THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS
and
THE SHIP STRUCTURE COMMITTEE

Paper presented at the Ship Structures Symposium '93
Sheraton National Hotel, Arlington, Virginia, November 16-17, 1993

Hydrodynamic Loads Prediction (including Slamming) and Relation to Structural Reliability

Paul Kaplan[1] and John F. Dalzell[2]

[1] Hydromechanics, Inc., Delray Beach, Florida
[2] Carderock Division, Naval Surface Warfare Center, Bethesda, Maryland

Abstract

A description is given of the analytical and computational techniques that are used to determine the hydrodynamic wave-induced loads acting on a ship in a seaway, including the effects on hull girder loads due to slamming. The relation between the magnitude and distribution of the various hydrodynamic loads, and the manner and form in which such information may be used in the context of structural reliability, are also addressed in this paper.

The methods used to find these hydrodynamic loads consider both frequency domain and time domain analysis via computer simulation, with the emphasis on time domain procedures incorporating the effects of nonlinearity. Both rigid body and vibratory responses (reflecting the influence of hull girder flexibility) are included, with the structural loads considered in these methods covering vertical and lateral shears and bending moments as well as torsion.

Introduction

With the current emphasis on reliability based design procedures for ships, the particular area of structural analysis requires development of specialized methods that would provide more extensive detailed knowledge of ship loads during the operational lifetime of various ships of interest. The use of such design procedures would then allow a rational means for structural design of ships which are outside the historical data base, as well as provide a more efficient approach to design of conventional vessels.

In reviewing the nature of the information on ship loads required for this type approach, the need for data describing the magnitude and distribution of such loads becomes apparent. The ship loads of importance are those arising from direct wave induced effects as well as those due to slam impacts. An ability to analytically predict these loads, and their associated basic statistical and/or probabilistic properties, is an essential feature for this overall methodology in contrast to extensive (and expensive) approaches from analysis of data from model tests or full scale measurements. The present paper describes the basic analytical and computational procedures used to establish such a predictive capability, together with the reliability-based motivation for development of this tool.

Background

Goals

The fundamental idea in reliability based design is that in practice neither the loads on a structure nor its resistance to load (strength) can be determined exactly. Under this hypothesis, all the pertinent parameters are considered to be uncertain to a greater or lesser extent, and the evaluation of the adequacy of the structure is evaluated in terms of a probability of failure, or of the magnitude of safety indices which are related to the probability of failure.

Though it is clear that the most desired overall result is a reliability based design code, it appears that a reliability based code must be "calibrated" with evaluations of safety indices by means of what is usually called "Level II" reliability methods, and these results must in turn be "calibrated" by means of estimates of probability of failure which are obtained by means of the so-called "Level III" or classical reliability theory. The net result is that, in order to develop reliability based design codes, means of synthesizing the "statistics" of loads and resistance must be in hand.

In this context, the most important task of the dynamic load analyst is to provide practical means by which the magnitude and distribution of wave induced and slamming loads may be analytically predicted. Moreover, in addition to being reasonably affordable and timely, the resulting methods and procedures must be consistent with the requirements of both the structural designer and the reliability analyst.

At present, the main interest is in primary loads on monohulls; that is, vertical, horizontal and torsional moments and vertical and lateral shears along the length of the ship. It is important to note in this context that the stress analyst's definition of primary loads includes what the hydrodynamicist tends to call wave induced loads, as well as the moments and shears which arise from beam-like elastic deflections of the hull in response to dynamic loads. To be responsive to the needs of the structural designer, the hydrodynamic load analyst must also adopt this definition.

Practical Synthesis Issues

In order to synthesize the final statistics required, it is necessary to synthesize the load statistics over ship lives. Numerous proposals about how this might be done are in the literature, for example, Mansour [1], [2], Faulkner and Sadden [3], Stiansen, et al. [4], and Mansour, et al. [5], where the usual emphasis is only upon the synthesis of vertical loads and merchant ship forms, primarily by means of frequency domain techniques.

The practical approach to the synthesis of lifetime load statistics for combatants, Sikora et al. [6], is a matter of weighting conditional statistics which are computed for each "cell" in an operational profile. When the dimension(s) of a typical combatant operational profile are added up, including the necessary variation in wave height for nonlinear system purposes, the number of conditions which might be taken as representing all the conditions likely during the ship life tends to be of the order of 2000.

For naval application, especially to relatively small combatants, the most demanding of the technical problems in evaluating statistics for each condition is that of estimating the component of loads corresponding to the transient structural response to slamming and flare shock. The preconditions for such response amount to a threshold problem; that is, the ship motions must attain some level of severity before wave impacts are likely to be severe enough to excite significant transient vibration of the hull. The slamming induced loads are thus nonlinear in an essential way. At the moment, we know of no better approach to this than simulation in the time domain.

Thus the ideal means for carrying out the required evaluations would be a non-linear time domain ship motions/loads/elastic response code. Given such a code, the mechanics of each evaluation would be to compute a long sample of loads for each statistically stationary condition required, and use each result as an "experiment" from which means, covariances, and possibly the parameters of probability density functions would be estimated. Such a procedure is essentially a Monte-Carlo simulation, and as such, is subject to sampling error, so that the length of time each evaluation represents becomes important.

