The MIT/Marine Industry Collegium

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INTERACTION of FLOW-FIELDS with CABLES, FLEXIBLE RISERS and TETHERS

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MIT Marine Industry Collegium
Building E38-308
292 Main Street
Cambridge, Massachusetts 02139

For symposium information, call John Moore Jr. Tel: (617) 253-4434
(617) 253-7092
FAX: (617) 258-5730

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INTRODUCTION

As we continue to delve deeper into the ocean to explore and utilize its marine resources, we must develop a greater understanding of the environment in which we work and how that environment interacts with man-made structures and systems. One important aspect of the marine environment's physical dynamic structure is ocean currents which are responsible for significant loads on marine structures and systems and are an important factor in the design process. Therefore, to ensure a design that is safe and reliable, as well as cost effective it is important to thoroughly understand the dynamic interactions that occur between the flow-field and the marine system or structure of interest .

This symposium, "Interaction of Flow-Fields with Cables, Flexible Risers and Tethers" will provide attendees with an opportunity to learn more about ongoing research in this important field. The MIT Sea Grant Marine Industry Collegium has joined with the MIT Department of Ocean Engineering to bring together leading researchers who will present the results of their current research during this one-and-a-half day meeting. Several presentors will describe the forces and responses of cylinders in differing flow regimes while others will address the dynamics of cables in flow-fields.

Through extended question-and-answer sessions and scheduled breaks, the symposium provide an environment that will be conducive to active information sharing. Through this symposium we hope to promote a greater understanding of complex fluid dynamical processes, thus leading to safer designs for future marine structures and systems.

John Moore Jr.
Manager,
Marine Industry Collegium

SYMPOSIUM AGENDA

Interaction of Flow-Fields With Cables, Flexible Risers and Tethers

APRIL 23

8:00-8:45	**Registration**
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9:45-10:15	**Nondimensional Parameters for Flow-Induced Vibration** J. Kim Vandiver, MIT
10:15-10:35	**Break**
10:35-11:20	**Drag Forces and Flow-Induced Vibrations of Long Vertical Marine Cables** Mark A. Grosenbaugh, WHOI
11:20-12:20	**Loading and Response of Flexible Cylinders in Oscillatory Flow and Waves** Peter W. Bearman, Imperial College
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1:45-2:30	**Control of Bluff Body Wake Instabilities** Donald Rockwell, Lehigh University
2:30-2:50	**Break**
2:50-3:20	**The Lift and Drag Forces on a Cylinder Undergoing Amplitude Modulated Vibrations in Cross-Flow** Ram Gopalkrishnan, MIT/WHOI

3:20-3:50 **Identification of Parametric Dynamic Models for Deeply-Towed Underwater Vehicle Systems**
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8:45-9:15 **Response Prediction of Moorings and Risers**
J. Kim Vandiver, MIT

9:15-10:00 **Chaos Hunt in the Motions of a Tethered Sphere**
Robert Cawley, Naval Surface Weapons Center

10:00-10:15 **Break**

10:15-11:15 **Numerical Simulation of Flows Past Bluff Bodies**
George Em Karniadakis, Princeton University

11:15-12:00 **Damping of Mooring Lines**
Mike S. Triantafyllou, MIT

12:00-1:00 **LUNCH**

1:00-2:30 **Lab Tour**
(depending on interest)

April 23

9:45

Forces on a Cylinder Oscillating in Steady Cross-Flow

Professor George S. Triantafyllou, The City College of New York

The modeling of vortex-induced forces on oscillating objects is very important for several engineering applications, and a vast amount of literature exists on the subject. Traditionally, it has been assumed that the object oscillates harmonically, and most existing experiments have been performed based on this assumption. Recently, it has been realized from field experiments that in real conditions structures perform amplitude modulated oscillations, and presently there is no information on how the forces can be modeled. I will present a simple way to model forces on structures that vibrate in an amplitude-modulated motion. The model is based on numerical experiments conducted through direct numerical simulation of the Navier-Stokes equations for the flow past a circular cylinder. It will be shown that the magnitude and frequency content of the vortex-induced forces is substantially different than those realized if the structure oscillates harmonically, but that they can be modeled in a relatively simple manner.

9:45

Nondimensional Parameters for Flow-Induced Vibration

Professor J. Kim Vandiver, MIT

Case studies drawn from fifteen years of field and laboratory experiments are used to demonstrate and explain why the flow-induced vibration of long cylinders in ocean currents varies from single mode lock-in to broad band random vibration. It is shown that the range of observed behavior is predictable with careful consideration of a few dimensionless parameters. New interpretations are given to the significance of familiar parameters such as mass ratio and reduced damping. In addition, the fractional variation in flow velocity over the length of the cylinder and the number of natural frequencies within the bandwidth of the vortex shedding frequencies are shown to be of considerable importance.

When consideration of the above parameters reveals that multiple mode response without lock-in is likely to occur, hydrodynamic damping is revealed to have a powerful influence on dynamic response, and the simple product of the total damping ratio and the mode number allows one to anticipate the whole range of response behavior, from the wave propagation properties of infinite length cables to the standing wave features of short cylinders.

10:35

Drag Forces and Flow-Induced Vibrations of Long Vertical Marine Cables

Dr. Mark A. Grosenbaugh, Woods Hole Oceanographic Institution

Presented in this talk are data from full-scale experiments on the quasi-static and dynamic characteristics of a long vertical tow cable and results from our efforts to model theoretically the flow-induced vibrations of long marine cables. The overall motivation for the study was to improve performance in the positioning of towed vehicles, such as ARGO-the Woods Hole Oceanographic Institution Deep Submergence Laboratory's search and survey system.

The experimental data was collected during two separate cruises. The first experiment took place in the Spring of 1987 at the U.S. Navy's Atlantic Underwater Test and Evaluation Center (AUTEC) in the Bahamas. The second experiment was carried out in the Summer of 1988 in the Tyrrhenian Sea.

The studies show that the drag coefficient of the cable is lower during unsteady towing operations (by as much as 40%) than during steady-state operations. We believe that the reason for this is related to the observed amplitude modulation of the flow-induced vibrations of the cable that are magnified during unsteady operations.

When the tow ship changes speeds (e.g. during maneuvering operations), there are differences in the normal component of the velocity along the cable because of the presence of a time delay in the response of the bottom of the cable to inputs at the top. The longer the cable, the greater are the delays. This creates large velocity gradients (in addition to those that already exist due to the ambient shear currents).

Our theoretical studies have shown that velocity gradients in the oncoming flow are responsible for the formation of 'beats' in the flow-induced vibrations of long marine cables. Because of fluid damping, the cable is infinitely long, and so it does not have natural transverse frequencies. Instead, the cable vibrates locally at whatever frequency it is being forced, in this case, the local Strouhal frequency. The local response creates transverse waves that travel along the cable and interact with the motion at nearby locations. In a shear flow, the forcing at a nearby location of the cable will be at a slightly different frequency, and thus the interaction of the traveling waves produces beats The beats, in turn, propagate along the cable and modulate the amplitude of the cable response. Modulation of the vibration amplitude acts to lower the root-mean-square of the motion, an effect that leads to a lowering of the cable drag coefficient.

