Marine Industry Collegium Opportunity Brief

OFFSHORE STATION KEEPING WITH INTRODUCTION TO NONLINEAR DYNAMICS

May 18-19, 1993
Ann Arbor, Michigan

MIT Sea Grant College Program

Massachusetts Institute
of Technology
Cambridge, Massachusetts
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The MIT/Marine Industry Collegium
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OFFSHORE STATION KEEPING WITH INTRODUCTION TO NONLINEAR DYNAMICS

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MIT Marine Industry Collegium
Building E38-306
292 Main Street
Cambridge, Massachusetts 02139

For workshop information, call John Moore Jr.
TEL: (617) 253-4434
FAX: (617) 258-5730

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INTRODUCTION

Increasing research, exploration and exploitation of continental slope and deep ocean resources requires a greater understanding of the interaction that occurs between structures and the surrounding fluid flow-fields. Such an understanding will provide for the more efficient and effective design of offshore station keeping systems leading to enhanced safety and increased productivity. The Massachusetts Institute of Technology Sea Grant Marine Industry Collegium joins with the University of Michigan/Sea Grant/Industry Consortium in Offshore Engineering to sponsor the workshop, "Offshore Station Keeping with Introduction to Nonlinear Dynamics." The workshop will bring together representatives of industry, government, and academia to discuss and exchange knowledge on the most recent developments in theoretical and numerical methods for the analysis, design and operation of offshore station keeping systems.

Significant advances have taken place in the past decade to understand the role that nonlinear dynamics plays in offshore systems. To update attendees on these advances, this workshop will begin with an introductory tutorial in nonlinear dynamics. The workshop will then proceed to describe specific research efforts, currently taking place, that will provide a greater understanding of the dynamics of offshore station keeping systems. In addressing offshore station keeping, three major areas will be covered. These areas are; slow-motion dynamics and station keeping stability, fast vessel motion and mooring line dynamics, and spread mooring systems and comparison to dynamic positioning. The majority of these presentations will focus on the critical contribution of nonlinear dynamics to these offshore systems.

By providing this forum for the exchange of knowledge among all participants, it is our hope that there will be a greater understanding of the important role that nonlinear dynamics plays in the design of offshore station keeping systems. This increase in understanding will contribute to a more reliable, safer and cost effective design for these systems.

Michael M. Bernitsas
Workshop Chairman

WORKSHOP AGENDA

Offshore Station Keeping (with Introduction to Nonlinear Dynamics)

May 18, 1993

8:00-8:45	REGISTRATION
8:45-9:00	**Welcome** *Mr. John Moore Jr., MIT Sea Grant Marine Industry Collegium* *Professor Michael M. Bernitsas, University of Michigan, Department of Naval Architecture and Marine Engineering*

PART I INTRODUCTION TO NONLINEAR DYNAMICS

9:00 - 10:15	**Review of Basic Concepts in Nonlinear Dynamics and Routes to Chaos** *Professor Steven W. Shaw, University of Michigan, Department of Mechanical Engineering and Applied Mechanics*
10:15 - 10:35	**BREAK**
10:35 - 11:10	**Application of Nonlinear Dynamics Analysis to Mooring Systems** *Professor Armin W. Troesch, University of Michigan, Department of Naval Architecture and Marine Engineering*
11:10 - 12:00	**Nonlinear Vehicle Guidance and Control Dynamics** *Professor Fotis A. Papoulias, U.S. Naval Postgraduate School, Department of Mechanical Engineering*
12:00 - 1:00	LUNCH
1:00 - 1:45	**Ice-Structure Interaction** *Professor Dale G. Karr, University of Michigan, Department of Naval Architecture and Marine Engineering*
1:45 - 1:55	**BREAK**

PART II OFFSHORE STATION KEEPING

1:55 - 2:40	**Single-Point Mooring Systems: Station Keeping Stability and Chaos** *Professor Michael M. Bernitsas, University of Michigan, Department of Naval Architecture and Marine Engineering*
2:40 - 2:55	**Two-Point Mooring/Towing: Station Keeping** *Professor Michael M. Bernitsas, University of Michigan, Department of Naval Architecture and Marine Engineering*
2:55 - 3:10	**BREAK**
3:10 - 4:10	**Fully Nonlinear Computations of Ship Motions** *Professor Robert F. Beck, University of Michigan Department of Naval Architecture and Marine Engineering*
4:10 - 5:00	**Effect of Second-Order Forces on Moored Vessel Dynamics** *Tin-Woo Yung, Exxon Production Research*
5:00 - 6:30	RECEPTION

Offshore Station Keeping (with Introduction to Nonlinear Dynamics)

May 19, 1993

8:00 - 8:30	**LATE REGISTRATION**
8:30 - 9:15	**Improved Methods for Processing Position Information for Dynamic Positioning** *Professor Michael G. Parsons, University of Michigan,* *Department of Naval Architecture and Marine Engineering*
9:15 - 10:00	**The Effects of Cable Motions and Loads on Moored Systems** *Professor Michael S. Triantafyllou, MIT,* *Department of Ocean Engineering*
10:00 - 10:20	**BREAK**
10:20 - 11:05	**Geometrically Nonlinear Three-Dimensional Dynamics** *Professor Noel C. Perkins, University of Michigan,* *Department of Mechanical Engineering and Applied Mechanics*
11:05 - 11:50	**Calibration of Mooring Design Codes for Catenary Spread Mooring Systems** *Dr. Y.S. David Tein, David Tein Consulting Engineers, Ltd.*
11:50 - 1:00	**LUNCH**
1:00 - 3:00	**Lab Tour** Ship Hydronamics Lab - *Stuart Cohen* Gravity/Capillary Wave Tank - *Marc Perlin* Low Turbulence Free-Surface Water Channel - *Dave Walker*

SYNOPSES OF PRESENTATIONS

May 18

9:00

Review of Basic Concepts in Nonlinear Dynamics and Routes to Chaos

Professor Steven W. Shaw, University of Michigan, Department of Mechanical Engineering and Applied Mechanics

In this review, I will present some of the fundamental concepts and tools used for investigating the dynamic response of systems where nonlinearities play an important role. For purposes of illustration, I will present two examples from marine applications.