On the basis of experience with model and full scale seakeeping experiments, if we want a reasonable (say plus or minus 15 percent) estimate of the population means and covariances of the hypothetical stationary process which would be modeled for each evaluation, we would need to simulate at least the equivalent of a half hour of real time. If in addition, we wish to estimate a probability density, we probably need to increase the sample by a factor of ten, at least, for marginally accurate determination. Thus, we are faced with a total simulation requirement of between 1000 to 10000 hours, real time.

Clearly, this simple arithmetic suggests that to achieve an affordable and practical approach to the problem with an exclusive use of nonlinear time domain simulation, the time domain code used must run at something of the order of 1000 times faster than real time, even assuming a state-of-the-art supercomputer.

The present understanding of the state-of-the-art in the yet undeveloped "fully" non-linear time domain simulations suggests that this order of simulation speed is not now achievable. It appears that, at least for the foreseeable future, we must count on using hydrodynamic technology of all levels of sophistication to overcome the problem. The fact that the form of the required answer is statistical rather than deterministic is what makes this prospect practical.

Tentative Strategy

It seems necessary to estimate the statistics of loads in all climatological and operational conditions - not just those which present critical (or necessarily even technically interesting) conditions. It is clear on the basis of existing data on world wide wave climatology that the usual large ship will spend a large part of its life in relatively mild wave conditions where wave impacts are unlikely, and in which purely wave induced loads are relatively low. It is also known that even when waves are sufficiently high, impacts are most likely to occur at high ship speed in head or bow seas.

Thus, for relatively large ships it seems likely that the computation of slamming and whipping loads will be unnecessary for a large portion of the population of conditions spelled out in the operational profile. Under these circumstances, linear frequency domain methods may be adequate for defining the statistics of the mild side of the profile and for defining a much reduced set of conditions under which time domain methods should be used.

We can contemplate three levels of sophistication of time domain wave induced and whipping codes; Quasilinear, Large Amplitude Strip, and "Fully Nonlinear". Present day estimates are that the Quasilinear type can be made to run at least an order of magnitude faster than real time, that the Large Amplitude Strip type can run at the same order as real time, and that (if a suitable code can be developed within the next few years) the Fully Nonlinear type should run about two orders of magnitude slower than real time.

At the moment a practical strategy appears to be to use fast quasilinear methods to provide at least a first estimate for whipping loads, and to use its results to define a reduced set of conditions in which the more time consuming codes may be usefully employed (after they are developed).

Analytical Procedures and Assumptions

The analysis used to predict the wave-induced motions and loads on a ship is primarily a linear strip theory method, as described by the SCORES II computer program and its underlying theoretical basis [7]. For these motions and loads the ship is assumed to be a rigid body, and the motion and load responses are linear with respect to wave amplitude, with consideration of all 6 degrees of freedom for motions and determination of all shear forces and moments at all stations of a vessel.

The application of this conventional ship motion theory provides linear frequency response information for the wave-induced motions and loads, for all headings and speed conditions. However when considering the total response of the craft, including the effects of slamming which are only determined in the form of time domain responses, the wave-induced motions and loads must be expressed in time history form so they can be combined with the slam-induced responses. The method for determining time histories from frequency response information used here is by use of a decomposed input wave spectrum as a sum of sinusoidal waves combined with the particular frequency response characteristics of the motion or load desired.

It is also assumed that the effects of slamming will not have any significant influence on the basic ship motion responses, viz. heave and pitch, since various model test results, reported by Kaplan [8], [9] have shown only a small influence of slam forces on the basic motion characteristics of hullborne SES craft which experienced very large impact forces. Therefore the effects of slamming, which will primarily manifest themselves in vertical acceleration values and in structural load responses such as vertical bending moment and shear, will be directly added to the time histories from the slowly varying wave-induced responses.

Considering the problem of slamming, the initial method of analysis will develop the theoretical values of impact force as a function of the degree of immersion and magnitude of vertical plane velocities and accelerations. This impact force is vertical, and it is determined from the rigid body motions of the vessel. No significant hydrodynamic forces are assumed to occur due to any elastic deflections of the ship structure. A similar type analysis, in terms of the degree of immersion and also the horizontal plane ship motions, will be applied to determine the impact-type force in the lateral direction. An additional force component due to crossflow drag is also included in determining the lateral impact force, similar to the approach used by Kaplan [10] in analysis of horizontal impact forces on offshore structure members. The use of an empirical value of the crossflow drag coefficient is the only aspect whereby empirical data is used in the present overall analysis.

The response of the ship to these slam impact forces is composed of both a rigid body response and a vibratory response due to the elasticity of the ship structure. The rigid body response to such impulsive forces is determined in terms of hydrodynamic forces of inertial nature as illustrated in [9], and separate analyses are provided for both the rigid body and vibratory responses. These separate responses are then combined to provide the total response to impulsive forces acting on the ship.

