquisition and processing required.

NEEDS:

1. Acquire six channels of data and FFT from 0 to 40 Hz at 0.08 Hz resolution, using a Hann window and 50 averages overlapped 50%.

2. For Runs 1 and 7 (see Run Schedule), compute APS of channels 1 and 6, and FRF & COH of channels 1-5 re channel 6. Store and plot.

3. For Runs 2-6

   a. Compute APS of ch. 1, and FRF & COH of ch. 2-6 re 1. Store and Plot. Designate F(i) to be the FRF for ch. i.

   b. For the frequency range (lines LY1-LY2, ≤ 64 in number) to be established to include the Y first lateral, calculate

   $$RS = \alpha_2 F(2)-1$$

   where α_2 is a calibration factor (complex) for the accelerometer on ch. 2. Then calculate, plot and list the following:

   $$S_j = \alpha_{j+2} F(j+2)/RS \qquad j = 1,4$$
   $$S_5 = S_2 - S_1$$
   $$S_6 = S_4 - S_3$$
   $$S_7 = S_5 - S_6$$
   $$S_8 = S_5 + S_5$$
   $$S_{j+8} = S_j \; RS/RSD \qquad j = 1,8$$

   where RSD = RS-S_5 from Run 2.

   c. For the frequency range (lines LT1-LT2, ≤ 64 in number) to be established to include the first torsion, calculate

   $$RT = \alpha_2 F(2) - 1.$$

TASK 4. Software (Cont'd)

Then calculate, plot and list the following:

$$T_j = \alpha_{j+2} F(j+2)/RT \qquad j = 1,4$$
$$T_5 = T_2 - T_1$$
$$T_6 = T_4 - T_3$$
$$T_7 = T_5 - T_6$$
$$T_8 = T_5 + T_6$$
$$T_{j+8} = T_j RT/RTD \qquad j = 1,8$$

where $RTD = RT - T_5$ from Run 2.

4. <u>For Runs 8-12</u>

a. Compute APS of ch. 1, and FRF & COH of ch. 2-6 re 1. Store and plot.

b. For the frequency range (lines LX1-LY2, ≤ 64 in number) to be established to include the X first lateral, perform the same operations as in Section 3b except

$RSD = RS - S_5$ from Run 8.

c. Same as Section 3c except

$RTD = RT - T_5$ from Run 8.

RUN SCHEDULE

RUN	CHANNEL NO. 1	2	3	4	5	6
1	A(1-0)	B(2-0)	C(1-1)	D(2-1)	E(1-2)	FORCE
2	↓	↓	↓	↓	↓	F(2-2)
3	↓	↓	G(1-3)	H(2-3)	↓	↓
4	↓	↓	↓	↓	E(1-4)	F(2-4)
5	↓	↓	G(1-5)	H(2-5)	↓	↓
6	↓	↓	G(1-Z)	H(3-Z)	E(4-Z)	F(2-Z)
7	A(3-0)	B(4-0)	C(3-1)	D(4-1)	E(3-2)	FORCE
8	↓	↓	↓	↓	↓	F(4-2)
9	↓	↓	G(3-3)	H(4-3)	↓	↓
10	↓	↓	↓	↓	E(3-4)	F(4-4)
11	↓	↓	G(3-5)	H(4-5)	↓	↓
12	↓	↓	G(4-Z)	H(1-Z)	E(2-Z)	F(3-Z)

NOTES: 1. A (1-0)

- 0 → LEVEL NO. (0 to 5) OR Z FOR VERTICAL AT LEVEL 5
- 1 → LEG NO. (1 to 4)
- A → ACCELEROMETER DESIGNATOR (A to H)

2. SPECIAL HYBRID PROCESSING REQUIRES -

oscilloscope; true rms voltmeter; tunable band pass filter (10 to 40 Hz); real-time, 2-channel FFT analyzer; eight channels of data (accels A to H) to be input via BNC connections to test unit furnished by Aerospace.

TASK 5. Model Changes

OBJECTIVE: Create selected changes to model and obtain flexibility parameters.

APPROACH: The following changes are required:

1. Mass addition to deck - add about 25% of baseline deck mass locally at periphery of deck.
2. Cut a diagonal member at mid level.
3. Cut a horizontal member at mid level.
4. Increase foundation flexibility by about a factor of two.