The starting point will be an introduction to some important geometrical properties of dynamical systems, including a summary of the types of steady-state responses that are possible for nonlinear systems. A brief outline of bifurcation theory and its use in describing qualitative changes in system response will then be given, followed by results from a simple model for a moored structure subjected to periodic wave excitation demonstrating some of these ideas.[1] In particular, it will be shown that, for certain parameter ranges, this system can exhibit various types of periodic and/or chaotic motions. The chaos results from a series of period-doubling bifurcations that originate from a simple periodic response. The effects of these transitions on the system response will be discussed.

A summary of the various routes to chaos and their common features will also be given. Specific examples for the most common of these routes (the period-doubling cascade, the breakdown of quasi-periodic motions, intermittency and the homoclinic bifurcation) will be provided. The example for homoclinic bifurcation deals with the problem of ship capsize.[2] It will be shown that a predictive tool, Melnikov's method, is useful for estimating conditions under which small vessels are prone to capsize when subjected to periodic beam seas.

The presentation will close with some personal views on the relative importance of the main ideas and the analytical techniques developed in the area of nonlinear dynamics.

References

1. Shaw, S.W. & Holmes, P.J., **A Periodically Forced Piecewise Linear Oscillator,** *Journal of Sound and Vibration*, Vol. 90, 1983, pp. 129-155.

2. Falzarano, J., Shaw, S.W. & Troesch, A., **Applications of Modern Geometric Methods for Dynamical Systems to the Problem of Vessel Capsizing with Water-on-Deck,** *International Journal of Bifurcation and Chaos*, Vol. 2, 1992, pp. 101-115.

10:35

Application of Nonlinear Dynamics Analysis to Mooring Systems

Professor Armin W. Troesch, University of Michigan, Department of Naval Architecture and Marine Engineering

Dynamic systems experiencing intermittent contact can produce surprisingly complicated behavior (Shaw and Holmes, 1983 and Troesch, Karr, and Beier, 1992). Three examples related to current research in nonlinear marine dynamics at the University of Michigan will be discussed. The first two examples examine the motions of a vessel moored next to a stationary, but flexible structure. The means of restraint will include the relatively stiff contact force between vessel and structure, the relatively soft tension provided by synthetic mooring lines, and the constant restraining force of constant tension winches. The sources of external excitation will be the result of incident waves in the first example and a passing ship in the second. The third example will describe ongoing work investigating the stochastic behavior of nonlinear systems. While this current effort in random analysis is concerned with vessel capsizing, the methods being developed are directly applicable to the extreme motions of mooring systems and their possible failure.

This first application of nonlinear analysis will consider a vessel moored next to a docking facility comprised of two vertical steel pile groups set in stiff, preconsolidated clays. The vessel is moored using two polypropylene lines attached to fixed stanchions. While the actual problem is quite complex, significant insight into the system's dynamic behavior can be attained if relatively simple dynamic models are used.

An initial analysis will treat the system as a single degree of freedom (sway only), with the effect of additional degrees (roll and heave) discussed later. Assumptions related to system modeling include the following: vessel displacements and velocities are sufficiently small so that the second-order terms in Euler's equations are ignored and the radiation hydrodynamics remain linear, and the linear hydrodynamic coefficients are assumed to be constant, selected at some representative frequency.

The last assumption states that a frequency domain representation for the hydrodynamic forces will be used instead of time domain hydrodynamics. This assumption is valid in the limit of narrow-banded response. The principal source of nonlinearities is due to intermittent contact of the vessel with the dock, nonlinear behavior of synthetic mooring lines, and nonlinear behavior of the dock structure itself (e.g. the effective stiffness of the pile cluster and clay foundation). These nonlinearities are all associated with rigid body displacements. Roll motion will add a viscous roll damping that is quadratic in roll velocity. Qualitative estimates of the effects of second-order excitation due to second-order incident waves will also be discussed. The effective system natural frequency is shown to have a strong dependence on the frequency of excitation and the amplitude of the response. Due to significant damping and the changing of the system parameters with changing frequency, the subharmonic and chaotic motions of similar systems described by Thompson, et. al. (1984) are generally not present.

The presentation will also address the dynamics of a moored vessel subject to the forces caused by a passing vessel. Similar to the first example, the moored vessel hydrodynamics are based upon small vessel motions. However, rather than applying the normal gravity wave boundary conditions, the hydrodynamic coefficients are determined from the low frequency limit, free-surface condition. This approximation is consistent with the long time constants associated with maneuvering-type motions. The excitation forces due to the passing ship may be estimated using the slender body theory of Yung (1977) or the three dimensional theory of Newman (1979 and 1991).

As before, a principal source of the system nonlinearity is the intermittent contact between the ship's hull and two piling clusters. Mooring restraint is provided by relatively soft, synthetic lines and relatively stiff constant tension winches. The constant tension winches introduce the added complexity of providing constant tension during payout or rendering followed by either periods of slack where the winch is left inactive or periods where the line maintains tension during take-up.

Results are presented for various operational scenarios, demonstrating the importance of proper line handling and positioning. Small changes in the initial conditions of the mooring system, such as initial slack in one of more of the lines, may result in significantly larger stresses than those expected from a relatively simple static analysis. In the more extreme cases, vessel break-away is possible and, in fact, may be predicted.

In this example, extreme vessel motions in a random seaway are considered. Previous efforts involving single frequency excitation (Falzarano, Shaw and Troesch, 1992), have applied modern geometric methods in the analysis of vessel stability. These modern geometric methods are not limited by the size of the nonlinearities, as a local stability and bifurcation analysis would be, but instead are capable of analyzing the global system behavior. For the presentation given here, the random nature of the seaway and its impact on vessel stability is included in a nonlinear, single degree-of-freedom stochastic model.

While this work is currently under development, initial results suggest that two probabilistic approaches can be considered. The first examines the relatively long-term (on the order of one hour) stability of a ship's motion in random seas. Using the analysis under development by Hsieh, Shaw and Troesch ("Melnikov's function for random excitations with application to ship capsizing," to appear in 1993), a probabilistic estimate of capsize during a given time of exposure is possible. The other statistical approach treats the equally important problem of transient ship stability as a short term (i.e. very few cycles), deterministic process with randomly distributed initial conditions and periodic seas. This is the situation of significant practical concern - a seemingly stable ship, undergoing quite regular motions, being struck by a sequence of large, regular waves and capsizing within a few oscillations.

