MIT-W-90-001 C3

CIRCULATING COPY
Sea Grant Depository

The MIT/Marine Industry Collegium

Opportunity Brief

STRUCTURAL ACOUSTICS: AN APPLIED SCIENCE WITH MANY APPLICATIONS

January 9, 1990

Cambridge, Massachusetts

A Project of the

MIT Sea Grant Program

The MIT/Marine Industry Collegium
Opportunity Brief #56

STRUCTURAL ACOUSTICS: AN APPLIED SCIENCE WITH MANY APPLICATIONS

January 9, 1990

Cambridge, Massachusetts

Report No. MITSG 89-33
Grant No. NA86AA - D-SG089
Project No. A-1

$4.00

Editor and Production Coordinator: John Moore Jr.

This publication is intended for distribution to Collegium member companies. Additional copies can be obtained from:

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

For workshop information, call Ms. Joan Corsaro Tel: (617) 253-7092
Fax: (617) 258-5730

CONTENTS

INTRODUCTION

Sound and vibration, which commonly accompanies both mechanical and flow processes, can be either useful or detrimental. Machine diagnostics and interrogation of mechanical systems are examples of useful applications of acoustic and vibration signals. Undesirable acoustics, however, can interfere with speech, and can damage hearing. Undesirable vibrations may cause structural fatigue, which may ultimately lead to catastrophic structural failure. In the marine environment, acoustics play a significant role because of the favorable acoustic properties of seawater. The acoustics of seawater can be either a boom or bust for the designer depending upon the design parameters. The design engineer, for example, may wish to enhance sound transmission to identify an object for retrieval, yet in a different design problem, the engineer may wish to minimize sound transmission and emphasize quieting for stealth purposes.

MIT formulated a program in February 1989 to address the varied issues involving structural acoustics. This program, the MIT-Industry Program in Structural Acoustics, not only addresses acoustical issues associated within the marine industry but also concentrates on similar issues in the aerospace, civil and mechanical industries. The MIT Sea Grant Marine Industry Collegium has joined with the MIT-Industry Program in Structural Acoustics to sponsor a one-day workshop, on Jan. 9, 1990, that will highlight current research areas of special interest to both marine industries and other organizations involved with structural acoustics research.

This workshop will address current research efforts and provide an opportunity for attendees to actively interact through their questions and comments. Presentations will cover such topics as the transmission properties of fluid storage tanks within vessels, recent developments in analytical models of machine systems for noise and vibration minimization, techniques to combine analytically and experimentally derived acoustic parameters for model definition, and the application of active and passive control techniques to minimize structural acoustic wave propagation.

These topics and others will provide a greater understanding of the research being conducted at MIT. Organizations that would like to learn more about the MIT-Industry Program in Structural Acoustics and how they might actively participate in future research are cordially invited to meet with faculty on Jan. 10. The meeting will provide an opportunity for closer interaction through small unstructured meetings on topics of mutual interest. If you are interested in this meeting on the 10th, I urge you to contact Prof. Richard Lyon directly at (617) 253-2214.

John Moore Jr.
Manager
Marine Industry Collegium

WORKSHOP AGENDA

STRUCTURAL ACOUSTICS: AN APPLIED SCIENCE WITH MANY APPLICATIONS

JANUARY 9

8:30 - 9:00	**REGISTRATION**
9:00 - 9:10	**Welcome, Brief Introduction** John Moore Jr., MIT
9:10 - 9:55	**Radiation and Scattering of Sound by Ship Structures** Richard H. Lyon, MIT
9:55 - 10:40	**Array and Omega-K Processing and Analysis** Arthur B. Baggeroer, MIT
10:40 - 11:00	**BREAK**
11:00 - 11:45	**Analytical Design Models of the Vibration and Noise in High Performance Machine Systems** Steven Dubowsky, MIT
11:45 - 12:30	**Active Control of Transmission, Scattering and Radiation** Andreas H. von Flotow, MIT
12:30 - 1:15	**LUNCH**
1:15 - 2:00	**Some Flow-Structure Interaction Problems** Triantaphyllos R. Akylas, MIT
2:00 - 2:45	**Design Criteria for Sound-Structure Interaction** Kazuhide Ota, Mitsubishi Heavy Industries

SYNOPSIS of PRESENTATIONS

JANUARY 9

9:10
Radiation and Scattering of Sound by Ship Structures
Prof. Richard H. Lyon, MIT

The noise transmitted within a ship and the sound that is radiated into the surrounding water is carried by a variety of paths, both structural and acoustical. The roles of these paths, and their sound energy distribution, are influenced by the placement of fluid-containing tanks within the structure. MIT has carried out a series of studies on the acoustical role of these tanks and their sound radiation characteristics. It has been found that the competing efforts of the mass loading of the structure, in combination with the transmission of sound by the fluid in the tanks, determines whether the sound transmission will be increased or decreased

MIT is studying these problems using a combination of experimental methods (reverberant water tank, and near-filled intensity scan tests) and analytical procedures (finite element, boundary element, and SEA techniques). The results of these studies indicate that the noise within the ship will be reduced by proper placement of the fluid tanks, which will block vibration paths. For example, if the tanks are adjacent to the full structure, the sound transmission through the tank will provide a good transmission path into the surrounding seawater. Application of these studies can be applied to other structures, such as offshore structures, transportation vehicles and civil structures.