Figure C-1. Setup Schematic Flexibility Monitoring Tests

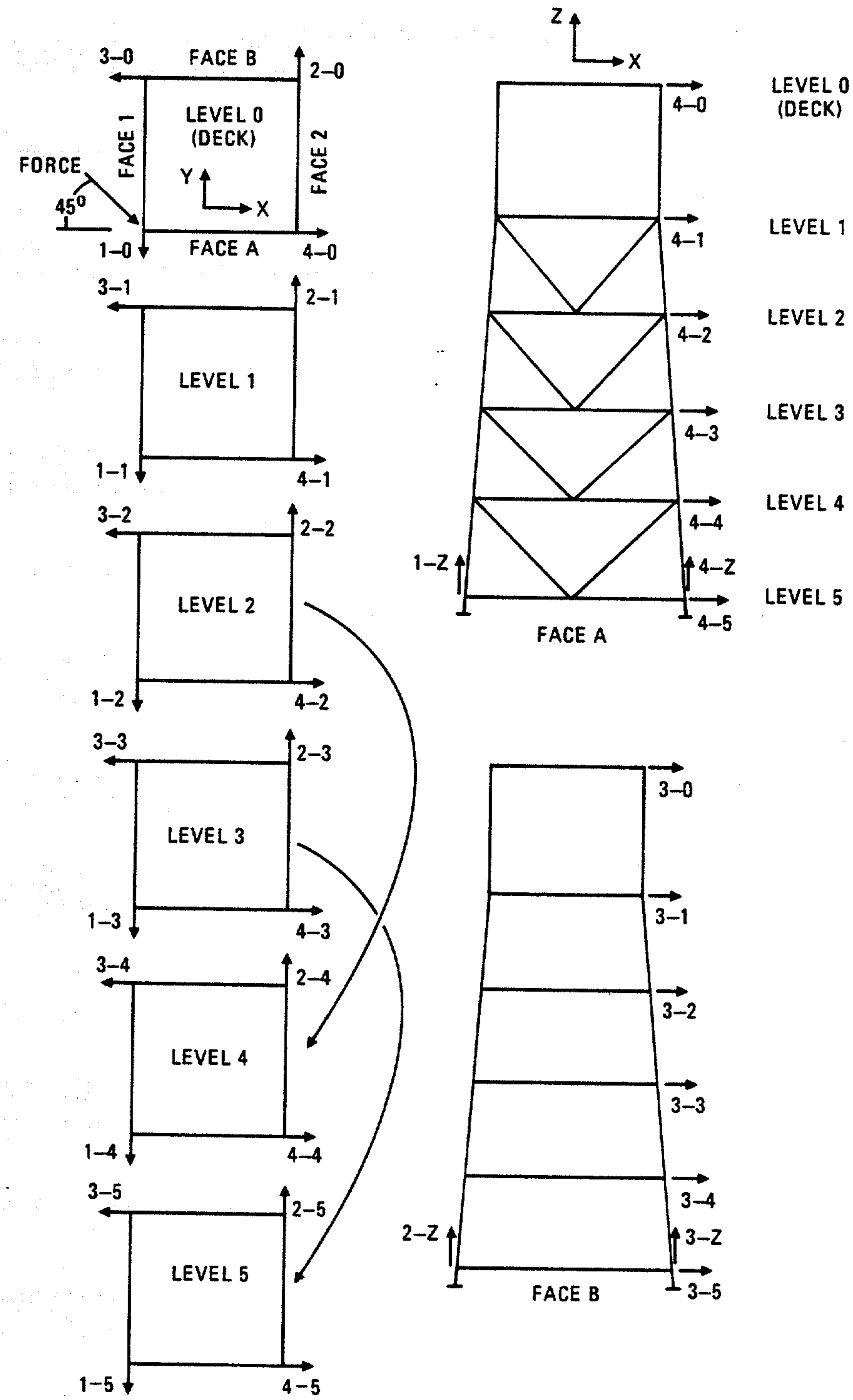


FIGURE C-2.

AEROSPACE CORPORATION	CALCULATION NO.	REPORT NO.	PAGE 1 OF 1
	PREPARED BY S. RUBIN	DATE 23 MAR 81	APPROVED CHECKED
TITLE SAMPLE DESIGN – FLEXIBLE SUPPORT			PROJECT RR MODEL

BARRY 30005 MOUNTING PAD (pp. G–31, 32 OF BULLETIN C5–178)

MODEL WEIGHT $W \doteq 230$ lb

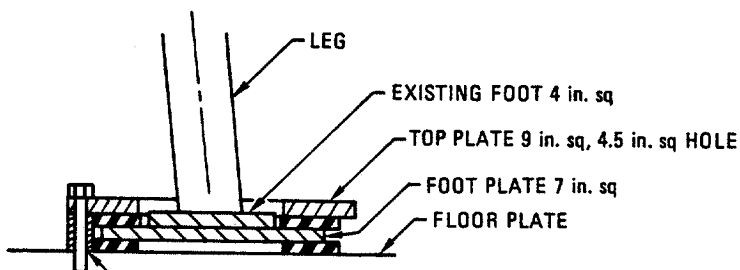
DESIRED NAT FREQ ON MOUNTINGS $f_n \approx 60$ Hz

LOAD ≈ 1.3 psi (SINGLE COMPRESSION PAD, p. G–32)

≈ 2.6 psi (DOUBLE ACTING PAD)

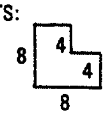
$$\text{PAD AREA/FOOT} = \frac{230 \text{ lb}}{(2.6 \text{ psi})\,4} = 22 \text{ in.}^2$$

