The MIT Marine Industry Collegium
Opportunity Brief #10

Vibration Response and the Structural Integrity of Deepwater Structures

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VIBRATION RESPONSE AND THE STRUCTURAL INTEGRITY OF DEEPWATER STRUCTURES

Opportunity Brief #10

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PREFACE

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Through Opportunity Briefs, Workshops, Symposia, and other interactions the Collegium provides a means for technology transfer among academia, industry and government for mutual profit. For more information, contact the Marine Industry Advisory Services, MIT Sea Grant, at 617-253-4434.

Norman Doelling

1 July, 1978

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1.0 A Business Perspective

The dynamic behavior of offshore platforms has always been an important consideration in their design, construction, and operation. The subject is now of urgent interest for two reasons. The first is a change in the United States regulatory environment and the second is a consequence of moving to deeper waters for the exploration and production of offshore oil and gas. With these two changes have come a wide range of opportunities for companies to provide new techniques, equipment, and services to the builders and operators of offshore platforms.

The regulatory change is reflected in a press release issued in May 1977, in which the U.S. Department of the Interior announced the establishment of

> A new program aimed at assuring that offshore oil and gas platforms are built to withstand the various forces of nature, especially in the deeper, more hostile 'frontier' areas of the Outer Continental Shelf...
>
> The Program will include verification and inspection during the design, construction, installation and operation stages to insure that the platforms meet minimum structural integrity standards to be established by the USGS.
>
> Third parties will conduct the inspections for most structures. Third parties may be either employed or contracted personnel hired by the platform operators or platform fabricators. They cannot be responsible, however, for the operation they inspect, and they must report directly to the management. In all cases, third party inspectors will have to be approved beforehand by the USGS and must meet and enforce USGS standards..

The second factor motivating this Opportunity Brief is that newer, larger structures for deeper waters have lower resonance frequencies that are closer to the peaks of the wave energy spectra. Hence the dynamic response of the structures and the control of that response becomes more urgent.

Analytic and experimental work at MIT over the past four years provides a basis for some new services and instrumentation, based on the long time vibration response histories of offshore structures. Some results have already been reported in the technical literature (1,2) and some commercial ventures and oil companies have already begun to exploit these techniques (4,5,6). In this Brief, we first address present and potential capabilities and limitations of the techniques as a monitoring or verification tool, and second, we address some important aspects of controlling dynamic response of deepwater structures.

2.0 Vibration Analysis as a Verification Tool

2.1 General

The taller structures associated with oil and gas production in deeper waters will have fundamental frequencies that fall near the peak of the wave excitation spectra. Thus, the dynamics of structures may become more important, and damping rather than stiffness may become the predominant mechanism in limiting stress.

At the Offshore Technology Conference in 1975, Professor J. Kim Vandiver of MIT introduced the petroleum industry to the concept of detecting below-the-waterline structural failure by periodically obtaining and analyzing dynamic response data (1). Research in this area has continued and, as evidenced by subsequent papers presented in 1976 at OTC, a number of other investigators have been implementing these ideas (3,4,5). By OTC 1977 several commercial ventures were offering structural monitoring services to the industry.

2.2 Vibration Response as a Measure of Structural Integrity

The basic notion of using vibration response as a measure of structural integrity is not new. It has been applied in many fields, as Vandiver notes:

> "The detection of structural failure by measurement of a related change in natural frequency is not without precedent. There is continuing industrial research in the field of expensive rotating machinery such as generators and jet engines. More closely related work has been performed by civil engineers interested in the seismic response properties of large buildings. For several years civil engineers have been able to measure the natural frequencies of large buildings using sensitive accelerometers. Wind and seismic forces have sufficient broadband random excitation that most buildings respond at one or more of the natural frequencies included in the band. Measurements made before and after earthquakes have revealed damage-related frequency reductions as large as 50%. In many cases visual

> inspection revealed no damage. For example, in steel-reinforced concrete buildings, microcracks that developed in the concrete were undetected in visual inspections, and yet caused a substantial reduction in the structural stiffness and, therefore, the natural frequency." (Ref. 1)

The technique of vibration analysis is based on the simple idea that if a resonance frequency changes, something else has changed as well. Elementary dynamics tells us the effective mass may have changed, the effective stiffness may have changed, or the boundary conditions may have changed. However, more information about the structure and its dynamics is needed to tell us exactly what has changed.