The response of the craft due to a slam impact results in excitation of the basic structural modes of vibration of the ship, which manifest themselves as a series of non-continuous high frequency oscillations (e.g. in accelerations, shear, and bending moments, for both the vertical and horizontal plane responses). This type of response will follow the occurrence of impact forces in the bow region, with the frequency of the vibratory response primarily that of the first structural mode in bending, and with these oscillations decaying as the result of the combined influence of both structural and hydrodynamic damping. The method of determining these structural responses due to slamming is by use of a modal model, with the solution represented in terms of a series of normal modes. It is assumed that the normal mode spatial distribution (mode shapes), as well as the values of the associated frequencies, are determined by a separate structural analysis where this modal information is appropriate to the vessel in the equilibrium reference condition when floating in calm water. The basic equations for modal analysis of this nature have been developed previously in earlier hip Structure Committee projects and applied to conventional surface ships by Kaplan et al. [11], [12], with the same general procedures used in the present case.

A general diagrammatic illustration of the various elements and procedures discussed above which are used in arriving at a theoretical prediction of the motions and loads of a monohull ship in waves, including slamming effects, is shown in Figure 1.

Mathematical Relations

An outline of the basic equations used in this analysis is presented below. For the rigid body vertical response to slam impact, the equations of motion are given by

$$a' \ddot{z}_s - d\, \ddot{\Theta}_s = Z_{slam} \tag{1}$$

$$A \ddot{\Theta}_s - d\, \ddot{Z}_s = M_{slam} \tag{2}$$

where the coefficients are defined in terms of inertial mass and hydrodynamic parameters corresponding to values at high frequency for the equilibrium immersion condition of the ship.

The total vertical slam force and pitch moment are given by

$$Z_{slam} = \int_{\substack{\text{immersed}\\ \text{region}}} (F_{z_{i_1}} + F_{z_{i_2}})\, dx \tag{3}$$

$$M_{slam} = -\int_{\substack{\text{immersed}\\ \text{region}}} x\, (F_{z_{i_1}} + F_{z_{i_2}})\, dx \tag{4}$$

where $F_{z_{i_1}}$ and $F_{z_{i_2}}$ are component sectional forces arising from the differences between the instantaneous hydrodynamic and hydrostatic forces for the actual ship immersion and that corresponding to the equilibrium condition linear theory values (7).

The resultant rigid body vertical acceleration due to slamming, at any location along the ship, is

$$\ddot{Z}_s - x\, \ddot{\Theta}_s = \frac{A\, Z_{slam} = dM_{slam} - x\, (dZ_{slam} + a'M_{slam})}{a'A - d^2} \tag{5}$$

The resultant total vertical loading at any section is

$$\frac{df_z}{dx} = -(\delta m + A'_{33_0})\, (\ddot{z}_s - x\ddot{\Theta}_s) + (F_{z_{i_1}} + F_{z_{i_2}}) \tag{6}$$

where δm is the local sectional mass and A'_{33_0} is the sectional vertical added mass corresponding to the equilibrium (linear theory) immersion condition. These quantities are then used to find the vertical shear force and bending moment due to slamming arising from rigid body responses, at any location x_0 along the ship length which given by

$$V_{z_{s_{rigid}}} (x_0) = \int_{x_0}^{x_b} \frac{df_z}{dx}\, dx \tag{7}$$

$$BM_{z_{rigid}} (x_0) = \int_{x_0}^{x_b} (x - x_0) \frac{df_z}{dx}\, dx \tag{8}$$

The vibratory responses due to slamming are described (for the vertical case) in terms of the vertical elastic deflection represented by a modal model given by

$$z_e = \sum_i \Phi_i (x)\, q_i(t) \tag{9}$$

The differential equation for the generalized modal response variable q_i, for the i^{th} normal mode, is

$$\bar{\mu}_i\, \ddot{q}_i + 2\, \zeta\, \omega_i\, \bar{\mu}_i\, q_i + \omega^2_i\, \bar{\mu}_i\, q_i = Q_i(t) \tag{10}$$

where

$\mu(x)$ = mass + added mass distribution (per unit length) along ship

$\Phi_i (x)$ = i^{th} normal mode shape

ζ = structural damping coefficient

ω_i = natural modal frequency

$$\bar{\mu}_i = \int_{x_s}^{x_b} \mu(x)\, \varphi_i^2(x)\, dx$$

$$Q_i = -\int_{\substack{\text{bow impact}\\ \text{region}}} x\, (F_{z_{i_1}} + F_{z_{i_2}})\, \varphi_i(x) dx$$

The responses to a slam impact are found by use of the mode acceleration method which separately considers the rigid body responses and the vibratory contribution. The resulting expression, for vertical acceleration, shear and bending moment due to slamming are then given by

$$a_z = (\ddot{z} - x\, \ddot{\Phi})_{\substack{\text{rigid,}\\ \text{slam}}} + \sum_i \Phi_i\, \ddot{q}_i \tag{11}$$

$$V_z (x_0) = V_z (x_0)_{\substack{\text{rigid,}\\ \text{slam}}} - \sum_i V_i(x_0) \frac{\ddot{q}_i}{\omega_i^2} \tag{12}$$

$$B\, M_z (x_0) + B\, M_z (x_0)_{\substack{\text{rigid,}\\ \text{slam}}} - \sum_i M_i(x_0) \frac{\ddot{q}_i}{\omega_i^2} \tag{13}$$

The term with the subscripts $\substack{\mathit{rigid} \\ \mathit{slam}}$, are given by the expression in Eq.(5), (7) and (8), and the associated definition of terms in Eq. (12) and (13) is

$$V_i(x_0) = \omega_i^2 \int_{x_s}^{x_0} \mu(x)\, \Phi_i(x)\, dx \qquad (14)$$

$$M_i(x_0) = \omega_i^2 \int_{x_s}^{x_0} (x - x_0)\, \mu(x)\, \Phi_i(x)\, dx \qquad (15)$$

As shown in Figure 1, the responses given by Eq.(11) - (13) are added to the linear theory wave-induced responses (in time history form) to find the total responses due to both wave-induced and slam inputs.