PRELIMINARY DESIGN:



$$\text{AVAILABLE PAD AREA} = 7^2 - 4.5^2 \doteq 29 \text{ in.}^2$$

PAD AVAILABLE IN 24 in. sq SHEETS, WILL MAKE 12 PARTS:



→8 NEEDED PER FOOT

∴ 3 SHEETS SUFFICIENT

DOUBLE FLEXIBILITY DESIGN:

REPLACE EACH PAD WITH TWO PADS SEPARATED BY 1/8 in. THICK STEEL PLATE. ANOTHER 3 SHEETS REQUIRED

AEROSPACE FORM 2165 REV 5-66 ENGINEERING ANALYSIS

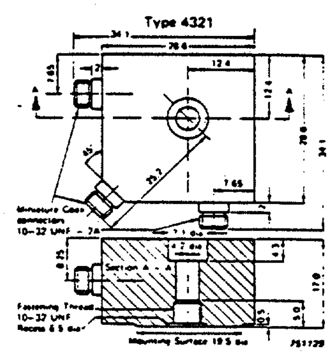
FIGURE C–3.

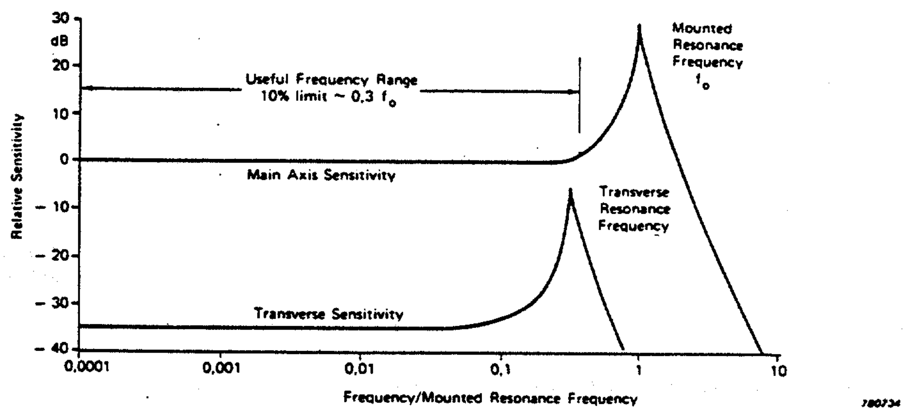
Transverse sensitivity

B & K measures the orientation and percentage of transverse sensitivity of each accelerometer manufactured by means of a special vibration table which vibrates sideways at a fixed frequency of 30 Hz and a fixed amplitude of 100 ms^{-2} (about 6 mm peak-to-peak). The accelerometer is mounted with its main axis perpendicular to the direction of vibration (i.e., vertical), on a mounting which enables it to be rotated about its main axis. The output of the accelerometer is monitored, and the mounting rotated, until a minimum is found. This is marked on the base of the accelerometer by means of a red spot. The mounting is then rotated 90° and the output recorded. If necessary, the accelerometer may also be mounted with its main axis parallel to the vibration direction in order to measure the main axis output under the same vibration conditions. The maximum transverse sensitivity is then the ratio of the maximum output obtained on the rotating mount to the output on the fixed mount (expressed as a percentage).

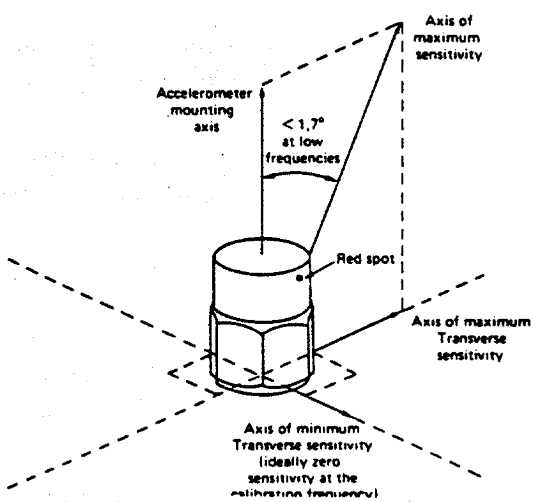
If a batch of accelerometers is being calibrated, this main axis measurement need be taken only on one of them, since that determines the acceleration amplitude. There is normally no requirement for users to repeat this kind of measurement, since small changes in main-axis sensitivity of an accelerometer would normally be accompanied by proportionate changes in maximum transverse sensitivity. If there occurs a significant change in main-axis sensitivity, it is probable that the accelerometer has been damaged, and the transverse sensitivity may in this case have altered considerably.