Previous experiments have shown that the drag coefficient for towed cables and cables moored in currents can vary greatly. The results, presented here, help to explain the large variation in drag coefficients that exists in the literature by showing just how important the time history of the flow conditions are to the magnitude of the drag forces.

11:20

Loading and Response of Flexible Cylinders in Oscillatory Flow and Waves

Professor Peter W. Bearman, Imperial College of Science, Technology and Medicine

The work to be described has been carried out as part of the research program of the Marine Technology Directorate and has been supported by the United Kingdom Government and the Offshore Industry.

Risers, tethers, cables and cylindrical members of offshore structures may respond under the action of wave loading. The level of response depends on component stiffness, mass and structural damping as well as on the level of excitation generated by wave action. There will be direct forcing of vertical components in the wave direction and this may be predicted by assuming that the loading is represented by the relative motion form of Morison's equation. This assumes, of course, that the relevant drag and inertia coefficients are known. Components are also observed to respond in a direction transverse to that of the waves due to a flow instability that leads to the generation and shedding of vortices. As in the case of a steady current, motion of the cylinder may lead to a modification of the vortex structure that may result in enhanced response in both the in-line and transverse directions. The presentation will report on investigations into the fluid structure interactions that take place between a large-scale, flexible cylinder and wave flow and between a small-scale, flexible cylinder and planar oscillatory flow.

Large-scale experiments are required in order to obtain design data for offshore applications. Experiments on a 0.5m diameter flexible cylinder mounted in the large Delta flume operated by Delft Hydraulics will be described. This cylinder, known as the Christchurch Bay Compliant Cylinder, was later tested in the sea off the south coast of England in 1987. These latter results still remain confidential to the sponsoring consortium. A unique feature of the cylinder is that its natural frequency can be varied by locking or unlocking hydraulic jacks at a number of positions along its length. In its stiffest mode it can be considered as an effectively rigid cylinder. Results will be described for the cylinder operating at its lowest frequency of about 0.5Hz. The Delta flume can generate waves up to 2m high with periods between about 3 and 10 seconds. Over this range of conditions the responses in the transverse and in-line directions were of comparable magnitude, with maximum peak to peak amplitudes approaching 1.5 to 2 cylinder diameters.

The results, reported by Bearman (1988), show that in the transverse direction the response was predominantly at the cylinder natural frequency, whereas in the in-line direction the cylinder responded at both the wave frequency and the cylinder natural frequency. When the cylinder responded in the transverse direction the drag coefficient was observed to increase. It appeared that the level of transverse response depended on both the Keulegan Carpenter number and the ratio of the cylinder natural frequency to the wave frequency. As this ratio is increased then the Keulegan Carpenter number for maximum response increases. However, in wave tank experiments it is difficult to vary the important parameters independently or over a very wide range. Hence some experiments have been carried out on a flexibly mounted circular cylinder in planar oscillatory flow.

A cylinder with a diameter of 50 mm was suspended from a pendulum support system in a U tube water facility such that the cylinder was free to move in approximately two-dimensional motion. By adjusting the length of the support arms the natural frequency of the cylinder could be varied and, if required, the frequency could be made an exact multiple of the tank frequency. In addition, the structural damping could be increasing in a controlled way. A description of the apparatus will be found in Bearman and Mackwood (1991). The results of these experiments, which revealed a number of interesting nonlinear features, will be described. First, it was found that at a particular frequency ratio the cylinder responded in the transverse direction over a wide range of Keulegan Carpenter numbers. Spectra of the response showed that the energy was concentrated at frequencies that were multiples of the tank frequency. However, when the cylinder was tuned such that its natural frequency was matched to a multiple of the tank frequency, the response was observed to decrease. Surprisingly, under this condition the response could be increased by increasing the structural damping. The reason for this unusual behavior is not clear but it is supposed that a complex fluid/structure interaction takes place whereby the increased damping alters the phase, during a cylinder oscillation cycle, at which a vortex generated by the cylinder induces its largest force.

It is interesting to note that although the two experiments described above were carried out at quite different scales and under different conditions, the response characteristics appeared to be quite similar.

1:00

Ordered and Chaotic Vortex Streets Behind Vibrating Circular Cylinders

Professor Morteza Gharib, University of California, San Diego

In this presentation, results of some experiments undertaken to investigate the origin of ordered and chaotic laminar vortex streets behind vibrating circular cylinders will be reported. We made simultaneous measurements of near- wake longitudinal-velocity and cylinder lateral vibration amplitude spectra for cylinder Reynolds numbers in the range from 40 to 160. For a non-vibrating cylinder the velocity energy spectra contained only a single peak, at the Strouhal frequency. When the cylinder was observed to vibrate in response to forcing by the vortex wake, additional dominants observed to vibrate in response to forcing by the vortex wake and dominants spectral peaks also appeared in the resulting 'ordered' velocity spectra. Cylinder vibrations too small to be noticed with the naked eye or from audible Aeolian tones produced a coupled wake-cylinder response with dramatic effects in hot-wire and cylinder vibration detector signals. The velocity spectra associated with these coupled motions had dominant peaks at the Strouhal frequency f_s, at a frequency f_e, proportional to the fundamental cylinder vibration frequency, and at sum and difference combinations of multiples of (f_s) and (f_e).

In windows of chaos the velocity spectra were broadened by switching between different competing coupling modes. The velocity spectra were very sensitive to the nature of the boundary conditions at the ends of the cylinder. Our measurements strongly suggest that the regions of 'order' and 'chaos' are due to aeroelastic coupling of the vortex wake with cylinder vibration modes.

1:45

Control of Bluff Body, Wake Instabilities

Donald Rockwell, Lehigh University

From a practical standpoint, an understanding of bluff-body wakes is of central importance in controlling flow-induced noise and vibration, mean drag reduction, and mixing and combustion processes. New experimental approaches to manipulating this class of wakes involves alteration of the mean boundary conditions at separation from the bluff body, as well as various types of periodic and aperiodic excitation of two- and three-dimensional bodies.

Alteration of the mean boundary conditions at separation involves symmetrical and asymmetrical suction of the boundary layer on either side of a blunt trailing edge. Even relatively small amounts of suction can have a substantial influence on the amplitude of the limit cycle oscillations of the globally-unstable wake. Moreover, the spanwise uniformity of the wake is a function of the relative thickness of the modified boundary layer at separation. In cases where the near-wake instability transforms from a globally unstable to a convectively unstable state, the well-known three-dimensionality in the form of oblique vortex formation and vortex splitting can be eliminated in favor of spanwise coherent, large-scale vortex formation.

Controlled periodic excitation of a bluff body at frequencies lying within synchronization range can lead to abrupt changes in the flow structure, corresponding to a change in sign of the energy transfer between the body and the surrounding fluid. The instantaneous topological structure of the near wake shows a discontinuous behavior when the wake is subjected to suitable forcing. This change in topological structure alters the phase of the lift acting on the cylinder relative to the cylinder displacement.