While the results described above are applicable to vertical loads, similar procedures are used for the lateral plane loads. Thus separate components due to wave-induced effects, rigid body responses to nonlinear impact forces, and vibratory responses are determined in order to establish the time histories of the total lateral shear and bending moment, as well as the torsional moment.

Computer Program Description

The simulation of wave induced responses, together with including effects due to slamming, requires the coordination and integration of three computer program elements. These elements are the SCORES II program [7], the Generalized Bending Response Code (GBRC) [13], and a new code called SLAM. As mentioned above, the SCORES II program provides the frequency domain wave-induced responses in regular waves as well as detailed sectional hydrodynamic coefficients for various degrees of ship section immersion. The GBRC is a program for solution of a finite difference modal of a ship as a Timoshenko beam, from which fundamental steady state properties such as natural mode shapes and frequencies are determined. The SLAM program uses outputs from the two other programs, along with user supplied data, to generate a time history of ship loads in a seaway according to the analysis by Kaplan [14], which is outlined briefly in preceding sections.

The system is designed to handle one case at a time; i.e. one ship speed, heading and sea state combination. However an unlimited number of sea states can be run using various files (from SCORES II and other files) that are independent of sea state. Results for both planes of interest (vertical and lateral) are produced with a single execution of the program. However the time histories provide vertical responses first, followed by lateral responses. For input purposes the ship is described by 21 stations, with Station 0 as FP. Primary concern for slam impact force determination is applied to the first 7 stations, with half-stations in the first two station spacing also considered in detail. Loads can be computed at up to 9 stations of interest in any one case that is run.

The outputs are written to two files showing bending moments and shears, from which additional spread sheet software allows graphical plotting of time histories. A timing of the program operation was made for the case of one station of interest, and not counting the time for preparatory processing, a speed-up relative to real time was found to be 7.4. The computer used was a desktop 486 type PC, with 33MHz speed. Considering earlier speed capability (in 1972) of about 100 times faster than real time [12], which used a somewhat related analysis method but carried out on a large mainframe computer (CDC 6600), the prospects for more rapid calculation than that reported for the present example are evident for near term applications.

Illustrative Examples

An illustration of the nature of results obtained using the present computer simulation methodology is given for a representative naval combatant, at a forward speed of 10kt. in a unidirectional hurricane storm sea, at a bow sea heading (waves at 30° to starboard, from head seas). The separate vertical bending moment contributions, as well as their sum (for the total vertical bending moment) at midships are shown in Figure 2-5 in time history form. The plots represent one minute of time, on either side of the time for occurrence of a peak value observed during a 30 minute time period. These values are shown in nondimensional form, defined by dividing the bending moment values by $\rho\, g\, H_{1/3}\, L^2\, B$, where $H_{1/3}$ = significant height of waves, L = LBP, B= maximum beam of vessel. Time histories of the total midship lateral bending moment and torsional moment, for the same time period, are shown in Figures 6 and 7.

The relative magnitudes of the different components, their overall pattern and appearance, etc. are exhibited in these results. The influence of vibratory response is more "prominent" in lateral bending moment responses, with the vertical bending moment only manifested primarily in the region associated with large slamming occurrence. Comparing the vertical bending moment peak responses with model test data show values within the band of about 10-15% difference from the measured values (for the present illustrative case). Observations in full scale test in storm seas show very prominent continuous lateral bow oscillations, as implied by the lateral bending moment time history in Figure 6.

Concluding Remarks

As a consequence of the development of the computational tool described here, it is now possible to achieve rapid assessment of hydrodynamic loads on different monohull ships for a range of operational and environmental conditions. The various features of statistical and/or probabilistic nature can then be found from the outputs of a series of Monte Carlo simulation studies, in a faster and more economic manner than via analysis of similar type time histories obtained from extensive model or full scale tests.

In addition to the above use of this basic methodology for conventional monohull vessels, the same procedure can be extended to other related areas. Particular examples exist for advance marine vehicles, as described by Kaplan [9], [15], with the only significant differences being the determination of the hydrodynamic forces due to wave-induced and slam effects for each particular type of vehicle, as well as evaluation of the natural mode shapes and natural frequencies. Another extension of the present analysis is the determination of the pressure distribution on different ship sections in the course of slam impact force generation, which can be found from the fundamental hydrodynamic terms established in the computation of various sectional properties used in the analysis. Thus the present procedures have the prospect of extended utility for additional problems of ongoing and future interest.