Ship capsize is represented in the phase space of the mathematical model by the escape of a solution trajectory from a (safe, non-capsizing) potential well under the action of external excitation. Collections of such trajectories can be studied using the ideas of transport in phase space. The transport of phase space across the "safety" boundary of the potential well is due to the external excitation. The rate of transport can also be measured in terms of the Melnikov function. While this theory is relatively complete for the case of periodic and quasi-periodic inputs, very little is known about phase space transport in nonlinear systems with random excitation.

11:10

Nonlinear Vehicle Guidance and Control Dynamics

Professor Fotis A. Papoulias, U.S. Naval Postgraduate School, Department of Mechanical Engineering

Routine inspection of offshore platforms is becoming increasingly important for environmental, safety, and economical reasons. The primary objective is to achieve a maximum window of operational capacity while conforming to a set of regulations and mission specifications. For this, it is imperative that the platform maintains a level of integrity within specified tolerances. Slight deviations from an assumed design condition should be recorded, reported, and corrected as early as possible.

Automated or semi-automated inspections are a viable alternative to human diving. Added advantages are regular scheduling of operations, increased reliability, and less total cost over a period of time. A number of submersible vehicle configurations can be used for such a purpose, and each system offers its own advantages and drawbacks. Remotely operated vehicles offer full on-line communication with the platform through a fiber optic link and, possibly, a power tether. Such applications are conceptually simple and, therefore, attractive. However, in the case of a vehicle operating in the close vicinity of a platform the existence of the tether is a very serious drawback. The alternative is to use an untethered vehicle that is acoustically linked to the platform. Acoustic communication is of relatively low bandwidth, though, and certain vehicle functions that need to be performed at a sufficiently high sample rate cannot be effectively performed unless the vehicle itself is equiped with a certain degree of autonomy. This is particularly true in an offshore station environment where the vehicle will have to operate in close proximity to other semi-stationary objects and will be subject to time dependent, periodic and random, excitation. Therefore, the need arises for a logical separation of the various vehicle functions. Higher-level decisions with regards to mission objectives can then be transmitted through the acoustic channel at a slow rate as the mission requirements change, while the mission execution details are left for the vehicle to perform at the high rate that is required for data collection and control.

Research on autonomous underwater vehicles at the Naval Postgraduate School is centered on similar requirements and is focused on advanced control techniques for mission execution and post mission analysis. A central problem as the vehicle attempts to negotiate with an unstructured environment is software organization. This is accomplished by a three layer structure consisting of an organizational layer, a coordination layer, and an execution layer. Each layer is in turn subdivided into additional levels, as needed, for vehicle operations according to mission objectives. In the overall system architecture, the mission planning expert system is executed first. The output is usually a planned series of geographical way points that avoid charted problem areas and lead the vehicle to its operational site with task descriptors at each target point. This is loaded into the vehicle computer for execution and consists of several sub-functional blocks, namely an environmental model data base, pattern recognition capability, obstacle avoidance decision maker, a navigation system (both absolute and relative), guidance and control, vehicle hardware systems, and a condition monitoring system for internal diagnostics.

At the heart of the execution level there exist the functions of navigation, guidance, and control. The fundamental breakdown of the motion control functions between guidance and autopilot relies on the notion that an autopilot is responsible for stabilizing the motion dynamics of the vehicle, eg., speed, heading, and depth. The guidance law combines commands for the path and position to be followed and other attitude requirements. It performs these tasks with navigational estimates of true position and orientation, to generate the speed, heading, and depth commands for the autopilot. Such a distinction between guidance and control is necessary in the present applications since it allows for the required flexibility in selecting the appropriate scheme for the chosen task.

Separation of guidance and autopilot functions is not without its problems. For accurate path keeping, the dynamics of the guidance law must be as fast as possible, which sets a lower bound for the autopilot reaction time. Ocean vehicles suffer from a number of dynamic lags in their motion response and actuator sizing, and these lags set an upper bound for their reaction time. At the intersection of these two bounds, it is possible that loss of stability of the entire guidance/autopilot scheme may occur. The loss of stability point is computable by linear methods, but it provides an incomplete picture of the system dynamics. Of interest here is to establish the vehicle response once primary stability is lost. This is necessary in order to establish practical measures of stability or domains of attraction.

Our results indicate that the mechanism of stability loss is through bifurcations to periodic solutions although solution branching has also been observed in certain cases. To analyze stability properties of the resulting periodic solutions we proceed with a systematic nonlinear study. To this extent we make extensive use of bifurcation theory, center manifold reduction, and integral averaging. The results indicate the existence of either subtle or catastrophic bifurcations to periodic solutions and estimates of their amplitude and period. It will be shown that application of nonlinear dynamics techniques is necessary for reliable estimates of vehicle operational envelopes for given environmental conditions and mission specifications.

1:00

Ice-Structure Interaction

Professor Dale G. Karr, University of Michigan, Department of Naval Architecture and Marine Engineering

Force versus time histories of ice-structure interactions show oscillations that are highly dependent on velocity, ice properties, and structure properties. Ice forces acting on the structure rise with time as stresses in the ice increase. The ice sheet eventually fails, often locally near the structure, causing an abrupt decrease in the interaction force. As contact is reestablished, contact forces again rise and cyclical forces continue as indentation progresses. This process is complicated by the variability of the ice properties, the complexity of the ice deformation response, and the geometry of the contact interface as well as the dynamics of the repeated impacts.

One of the first mechanical models used to analyze this process was presented by Matlock, Dawkins and Panak. The offshore structure is represented by a single degree-of-freedom mass-spring-dashpot system and the ice sheet is represented by a system of cantilevered bars. The ice bars are modeled as linearly elastic beams or springs that fracture completely at a characteristic deflection. This idealization captures, in a simple manner, the intermittent build-up of contact stress and subsequent failure of the ice.

The dynamic response of this simple analogue model of ice-structure interaction is studied in considerable detail. The complicated, highly nonlinear dynamic response is due to intermittent ice breakage and intermittent contact of the structure with the ice. Periodic motions are found and the periodicity for a particular system is dependent upon initial conditions. Phase space concepts of modern dynamical systems theory are applied in order to structure the investigation of the motions of the system. For representative systems, "Poincare" maps are presented showing the fixed points and basins of attraction. Two types of threshold solutions are found, each necessary but not sufficient in defining local separatrices. A description of some of the effects of random variations in system parameters is also presented. Some implications of these findings regarding structural design for ice interaction are also discussed.