Control of the near wake using aperiodic excitation, in the form of amplitude and frequency-modulated perturbations, can give rise to new types of vortex arrangements in the near-wake region. In turn, this vortex arrangement can undergo severe distortion as it evolves into the far-wake region. The periodic or low-order chaotic behavior of the far wake is therefore directly linked to the near-wake distortion mechanisms. Velocity spectra show a succession of well-defined states of increasing disorder, corresponding to the onset of chaotic behavior. Period doubling of the vortex formation process is an essential feature of the transformation from a phase-locked to a chaotic near-wake structure.

For the case of *periodic excitation of bodies having localized nonuniformity along their span,* it is possible to attain several states of response as a function of the forcing frequency. Proper forcing can generate a globally locked-in wake, where the structure is phase-locked along the entire span of the cylinder. Another state involves a region of period-doubled vortex formation embedded within locked-in vortex formation. Further period doubling, though not as consistent, can also be observed.

Whereas all the foregoing investigations have focused on the case of single bodies, periodic excitation of adjacent bodies can give rise to several new types of vortex patterns. The mechanisms of vortex formation in the gap between the oscillating cylinders have profound consequences on the downstream vortex pattern of the system of bodies.

In characterizing these types of wake response, extensive use is made of visualization-tracking techniques, involving hydrogen bubble timelines and high resolution particle imaging. New types of particle image velocimetry allow characterization not only of the instantaneous topology in terms of streamline patterns, but also instantaneous vorticity fields of the unsteady wake.

2:50

The Lift and Drag Forces on a Circular Cylinder Undergoing Amplitude Modulated Vibrations in Cross-Flow

Mr. Ram Gopalkrishnan, MIT/WHOI

It is well known that fluid flow around a bluff body such as a circular cylinder induces oscillating lift and drag forces on the body due to the formation of a vortex wake. For the Reynolds numbers of interest in typical mooring- or tow-cable applications, (typically 10,000 - 30,000) the lift and drag force coefficients and their relation to the body motion cannot be predicted by computer simulations of the Navier-Stokes equations. Recourse must be taken to laboratory scale experiments of fluid-structure interaction, and indeed, a wealth of experimental data on flow-induced forces and vibration have been accumulated over the years for sinusoidally oscillating circular cylinders in steady flow.

Recent full-scale observations point to the fact that long marine cables in shear currents sustain not simple harmonic oscillations, but rather complex motions that exhibit both spatial and temporal amplitude modulation, or 'beating.' It has been shown from low Reynolds number numerical simulations that this beating motion changes the nature of the oscillating lift and drag forces in a manner that cannot be predicted by a linear superposition of purely harmonic results. In essence, laboratory experiments on beating motion must be conducted to predict the forces on beating cables.

This presentation will describe the results of force measurements on a circular cylinder undergoing amplitude modulated motion. Experiments were conducted in the Towing Tank facility of the Department of Ocean Engineering at MIT, involving a circular aluminum cylinder towed through still water and forced to oscillate with dual frequency beating motion transverse to the direction of towing. Lift and drag forces were measured and were analyzed for mean, root-mean-square, spectral amplitude and phase information. The results are presented with comparison to pure sinusoidal excitations using the same apparatus. It is shown that there are marked differences between these and the newly acquired beating results. Hypotheses on the origins of this phenomenon are presented.

The work described in this presentation is part of an ongoing effort to experimentally characterize the fluid forces on cylinders undergoing complex motions. It is expected that the results of this effort will be very helpful in predicting the behavior of marine tow cables, as well as other similar structures.

3:20

Identification of Parametric Dynamic Models for Deeply-Towed Underwater Vehicle Systems

Mr. Franz S. Hover, MIT/WHOI

Tethered underwater vehicles have an important place in ocean work, for exploration, inspection, manipulation, and other tasks. As the deployment depth becomes greater, the dynamics of the system become increasingly dependent on the response of the tether itself, so that understanding the vehicle motions alone is no longer adequate for characterizing the entire system. In some cases, the heave dynamics of a high-tension system are influenced only slightly by the length of tether; in contrast, the horizontal coupling between the tether endpoints always becomes more sluggish with greater depth. Practically speaking, a clump weight that is maneuvered by a surface ship may suffer 30-minute time constants in the step response and tracking a specified trajectory can present similar difficulties. It is therefore appropriate to study the horizontal dynamics of the system with an eye toward control and improving on this slow response.

The equations of motion that describe the tether dynamics are partial differential equations whose structure is often times difficult to work with in controller design. Our work consists of making low-order finite difference approximations to the infinite-dimensional system. Approximate systems of order as low as two are advocated for several reasons. First, because a high-tension system may undergo relatively small deflections from the static shape, and because spatially localized motions in the cable are unlikely, only several nodes may be necessary to model the overall motions. Secondly, a model with only several nodes can be fully instrumented with a reasonable number of acoustic navigation elements.

Because the model order is very low, identification of the parameters is necessary- these parameters may be dissimilar to those that would be known in a higher resolution finite-difference approach. To provide data sets for this identification, we use a spectral model that was verified against actual sea data in earlier works. This procedure of low-order identification from a fine-grained model can be carried out in the laboratory, and for scenarios for which no experimental data exist. As a final step, the parametric models are tested with respect to real data, in order to validate the process.

The best model that emerges from the test group has a single midpoint node, and one lower endpoint node. No explicit time delay or zeros are included, and the effects of inertia are neglected, leaving the system order at two. We demonstrate the usefulness of this model in an open-loop slewing maneuver, which provides a significant reduction in vehicle settling time from the pure step response.

In conclusion, it is expected that very simple models will be useful for control in this context, and work underway points to promising advances in regulation and tracking for tethered ROV systems.

3:50

Numerical Analysis of 2-D Nonlinear Cable Equations with Applications to Low-Tension Problems

Mr. Christopher T. Howell, MIT/WHOI

The dynamics of submerged cables has been the subject of substantial research in the past. The relevant governing equations have been well established for some time, but their inherent nonlinearities have proven difficult to overcome. Traditional solution techniques treat the dynamics as perturbations from some known static configuration. Often the equations are linearized about the static shape and therefore are not valid for large displacements. For many important problems, such as the free-fall deployment of an anchor, a meaningful static configuration does not exist, thereby requiring an alternative solution method. Problems involving low-tension fall into this category, as the large displacements that can develop render any static shape useless. Low-tension problems also prove exceedingly difficult as stability, both physical and numerical, becomes a major issue. For such problems, bending stiffness, which is typically neglected, becomes important.

Research was aimed at developing a numerical algorithm capable of solving the fully nonlinear two dimensional equations, independent of any static configuration. Particular emphasis was placed on low-tension problems, such as applying a zero-tension boundary condition, and overcoming the instabilities they generate. The complete formulation also includes the effects of bending stiffness, nonlinear drag and the cable self weight, however, elasticity has been neglected.

Existing algorithms are limited in their ability to treat low-tension problems because they become singular when the tension vanishes anywhere along the cable. This limitation created a need for novel approaches to the low-tension problem. As a result, two alternative methods were developed. The first method implements an explicit time integration finite-difference scheme that casts cable tensions as the only unknowns in a matrix problem. Therefore, the onset of zero tension along the cable does not present a problem computationally. The method proves stable if artificial dissipation is added to the scheme. The second method developed incorporates the effects of bending stiffness in an implicit finite-difference formulation. By including bending stiffness, the singularity encountered by other researchers is removed and the method proves stable, regardless of the cable tension. These two algorithms provide an efficient means to study a wider class of initial value problems.

