The MIT/Marine Industry Collegium
Opportunity Brief #22

Measurement and Prediction of Vibration Response of Deepwater Offshore Structures

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The MIT/Marine Industry Collegium

MEASUREMENT AND PREDICTION OF VIBRATION RESPONSE OF DEEPWATER OFFSHORE STRUCTURES

Opportunity Brief #22

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PREFACE

This Opportunity Brief and the accompanying Workshop held on October 22, 1980 were presented as part of the MIT/Marine Industry Collegium program, which is supported by the NOAA Office of Sea Grant, by MIT and by the more than 100 corporations and government agencies who are members of the Collegium. The Workshop was held to provide Collegium members an opportunity to discuss this topic with the faculty and students involved in the research outlined herein. The program of the Workshop is given in the Appendix.

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.

The underlying studies at MIT were carried out under the leadership of Professor J. Kim Vandiver, but the author remains responsible for the interpretations and conclusions presented herein.

Norman Doelling

July 1, 1981

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1.0 A Business Perspective

As the size of offshore rigs and platforms increases to accomodate deep-water operations, a new set of structural engineering problems is introduced. These problems are associated with a downward shift in the natural resonance frequencies of the structures due to their increased size. The implications of this shift bear importantly on questions of structural fatigue and failure. Moreover, these problems are inherently different than those encountered in smaller structures designed to operate in shallower waters.

In the past, an offshore structure was designed to withstand the largest expected storm in its service life. The resulting structure was so stiff it had relatively high resonance frequencies. Such stiffness minimized the possibility of low-level, high-cycle fatigue -- that is, structural fatigue resulting from normal to moderate wave excitation over long periods of time.

However, good engineering practice for the design of very large structures leads to structures with lower resonance frequencies. These natural resonance frequencies are within a range at which waves from small storms are quite energetic. The dynamic amplification of the motion at the natural resonances leads to a serious possibility of damage due to moderate stress, high cycle fatigue. For this reason, detailed knowledge of the vibration response of large offshore structures excited by wave forces is essential for making a safe and effective design.

An extensive research program led by Professor Kim Vandiver of MIT's Department of Ocean Engineering has been in progress for more than five years with major support from the Branch of Marine Oil and Gas Operations of the United States Geological Survey and the NOAA Office of Sea Grant. Important research results were made possible by active support, cooperation, and assistance of several major oil companies.

This Brief focuses on three related aspects of the work conducted by Professor Vandiver and his graduate students. First, a powerful new method is described for predicting displacement responses (and thereby strain) of a structure at its natural frequencies when excited by random wave forces. This method is based on what is known in electrical engineering as reciprocity. Using some simple, but realistic assumptions, this new method predicts displacement response <u>without explicit calculation of the wave forces</u>. The theory points toward model experiments that can be used to refine the estimate of displacement. The experiments involve measurements of <u>forces</u> on fixed, non-moving models in a wave tank, rather than measurements of <u>motion</u> of an unconstrained model.

The reciprocity approach shows that radiation damping (i.e., the damping due to radiation of energy from the structure in the form of waves) and wave forces are not independent. Rather, the wave forces acting on a structure are uniquely related to the ability of the structure to radiate waves when the structure is vibrated. While limited to wave heights for which linearity can be assumed, the implications of the reciprocity concept are important and are more fully discussed in Section 2.

The second aspect of the work, new approaches to the measurement of damping, is discussed in Section 3. While resonance frequency can be measured easily and accurately, measurement of damping at resonance is difficult. When dealing with an actual offshore structure excited by wind and waves such measurement becomes almost impossible. Section 3 discusses efforts to solve these difficulties.

The third area covered in this Brief describes analytical and experimental work in predicting damping of structures in the ocean environment, and especially the dependence of damping on sea state. Progress in understanding and forecasting of damping arising from non-linear interaction of structural vibration and wave motion is described in Section 4.