References

1. Mansour, A.E., "Probabilistic Design Concepts in Ship Structural Design," Trans. SNAME, Vol. 80, 1972.
2. Mansour, A.E. and Faulkner, D., "On Applying the Statistical Approach to Extreme Sea Loads and Ship Hull Strength," Trans. RINA, Vol. 114, 1972.
3. Faulkner, D. and Sadden, J.A., "Toward a Unified Approach to Ship Structural Safety," Trans. RINA, Vol. 120, 1978.
4. Stiansen, S.G. et al, "Reliability Methods in Ship Structures," Trans. RINA, Vol. 121, 1979.
5. Mansour, A.E. et al, "Implementation of Reliability Methods to Marine Structures," Trans. SNAME, Vol. 92, 1984.
6. Sikora, J.P. et al, "A Method for Estimating Lifetime Loads and Fatigue Lives for SWATH and Conventional Monohull Ships," Naval Eng. Jnl., Vol. 95, No. 3, May 1983.
7. "User's Manual for SCORES II Program," Hydromechanics, Inc. Rpt. No. 79-02, June 1979 (revised July 1982 and June 1987).
8. Kaplan, P. and Andersen, P.; "Ship Motion and Slamming Phenomena for Hullborne SES Craft in Waves," Oceanics, Inc. Rpt. No. 78-147A, December 1978.
9. Kaplan, P.; "Analysis and Prediction of Flat Bottom Slamming Impact of Advanced Marine Vehicles in Waves," Int. Shipbuilding Progress, Vol. 34, No. 391, March 1987.
10. Kaplan, P.; "Impact Forces on Horizontal Members of an Offshore Test Structure," Proc. Civil Eng. in the Oceans IV' Conf., ASCE, San Francisco, CA, Sept. 1979.
11. Kaplan, P. et al, " An Investigation of the Utility of Computer Simulation to Predict Ship Structural Response in Waves," Ship Structure Committee Rpt. SSC-197, June 1969.
12. Kaplan, P. and Sargent, T.P.; "Further Studies of Computer Simulation of Slamming and Other Wave-Induced Vibratory Structural Loading on Ships in Waves," Ship Structure Committee Rpt. No. SSC-231, 1972.
13. Cuthill, E.H. and Henderson, F.M.; "Description and Usage of General Bending Response Code 1 (GBRC 1)," DTMB Rpt. No. 1925, July 1965.
14. Kaplan, P., "Hydrodynamic Loads in Waves, Part I - Description of Theoretical Analysis," Hydromechanics, Inc. Rpt. 93-88, March 1993.
15. Kaplan, P., "Advanced Marine Vehicle Structural Loads -Present State of the Art," Proc. Intersociety High Perf. Marine Vehicles Conf., Arlington, VA, June 1992.