April 24

8:00
Response Prediction of Moorings and Risers
Professor J. Kim Vandiver, MIT

A method for predicting the response of long cylinders in sheared flow is introduced. This method includes the effects of correlation length, hydrodynamic damping, higher-order harmonics of lift coefficients, and turbulence. Comparisons are made between predicted and measured response, for a constant tension cable in a linear sheared flow. The response is shown to contain significant amounts of vibration up to the fifth harmonic of the vortex shedding frequency. Hydrodynamic modal damping is shown to have a dramatic effect on the response and to decrease with increasing frequency of vibration. Comparisons are made between the measured response of short cables, which respond in their first few modes, and cables with infinite-length response characteristics.

The response prediction technique requires the combination of a lift force model and a structural model. Green's function structural models are used in the cases of uniform cables and risers with linearly varying tension. The results of a recent combination of the lift force model with a finite element model of a riser are presented. The response prediction of an oceanographic mooring with lumped masses, such as current meters, is also discussed.

9:15
Chaos Hunt in the Motions of a Tethered Sphere
Dr. Robert Cawley, Naval Surface Weapons Center

The problem of the dynamics of the motion of a tethered sphere at low to moderate Reynolds numbers is being investigated experimentally by NSWC. The effort is to acquire data on coupled fluid-bluff body motion to determine if evidence exists for low dimensional dynamics, in particular whether for some parameter regimes, observed irregular behavior might be chaotic.

The problem of the detection and diagnosis of chaotic behavior becomes considerably complicated by the presence of background disturbances such as random noise or possible weak coupling to higher mode dynamics. This kind of background contamination problem is very widespread, not only in fluid flow and problems of dynamics of structures, but also in geophysics, meteorology, physiology, signal processing and even chemistry and physics. Conventional Fourier-based linear band-passing methods can be problematic for application to this sort of problem, where both signal (chaos) and noise (background contamination) are broad-band.

Accordingly, we have also developed a new geometric projection technique for noise reduction that is applicable to this case. This nonlinear 'filtering' method is based on the theory of dynamical systems, but has a wider range of application than to just those time-series possessing an underlying chaotic signal. The method we have developed does not require prior knowledge of any assumed underlying dynamics, and performs well in high noise cases as well as low.

The presentation will describe the tethered-body experiment, and present very preliminary results from our initial run. I will also describe the noise reduction method and how it performs in numerical trial cases where the true (chaotic) signal is known ahead of time and the noise has been produced artificially. If sufficient data analysis has been completed, I will also present results of application of the geometric projection method to the tethered sphere motion time-series from the initial run. This work is a collaboration among myself, Prof. Guan--Hsong Hsu, Department of Mathematics, University of Missouri, Columbia, and Dr. Steve N. Rauseo of the Information and Mathematical Sciences Branch, NSWC.

10:15
Numerical Simulation of Flows Past Bluff Bodies
Professor George Em Karniadakis, Princeton University

External flows, such as the flows behind bluff bodies, are unsteady even at very low Reynolds number and go through a "fast" transition from a laminar two-dimensional state to a turbulent wake at Reynolds numbers typically less than 1,000. These classes of flows formed in open domains present a challenge to simulation; their accurate prediction requires first, the use of high-order discretization techniques for the governing equations of motion that eliminate numerical artifacts (e.g. diffusion and dissipation), and second, the ability to handle arbitrary geometric complexities (e.g. non-smooth surfaces). The issue of efficiency is of great importance also, as the computational complexity involved and corresponding CPU requirements are directly related to the discretization technique employed.

In this talk, I will present a hybrid numerical scheme (spectral element method) that embodies both high accuracy features and geometric flexibility for numerical simulation of flows past three-dimensional bodies of arbitrary shape. The method is based on the common weighted-residual principles of spectral techniques and finite element methods. The computational domain is subdivided into elements (quadrilaterials or three-dimensional bricks) that are then mapped isoparametrically to canonical squares or cubes; spectral expansions are then employed in the mapped domain to represent dependent variables and data. The geometry is also represented with high-order expansions so that high accuracy is maintained in three-dimensional non-planar surfaces. Recent advances include the development of composite meshes that employ finite-difference "patches" and can be used in discretizations of flows over randomly rough surfaces. An effective adaptive scheme based on the vorticity-evolution equation has also been developed that monitors the accuracy of the computation. In addition, new outflow boundary conditions were developed for external flows that utilize 'viscous sponges' at the boundaries of the truncated domain and allow for smaller computational domains and thus more economical computations. The method is naturally suited for parallel-computing environments; high efficiency is achieved by implementing the method on the HyperCube iPSC860-32.

Several simulations will be discussed including flows past circular and square cylinders, spheres in stratified environments, and vehicles. The method is particularly suited to analyzing the transition process and to quantifying the effect of the wake dynamics on the transport measures of the bluff body (e.g. lift and drag forces). We will demonstrate that two-dimensional computations (however accurate) overestimate the draft and lift coefficients both in its mean and its root-mean-square values. An interesting result we have obtained in the case of a circular cylinder is that the wake becomes three-dimensional at Reynolds number 200 and subsequently becomes chaotic (at Reynolds number around 500) through a series of well-defined period doubling sequences as the Reynolds number,further increases. Such simple flow dynamics can be modeled through low-order models that are based on ordinary differential equations and thus can be used efficiently in flow control applications. At a high Reynolds number, direct numerical simulation is not appropriate as the excited number of degrees of freedom (n) in the flow exceeds by far the resolution capabilities affordable on today's supercomputers. We will present a subgrid scale model that is based on renormalization group theory of turbulence (Yakhot and Orszag, 1986) that can be incorporated into the spectral element formulation for large eddy simulations of flows past bluff bodies.

11:15

Damping of Mooring Lines

Professor Mike S. Triantafyllou, MIT

The drag forces acting on the mooring lines of an anchored vessel are a major part of the damping force of the overall system, which resonates due to the second-order, slowly varying wave force excitation. Given that mooring systems are largely underdamped, it becomes critical to have reliable estimates of the forces contributed by the mooring lines. These drag forces are caused through a complex interaction of several physical mechanisms: vortex shedding accompanying the low-frequency, large-amplitude cable motions caused by the resonant motions of the anchored structure, and reinforced by local currents, causes the well-known drag amplification; the wave-induced, high-frequency, small-amplitude motions of the cable contribute significantly to the drag force, combining in a nonlinear fashion with the slow motions to increase the value of the effective drag coefficient. In this talk the state of the art is reviewed and current efforts to improve our modeling capabilities and understanding of the phenomenon will be outlined.

Gopalkrishnan, G., Grosenbaugh, M.A. & Triantafyllou, M.S., 1991, **Influence of Amplitude Modulation on the Fluid Forces Acting on a Vibrating Cylinder in Cross-Flow**, to appear in the Proceedings of International Conference on Offshore Mechanics and Polar Engineering, Edinburgh, U.K., August 1991.