The efforts summarized here open new avenues for measuring, predicting, and controlling resonance responses of very large offshore structures excited by waves. Such knowledge is crucial as these structures are made larger. Thus, the cost effective design and safe operation of these large structures is closely tied to an ability to understand and estimate the effects of damping.

2.0 Vibration Response at Resonance of Off-Shore Structures Excited by Random Waves

Vandiver's work (Reference 1) is based on an extension of certain reciprocity relationships which show that the forces exerted on a fixed structure by incident waves have a direct relationship to the waves created by that same structure when it is vibrated. For example, there is not much force on a thin wire excited by an incident water wave; the wire when vibrated makes very small waves, i.e., it has low radiation damping. Similarly a large plate will have large forces on it when hit by a wave and it will, when vibrated, make large waves, i.e., it has large radiation damping.

At resonance, when the vibration level is limited by damping, reciprocity considerations show that the vibration response is not inversely proportional to total damping, but to the ratio of radiation damping to total mechanical damping, which includes the radiation damping. This result, which is a consequence of the reciprocity between wave force and radiation damping, is contrary to the usual assertion that vibration levels depend on total damping alone.

Using reciprocity relations, Vandiver shows that the mean square displacement response in a half-power bandwidth, $2\xi\omega_0$, can be written as

$$\langle s^2 \rangle_{\Delta\omega} = \frac{2C_1 \rho g^3 S_\eta(\omega_o)}{m_{tv}\omega_o^5} \, \frac{R_{rad}(\omega_o)}{R_T(\omega_o)} \, .$$

R_{rad} is the radiation damping and R_T is the total mechanical damping. C_1 depends upon the directional spreading in the wave spectrum and the shape of the structure. C_1 equals 1.0 for symetrical bodies in a randomly incident sea and the other symbols are as usually defined.

It may appear that the problem of calculating wave forces has simply been replaced by the problem of calculating R_{rad}. However, one must evaluate only R_{rad} / R_T and frequently this ratio can be more easily evaluated analytically and experimentally than can radiation resistance R_{rad} alone. Also, since radiation damping is a part of total damping, the ratio can never be greater than 1.0. Put in another way, even if other sources of damping go to zero, the radiation damping is a lower limit of damping that places an upper bound on achievable vibration levels. If the radiation damping is decreased, so also is the excitation. Thereby a bounded response is achieved.

The analysis of reciprocity also suggests several engineering applications, which are discussed in Reference 1. One result has been the development of a new model testing procedure which may be useful in predicting the dynamic response of large caissons, TLP's and bottom pivoted buoyant structures.

3.0 Measurement of Resonance Frequencies and Damping Ratios

Although resonance frequencies and damping are important parameters in the design and analysis of performance for offshore structures, measurement of these properties in actual offshore structures is notoriously difficult. Estimates of natural frequencies and damping ratios may be computed from the location and half-power bandwidths of resonant peaks in the power spectrum of the structure's ambient response. It is generally agreed that estimates of resonance frequencies obtained this way are sufficiently accurate. However, the damping estimates have been shown to be highly sensitive to the method used to analyze response spectra.

Another limitation to most of the present techniques for estimating damping is that they do not provide a measure of possible error. More accurate estimates of damping and some estimates of the confidence limits or standard deviation of error that might be involved in the method are both needed.

For most vibrating systems, damping estimates are usually obtained by one of the following three methods:

1) When possible the system under investigation is excited by a slowly varying single frequency signal. The response is monitored with an accelerometer and the half-power bandwidth is determined directly from the

measured transfer function. This technique has been attempted for an offshore structure, but is too expensive and awkward for general use. Furthermore, the background "noise" created by ambient wind and waves and normal drilling or production activities on an offshore platform further complicates the problem, and inordinant amounts of time and money may be lost while waiting for an adequately calm and quiet day. Because damping may vary with response amplitude and sea state, artificial excitation may not completely represent normal combinations of sea state and response level.