1:55

Single-Point Mooring Systems: Station Keeping Stability and Chaos

Professor Michael M. Bernitsas, University of Michigan, Department of Naval Architecture and Marine Engineering

Since 1982, the University of Michigan has conducted extensive research on the station keeping stability of Single-Point Mooring (SPM) systems and the course keeping stability of towing systems. Those two problems are closely related. This effort has been funded by the University of Michigan/Sea Grant/Industry Consortium in Offshore Engineering and the University Research Program of the Department of Transportation. The outcome of this research is a comprehensive assessment and design methodology for SPM systems based on their nonlinear dynamic behavior.

Repeated accidents in towing and SPM systems and conflicting theoretical and experimental recommendations regarding the selection of the towline length instigated this research. Specifically, in 1950 Strandhagen et al. performed linear stability analysis using the horizontal plane linear maneuvering equations and an inextensible towline and concluded that stability can be improved by shortening the towline length, l_w, and by moving the fairlead location, x_p, forward. Observations made by Benford in 1955 on towing of Canadian barges, and experiments conducted by Brix in 1971 concluded the opposite regarding l_w. They all agreed that increasing x_p improves course keeping stability. The methodology developed in this work has resolved this contradiction and has proven that increasing x_p may not improve stability. Each researcher was focusing one small part of the design domain, thus looking only at a small part of the catastrophe set.

Nonlinear stability and parametric bifurcation analysis are used to define regions of similar dynamics in a parametric design space. Thus, regions of safe and hazardous dynamic behavior can be identified making it possible to design and operate an SPM safely. SPMs may exhibit asymptotically divergent, convergent, or periodic response, and short-term quasiperiodic, or unpredictable (chaotic) dynamics. Simulations are used to verify theoretical conclusions. This method also proves that the large amplitude slow motion response that SPM systems often exhibit in practice, are due to inherent system instabilities and can be instigated by time independent excitation such as wind, current or mean drift forces.

The mathematical model consists of the horizontal plane maneuvering equations (surge, sway, yaw) that are nonlinear of third order without memory, and time-independent excitation from current, wind, and mean wave drift forces. Three different quasistatic mooring line models for nylon ropes, chains, or steel cable are used. The latter, a three-dimensional finite element model, accounts for extensibility, Poisson effect, deformation dependent hydrodynamic loads, and variable cable submergence. The developed design methodology is applied numerically to SPMs of a barge and a tanker. For these systems the effects of current velocity, type of mooring line, and wave direction, on the design graphs (catastrophe sets) are studied.

2:40

Two-Point Mooring/Towing: Station Keeping

Professor Michael M. Bernitsas, University of Michigan, Department of Naval Architecture and Marine Engineering

A methodology similar to the one developed for SPM systems is developed for Two-Point Mooring/Towing (TPM/T) systems. The nonlinear dynamic analysis approach is similar but the design graphs (catastrophe sets) are much more complex because TPM/Ts may have three possible equilibria out of nine (instead of 3 for SPMs). The method is based on the horizontal plane (surge, sway, yaw) third order maneuvering equations of the moored vessel. It analyzes the nonlinear, slow-motion dynamics of TPM/T systems.

The time evolution of the corresponding autonomous dynamical system is described in a six-dimensional state space. Branching diagrams identify supercritical pitchfork bifurcations and turning points that result in static loss of stability. TPM/Ts also exhibit Hopf bifurcations that result in dynamic loss of stability and periodic solutions. Stability charts are developed to show catastrophe sets and regions of qualitatively similar dynamics. Thus, regions of hazardous dynamics and line breaking, such as unstable equilibrium, unstable limit cycle, and chaotic dynamics, are identified. Theoretical conclusions are verified by numerical simulations of tanker and barge TPM/Ts. Based on this methodology, only a limited number of simulations is needed for analysis and design of TPM/Ts. Lines can be selected then to complement -- rather than counter -- each other and allow the system to attain a safe equilibrium.

3:10

Fully Nonlinear Computations of Ship Motions

Professor Robert F. Beck, University of Michigan, Department of Naval Architecture and Marine Engineering

For the past several years we have been working under support of the Office on Naval Research and more recently the University of Michigan/Sea Grant/Industry Offshore Consortium to develop techniques to predict the time-domain, fully nonlinear hydrodynamic loads and motions of ships and offshore structures. All our work to date has assumed that the water can be considered as incompressible and inviscid and that the flow around the body remains irrotational. In this case, the Laplace equation is valid everywhere in the fluid domain and the hydrodynamic forces acting on the body are determined as the solution to a boundary value problem. This is not to imply that viscous effects are unimportant. On the contrary, for certain phenomena they are dominant. However, the inviscid fluid problem is an order of magnitude easier to solve and therefore has been the basis for much of the research in the area. For certain types of problems and geometries the inviscid assumption gives acceptable accuracy. A more realistic approach would be to use a viscous solution in the near-field and match it to an inviscid far-field solution. This is beyond the present state of the art.

Fully nonlinear calculations can be performed in a variety of ways. We use a variant of the Euler-Lagrange method first proposed by Longuet-Higgins and Cokelet in 1976 to solve two-dimension water wave problems for steep and breaking waves. This time-stepping procedure requires two major tasks at each time-step: the linear field equation is solved in an Eulerian frame; then the fully nonlinear boundary conditions are used to track individual Lagrangian points to update their position and potential values. The method has been applied to a wide variety of two- and three-dimensional problems.

Several difficulties are associated with the application of the Euler-Lagrange method. The most important is the numerical stability of the time integration of the free-surface boundary conditions. Instabilities can easily develop that quickly overwhelm the solution. Other difficulties are the implementation of a far-field closure condition, the treatment of the intersection line between the body and the free-surface with its associate spray root, and the physically realistic but numerically difficult possibility of breaking waves.

In the Euler-Lagrange method a time-stepping procedure is used in which a boundary value problem is solved at each time-step. At each step, the value of the potential is given on the free-surface (a Dirichlet boundary condition) and the value of the normal derivative of the potential (a Neumann boundary condition) is known on the body surface and bottom surface. The potential and its normal derivative are updated at the end of each time-step. The free-surface potential and elevation are determined by integrating with respect to time (or time marching) the free-surface boundary conditions. In our calculations, a Runge-Kutta-Fehlberg technique is used to do the time-stepping. The body and bottom boundary conditions are prescribed for the forced motion problem or determined by integration of the equations of motion for a free body.