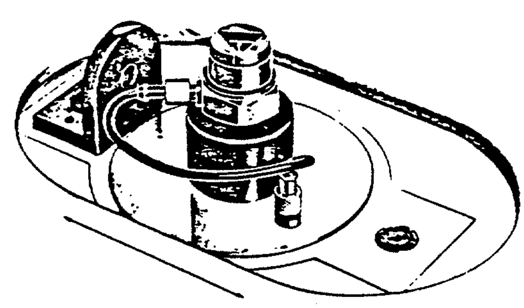
The 30 Hz transverse sensitivity calibration is valid over a large part of the working frequency range of the accelerometer, but reliance should not be placed on it at frequencies within a decade of the mounted resonant frequency. The Calibration Chart for the Type 4321 Triaxial Accelerometer includes frequency response curves for both main and transverse axes.





The Transverse Sensitivity of a piezoelectric accelerometer is normally a small percentage of Main Axis Sensitivity, except at the higher frequencies, where the transverse sensitivity exhibits a mounted resonant peak at a frequency of approximately one-third of the main-axis mounted resonant frequency. The Transverse Sensitivity curve illustrated is idealized. Transverse sensitivity measurement is hampered by the difficulty of ensuring purely axial excitation. Practical curves exhibit many irregularities.





APPENDIX D

PHASE II

OFFSHORE PLATFORM

COGNAC TEST PLAN

(Including sample test data sheets)

Offshore Platform Test Plan (COGNAC)

I. Component Test

The data acquisition system (MODAL UNIT) shall be checked out for operational capability prior to being transported to the offshore platform.

The instrumentation packages (5) shall be subjected to 1g calibration procedures in all three axes in the laboratory of the Shell Development Company.

II. System Test

Upon arrival at the COGNAC platform the data acquisition hardware shall be interconnected as necessary and power shall be applied. Cables from the MODAL unit to the instrumentation packages shall be routed to the appropriate areas of the platform (A1, A4, B1 and B4 legs) and connected to the packages. The operation of the system hardware shall be checked out and DC voltage step calibrations, synchronous signal tests and instrumentation package and resident accelerometer relative calibrations shall be monitored in real time and recorded on tape.

Two biaxial accelerometers are permanently mounted at the +55 foot deck on structure legs A1 and B4. The four instrumentation packages are deployed, one per instrumentation chute as follows:

Package 1 (P1) at leg B4
Package 2 (P2) at leg A1
Package 3 (P3) at leg A4
Package 4 (P4) at leg B1

The first test, Bay #1, shall have packages 1 and 2 at the +12' boat deck level and packages 3 and 4 at the -32 foot level. Each succeeding test shall require the repositioning of two packages only, i.e. for the Bay #2 test, packages 1 and 2 shall be moved to the -92 foot level etc. After the Bay #4 test, repeats of Bays #3, 2 and 1 may be conducted. Real time signal monitoring, data analysis and tape recording will be employed for all platform tests.

At the conclusion of the platform tests a post test synchronous signal calibration shall be recorded.

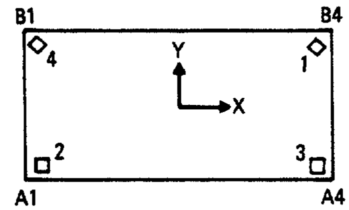
Sample data worksheets are included in this appendix.