2) A second method is to excite the system under investigation with a transient excitation either by shaker or snapback after being pulled by a work boat, to watch the resulting decay of vibration, and to measure the damping ratio from the envelope of that decay. This technique has been used on a number of occasions with offshore structures. It is hampered by the variation of damping with amplitude of decay, and also by beating with other modes. In addition, it does not provide the proper combinations of response amplitude and sea state.

3) A third technique utilizes measurements of the platform's response to wind and wave excitation. Time-synchronous vibration records are gathered and then auto- and cross-correlated. The auto- and cross-correlation functions are then processed into spectra using Fast Fourier Transform (FFT) spectral estimators. This method has obvious operational simplicities, is widely used, and is referred to as the "conventional" method herein. Spectra obtained from Direct Fourier transforms are also commonly used and have properties essentially the same as those obtained by the correlation function approach.

3.1 Conventional Damping Estimation

Campbell (Ref. 2 or 3) applied conventional damping measurement techniques to a wide range of systems to gain insights into the damping estimates and to study the biases introduced by such systems. Fifty independent response histories were numerically generated for one- and two-degree of freedom mechanical systems with known natural frequencies, damping ratios, and signal-to-noise ratios. Spectra were computed for each of the fifty time histories systems at thirteen different resolutions. Conventional techniques were used to estimate damping for each of the resulting spectra. The results for the one-degree of freedom system with a one-Hertz resonance frequency, a 3% damping ratio, and 30dB signal-to-noise ratio are shown in Figure 1. The data points represent the value of the average damping (upper figure) or its standard deviation (lower figure), obtained from the fifty time histories. The abscissa in both figures is a nondimensional quantity that can be interpreted in terms of spectral resolution or variance. Since the record length is fixed for the results shown in Figure 1, the lag-to-record length ratio ($R = L/T$) is inversely proportional to resolution ($\text{resolution} = 2/TR$) and directly proportional to the variance of the spectral estimator. The dashed line in the top figure shows the true value of the damping and in the bottom figure represents the Cramer-Rao bound* on the standard deviation of the estimator.

Note that for maximum lag to total record length ratios up to 5% the average damping as measured is always higher than the true value. That is, this technique provides a biased estimate. As we increase the Lag to Total Record Length Ratio the average of many measurements may approach the true value, but the variance is larger implying any single measurement is subject to large errors and more measurements are needed.

In a laboratory experiment it was possible to guarantee stationarity for the simulation of fifty experiments, each with a 21 minute record length in order to obtain the statistics presented here. At sea better techniques are needed, such as the maximum entrophy method discussed below, because stationarity is rarely achieved for long time periods.

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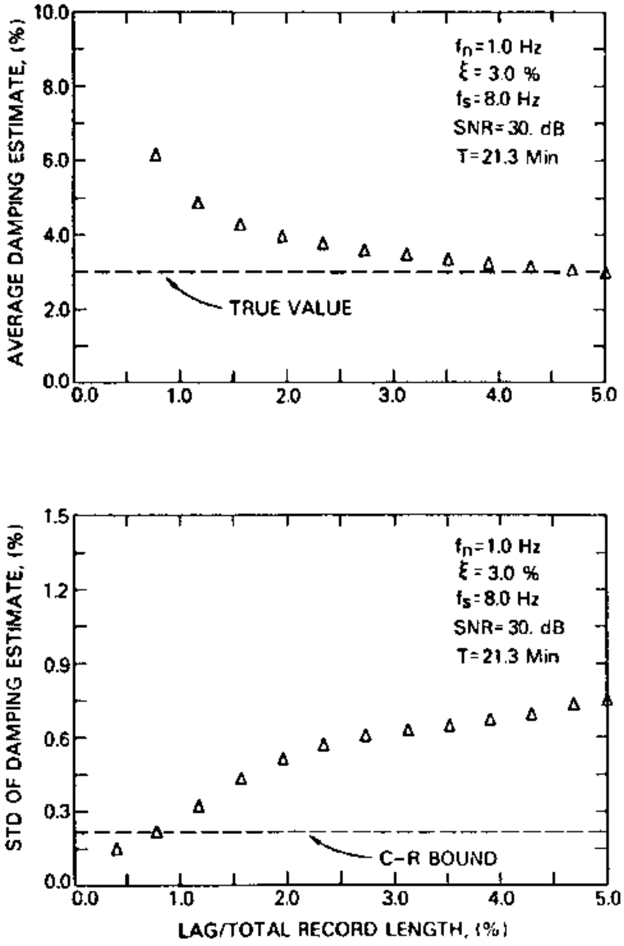
* This bound is the smallest standard deviation that any unbiased estimator of the damping can have, for the specified record length and resonator characteristics. Any unbiased estimator that achieves this bound is called an efficient estimator and can be shown to possess numerous desirable properties.