On the free-surface, the kinematic condition is used to time-step the free-surface elevation and the dynamic condition is used to march the potential. Several different approaches are possible in the time integration of the free-surface boundary conditions. The most common is a material node approach in which the nodes follow the individual fluid particles. Another technique is to prescribe the horizontal movement of the node but allow the node to follow the vertical displacement of the free-surface. The prescribed movement may be zero such that the node locations remain fixed in the x-y plane. Depending on the problem, one of the techniques may be easier to apply than the others.

Many methods can be used to solve the resultant boundary value problem at each time-step; in our research, we have used a desingularized boundary integral method. Similar to conventional boundary integral methods, it reformulates the boundary value problem into a boundary integral equation. The difference is that the desingularized method separates the integration and control surfaces, resulting in no singular integrals. The solution is constructed by integrating a distribution of fundamental singularities over a surface (the integration surface) outside the fluid domain. The integral equation for the unknown distribution is obtained by satisfying the boundary conditions on the problem boundary (the control surface).

The desingularized approach has been used by a number of researchers. It has been successfully applied to the flow past an arbitrary three-dimensional body in an infinite fluid, the wave resistance of submerged bodies and surface ships, and the creation of solitons by disturbances moving in shallow water.

The desingularized method has several computational advantages. First, because of the desingularization, the kernels are no longer singular and no special care is required to compute the integrals. Simple numerical quadratures can be used to greatly reduce the computational effort, particularly by avoiding transcendental functions. In fact, for the source distribution method the distributed sources can be replaced by simple isolated sources. This greatly reduces the complexity of the form of the influence coefficients that make up the elements of the kernel matrix. Higher order singularities such as dipoles can easily be incorporated. The isolated Rankine sources also allow the direct computation of the induced velocities on the free-surface. The resulting code does not require any special logic and is thus easily vectorized. As presently implemented, we are using an iterative solver (GMRES) and preconditioning as necessary to solve for the unknown source strengths. We are working on installing the code to run on a new massively parallel processor at the University of Michigan. At present, the method is $O(N^2)$, but by using multipole expansions it could be reduced to an O(N 1nN) method with the accompanying reduction in computer time for very large numbers of unknowns.

Results, convergence rates, and comparisons with experiments will be presented for various fully nonlinear calculations that have been done to date. These include solitons in shallow water, the added mass and damping of a two-dimensional box in heave and sway, the radiation forces acting on axisymmetric bodies in deep and shallow water, and the wave resistance of a Wigley hull form. The results obtained to date are very promising. The desingularized Euler-Lagrange method appears to be a robust method that is easy to implement on vector and parallel machines. It also has the capability to be extended to an O(N log N) method.

4:10

Effect of Second-Order Forces on Moored Vessel Dynamics

Tin-Woo Yung, Exxon Production Research

[Paper not available at time of publication.]

MAY 19

8:30

Improved Methods for Processing Position Information for Dynamic Positioning

Professor Michael G. Parsons, University of Michigan, Department of Naval Architecture and Marine Engineering

The need for Dynamic Positioning (DP) systems has increased as oil production has moved to deeper water. During the past two decades, DP systems have been improved through the introduction of modern control schemes. The accuracy and reliability of the DP system is, however, heavily dependent upon the position sensors. As the drill-ship or the semisubmersible platform moves into deeper waters, the possibility of degradation of position information from acoustic sensors, in particular, is dramatically increased. With the degradation, malfunction, or failure of position sensors, the control actions based on the false position information might result in serious operational or safety problems. In this study, the concept of a third-generation DP control system using an integrated hierarchical control structure including an improved method for the processing of the position information is introduced and evaluated.

The overall control would have a hierarchical structure as illustrated in Figure 1. Multiple sensors could be used for position and motion reference, including Global Positioning System (GPS) satellite, navigation radar, LORAN-C, acoustic position reference systems, local radar transponder systems, gyro compass and rate gyro. The redundant position sensors provide inputs to both sensor failure detection filters and to optimal stale estimation filters for position estimation.

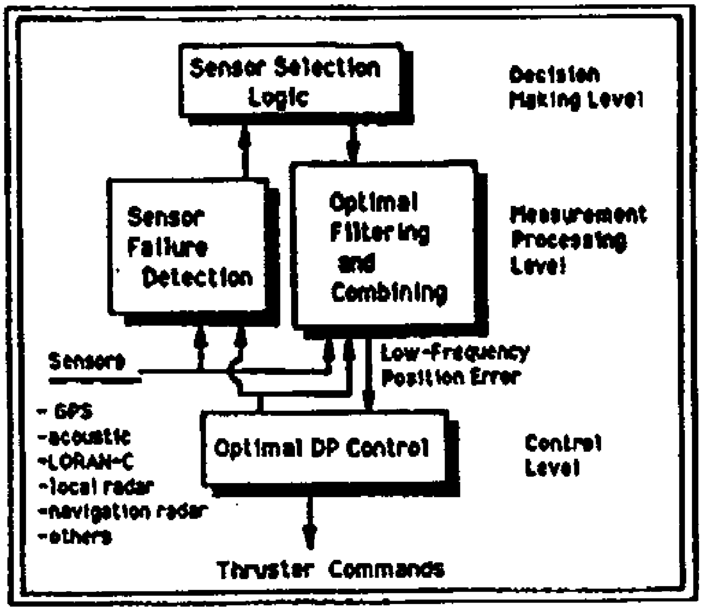

Figure 1. Hierarchical arrangement of third-generation DP control system

Failure detection theory is used to monitor position sensor performance. While the Beard-Jones Detection Filter (BJDF) is generally used for the detection of actuator failures and changes in system dynamics, the Binary Phase Detection Filter (BPDF) can be used for the detection of the sensor failures. The sensor failure detection information is provided to the decision logic that selects the sensors and optimal state estimation filter to be used to control the vessel. The decision on the sensor selection is passed to the optimal filtering and combining function that uses Kalman filters to estimate the low-frequency position error for the vessel. This error is the input to the optimal DP control algorithm designed by the Linear Quadratic approach commonly in use.

The deterministic BPDF concept was initially developed by Min for use in an open loop system. The DP system of interest here must apply the failure detection filter within a stochastic state estimate feedback control system. Also, the DP system has redundancy in the measurement system. The BPDF for sensor failure detection in a deterministic state estimate feedback control system was developed. In the application of the BPDF to the stochastic system, standard Kalman filter theory can be used to design a BPDF for the sensor failure detection in a stochastic state estimate feedback control system. The failure identification is obtained from the residuals generated by the detection filters. The sensor selection decision logic for the detection, isolation, and identification of the sensor failures is developed.