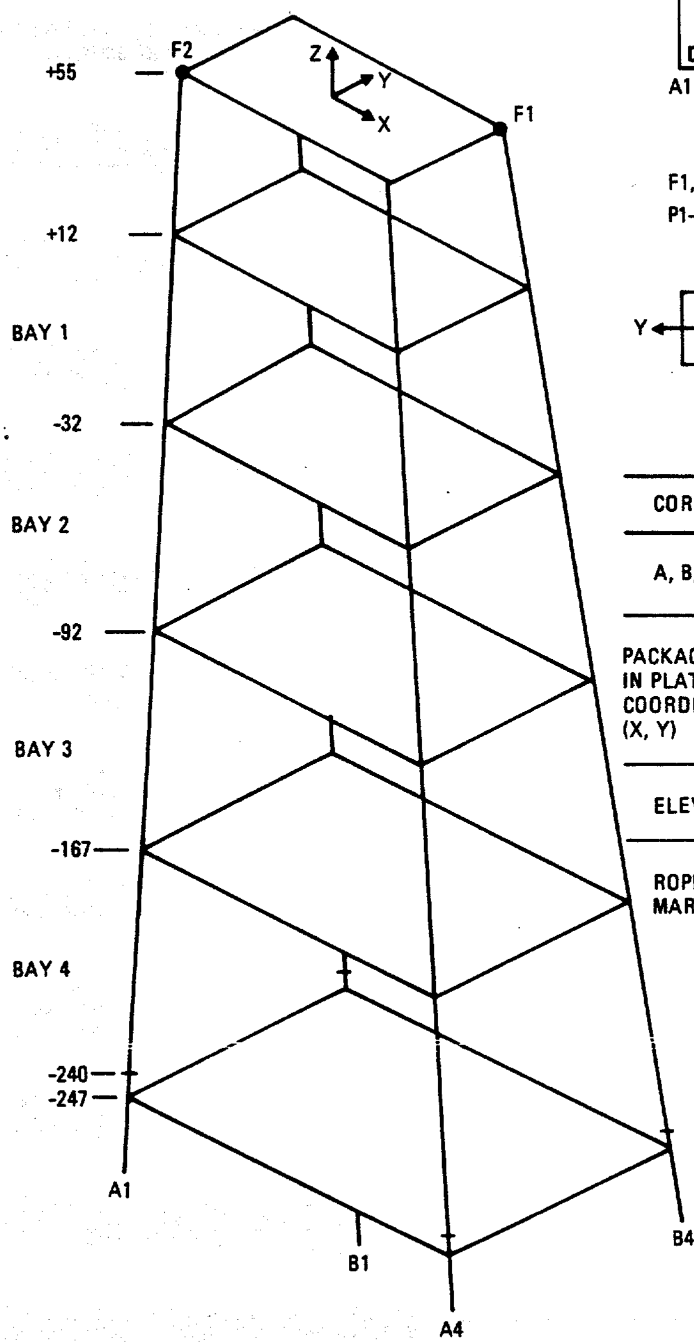
PAGE ____ OF ____

COGNAC Platform – Test Configuration

TEST No. ________ DATE 4/ /82

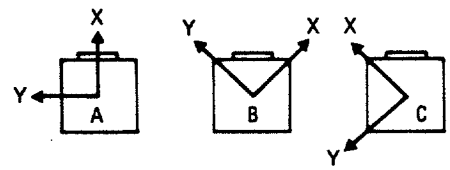
TIME ________ BY ________





F1, F2 FIXED ACCELS

P1–P4 PACKAGES



	P1	P2	P3	P4
CORNER	B4	A1	A4	B1
A, B, C		A	A	
PACKAGE AXES IN PLATFORM COORDINATES (X, Y)				
ELEV				
ROPE MARK				

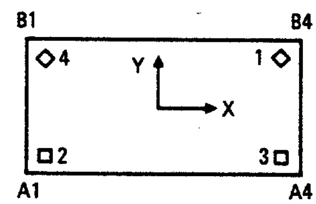
Modal Data Sheet

PAGE ____ OF ____
DATE ____
BY ____
TIME ____

PLATFORM COGNAC
TEST No. ____

1.

CHANNEL	MEAS.
1 2	
3 4	
5 6	
7 8	
9 10	
11 12	
13 14	



SHOW
WIND
WAVE

2. SIGNAL PROCESSING RACK

	x	y	z	x	y	z	x	y	z	x	y	z	x	y	z	
RACK CHANNEL BNC	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
NORMAL / TEST																
POLARITY FWD / REV																
DIFF/BUFFER/RECEIVER BNC																
X100 AMPLIFIER BNC																
LOW PASS FILTER (2 Hz) BNC / IN / OUT																
HIGH PASS FILTER (0.02 Hz) BNC / IN / OUT																
DIFF/BUFFER/DRIVER BNC																