Griffin, O.M. & Vandiver, J.K., **Vortex-Induced Strumming Vibrations of Marine Cables with Attached Masses,** Journal of Energy Resources Technology, Vol. 26, December 1984.

Grosenbaugh, M.A., Yoerger, D.R., Hover, F.S & Triantafyllou, M.S., **Drag Forces and Flow-Induced Vibrations of a Long Vertical TowCable - Part II: Unsteady Towing Conditions,** ASME Journal of Offshore Mechanics and Arctic Engineering, in press, 1991.

Full scale experimental data on the dynamics and flow-induced vibrations of a long, vertical tow cable are analyzed. The data were measured while the surface ship was going through a series of starting, stopping, and backing maneuvers. The results of the study show that the amplitude of the flow-induced vibrations of the cable is strongly modulated during maneuvering operations. Maneuvering creates situations where different sections of the cable are translating at different speeds causing an "artificial" shear current that at times is severe, depending on the difference in speed between the top and bottom of the cable. The artificial shear is responsible for the intensification of the amplitude-modulation above the level that is observed during steady-state towing conditions with the overall effect of being a reduction in the hydrodynamic drag forces.

Grosenbaugh, M.A., **The Effect of Unsteady Motion on the Drag Forces and Flow-Induced Vibrations of a Long Vertical Tow Cable,** International Journal of Offshore and Polar Engineering, in press, 1991.

Drag coefficients and flow-induced vibrations of a long, vertical tow cable are measured under steady and unsteady towing conditions. The steady-state drag coefficients range from 2.2 to 2.5. For unsteady towing conditions, the drag coefficient was lower by as much as 40%, depending on the frequency content of the planar ship motion. For purely oscillatory motion, the drag coefficient decreased as the frequency of motion increased. The reduction in the drag coeffiicent may be related to the amplitude modulation of the flow-induced vibrations of the cable which are magnified during unsteady operations. When the surface ship changes speed, differences in the normal component of the velocity along the cable are present because of time delays in the response of the bottom of the cable to inputs at the top. The longer the cable, the greater are the delays. This creates large velocity

gradients in the oncoming flow that are responsible for the intensification of the amplitude-modulation above the level that is observed during steady-state towing conditons. The overall effect of the amplitude modulation is a reduction in the hydrodynamic drag forces.

Grosenbaugh, M.A., Yoerger, D.R., & Triantafyllou, M.S., **A Full-Scale Experimental Study of the Effect of Shear Current on the Vortex-Induced Vibration and Quasi-Static Configuration of a Long Cable,** Proceedings of Eighth International Conference on Offshore Mechanics and Arctic Engineering (ASME), The Hague, March 1989, pp.285-302.

Howell, C.T., **Numerical Analysis of 2-D Nonlinear Cable Equations with Applications to Low-Tension Problems,** to appear in the Proceedings of the First International Offshore and Polar Engineering Conference, Edinburgh, U.K., August 1991.

Karniadakis, G.E., **Spectral Element-Fourier Methods for Incompressible Turbulent Flows,** Computer Methods in Applied Mechanics and Engineering, 80, 1990, pp.367-380.

A mixed spectral element-(Fourier) spectral method is proposed for solution of the incompressible Navier-Stokes equations in general, curvilinear domains. The formulation is appropriate for simulations of turbulent flows in complex geometries with only one homogeneous flow direction. The governing equations are written in a form suitable for both direct (DNS) and large-eddy (LES) simulations allowing a unified implementation. The method is based on skew-symmetric convective operators that induce minimal aliasing errors and fast Helmholtz solvers that employ efficient iterative algorithms (e.g. multigrid). Direct numerical simulations of channel flow verified that the proposed method can sustain turbulent fluctuations even at 'marginal' Reynolds numbers. The flexibility of the method to efficiently simulate complex-geometry flows is demonstrated through an example of transitional flow in a grooved channel and an example of transitional-turbulent flow over rough wall surfaces.

Kim, Y.H., Vandiver, J.K. & Holler, R., **Vortex-Induced Vibration and Drag Coefficients of Long Cables Subjected to Sheared Flow,** Journal of Energy Resources Technology, Vol. 108, March 1986.

Mavrakos, S., Papazoglou, V. & Triantafyllou, M.S., **An Investigation into the Feasibility of Deep Water Anchoring Systems,** Proceedings of Eighth International Conferences on Offshore Mechanics and Arctic Engineering (ASME), The Hague, March 1989, pp.675-682.

Papazoglou, V., Mavrakos, S. & Triantafyllou, M.S., **Nonlinear Cable Response and Model Testing in Water,** Journal of Sound and Vibration, 140 (1), 1991, pp.103-115.

Rockwell, D., **Active Control of Globally-Unstable Separated Flows,** Proceedings of Symposium on Unsteady Flows, American Society of Mechanical Engineers, Toronto, Canada, June 3-9, 1990.

The concept of a globally-unstable system has emerged from recent theoretical advances describing absolutely-unstable shear flows, e.g., bluff-body wakes. An analogous global instability can exist in a convectively-unstable shear flow in the presence of a downstream impingement surface. These two types of globally-unstable systems exhibit similar response to controlled forcing at freqencies near/at synchronization: a resonant amplitude peak at the frequency of the imposed forcing; attenuation of the amplitude at the inherent instability frequency of the system; and a large phase shift between the motion of the body (or surface) and the loading upon it.

Principal features of the response of the bluff-body wake are assessed, with the intent of stimulating analogous investigations and interpretations of other types of globally-unstable systems. These features encompass: alteration/attenuation of the possible modes of large-scale vortex formation and their timing with respect to the motion of the body; and modulation of these various modes of vortex formation, which may be linked to a low order chaotic description of the excited system.

Rockwell, D. & Ongoren, A., **Flow structure from an Oscillating Cylinder Part 1. Mechanisms of Phase Shift and Recovery in the Near Wake,** Journal of Fluid Mechanics, vol. 191, 1988, pp.197-223.

Cylinders of various cross-section were subjected to controlled oscillations in a direction transverse to the incident flow. Excitation was at frequency f_e, relative to the formation frequency f^* of large-scale vortices from the corresponding stationary cylinder, and at Reynolds numbers in the range $584 < R_e < 1300$. Modifications of the near wake were characterized by visualization of the instantaneous flow structure in conjunction with body displacement-flow velocity correlations.

Rockwell, D. & Ongoren, A., **Flow Structure from an Oscillating Cylinder Part 2. Mode Competition in the Near Wake,** Journal of Fluid Mechanics, vol. 191, 1988 pp.225-245.

A circular cylinder subjected to forced oscillations at angle a with respect to the free stream shows a number of admissible modes of vortex formation synchronized with the body motion. These modes can be categorized into two basic groups: symmetrical vortex formation; and antisymmetrical vortex formation. Whereas there is a single symmetrical mode, there are four basic antisymmetrical modes. Three of these antisymmetrical modes show period doubling relative to the classical

Karman mode. This doubling arises from the symmetrical perturbation component induced by the cylinder motion at a ≠ 90°. Synchronization, i.e. phase-locking of the vortex shedding with the cylinder motion, is possible for all of these modes. It occurs even when streamwise (a = O°) motion induces an antisymmetrical mode.