A complete DP system using sensor failure detection filters and sensor selection logic is designed and implemented for a model of the Götaverken GVA 4000 semisubmersible to evaluate the overall system concept and performance. The concept was found to provide good performance and the desired sensor failure detection capabilities.

9:15

The Effects of Cable Motions and Loads on Moored Systems

Professor Michael S. Triantafyllou, Massachusetts Institute of Technology, Department of Ocean Engineering

Mooring line damping is a major source for damping in the slow, resonant motions of moored vessels, whose amplitude influences considerably the design and cost of mooring systems. There is great uncertainty on the value of the equivalent drag coefficient (up to a factor of 10 !), while mooring line damping is certain to exceed 30% (up to 80%) of the total damping. Recent experimental and numerical progress in handling this problem will be outlined.

In the case of the mooring lines, it is well known that the value of the equivalent drag coefficient increases dramatically (from a nominal value of 1.2 to a value of 3.0 or even higher). The combination of slow motions and wave-induced motions has been found to amplify the equivalent drag coefficient, and various methods of linearization have been proposed. Also, the out-of-plane motions (vortex induced) cause the already amplified drag coefficient to rise by a factor of between 1.4 and 4. No established method has been capable of predicting accurately these amplifications.

A related problem, is that of the forces on a cable in a current. This becomes important in light of recent experience with strong ocean currents, such as the loop current in the Gulf of Mexico and the currents associated with the gyres of the Gulf Stream. Due to drag coefficient amplification the forces can be substantial, and well above what the state of the art would predict.

We have recently described, in a series of papers, the basic mechanism of drag amplification in flexible cylinders, such as cables, chains, and risers: A beating oscillation develops, whose beating period depends on the shear of the local relative velocity. This beating oscillation changes entirely the hydrodynamic mechanisms, and existing data become inapplicable. This explains the failure so far to have reliable predictive tools. Also, the slow motion-wave motion interaction mechanism must be viewed as a second amplification mechanism, acting in addition to the vortex-induced amplification.

In the talk, I will first outline the decomposition of mooring line motions into slowly varying motions, wave-induced motions, and vortex-induced motions, in a systematic way. Then the interactions among these motions will be discussed and their effect on the moored vessel motions will be assessed.

Next, recent experiments will be shown, explaining the principal mechanisms of interaction between slowly-varying motions and vortex-induced motions; and slowly-varying motions and wave-induced motions. The importance of the amplification mechanisms on mooring system performance will be addressed.

Finally, a methodology for numerically calculating the response of mooring lines including all three modes of response and their interactions will be outlined, and the effect on the overall response of moored systems will be assessed.

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10:20

Geometrically Nonlinear Three-Dimensional Dynamics

Professor Noel C. Perkins, University of Michigan, Department of Mechanical Engineering and Applied Mechanics

The performance of offshore station keeping systems is governed, in part, by the dynamic response of mooring lines. A prerequisite to predicting this dynamic response is the development of suitable structural models for cable elements. As a step towards this goal, this presentation will provide an overview of research efforts at the University of Michigan that have focused on the nonlinear dynamics of suspended cables.

This overview includes: 1) a summary of a nonlinear continuum model for elastic cables, 2) analytical and numerical results for nonlinear response, and 3) results from companion experimental studies. Results of this research has led to a fundamental understanding of the nonlinear mechanisms governing the large amplitude dynamics of cables suspended in air. As such, these results provide a foundation for models and analysis techniques that may be further used to explore the complex dynamics and interactions that arise in offshore station keeping systems.

The first part of this presentation will focus on a nonlinear model that governs large, three-dimensional oscillations of a suspended cable. The nonlinearities considered are geometric and result from modeling *finite* stretching of the cable as it oscillates about a planar equilibrium profile. For small amplitude oscillations (i.e., infinitesimal stretching), this model reduces to the linear theory for suspended cables developed by Irvine and Caughey (1974). As an important conclusion, this linear theory dictates that motion in the equilibrium plane decouples from motion normal to this plane. Moreover, the in-plane and out-of-plane motions may be further decomposed into modal sums of so-called "in-plane" and "out-of-plane" modes that act independently. At least this is the conclusion reached before consideration of finite stretching. The nonlinear model shows that finite cable stretching leads to both quadratic and cubic nonlinearities that may couple in-plane and out-of-plane modes. As a result of this coupling, large amplitude, three-dimensional cable motions may ensue. In fact, experimental results on laboratory cables suspended in air demonstrate that such coupled nonlinear motions are truly the rule rather than the exception! The mechanisms that lead to these strongly coupled motions are identified in the second part of this presentation.

Part Two of the presentation reviews a series of analytical and numerical results for nonlinear cable response. Two general classes of response problems will be discussed. The first of these considers a generic type of "boundary" excitation wherein a suspended cable is driven by small oscillations of one support (e.g., tow-point excitation). This is followed by an analysis of "domain" excitation wherein the suspension is subject to distributed in-plane excitation. Analytical solutions for both classes of nonlinear response problems are obtained using discrete forms of the continuum cable model and are compared with the results of numerical simulations. The analytical solutions are found using perturbation methods which, in this study, permit one to determine the existence and stability of periodic motions under harmonic boundary and domain excitation. More importantly, however, the perturbation analyses reveal that *internal resonances* are key nonlinear mechanisms that lead to strongly coupled response. In the presence of an internal resonance, a substantial amount of vibration energy is exchanged between participating cable modes leading to strongly coupled dynamics. Results show that a single pair of in-plane and out-of-plane modes may couple through either of two particular types of internal resonances, namely "two-to-one" and "one-to-one" type internal resonances. Results further show that three or more cable modes may couple through several types of "simultaneous" internal resonances. All of the above internal resonances arise naturally in suspended cable dynamics whenever the natural frequencies of the participating modes are in particular ratios. Thus, the propensity towards coupling, and the "modal content" of the response, are ultimately governed by the cable natural frequency spectrum and can therefore be anticipated from relatively simple computations. Advanced knowledge of modal content may pave the way towards efficient numerical algorithms for simulating nonlinear cable dynamics.

The presentation will conclude with results from laboratory tests that serve to validate theoretical predictions of nonlinear cable response. The tests were performed on simple suspensions subject to either boundary or domain excitation. Measurements of large amplitude, non-planar cable response were measured using a novel two-axis optical displacement probe. The measurements confirm the existence of the fundamental classes of internally resonant responses discussed in Part Two.