Obviously if we are to know that a change has taken place, resonance frequencies must be monitored on a long-term basis. Such measurements are non-trivial and "detectability thresholds" for measurable changes in frequency are important considerations. Also, two simultaneous events, such as reducing the mass at the top of an offshore structure and failure of a brace can in principle have offsetting compensating effects on resonance frequency, which could result in no change in resonance frequency, although substantial changes took place in the structure.

The above observations indicate some obvious limitations of the technique. However, these limitations do not appear to invalidate the significant potential for using the techniques to monitor and "verify" the integrity of offshore structures and to play a useful role in their design and analysis.

Successful applications of the technique require that careful measurements in the field and thorough analysis of the resulting data be coupled with careful *a priori* dynamic analysis of a structure before undertaking any measurements. The addended paper provides a specific example of how vibration analysis was effectively used on a specific structure. We outline below the methodology that can be applied generally.

2.3 Computation of Changes in Resonance Frequency

2.3.1 An Ideal Structure

A break in a structural member of an offshore tower will cause a change in the stiffness of a structure (assuming all other variables are constant) and a change (Δf_o) in some resonance frequency. Two questions immediately arise. First, how large will the change be? And second, can the change be measured?

In order to answer the first of these questions, we can compute the resonance frequencies (f_{x1}, f_{x2}, ... ; f_{y1}, f_{y2}, ... ; $f_{\theta 1}$ ...) of a structure by using a computer program such as ICES-STRUDL or an equivalent. By rerunning the program with successive structural members removed (i.e., broken), we can compute new resonance frequencies; the change in resonance frequencies is thus found for each successive case.

To estimate how small a change in resonance frequency is detectable requires a knowledge of many variables that are specific to a particular structure and location. For example, Vandiver (Ref. 1) estimated that a change in resonance frequency of 1% could be detected in a Coast Guard tower located at the entrance of Buzzards Bay, Massachusetts. Using a 1% criterion, he found that the complete failure of 36 key structural members would cause a detectable Δf_o, and the failure of 16 would <u>not</u> cause detectable Δf_o.

Although this is not too impressive a result at first glance, one should note that small changes in f_o are associated with small changes in static stiffness so that the undetectable "breaks" tend to be the unimportant ones structurally. Conversely, important structural breaks tend to be detectable. Furthermore, since removal (or breaking) of a member generally causes different changes in f_x, f_y, and f_θ, some information can be obtained about which member might be broken.

2.3.2 Non-Ideal Structures

In the analysis above, one must make assumptions that certain parameters, which in fact may change, do not change. Two important such assumptions in the computer analysis are that the foundation stiffness is of a known, fixed magnitude, and that the mass distributed throughout the structure is fixed. Both assumptions may be invalid. Scour around a pile is common and may have a very important effect on resonance. For example, unpublished experiments on a U.S. Coast Guard platform near Cape Hatteras, which has experienced 10 feet of scour around its pilings, indicate that scour has caused an 8% decrease in fundamental natural frequency of the structure.

Properties of the bottom soil itself may change radically when the soil is subjected to long-term variable loads. In a paper presented at OTC 1976, Mike Utt, et al of Union Oil (5) reported that due to softening of the soils near the mudline, the natural period of the Union Oil Monopod platform in Cook Inlet, Alaska had increased by 18%.

Thus, monitoring of natural frequencies may yield valuable information about the condition of supporting soils. This may be especially useful with large gravity structures, where soil stability and soil liquification are of concern, and in earthquake prone areas where partial, undetected soil failures may occur during an earthquake, leaving the structure more vulnerable to subsequent earthquakes or storms.

Changes in mass distributed through the structure can have important effects on natural frequencies. On a drilling platform, pipe and drilling mud are changeable masses on top of the structures. On production platforms, diesel fuel, water, and supplies for personnel may represent significant variable masses. These changes in mass must be taken into account during analysis of vibration data; otherwise, one might infer damage or change in foundation conditions where none existed.