When synchronization does not occur, there is competition between the symmetrical and antisymmetrical modes; the near-wake structure successively locks-on to each mode over a defined number of cycles, abruptly switching between modes. The number of occurrences of each mode is a well-defined function of excitation frequency and angle a.

Rockwell, D., **Oscillations of Impinging Shear Layers,** AIAA Journal, Vol. 21, no. 5, May 1983.

Coherent oscillations of impinging shear layers, giving rise to unsteady loading of the respective impingement edges/surfaces as well as associated noise radiation, occur in a variety of configurations, including: aircraft weapon bays and wheel wells; supersonic intakes; cavities/depressions in submarine and ship hulls; adjacent tall structures; leading tubes in tube bundles of heat exchanger and reactor equipment; steam regulation and control valves; and hydraulic gates.

In this review, attention will first be given to the character of self-oscillations of nonimpinging flows, emphasizing the role of upstream influence. Then, the central thrust of this work, the essential aspects fo impinging flows, involving leading-edge interaction, the nature of the upstream influence, disturbance-instability wave conversion at the separation (trailing) edge, and disturbance growth in the shear layer, will be addressed. This will be followed by an assessment of various models for predicting the nature of these oscillations, the effects of resonators, certain features of lower frequency impinging flows that distinguish them from the classical, highly coherent oscillations, and oscillations associated with supersonic flow.

Shargel, R. & Vandiver, J.K., **The Drag Coefficient for a Randomly Oscillating Cylinder in a Uniform Flow,** M.I.T., Department of Ocean Engineering, December, 1982.

Triantafyllou, G.S., Triantafyllou, M.S. & Chryssostomidis, C., **On the Formation of Vortex Streets Behind Stationary Cylinders,** Journal of Fluid Mechanics, 170, 1986.

Triantafyllou, G.S., Triantafyllou, M.S., Chryssostomidis, C.,**Stability Analysis to Predict Vortex Street Characteristics and Forces on Circular Cylinders,** Journal of Offshore Mechanics and Arctic Engineering (ASME), Vol. 109, pp.148-154.

Triantafyllou, M. & Bliek, A., **Dynamic Analysis of Mooring Lines Using Perturbation Techniques,** Oceans, September 1982, pp.496-501.

The linearized, two-dimensional equations of the mooring line dynamics are solved using perturbation techniques. It is shown that the solution can be separated into two parts. One represents the near transverse oscillations of the line and is rapidly varying along the length of the cable compared with the static solution, while the other part is slowly varying along the cable length. The two cases of a catenary line and of a neutrally buoyant cable in a strong current are studied in detail.

Mooring line terminal impedances are also presented since they can be used for an efficient analysis of the dynamics of a moored structure. Finally, the perturbation solution and a direct numerical matrix solution are compared and the range of validity of the asymptotic analysis is discussed.

Triantafyllou, M.S., **Preliminary Design of Mooring Systems,** Journal of Ship Research, Vol. 26, no. 1, March 1982, pp.25-35.

The preliminary design of mooring systems is formulated by separating the quasi-steady solution from the dynamic solution. A multiple time-scale expansion provides the appropriate equations, which are nonlinear for the quasi-steady part and linear space varying for the dynamic part. The fast dynamic solution consists of a fast varying and a slowly varying part with respect to space. An asymptotic solution is obtained by using the WKB method for the fast part, while an approximate expression is derived for the slow part. The resulting solution is simple and can be used to determine the dynamic behavior of complex systems, while permitting an extensive parametric search and the use of spectral techniques. This formulation leads to rational measures of the dynamic performance which, combined with cost considerations obtained from the static solution, permit an optimal selection of the system parameters. An example demonstrates the features of this methodology.

Triantafyllou, M.S., **A Consistent Hydrodynamic Theory for Moored and Positioned Vessels,** Journal of Ship Research, Vol. 26, no. 2, 1982, pp.97-105.

Triantafyllou, M.S., Bliek A. & Shin, H., **Dynamic Analysis as a Tool for Mooring System Design,** Transactions of the Society of Naval Architects and Marine Engineers 93, 1985, pp.303-324.

Vandiver, J.K., **Drag Coefficients of Long Flexible Cylinders,** Proceedings 1983 Offshore Technology Conference, OTC 4490, Houston, 1983.

Vandiver, J.K., **The Predictions of Lock-In Vibration on Flexible Cylinders in a Sheared Flow**, Proceedings of 1985 Offshore Technology Conference, OTC 5006, May 1985, Houston, TX.

Vandiver, J.K. & Chung, T.Y., **Hydrodynamic Damping on Flexible Cylinders in Sheared Flow**, Proceedings 1987 Offshore Technology Conference, OTC 5524, Houston, May 1987.

Vandiver, J.K. & Chung, T.Y., **Predicted and Measured Response of Flexible Cylinders in Sheared Flow**, ASME Winter Annual Meeting, Symposium on Vortex-Induced Vibration, Chicago, December 1988.

BIOGRAPHIES OF PRESENTERS

Professor Peter W. Bearman
Imperial College of Science, Technology and Medicine,
Department of Aeronautics

Peter W. Bearman is a Professor of Experimental Aerodynamics and Head of the Department of Aeronautics at the Imperial College of Science, Technology and Medicine. Prior to joining the faculty of Imperial College, Professor Bearman was a Senior Scientific Officer in the Industrial Aerodynamics Group of the National Physical Laboratory of England. In 1990, he was appointed Managing Agent for the SERC/MTD Marine Technology Programme of Research into the Behavior of Fixed and Compliant Offshore Structures and was also elected a Fellow of the Royal Aeronautical Society.

Professor Bearman received his B.A., M.A. and Ph.D. from Jesus College in Cambridge. His doctoral thesis was "A Study of Unsteady Base Flows."

Dr. Robert Cawley
Naval Surface Weapons Center, Mathematics and Information
Sciences Branch

Dr. Cawley is a Research Physicist and Leader of the Nonlinear Dynamics Group in the Mathematics and Information Sciences Branch of the U.S. Naval Surface Weapons Center. Prior to joining the Naval Surface Weapons Center, Dr. Cawley was an Assistant Professor of Physics at Clarkson University. Dr. Cawley's research interests are on the science and application of fractals and chaotic dynamics.

Dr. Cawley received a B.S. in physics from MIT and his M.S. (with a minor in astronomy) and Ph.D. in physics from the University of Illinois.

Professor Morteza Gharib
University of California, San Diego, Department of Applied Mechanics
and Engineering Studies

Professor Gharib is an Associate Professor of Mechanical Engineering at the University of California, San Diego. Prior to joining the University of California, he was a Senior Scientist at the Jet Propulsion Laboratory and the California Institute of Technology. In 1983, 1987 and 1989, Professor Gharib received the Flow Visualization Award from the American Physical Society.

Professor Gharib received his B.S. in mechanical engineering from Tehran University, an M.S. in mechanical and aerospace engineering from Syracuse

University and a Ph.D. in aeronautics (fluid mechanics) from the California Institute of Technology.