Figure 1

Performance of conventional half-power damping estimator.



3.2 The Maximum Entropy Method

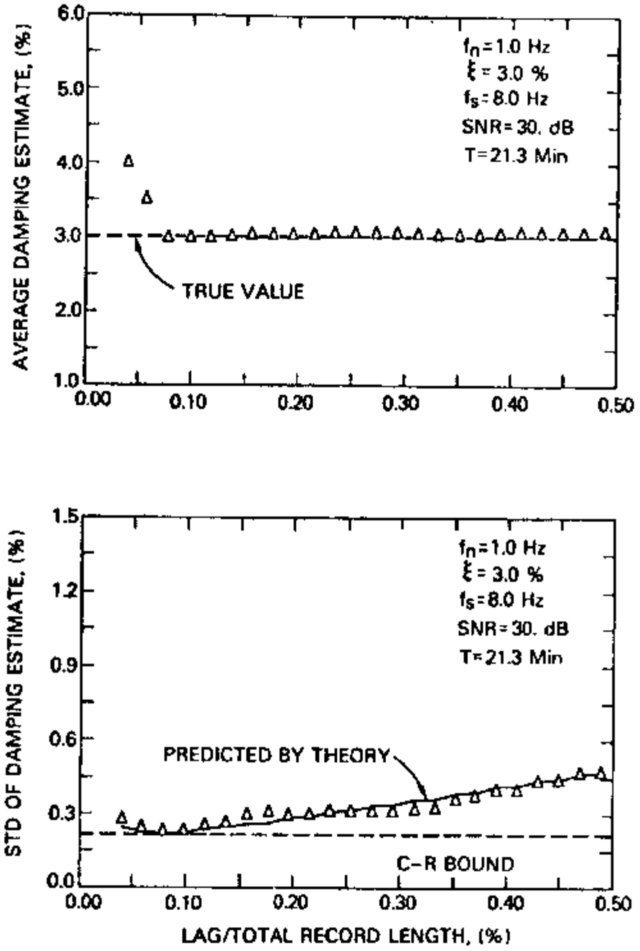
This method is an extension of the standard spectral estimates based on Fourier Transforms of auto-correlation functions that are estimated from finite duration time histories. The maximum entropy method (MEM) is described in detail in Reference 2 or 3. The MEM technique basically extends the auto-correlations estimated from finite duration time histories so that they approximate the auto-correlations that would be estimated from infinite time histories. Most important, the MEM technique provides an estimate of the bias introduced and an estimate of the standard deviation of error or the confidence bounds associated with a particular measurement of damping. As noted, this technique is derived from a "rather grueling exercise in mathematics."

A comparison of the average damping estimate and the standard deviation of the damping estimate for a replication of the experiment described in 3.1 above is shown in Figure 2. Notice that the true value of damping is approached for quite small ratios of lag to total record length, and for those ratios the calculated and predicted values of standard deviation of the estimate agree very closely.

This experiment and others lend credence to the theoretical results and suggest that the MEM technique is useful for measuring offshore platforms excited by noise.

Figure 2

Performance of the mem damping estimator - 1 dof.



4.0 Damping Related to Separated Flow Around Offshore Structures

The radiation damping considerations described above are based on linear theory. Additional energy dissipation or damping arises from the separated flow drag associated with the relative velocity between the structure and the wave-induced water particle velocity.