On some structures, such as automated production platforms, long-term changes in mass may be accurately accounted for, resulting in a very sensitive detection threshold. On others, such as active drilling rigs, the detection threshold may result in a poorer sensitivity, due to the uncertainty in accounting for changes in structural mass. Each platform will have its unique features and challenges to the engineer. Vibration analysis may prove to be unsuitable in some cases and very reliable in others. When appropriate, it is far cheaper than the alternatives, particularly diver inspections, and far quicker. When economically justifiable, a permanent monitoring system might be used to account for the everyday changes in resonance frequencies, and to raise an alarm when something unusual occurs.

3.0 Design for Vibration Control for Offshore Structures

Parallel efforts in the Department of Civil Engineering and the Department of Ocean Engineering at MIT have been concerned with the issue of how to use dynamic absorbers as a vibration control measure in the design stage for offshore structures. The major cyclical stress response (and the case of fatigue failure) of very large structures in an ocean environment occurs at frequencies near the fundamental vibration frequencies of the structure. Control of stress at these low frequencies can be achieved by the introduction of carefully designed dissipative dynamic vibration absorbers, since the maximum stress when excited by the wideband wave spectrum in most cases will be inversely proportional to the damping. Two mechanisms of "artificial" damping are discussed below.

3.1 Tuned Mass Damping

The addition of a tuned mass damper, or a resonant dynamic absorber, to control vibration response is not new. However, the application of tuned mass damping to very large structures such as buildings or offshore structures is more recent. The propensity of Boston's new John Hancock Building to shed its glass windows led to detailed studies of the dynamic behavior of very large structures and an analysis of the possible effects of a very large tuned mass damper in controlling vibration stress forced by a random excitation, with reasonable success.

Application of the technique to an offshore platform has been studied by Glacel (7) using finite element models of three offshore platforms. He investigates also the effect of dynamic absorbers on reducing cyclical stress in the soil beneath gravity type structures.

The investigation included the 1000 foot steel jacketed platform being developed by Shell Oil Company, a 1200 foot platform of theoretical design, and the Condeep Brent B platform. Results show that cyclic stress could be reduced substantially, i.e. decreases on the order of 40% to 50% in certain cases. The cited reductions were achieved with mass ratios on the order of 5%. That is, the added dynamic mass was as much as 5% of the total mass of the structure, or about 1% to 2% of the total mass.

The most interesting aspects of Glacel's analysis have been the insights into the effects of the dynamic vibration forces on the supporting soil stability, and conversely, the effects of the changing soil condition on the dynamic behavior of the platform. Considerable mechanical ingenuity will be needed to design, install and test the efficacy of tuned absorbers, but the results obtained by computer models are sufficiently promising to demand such tests.

The motions of a rigid mass tuned dynamic absorber relative to the platform can become quite large. Thus, a relatively large free area on the top of the platform will be needed for the tuned dynamic absorber, by the associated equipment and for the free area needed to allow motion of the absorber mass. The need for free area limits the applicability of traditional tuned dynamic absorbers on offshore structure, since "free areas" on them are virtually non-existent.

Pipes, compressors, pumps, diving equipment, fine control equipment, operational controls, loading and unloading facilities and innumerable other items related to the prime function of the structure have more important claims on the very limited space available.

3.2 Tuned Liquid Damping

A vexing problem encountered in the MIT studies of the Buzzard's Bay Entrance Tower was the total effective mass carried on the top of the tower, since a large fraction of the mass was water or fuel oil. The apparent effective mass was found to depend on the dynamic response properties of the liquids in the tanks. Small changes in depth caused substantial changes in the standing waves (sloshing) of the liquids in the tanks. Simple analysis quickly reveals that tank geometry and depth control the standing wave natural frequencies of the tank. Since the liquids are viscous, energy is dissipated in sloshing, and some damping is imparted to the structure. Both the effective mass of the structure and its damping depend on the tuning of the waves in the tank.

Preliminary analysis also reveals that a liquid storage system may be intentionally configured to provide the structure with a maximum of additional damping. In effect the liquid storage system can be designed to approximate the effects of a tuned dynamic absorber.

Unlike the rigid mass dynamic absorber, the liquid dynamic absorber requires little "free space" and may only require proper design of tanks, which would be on board the platform in any event for water, fuel, drilling mud, and storage.