3. TAPE RECORDER

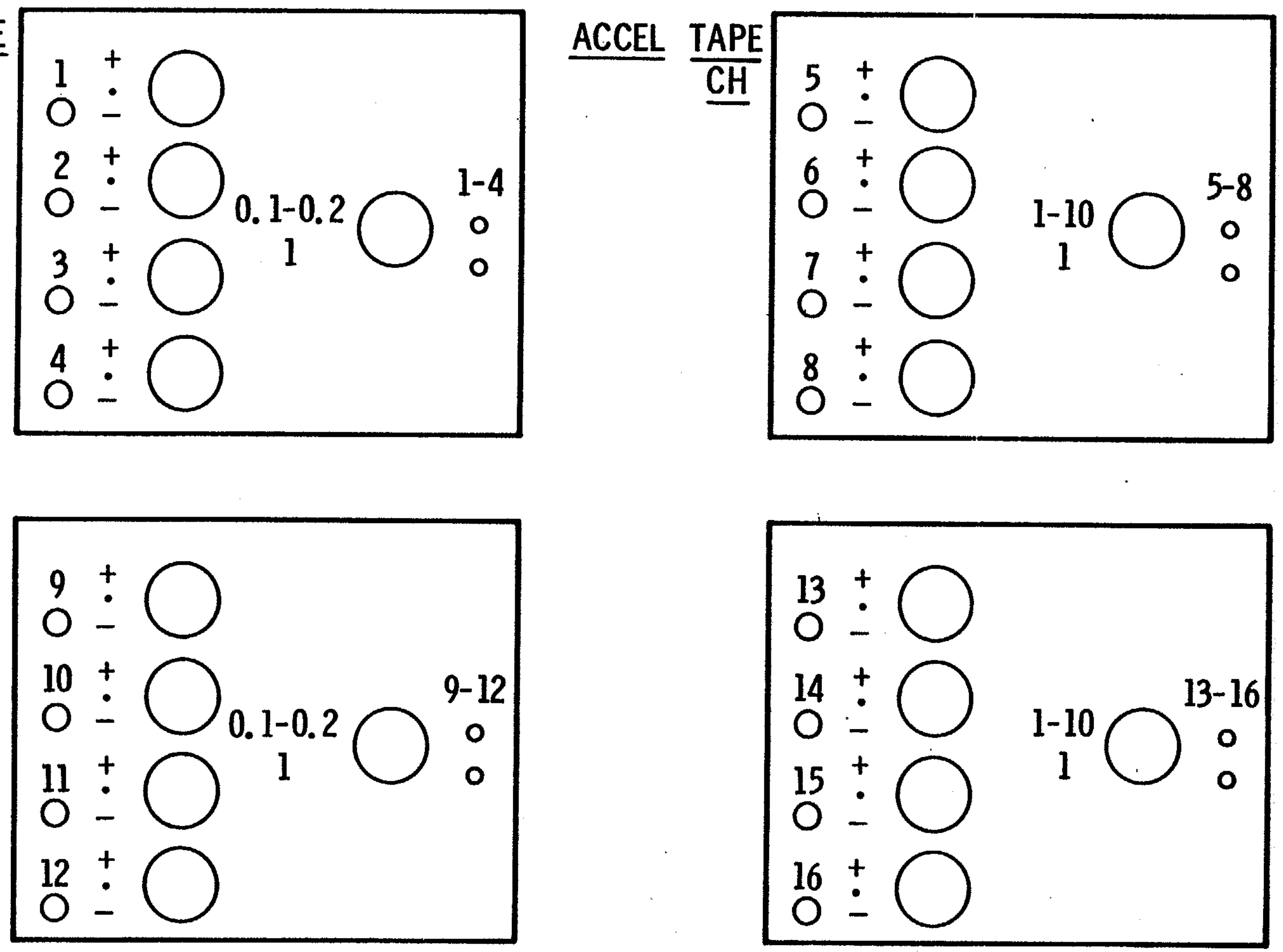
RECORD BNC														
PLAYBACK BNC														
TAPE TRACK*	1	2	3	4	5	6	7	8	9	10	11	12	13	14
ATTENUATION														

Analog Summing Unit Setup

PLATFORM ________ TEST No. ______

DATE __/__/__ TIME ________ BY ______ PAGE ___ OF ___

ACCEL TAPE/CH ACCEL TAPE/CH



COGNAC

MODAL DATA SHEET PAGE___OF___

TEST No. ______ DATE ___/___/___

4. DATA TAKING TAPE LABEL: ______

RESET OFFSET IN DIFF/BUFFER/RECEIVER YES ☐ NO ☐

COMMENT ____

TAPE CALIBRATION – AT TIME ______ FOOTAGE ______

____ VOLTS FROM ____ FEET TO ____ FEET ON CHANNEL ____

____ VOLTS FROM ____ FEET TO ____ FEET ON CHANNEL ____

BEGIN DATA RECORD: TAPE SPEED ____ ips

TIME _____ TAPE _____ FEET

DURING TEST:

END DATA RECORD:

TIME _____ TAPE _____ FEET

OTHER NOTES:

APPENDIX E

PHASE III
OFFSHORE PLATFORM
GARDEN BANKS TEST PLAN

(Including sample test data sheets)

Offshore Platform Test Plan (GARDEN BANKS)

I. Component Test

The data acquisition system and the instrumentation packages (4) were recently exercised on the platform, therefore, no preliminary checkout shall be necessary.

The supplementary instrumentation, (analog summing unit, FFT Signal Analyzer, and the HP 85) were checked out at the Aerospace facility prior to shipping to the offshore platform.

II. System Test

Upon arrival at the Garden Banks platform, the data acquisition hardware shall be interconnected as necessary and power shall be applied. Cables from the data acquisition system shall be routed to the appropriate areas of the platform (A1 and B4 legs) and connected to the instrumentation packages. The operation of the system shall be checked out prior to running absolute and relative calibration tests which will be recorded on tape and monitored in real time.

The resident triaxial accelerometers used for the field test are mounted on legs A1 and B4. Relative calibrations are accomplished by placing the instrumentation packages on deck plating about one meter away from the resident accelerometers which are affixed to the legs. The four instrumentation packages are deployed, two per instrumentation chute as follows:

Package 1 at leg B4 (lower)

Package 2 at leg B4 (upper)

Package 3 at leg A1 (lower)