The key point is that the damping is non-linear and depends on relative velocity between the vibrating structure and the water particle velocity caused by wave motion. Since the wave motions and the response of the structure are both random phenomena, and since their relative motion will also be a random function, the analytic problem is to deal with a non-linear, random process.

This problem has been addressed analytically and experimentally in a doctoral thesis by A. B. Dunwoody (Ref. 4 and 5). The work is based on non-linear drag for cylindrical, vibrating structures exposed to water waves. Model experiments were carried out to verify the theoretical results for wave conditions corresponding to fully developed seas with 20, 30, 40, and 50 knot winds.

Both the analysis and the model experiments demonstrated that separated flow leads to an effective hydrodynamic damping which increases with sea state. In the model tests the root mean square displacement response actually decreased as the sea state increased. In effect the large low frequency waves present in the high sea states contributed substantially to the damping, but not to the excitation at the higher natural frequency of the structure. The theoretical work includes the prediction of response spectra, while retaining (not linearizing) the non-linear drag force excitation.

5.0 References

1. Vandiver, J. K., "Prediction of the Damping-Controlled Response of Offshore Structures to Random Wave Excitation" in Society of Petroleum Engineers Journal, February 1980, pp. 5-14.

2. Campbell, R. B. and J. K. Vandiver, "The Estimation of Natural Frequencies and Damping Ratios of Offshore Structures," in Paper No. 3861, Proceedings of the 1980 Offshore Technology Conference, Houston, May 1980.

3. Campbell, R. B. and J. K. Vandiver, "The Determination of Modal Damping Ratios from Maximum Entropy Spectral Estimates," Paper No. 80-WA/DSC-29, Winter Annual Meeting, American Society of Mechanical Engineers, Chicago, November 1980.

4. Dunwoody, A. B., "The Role of Separated Flow in the Prediction of the Dynamic Response of Offshore Structures to Random Waves," MIT Doctoral Thesis, Department of Ocean Engineering, May 1980.

5. Dunwoody, A. B. and J. Kim Vandiver, "The Influence of Separated Flow Drag Forces on the Dynamic Response of Offshore Structures to Random Waves," Int. Symposium on Hydrodynamics in Ocean Engineering, Trondheim, Norway, August 1981.

6.0 Appendix

MIT/Marine Industry Collegium

Workshop #22

MEASUREMENT & PREDICTION OF VIBRATION RESPONSE
OF DEEPWATER OFFSHORE STRUCTURES

October 22, 1980

Marlar Lounge, MIT Building 37, 2nd Floor
(70 Vassar Street, Cambridge)

8:30 Coffee & Registration

9:15 Welcome

Dean A. Horn, Director, MIT Sea Grant Program
Norman Doelling, Manager, Marine Industry Advisory Services

9:30 The Estimation of Natural Frequencies and Damping Ratios Using Maximum Entropy Spectral Analysis

Dr. B. R. Campbell - Exxon Production Research

10:30 Coffee Break

11:00 The Prediction of the Damping Controlled Response of Offshore Structures to Linear Random Wave Forces. The significance of wave radiation damping and the use of wave force measurements from model tests will be included.

Professor J. Kim Vandiver - Ocean Engineering Department, MIT

12:00 Lunch

1:00 Sea Grant Objectives for University-Industry Partnerships

Dr. Ned A. Ostenso, Director, National Sea Grant College Program and Assistant Director, NOAA Research & Development

1:30 The Prediction of Dynamic Response to Random Wave Forces; including the effects of separated flow drag forces. The estimation of the separated flow contributions to modal damping is emphasized.

Professor J. Kim Vandiver

2:30 General Discussion and an opportunity for guests to present their ideas and opinions on these and related subjects.

3:00 Closing Remarks

3:15 For those guests who have a special interest in our computer programs for estimating modal damping ratios and natural frequencies from random vibration time histories, a hands-on demonstration is planned at our computer lab. The programs are of an interactive nature and may be tried out or simply observed by anyone interested. The formation of a users group will be discussed at that time.