A feasibility study was conducted by Vandiver and Mitome at MIT. The results were presented in a paper given at the May 1978 OTC (8). This paper provides an excellent introduction to the potential of tuned liquid dynamic absorbers. Hardware implementation and field tests are needed to prove the concept.

4.0 Future Directions

Vibration monitoring is a very good index of structural changes in an offshore structure. Thus, vibration analysis services appear to have an important role in monitoring the structural behavior of offshore platforms. Appropriate measurement techniques and data analysis need continuing development and clearly need to be coupled closely with studies of the dynamics of the system in order to interpret the significance of the data; that is, the nature and location of the structural change that caused the change in resonance frequency. Divers and other contemporary means of inspection may still be needed, but on a less frequent, less time consuming, and less expensive basis than without vibration monitoring.

Structural design incorporating vibration control will be essential to the structural integrity of very deep offshore structures. The studies cited here indicate several important points. First, design for vibration control can obviate serious resonance problems. Second, liquid damping techniques, using liquids that are going to be part of the platform in any event, hold great promise as vibration control tools if properly applied. Third, the effects of vibration and attendant cyclic stress on soil foundations are extremely important, and very poorly understood.

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APPENDIX

"Detection of Structural Failure
on Fixed Platforms
by Measurement of Dynamic Response"

Professor J. K. Vandiver

M. I. T.

Detection of Structural Failure on Fixed Platforms By Measurement of Dynamic Response

J. K. Vandiver, Massachusetts Institute of Technology

Introduction

As offshore platforms are erected in progressively deeper waters, the problem of on-site inspection of subsurface structural members becomes increasingly difficult and expensive. The current use of divers is hampered by poor visibility, poor lighting, and hazardous conditions. These obstacles worsen rapidly with increasing depth. In addition, marine growth and corrosion may conceal structural defects.

The inspection technique described here requires periodic measurement of selected natural frequencies that show direct response to wind and waves. Wind- and wave-force spectra have sufficient broad-band random excitation to drive most offshore structures at one or more of their natural frequencies. Accelerometers can be used to measure the platform response, and the natural frequencies can be determined from the records. Such determinations might be made on a semiannual or annual basis. A detected shift in natural frequency between successive measurements would indicate a change in the mass or stiffness of the structure. A reduction in stiffness implies failure in the structural members and joints, or in the supporting bottom conditions. In some circumstances the measurements might be helpful in determining the location of the failure. At the very least, the periodic inspection can be used to determine whether a much more expensive diver survey should be conducted.

A detailed study of one offshore pile-supported tower was conducted. The tower is a welded-steel space frame with four primary legs, braced with horizontal and diagonal members. It is fixed to driven steel piles, stands 150 ft above the mud line in 70 ft of water, and weighs about 600 tons. The tower serves as a manned U.S. Coast Guard light station near the Massachusetts coast. Though small by most standards, its limited size made an in-depth survey possible.

A computer simulation of the Buzzards Bay light station was prepared using the Massachusetts Institute of Technology ICES-STRUDL II structures program.[1] A systematic study of the effect of structural damage was conducted and the results were compared with the accuracy of experimental determinations of natural frequency. It was found that, except for a few of the most insignificant members, the determination of natural frequency was accurate enough to detect failure of individual subsurface members. In some circumstances it would even be possible to isolate the general location of the break. It was also determined that widespread corrosion would cause a detectable change.

Before dawn on May 6, 1974, a vessel displacing about 900 tons struck the Buzzards Bay entrance tower. One crew member on the tower was thrown from his bunk by the impact. After dawn a visual inspection revealed no damage above the water line. Most of the supporting jacket is hidden below the water line and its condition was unknown.

Fortunately, the natural frequencies of this tower in flexure and rotation had been determined previously. By noon a Coast Guard helicopter had transported the author and the necessary measurement equipment to the tower. By 6 p.m. it was determined that there was no significant

Subsurface structural failure of fixed offshore platforms can be determined with a technique that detects changes in the natural frequencies of the structure. One tower was studied extensively, and the dynamic measurement and analysis techniques are described.

damage below the water line. Ultrasonic tests conducted by divers in Aug. 1974 confirmed these findings. The following sections discuss the testing techniques that were used and present the appropriate background theory.