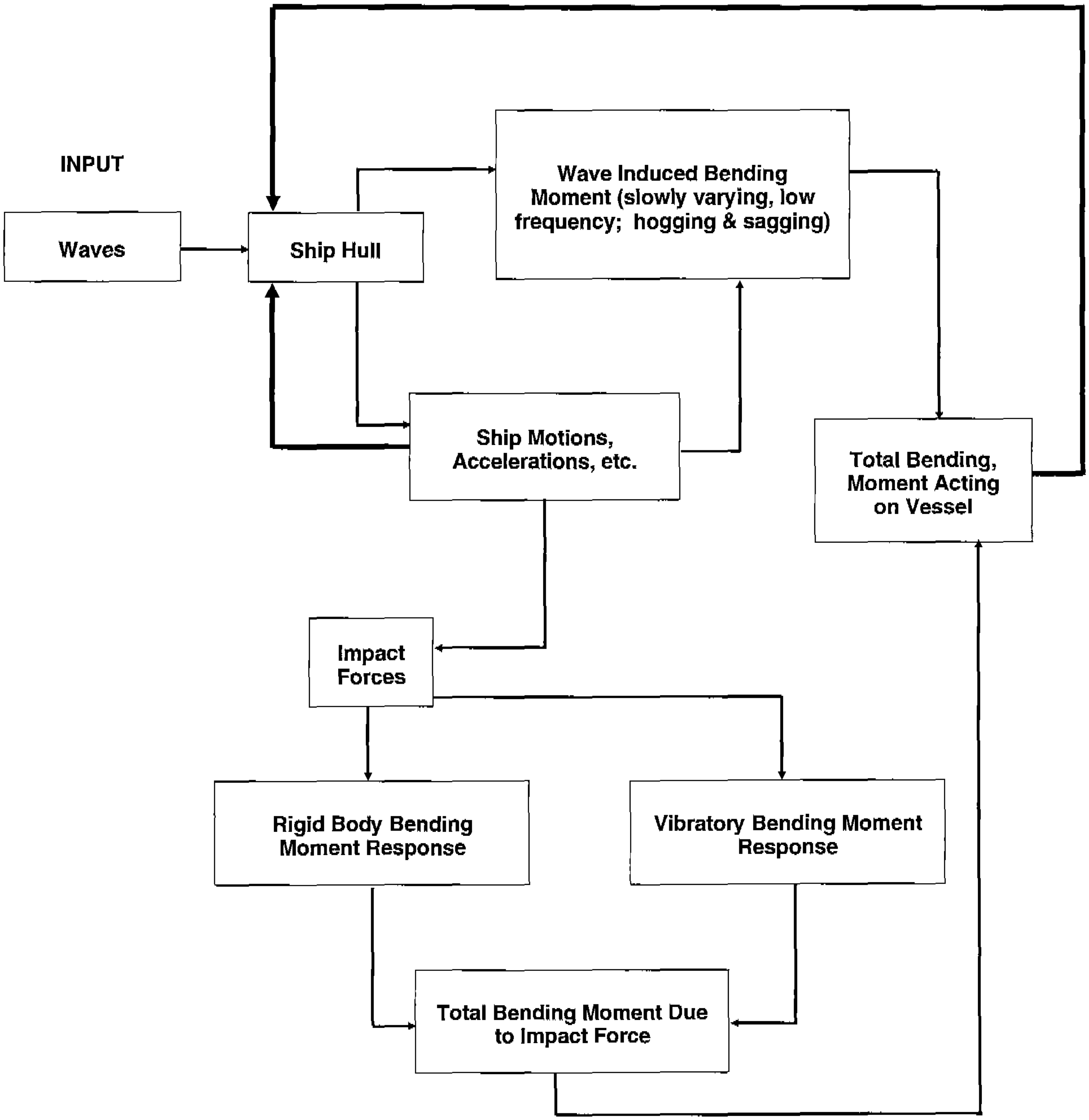

Figure 1
Combined Loads on Ship Hull in Waves

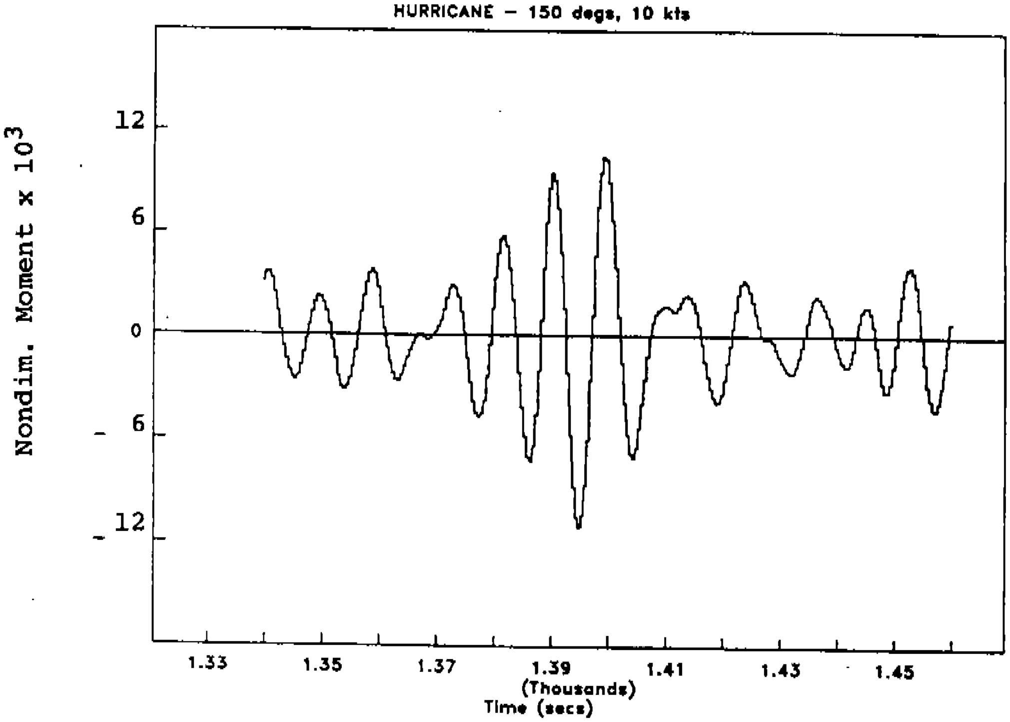

Figure 2
Vertical Moment (Wave Induced)