11:15

Calibration of Mooring Design Codes for Catenary Spread Mooring Systems

Dr. Y.S. David Tein, David Tein Consulting Engineers, Ltd.

A Joint Industry Project is being conducted to deterministically calibrate mooring design codes and develop the methods needed for a formal reliability based code calibration. The American Petroleum Institute, through its mooring design panel, is providing important guidance in developing these codes. Industry sponsors include oil companies, drilling contractors, regulatory bodies, and manufacturers.

This paper highlights the technical background of the Joint Industry Project. First, the mooring design codes are compared in terms of aspects important to mooring designs, specifically, design environmental criteria, methods of calculation, and design factors of safety. Second, the estimation uncertainties with mooring loads and resistance are discussed. The accuracy of predicted mooring loads is mainly affected by the strength and limitation of theoretical and experimental techniques. The scatters of mooring resistance, on the other hand, relate to the quality of manufacturing, maintenance, inspection, and operations. Finally, the need to transform basic research into practical design technology is emphasized. The challenging task is to design safer and more cost-effective mooring systems, taking advantage of the latest advantages in theoretical, numerical, and experimental technologies.

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BIOGRAPHIES OF PRESENTERS

Professor Robert F. Beck
University of Michigan, Department of Naval Architecture and Marine Engineering

Professor Beck is chairman of the University of Michigan's Department of Naval Architecture and Marine Engineering, where he has been affiliated since 1972. Widely published, his current research focuses on nonlinear ship hydrodynamics. Among his professional commitments, Professor Beck is a member of the Michigan Sea Grant Research Advisory Committee, and chairs a panel on analytical ship wave relations for the Society of Naval Architects and Marine Engineers.

Professor Beck received his B.S. degree from the University of Michigan and his Ph.D. in Naval Architecture and Marine Engineering from MIT.

Professor Michael M. Bernitsas
University of Michigan, Department of Naval Architecture and Marine Engineering

Professor Bernitsas has been affiliated with the University of Michigan's Department of Naval Architecture and Marine Engineering since 1979. He established the MS and Ph.D. programs in Offshore Engineering and helped to establish the University of Michigan/Sea Grant/Industry Consortium. His research interests include the design of ship and offshore structures and the dynamics of two-line and single point mooring systems.

Recently, Professor Bernitsas organized and chaired the NSF International Workshop on Riser Mechanics, held in 1992. He is currently a member of the SNAME Committee on Mooring Systems and the American Petroleum Institute's Work Group on Marine Risers.

Professor Bernitsas received a Diploma from the National Technical University of Athens, an S.M. in Naval Architecture and Marine Engineering and Ocean Engineering from MIT, and a Ph.D. in Ocean Engineering, specializing in Offshore Structures Design, from MIT.

Professor Dale G. Karr
University of Michigan, Department of Naval Architecture and Marine Engineering

Professor Karr joined the Department of Naval Architecture and Marine Engineering at the University of Michigan in 1990. Previously, he was associate professor at MIT, where he had been affiliated since 1984. Dr. Karr's research focuses on ice structure engineering, nonlinear dynamics of ice-structure interaction, and numerical modeling of continuum damage evolution during ice-structure interaction.

Professor Karr received a B.S. from Michigan State University, an M.S. from the University of Tennessee, and his Ph.D. degree from Tulane Unversity.

Professor Fotis A. Papoulias
U.S. Naval Postgraduate School, Department of Mechanical Engineering

Professor Papoulias joined the Department of Mechanical Engineering, U.S. Naval Postgraduate School in 1988. His primary research interests include nonlinear dynamics and control, ship/submarine response and motion control, global dynamics and chaotic response, and bifurcation theory.

Professor Papoulias received a Diploma from the National Technical University of Athens, Greece, an M.S. degree from both the Aerospace Engineering and Naval Architecture and Marine Engineering Departments at the University of Michigan, and his Ph.D. in Naval Architecture and Marine Engineering from the University of Michigan.

Professor Michael G. Parsons, University of Michigan, Department of Naval Architecture and Marine Engineering

Professor Parsons has been affiliated with the University of Michigan since 1971, and was named Outstanding Faculty Member in Naval Architecture and Marine Engineering in 1991. He also serves as Associate Dean for Undergraduate Education in the College of Engineering, and previously served as Director of the Michigan Sea Grant College Program and Chairman of the Department of Naval Architecture and Marine Engineering. Professor Parsons's research interests include ship hydrodynamics, ship operational and safety aspects of ballast water exchange at sea, and marine diesel engine shafting systems. Among his professional commitments, Professor Parsons is chairman of the Great Lakes and Great Rivers Section of the Society of Naval Architects and Marine Engineers.

Professor Parsons received his B.S. from the University of Michigan, a certificate from the Westinghouse Reactor Engineering School, an M.M.E. in Mechanical Engineering from the Catholic University of America, and a Ph.D. in Applied Mechanics from Stanford University.

Professor Noel C. Perkins
University of Michigan, Department of Mechanical Engineering and Applied Mechanics

Professor Perkins joined the Department of Mechanical Engineering and Applied Mechanics at the University of Michigan in 1987. Recently, he was the 1990 recipient of the University of Michigan's College of Engineering Teaching Excellence Award. Professor Perkins's research interests include applied mechanics, dynamics, vibration analysis, conservative and nonconservative stability, nonlinear dynamics, machine dynamics, and experimental methods in dynamics and vibrations. His current research focuses on the dynamics of cables, cable structures, and axially moving continua. Professor Perkins is a Technical Committee Member and symposium organizer for the 14th Biennial Conference on Mechanical Vibration and Noise (1993).

Professor Perkins received his B.S., M.S. and Ph.D. degrees in Mechanical Engineering from the University of California.

Professor Steven W. Shaw
University of Michigan, Department of Mechanical Engineering and Applied Mechanics

In 1991, Professor Shaw joined the Department of Mechanical Engineering and Applied Mechanics at the University of Michigan. Previously he was affiliated with the Department of Mechanical Engineering at Michigan State University. Dr. Shaw's research focuses on: nonlinear dynamics and vibrations; application of stability and bifurcation theories to engineering systems; chaotic motions in mechanical systems; large amplitude ship dynamics; and capsize, design of vibration absorbers. Professor Shaw is currently organizer for the forthcoming Asia-Pacific Vibration Conference, to be held in Japan in November 1993.