State of the Art

The detection of structural failure by measurement of a related change in natural frequency is not without precedent. There is continuing industrial research in the field of expensive rotating machinery such as generators and jet engines. More closely related work has been performed by civil engineers interested in the seismic response properties of large buildings. For several years civil engineers have been able to measure the natural frequencies of large buildings using sensitive accelerometers. Wind and seismic forces have sufficient broad-band random excitation that most buildings respond at one or more of the natural frequencies included in the band. Measurements made before and after earthquakes have revealed damage-related frequency reductions as large as 50 percent.[2] In many cases visual inspection had revealed no damage. For example, in steel-reinforced concrete buildings, microcracks that developed in the concrete were undetected in visual inspections, and yet caused a substantial reduction in the structural stiffness and, therefore, the natural frequency.

Force-balance-type accelerometers that have been developed for seismic work can be applied directly to measuring dynamic response of offshore towers to wind and wave forces. These devices are capable of resolving 10^{-6} g's, one-millionth of the acceleration of gravity. In extremely calm weather conditions the Buzzards Bay tower responds at 10^{-5} to 10^{-4} g's at its natural frequencies. Much of the instrumentation that works on buildings is readily adaptable to offshore towers.

Fast Fourier Transform (FFT) techniques have been used to analyze the dynamic response of offshore structures.[3] FFT spectrum analysis was used in this work to obtain estimates of natural frequency and damping.

Experimental Methods

Theory

The lowest frequencies of vibration that are found on bottom-supported towers in the ocean are the flexural and rotational frequencies associated with the bending and twisting of the entire structure relative to the point of bottom attachment. These frequencies are important for structural reasons because they are low enough to be driven by the higher-frequency components of the wind- and wave-force spectra. Moreover, because they result in relatively large periodic motions of the entire structure, they represent a significant source of cyclic stress on the major supporting members. Monitoring these modes can yield information pertinent to the integrity of the entire structure. Although it is possible to measure the natural frequencies of individual plates, columns, and beams, the results are applicable to only those particular members. The emphasis in this work was on the development of an inspection technique that provided a measure of the general integrity of the structure rather than a one-at-a-time inspection of individual members.

The bending or rotational vibration of an offshore tower is usually dominated by a low-frequency fundamental with occasional second- and even third-order frequencies superimposed. The lowest frequency usually dominates because it has more energy available from the wind and waves than do the higher-order modes. In many cases, as with the Buzzards Bay entrance tower, only the fundamental modes are regularly excited; consequently, the measurement and analysis were necessarily confined to the fundamentals. Had the higher modes been excited during any measurement period, they would have been detected and used for comparison with later measurements. The important point is that deductions can be made from the fundamental frequencies only; and the occasional or even continuous superposition of higher modes does not hinder the tests, but provides additional data for comparison with later tests. It is possible that the higher-order natural frequencies may be more sensitive to certain types of damage. Future applications of this testing technique should exploit this fact.

Accelerometers

Accelerations caused by the fundamental modes are largest at the top of the tower. The purely translational vibrations can be resolved into two perpendicular components. In the case of a tower with a rectangular platform and symmetric mass distribution, the two flexural motions are parallel to the two principal vertical planes of the structure and the rotational motion is around a vertical axis through the geometric center of the structure. Thoughtful placement of the accelerometers that measure these motions can make analysis of the data relatively simple.

Fig. 1 shows the recommended placement of accelerometers on the top of a tower with a rectangular platform. Looking down on the top of the tower, it is obvious that placing two accelerometers at the center of

ienting them to measure horizontal accel-
$\ddot{x}$ and $\ddot{y}$ directions allows measurement of
and $\ddot{y}$ flexural accelerations at the top of the
interference from the rotational mode. The
the third accelerometer at the extreme y

rotation and o
erations in the
the principal $\ddot{x}$
tower with no
placement of