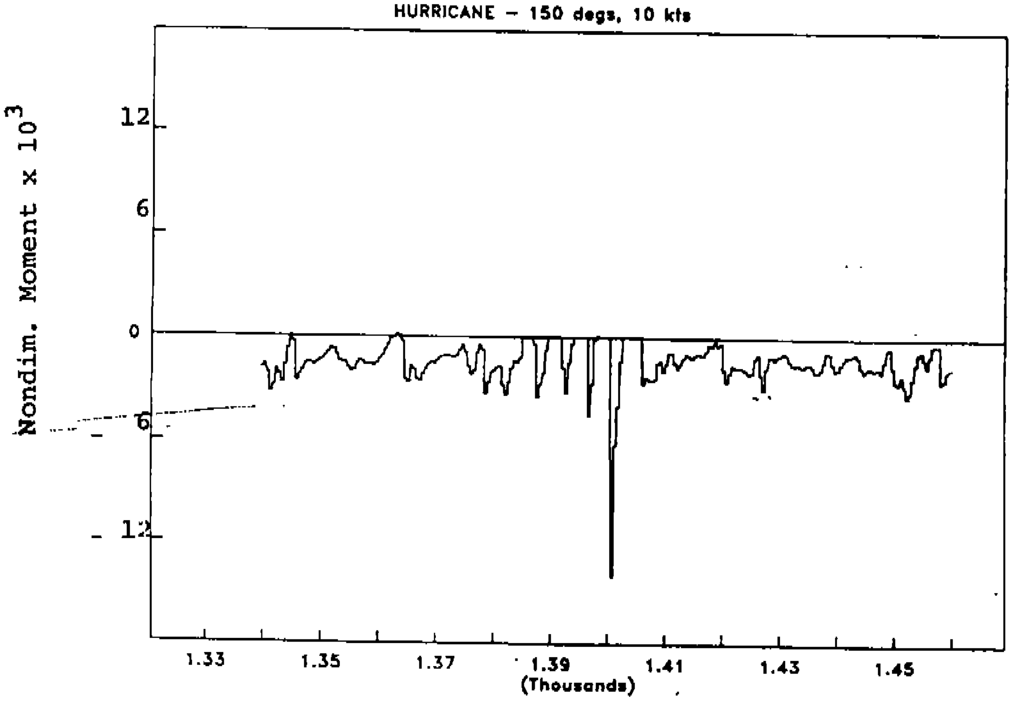

Figure 3
Vertical Moment (Rigid Body)

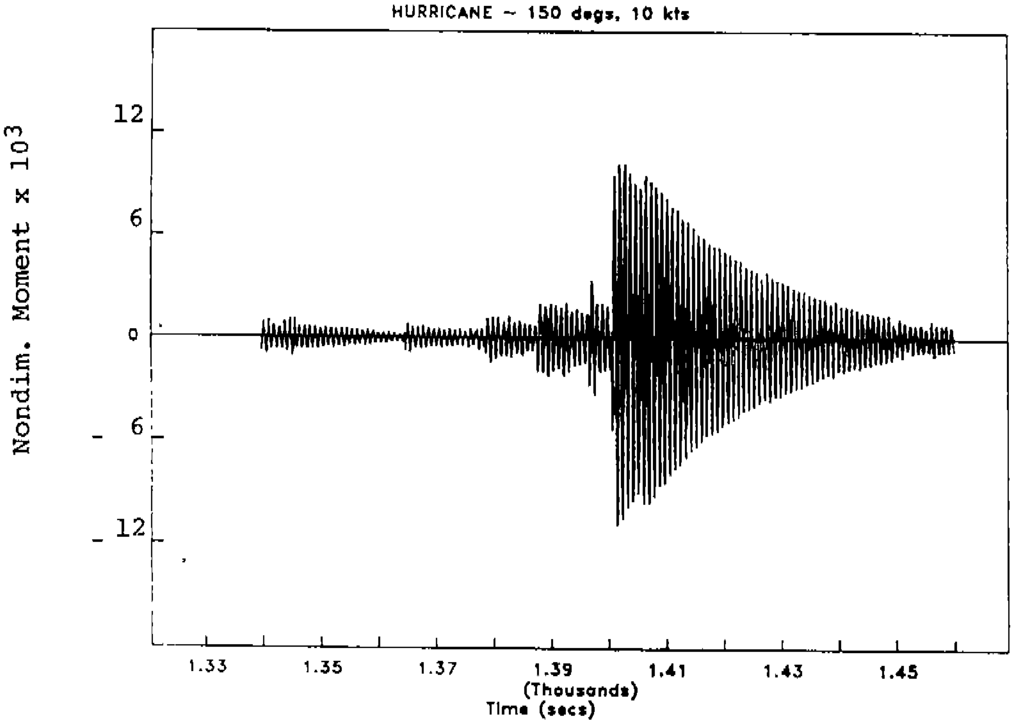

Figure 4
Vertical Moment (Vibratory)

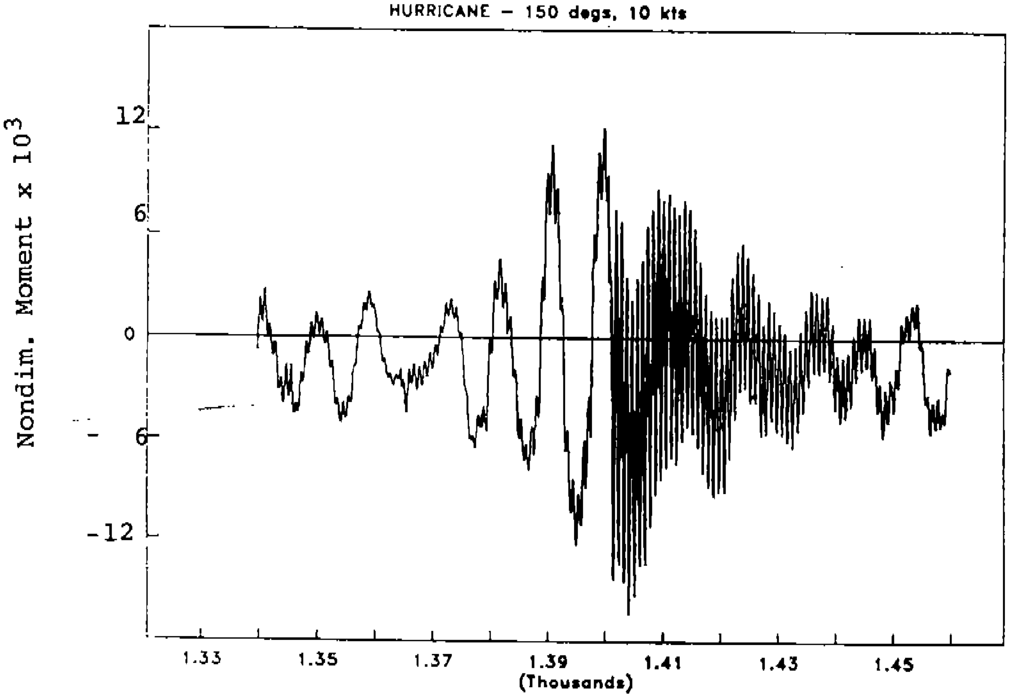

Figure 5
Vertical Moment (Total)