Mr. Ram Gopalkrishnan
MIT/WHOI, Joint Program in Ocean Engineering

Mr. Gopalkrishnan is currently working towards a doctorate in Ocean Engineering through the joint MIT/WHOI program. His research activities have included the synthesis, design and conduction of fluid-mechanical laboratory experiments at MIT's towing tank facility and WHOI's Deep Submergence Laboratory. Current experiments are on the forces acting on cylinders undergoing regular and irregular motions.

Mr. Gopalkrishnan received a B.Tech in naval architecture from the Indian Institute of Technology. He is currently conducting his thesis research under the guidance of Prof. Michael Triantafyllou of MIT and Dr. Mark Grosenbaugh of WHOI.

Dr. Mark A. Grosenbaugh
Woods Hole Oceanographic Institute, Department of Applied Ocean Physics and Engineering

Dr. Grosenbaugh is an Assistant Scientist with the Deep Submergence Laboratory at the Woods Hole Oceanographic Institution and a Lecturer in the Department of Ocean Engineering at MIT. Prior to these positions, Dr. Grosenbaugh worked as a Research Assistant at the University of California, Berkeley and as a Consultant for Earl and Wright Consulting Engineers.

Dr. Grosenbaugh received a B.S. and an M.S. in geophysics and an M.S. in mechanical engineering from Stanford University. He received his Ph.D. in naval architecture and offshore engineering from the University of California, Berkeley.

Mr. Franz S. Hover
MIT/WHOI, Joint Program in Ocean Engineering

Mr. Hover is currently pursuing his doctorate degree in Ocean Engineering in the joint MIT/WHOI program. Since joining the MIT/WHOI program, Mr. Hover has been involved in a range of design and analysis projects for cable systems, working with the U.S. Navy, MBARI, Marquest and WHOI Deep Submergence Lab. Although his initial research interests were in cable system dynamics (specifically underwater robotic systems) his interests have shifted to the study of the control problem that exists whenever you try to position a remote object through a distributed element.

Mr. Christopher T. Howell
MIT/WHOI, Joint Program in Ocean Engineering

Mr. Howell is presently enrolled in the joint MIT/WHOI program in Ocean Engineering, conducting research that will lead to a doctoral degree. His current research is focused on the numerical and analytic analysis of low-tension and impulsively loaded cables. Mr. Howell is developing an algorithim to predict the three-dimensional nonlinear motions of submerged cables subjected to arbitrary loadings.

Mr. Howell received a B.S. in ocean engineering from Texas A&M and an S.M. in ocean engineering from MIT.

Professor George Em Karniadakis
Princeton University, Department of Mechanical and Aerospace Engineering

Professor Karniadakis joined the faculty of Princeton University in 1988 as an Assistant Professor in Mechanical and Aerospace Engineering and is also an Associate Faculty member with the Program of Applied and Computational Mathematics. Professor Karniadakis has worked at MIT as a Research Associate and was a Research Fellow at the Center of Turbulence Research at Stanford/NASA Ames. Current research interests include hydrodynamic stability theory, direct and large-eddy simulation of turbulent flows and the development of high-order numerical techniques for discontinuous problems in complex geometrics.

Professor Karniadakis received his Engineering Diploma from the National Technical University of Athens and his S.M. and Ph.D. from MIT.

Professor Donald Rockwell
Lehigh University, Department of Mechanical Engineering and Mechanics

Donald Rockwell is a Professor of Mechanical Engineering and Mechanics at Lehigh University and has directed research programs on a range of unsteady flow topics sponsored by NSF, NASA, the Office of Naval Research, the Air Force Office of Scientific Research, the Volkswagen Foundation, and Pratt and Whitney-United Technologies.

Professor Rockwell has interacted extensively for over a decade with researchers in Germany on topics of unsteady flow, and has served as Joint Director of the Volkswagen Foundation Project Flow-Induced Vibrations during this period. This involvement is leading to publication of a engineering guide to flow-induced vibrations, which allows identification and classification of a wide spectrum of unsteady flow mechanisms.

Professor George S. Triantafyllou
City College of the City University of New York, The Benjamin Levich Institute for Physico-Chemical Hydrodynamics

Professor Triantafyllou is currently an Associate Professor at the Levich Institute. Prior to joining The Levich Institute he was a Principal Research Associate within the Department of Ocean Engineering at MIT. Professor Triantafyllou's research interests include fluid mechanics, stability theory, water waves, and non-linear dynamics and turbulence.

Professor Triantafyllou received a Diploma in civil engineering from the National Technical University of Athens, a M.S. in civil engineering from the California Institute of Technology, and a S.M. and Ph.D. from MIT in ocean engineering.

Professor Michael S. Traiantafyllou
MIT, Department of Ocean Engineering

Professor Triantafyllou is currently a Professor in the Department of Ocean Engineering at MIT. His primary research interests are: the analysis and design of ships and floating systems and control of marine vehicles and underwater robotics. In 1983, Professor Triantafyllou received the Doherty Professorship in Ocean Utilization.

Professor Triantafyllou received his Diploma in naval architecture and marine engineering from the National Technical University of Athens and an S.M. and Ph.D. in ocean engineering from MIT.