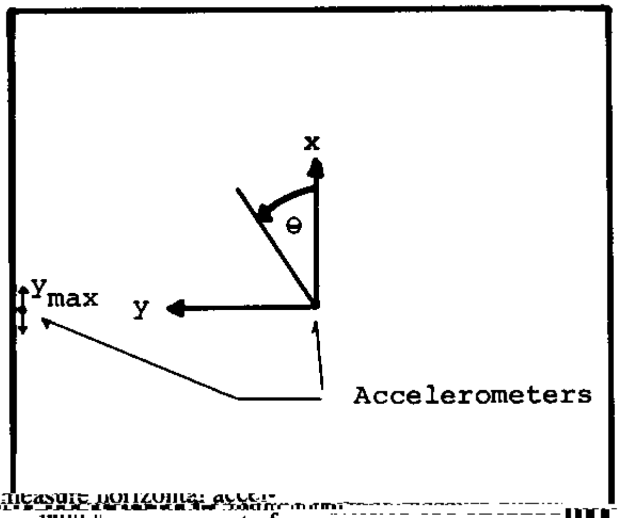

Fig. 1—Accelerometer placement, top view.

coordinate of the structure, y_{max}, is oriented to measure accelerations that are the sum of the $\ddot{x}$ flexural and the $y_{max}\theta$ rotational components. The Buzzards Bay tower has a square platform with four primary steel legs and a symmetric arrangement of horizontal and diagonal braces in the welded steel jacket. The mass distribution in the house at the top of the tower is symmetric in two planes. The symmetry of mass and structure is reflected by two identical x and y flexural fundamental frequencies at 0.985 Hz, and a torsional mode that rotates around the geometric center of the tower at 1.085 Hz.

Recording Techniques

The instrument package was designed to simultaneously measure and record accelerations at three locations. A four-channel FM recorder was used to record the accelerometer signals. Later, the data were played back into a spectrum analyzer that identified the natural frequencies.

The spectrum analyzer determined the natural frequencies to a resolution of ±0.005 Hz and required 200 seconds of recorded data. A sample power spectrum of the $\ddot{y}$ accelerations is shown in Fig. 2. The spectrum analyzer is capable of resolving the signal recorded at y_{max} into the appropriate $\ddot{x}$ and $y_{max}\theta$ components.

Significance of Damping

In a statistical sense, the ability to measure accurately the natural frequency depends on the bandwidth of the resonant peak of the response spectrum. Fig. 2 shows the acceleration spectrum for the flexural natural mode in the y direction. The width of this peak is dependent on the damping of the structure. The greater the damping, the broader the peak. The broader the peak, the more difficult it is to establish accurately the true center frequency. By measuring the width of the peak at a point equal to one-half the height, one can estimate the damping from the following formula.

$$\text{Fraction of critical damping, } \zeta = \frac{\Delta f}{2f_0}\ , \quad \ldots\ldots\ldots \quad (1)$$

where

Δf = width of peak, Hz

f_0 = center frequency (that is, natural frequency).

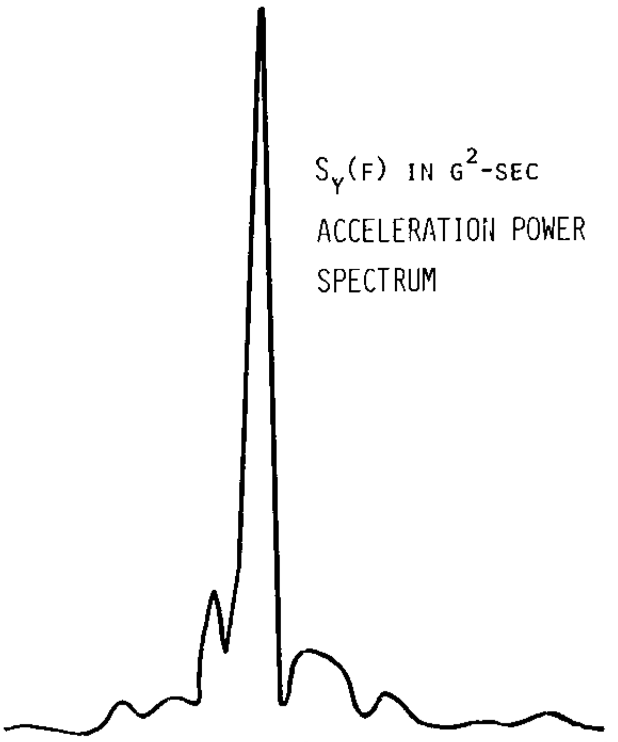

Fig. 2—Sample power spectrum of $\ddot{y}$, wind at 8 knots, seas calm.