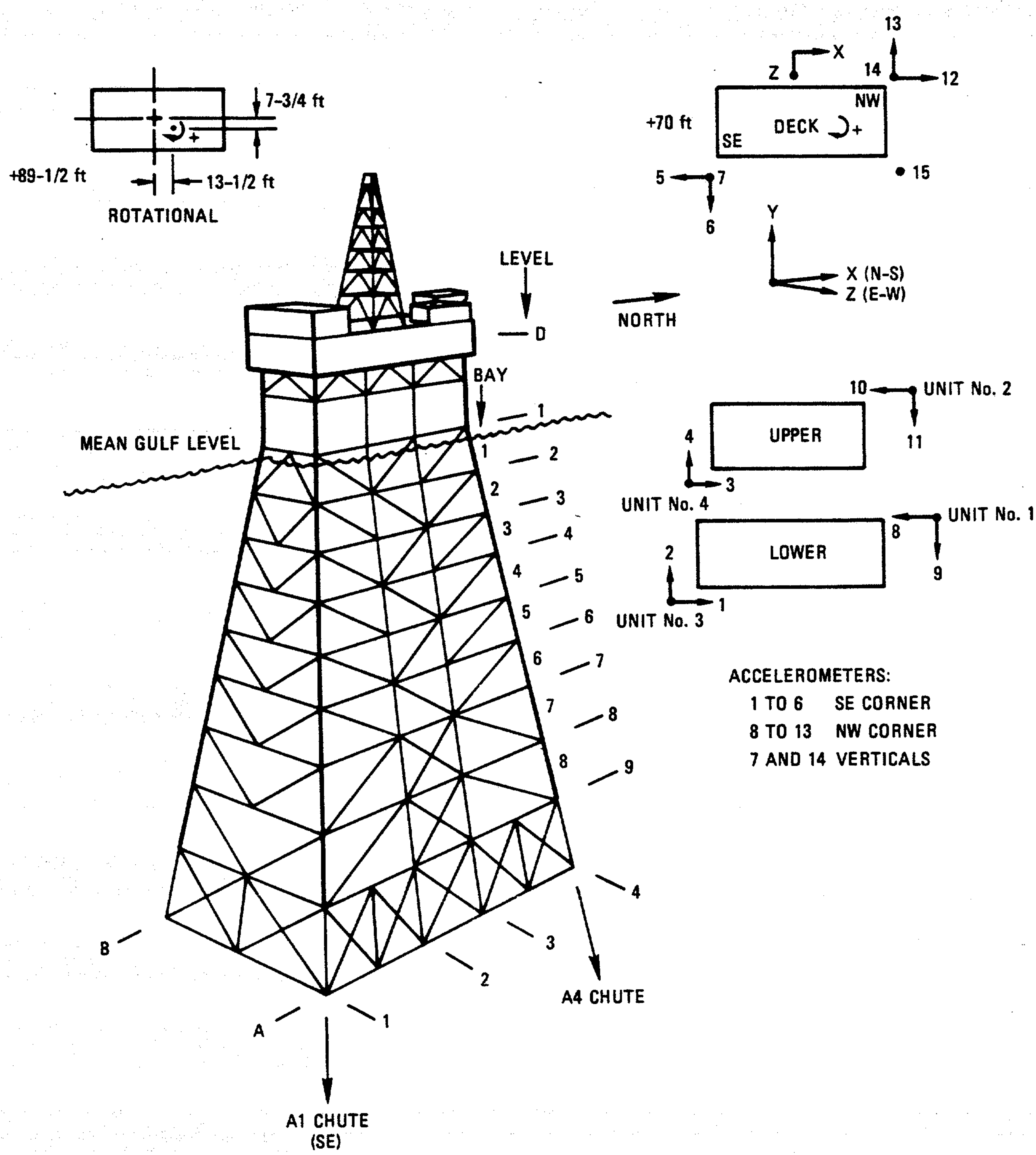
Package 4 at leg A1 (upper)

The first test, Bay #1 shall have packages 2 and 4 at the +12 boat deck level and packages 1 and 3 at the -37 foot level. Each succeeding test requires the repositioning of all four packages to define each bay. Bays 1-8 shall be tested in succession with possible retests of selected bays as the packages are brought up from the lowest levels. Real time signal monitoring, data analyses and tape recording of the data will be employed for all platform tests.

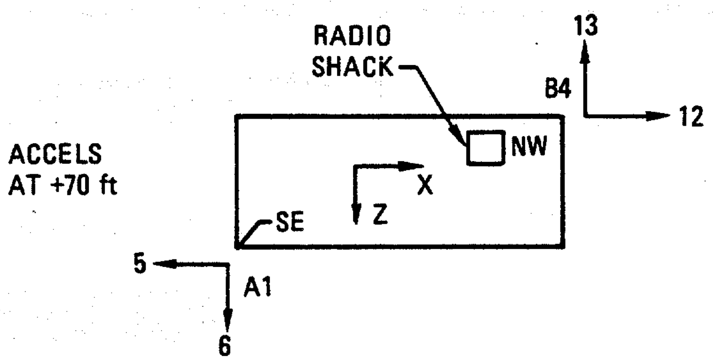
At the conclusion of the tests of all bays, post calibrations of all pertinent instrumentation shall be accomplished and recorded on tape.

Sample data worksheets are included in this appendix.