Professor Shaw received his B.A. and M.S. degrees from the University of Michigan, and his Ph.D. degree from Cornell University.

Dr. Y.S. David Tein
David Tein Consulting Engineers, Ltd.

As principal consultant of David Tein Consulting Engineers, Ltd., Dr. Tein has recently performed or coordinated mooring, riser, and flowline analyses for ships, and reviewed modeling of wave dynamic loads for double hull tankers. Previously he had been engineering manager for Nobel, Denton & Associates Inc.

Since 1976, Dr. Tein's work has focused on floating arctic structures, hydrodynamics, seakeeping analysis, structural analysis and computer-based model simulations. Currently, Dr. Tein chairs the panel on station keeping and mooring terminals for the Society of Naval Architects and Marine Engineers.

Dr. Tein received a B.S. from the National Marine Technology University in Taiwan, an M.S. from the University of New Mexico, a Ph.D. in Naval Architecture and Marine Engineering from the University of Michigan, and an M.B.A. in Marketing from Rice University.

Professor Michael S. Triantafyllou
Massachusetts Institute of Technology, Department of Ocean Engineering

Professor Triantafyllou has been affiliated with the Department of Ocean Engineering at MIT since 1978. He also serves as director of the Ocean Engineering Testing Tank Facility at MIT, and since 1991 serves as a visiting scientist at Woods Hole Oceanographic Institution. Professor Triantafyllou held the H.L. Doherty Professorship in Ocean Utilization from 1983-85. His current research interests include mechanics of cables, dynamics and control of marine vehicles and structures, and wake dynamics and vorticity control. He is vice-chairman of the committee on moorings and offshore terminals, Society of Naval Architects and Marine Engineers.

Professor Triantafyllou received a Diploma from the National Technical University of Athens, an S.M. in both Ocean Engineering and Mechanical Engineering from MIT, and his Sc.D. in Ocean Engineering from MIT.

Professor Armin W. Troesch
University of Michigan, Department of Naval Architecture and Marine Engineering

Professor Troesch has been affiliated with the University of Michigan's Department of Naval Architecture and Marine Engineering since 1976, and was the 1992 recipient of the Departmental Teaching Award. From 1980-1987 he served as Director of the Ship Hydrodynamics Laboratory. Professor Troesch is currently a member of the Executive Committee for the American Towing Tank Conference. His research interests include hydrodynamic impact investigations, thermal wake imaging, dynamical systems of ship rolling motion and capsizing.

Professor Troesch received his B.S., M.S., and Ph.D. degrees in Naval Architecture and Marine Engineering from the University of Michigan.

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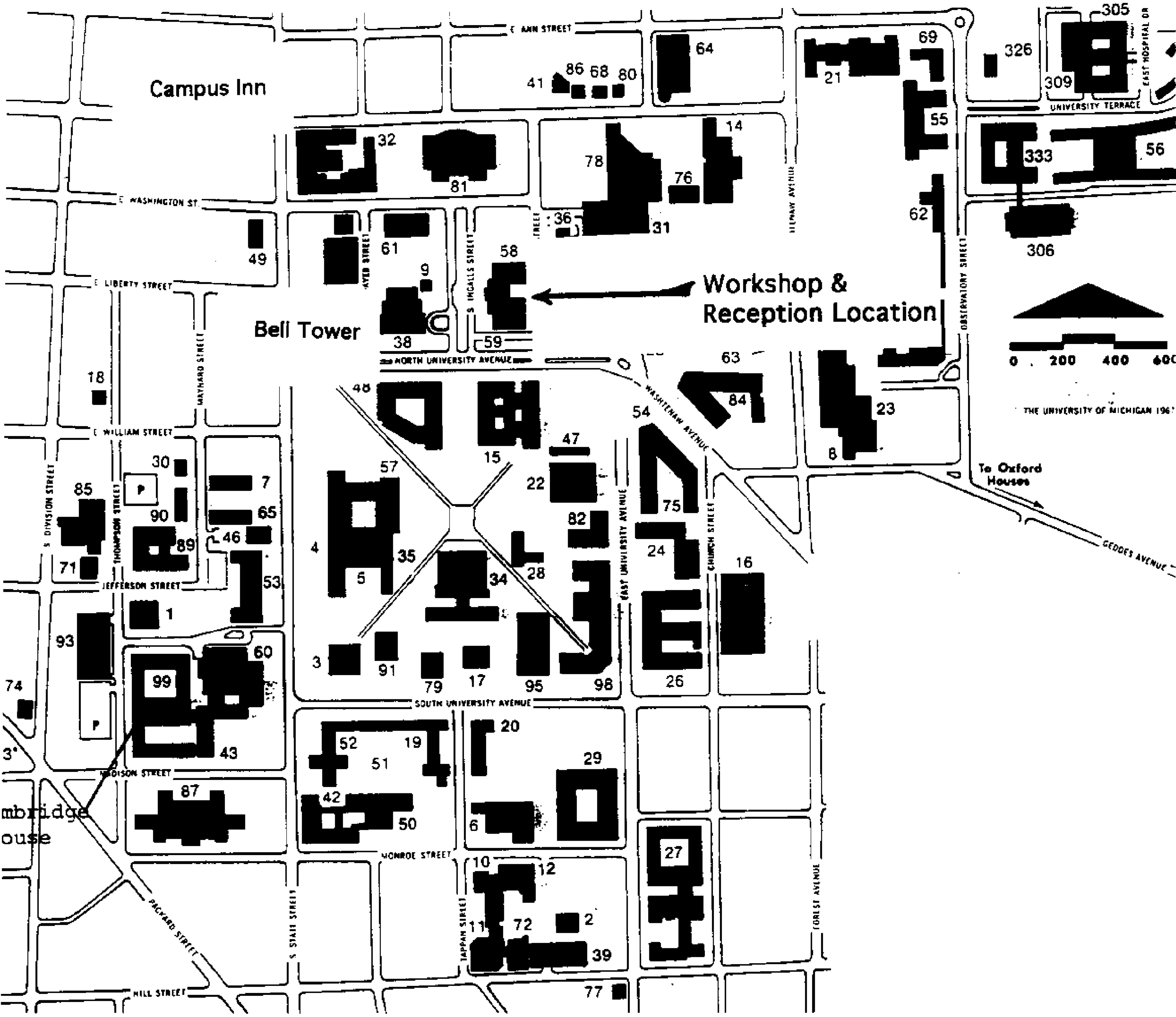

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