Typically, for the three fundamental modes on the Buzzards Bay tower, this value was about 1 percent, which is very low. Transient decay measurements also made on the tower confirm the estimates from the power spectra. It was noticed that nonlinear effects cause the damping to be amplitude-dependent. Under very calm conditions the measured damping was lower than during stormy conditions and much larger response amplitudes. The rather low value of damping is a consequence of the size and simplicity of the structure. The principal sources of damping are the interaction of the structure with the water and soils, and the internal damping of the structure. The four legs are only 33 in. in diameter at the water line. Each leg extends into the soil as a single pile. The structure has all welded joints and relatively few members. The net result is a damping value of about 1 percent as compared with 3 to 5 percent on larger, more complex structures.

Computer Simulation

Concurrent with the instrumentation program, a computer model was formulated to predict the natural frequencies of the Buzzards Bay tower. The ultimate purpose of this model was to conduct a parametric study of the effect of simulated structural damage on natural frequency. Since it was impossible to actually conduct a systematic survey on a full-scale structure in which members would actually be removed or broken, it was reasoned that a computer simulation would be the next best thing.

Once the results of the full-scale test were in and the accuracy of the natural frequency determinations was known, a comparison with the computer simulation would specify the minimum detectable level of damage that this inspection technique could resolve.

Like a cantilever beam, a pile-supported tower has a theoretically infinite number of flexural and rotational natural frequencies. For a spatially complex structure like an offshore tower, with large variations in mass distribution, a standard way of estimating natural frequency is by developing a lumped mass model with a finite number of masses and an equal number of degrees of freedom.[4] Such models generally predict the lowest natural frequencies most accurately and yield progressively less accurate estimates of the higher modes. In modeling the Buzzards Bay tower it was important that the computer simulation be able to predict with reasonable accuracy all the observable natural frequencies. It was also desirable to use a computer model that had the fewest number of degrees of freedom (lumped masses) to minimize computer costs.

A three-lumped-mass model was tried and the results were compared with those of a simple single-lumped-mass model. The model with a single degree of freedom was found to yield acceptable values for both the flexural and torsional fundamental natural frequencies. Since it

[redacted]

the top of the tower, the STRUDL program computes the reaction force at the joints where the displacement was specified. This reaction force is the spring constant K_x,

TABLE 1—REDUCTION IN NATURAL FREQUENCY CAUSED BY STRUCTURAL DAMAGE

Damaged Member (see Fig. 3)	Reduction in Frequency (percent)			Is Damage Detectable?
	Δf_x	Δf_y	Δf_θ	
None	0.0	0.0	0.0	N/A
1	17.14	17.14	12.13	Yes
2	11.15	11.15	0.17	Yes
3	5.92	5.92	0.96	Yes
4	8.80	8.80	6.62	Yes
5	0.12	0.0	0.03	No
6	0.005	0.005	0.02	No
7	6.10	0.17	2.25	Yes
8	0.17	6.10	2.25	Yes
9	0.005	0.005	0.008	No
10	3.19	0.0	1.36	Yes
11	7.18	0.0	2.05	Yes
12	3.31	0.0	2.08	Yes
13	0.008	0.008	0.005	No
0.050 in. rust	3.71	3.71	1.41	Yes

ing of structural members are also potential sources of error that must be detected and eliminated from structural-failure considerations.

The computer simulation can reveal the percentage of change in natural frequency as a function of member damage. The severity of damage that the inspection can potentially detect is determined by comparing the computer results with the in-practice ability to detect the long-term changes in structure mass. This will vary from one structure to the next. Unmanned producing wells have rather constant masses and, hence, will have a very sensitive detection threshold. Exploratory drilling rigs will have much less sensitive detection limits.

Instrumentation errors also must be considered. The 0.005-Hz spectrum-analyzer resolution was a compromise that gave several data points over the band width of the resonant peak, and yet did not require awkwardly long acceleration records or exceed the memory capacity of the spectrum analyzer. It was hoped that the errors in estimating the mass would not introduce errors into the frequency calculations of more than ±0.005 Hz.