Garden Banks 236 "A" Structure

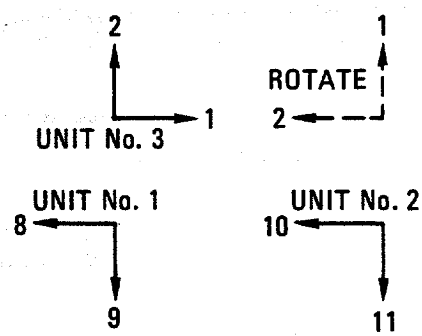


Relative Calibrations



REF ACCEL No. 1

SETUP 1 AT NW



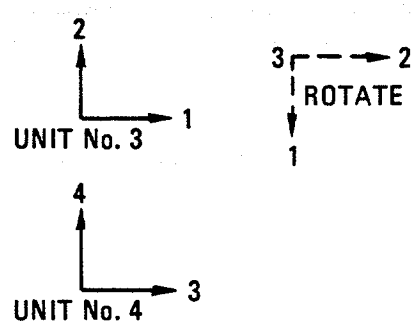
NORMAL POSITION OF UNIT No. 3

8/1, 12/1, 10/1

ROTATE UNIT No. 3

9/1, 13/1, 11/1

SETUP 2 AT SE



NORMAL POSITION OF UNIT No. 3

3/1, 5/1 2/6 THEN $2/1 = \frac{2}{6} \cdot \frac{6}{1}$

ROTATE UNIT No. 3

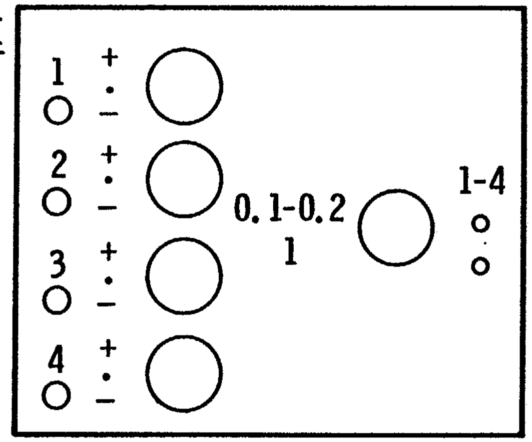
6/1, 4/1

Analog Summing Unit Setup

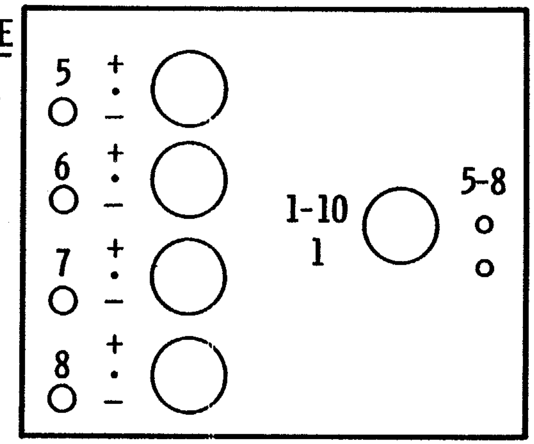
PLATFORM ________ TEST No. ______

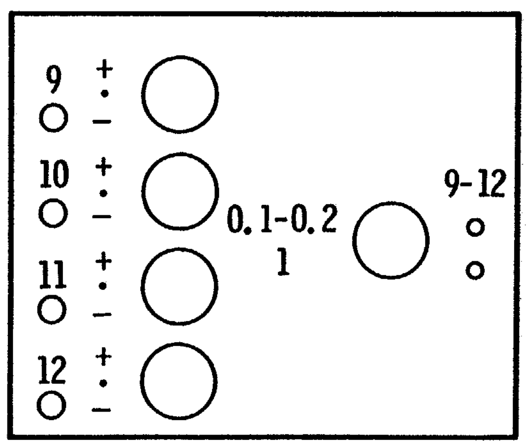
DATE __/__/__ TIME ________ BY ______ PAGE ___ OF ___

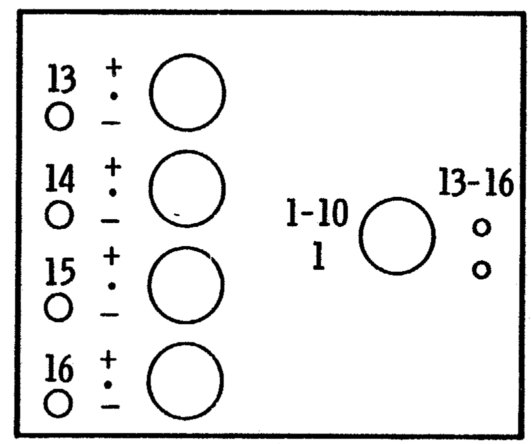
ACCEL | TAPE/CH



ACCEL | TAPE/CH







Garden Banks 236 "A"
DECEMBER 1982
REAL TIME TF ANALYSES

DATE TIME FOOTAGE	ID	CAL/BAY	MEAS.	F/N	MAG	ϕ/γ^2	COMMENTS (KB or H, M2, Z?)			