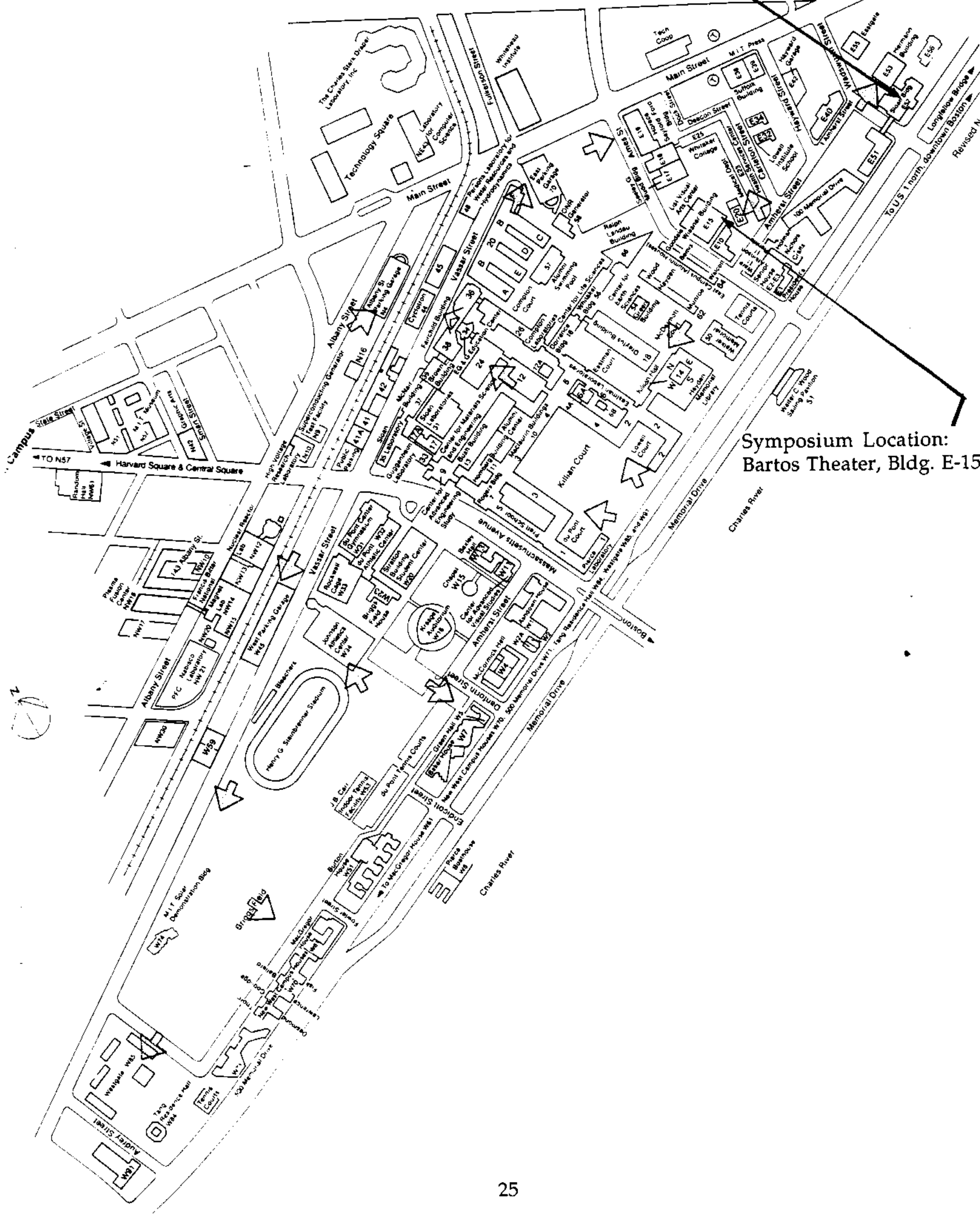
Professor J. Kim Vandiver
MIT, Department of Ocean Engineering

Professor Vandiver is a Professor in the Department of Ocean Engineering at MIT and has had a long association with MIT which began as a Teaching Assistant to the late Professor Harold Edgerton of the Department of Electrical Engineering. In addition to his teaching and research responsibilities at MIT, he also provides consulting services in structural dynamics, ship vibration and downhole drillstring dynamics.

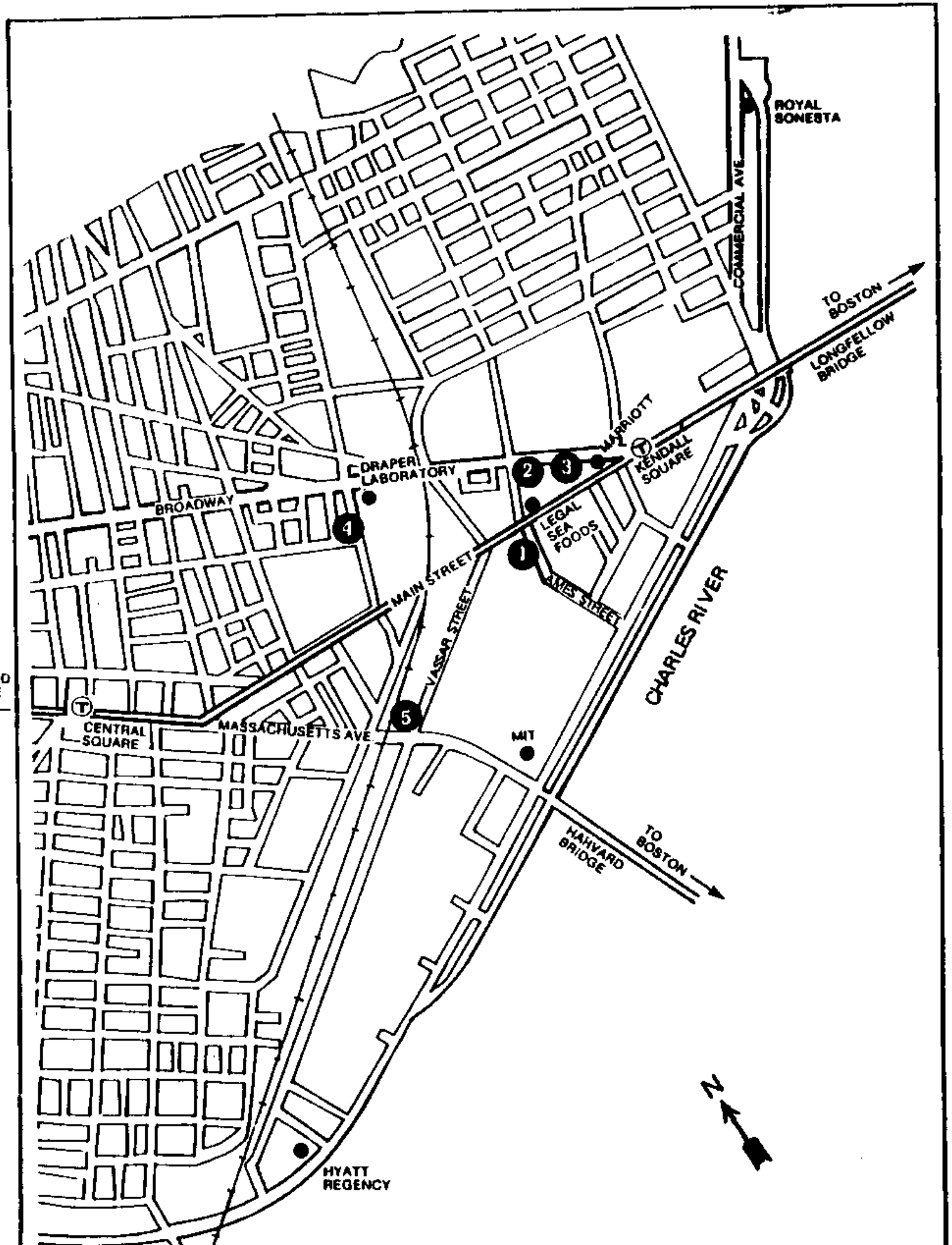
Professor Vandiver received a B.S. in engineering from Harvey Mudd College of Science and Engineering, an S.M. in ocean engineering from MIT and his Ph.D. through the MIT and WHOI Joint Program in Ocean Engineering.

MAP OF MIT CAMPUS

Reception Location:
Faculty Club, Bldg. E-52, 6th flr.



Symposium Location:
Bartos Theater, Bldg. E-15



Kendall Square Vicinity Parking

1. Ames Street Lot
   Ames and Main Street
   225-0847

2. Cambridge Center Garage
   5 Cambridge Center
   Broadway and Ames Street
   (off of Main St., next to Legal Sea Foods)
   492-1956

3. Cambridge Center Marriott Hotel
   2 Cambridge Center (Valet parking)
   494-6600

4. Polaroid Parking Garage
   Adjacent to Draper Employee Parking Garage
   Technology Square

5. Vassar Street Lot
   Vassar St. and Massachusetts Ave.
   (next to BayBank Automated Teller machine)

NOTES