Of all the potential changes in mass, the only serious source of error on the Buzzards Bay tower was the variable quantities of fuel and fresh water. As much as 40 percent of the weight of the tower was liquid; although their exact amount could be determined, these liquids could not be treated as rigid-body masses. They were stored in four identical rectangular tanks. Even when full, the tanks had a free surface. The natural frequencies of the first three standing-wave modes in both x and y directions were usually lower than 1 Hz. From potential flow theory it is possible to estimate the rigid-body equivalent of a liquid in an oscillating rectangular tank. The result is not given in detail here but, in general, the nearer the natural frequency of the tower to a natural frequency of a standing wave mode in a tank, the higher the effective rigid body mass of the fluid.^{5} The standing wave natural frequencies are strongly dependent on the fluid depth and, therefore, the effective rigid-body-equivalent mass also depends on the liquid depth. Normal day-to-day consumption of liquids can cause complicated changes in the natural frequencies of an offshore structure. For the tests performed on the Buzzards Bay tower, the effective mass of the liquids was computed from potential flow theory. For all the tests, the natural frequencies of the tower and tanks were substantially different. This resulted in the fluid being vibration-isolated from the motion of the tower, and the calculated rigid-body-equivalent mass was usually 2 to 3 percent of the total liquid mass. This will not always be the case. When natural frequencies of the tower and of the tank are very close together, the potential flow solution breaks down and an experimental approach may be required. In such cases the detection sensitivity might be improved if the relation between natural frequency and liquid level is determined empirically. That is, an experiment can be conducted in which the natural frequencies are measured as the tanks are varied from full to empty. This was not possible on the Buzzards Bay tower. However, this type of experiment could be included as part of the construction program for other towers, especially since pile-supported towers are likely to be erected with empty tanks and then filled.

For the Buzzards Bay tower the error involved in estimating the rigid-body-equivalent mass, when combined with the cumulative small errors from other sources, led to the conclusion that when structural failure caused changes in frequency of 1 percent or greater, this inspection technique would be capable of detecting the damage.

By comparing the above result with Table 1, we can see the severity of structural damage that could be detected with confidence above the error level associated with changes in mass. These results indicate that, at least for the Buzzards Bay tower, this is a valid method for detection of member breakage for much of the submerged structure. For large drilling rigs, the ability to account for drillpipe, mud, and heavy equipment may be considerably more difficult. For unmanned production platforms, the mass may change very little with time and a very sensitive threshold might be attained. It is significant for the Buzzards Bay tower that the only undetectable breaks occur in small, nonload-bearing members.

Locating Structural Damage

Certainly from the magnitude of the frequency change, a surveyor could obtain an indication of the severity of the damage. In addition, by comparing the frequency changes between modes, one could determine whether the damage was in a location that causes stiffness in a predominantly x or y direction. It is obvious from Table 1 that certain types of failure cause the rotational frequency to change more or less than the flexural ones. Of course, the availability of a computer model is important in making such evaluations; but in the absence of a computer model, sound engineering reasoning in comparing frequency changes could reach many of the same conclusions.

Extension of Results to Other Offshore Structures

The large reinforced-concrete towers currently under construction for use in the North Sea are among the most promising candidates for this testing technique. It is likely that microcracks in the concrete may cause large frequency shifts, much like those observed in earthquake-damaged buildings. Microcracks defy visual inspection, especially under water. Difficult weather conditions and deep water amplify the difficulties associated with diver-conducted inspections. For this type of tower, under these circumstances, this technique may be particularly useful.

Though the variable geometry of a jack-up rig presents some unique problems, we are currently working to extend this technique to them as well.

Of the more than 2,000 offshore structures in use today, many are suited to this inspection technique. Its mobility and low cost make frequent inspections possible, even on relatively low-priority, shallow-water producing platforms. Unscheduled inspections could be made easily on towers after severe storms or even collisions with large vessels.

Nomenclature

f_o = center frequency of power spectrum
f_x, f_y, f_θ = natural frequencies in the x, y, and θ directions
Δf = one-half power band width of power spectrum, Hz
K_x, K_y, K_θ = structural stiffness in the x, y, and θ directions
m, J = effective structure mass and mass moment of inertia for a single-degree-of-freedom model
$S_y(f)$ = acceleration power spectrum in the y direction
$x, y, \ddot{x}, \ddot{y}$ = displacement and acceleration in the two principal coordinates
ζ = fraction of critical damping
$\theta, \ddot{\theta}$ = angular displacement and acceleration

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