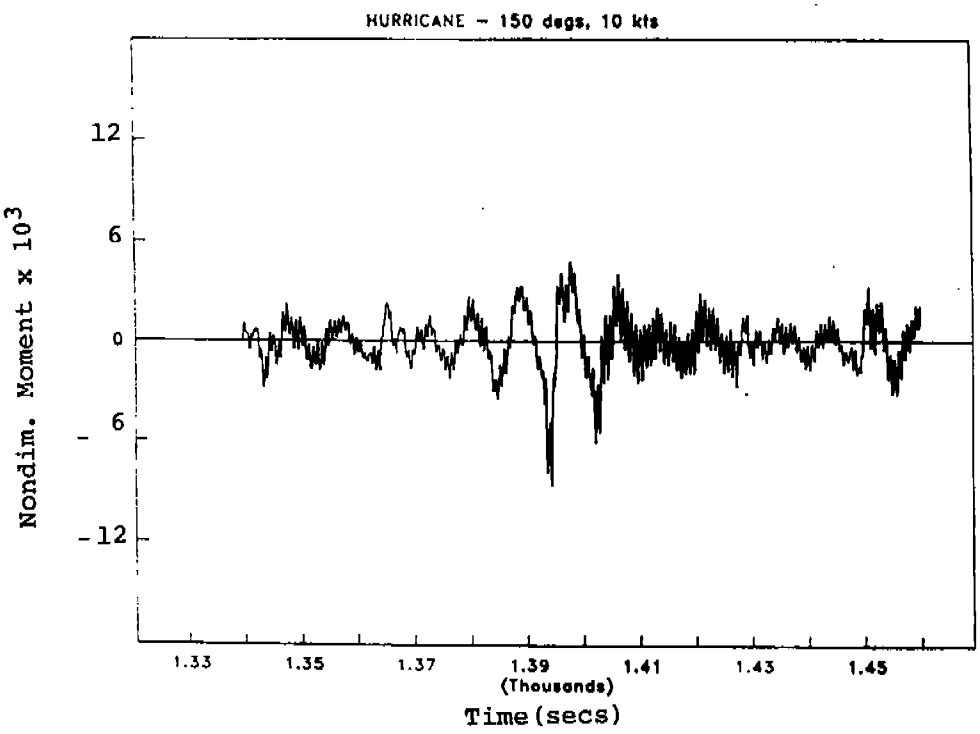

Figure 6
Midship Lateral Moment (Total)

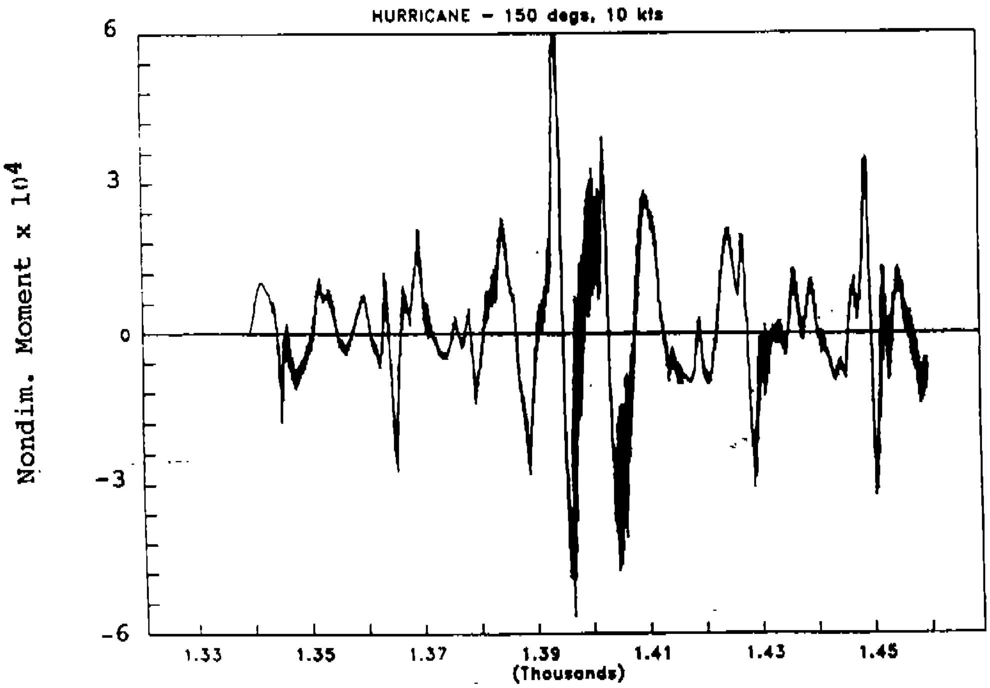

Figure 7
Torsional Moment (Total)