The scattering of sound by submerged structures is also under study for possible modification by the use of "active control." The concept involves the sensing of incoming sound waves being used to illuminate the structure and exciting vibrations in the structure so that the sound reflected (or scattered) is diminished. Although the approach is primarily experimental, we expect to develop analytical tools as the effort progresses. Inversely, the results of this work may be applied to reduce scattering thereby making submerged objects more detectable for retrieval or safety purposes.

9:55
Title
Prof. Arthur B. Baggeroer, MIT
Not Available at time of printing.

11:00
Analytical Design Models of the Vibration and Noise in High Performance Machine Systems
Prof. Steven Dubowsky, MIT

As machines are designed to operate with higher performance, such problems as premature failures, accelerated wear and increased noise and vibration often occur. A key to preventing such problems is to develop accurate analytical models of machine systems for the designer. Current research at MIT seeks to develop such models. This research considers a number of factors that degrade the performance of machine systems that are neglected in the models currently used by industrial designers. These factors include the impact forces due to the clearances in machine connections and the mechanical noise and vibration that result from the structural flexibility of a machine's elements, supporting structure and enclosures.

To date, significant progress has been made in developing useful computer-based design methods to predict the performance and behavior of machine systems that exhibit these limiting factors. Experimental studies have been performed to demonstrate the validity of the analytical models as they are developed. The results of this work should ultimately lead to the improved performance of high-speed machine systems.

11:45
Active Control of Transmission, Scattering and Radiation
Prof. Andreas H. von Flotow, MIT

This presentation discusses opportunities for use of active control techniques in structural acoustics, with emphasis on the naval structural acoustics application. The point of view is taken that active control cannot, for reasons of cost, reliability and guaranteed stability, be applied indiscriminately. Rather, these techniques should be applied very selectively to situations in which a significant payoff can be anticipated.

After an overview of the naval structural acoustics problem from the perspective of active control, the presentation will focus upon three situations in which work appears promising.

1) Active cancellation of the far field of a compact source. In situations where the acoustic medium is not resonant (such as infinite fluid spaces) this cancellation can safely be attempted over a broad frequency range. When the "far field" is actually a resonant response of a finite system (such as a compact machinery mount radiating onto a flexible vehicle) attempts at broadband control lead to major risk of instability. In such situations narrowband control is still a viable and useful option.

2) Active control of wave propagation in structural components. This work is applicable to the problem of high frequency transmission in, and scattering from, naval vessels. The presentation will describe recent theoretical research and discuss laboratory successes and failures.

3) Broadband control of a reverberant structure. This is the most difficult problem of the three that will be discussed, and has a long history of research in the field of Aeronautics and Astronautics, with application to the control of large flexible aircraft. The presentation will outline the methods applied in this area and describe the limitations because of to the difficulty of accurately modeling the structural response and the resulting high risk of unstable interaction between the control system and the resonant structural dynamics.

1:15
Some Flow-Structure Interaction Problems
Prof. Triantaphyllos R. Akylas, MIT

The majority of previous work dealing with fluid loading of structures has ignored the effect of the mean flow, which may be present in the case where a structure is moving in stationary fluid or, equivalently, if there is a steady flow past the structure. Two elementary examples will be discussed that demonstrate the dramatic effect that mean flow may have. For simplicity, the fluid is taken to be inviscid and incompressible, and the mean flow is modeled by a piecewise linear boundary-layer profile.

As a first example, we examine the effect of a non-uniformity (a bump) on the surface of a rigid plate in the presence of a mean flow. Assuming that the extent of the non-uniformity is long compared with the boundary-layer thickness, it is shown that strong periodic upstream disturbances occur in the fluid owing to a resonance phenomenon (i.e. no steady state is reached).

The second example deals with a flexible plate subject to time-harmonic forcing in the presence of mean flow. It is shown that the mean flow can transfer energy to the plate leading to an instability phenomena. Depending on the flow speed, the instability can be 'convective' or 'absolute'. In the latter case, no steady state is reached. Clearly, this instability is a direct consequence of the flow-structure coupling since both the plate and the mean flow are stable by themselves.

2:00
Design Criteria for Sound-Structure Interaction
Kazuhide Ota, Mitsubishi Heavy Industries

Understanding the acoustics of ship structures with external and internal fluid spaces is very difficult. If we add to this problem the loading structure of sound impinging on it from an external source, forces within the structure because of the operation of machinery, and forces deliberately introduced for the purpose of active control or sonar operations, we have a problem of great complexity. A number of computer codes have been developed (for example, NASHUA code at DTRC) to try to deal with such problems, but their success is limited.

To minimize structural sound radiation or scattering through use of actuators that excite structural vibrations, a procedure must decide what the phases and magnitudes of the exciting forces will be. One approach uses experimentally determined values that measure the structural response, and adjust the excitation signals to achieve the desired result in a "closed loop" control system. Such a procedure assumes no knowledge of the other excitations or the structural characteristics and in effect "learns" what these are by measurement.

By having an analytical model of the structure and the other acoustic sources, rules can be developed for minimizing radiated or scattered sound. A model has been developed at MIT that may not be completely accurate but can be useful as a "first guess" in complicated situations, or in simpler situations in which part of the system is known but some information, such as the waveform of the incoming sound wave, is not. As this model is applied more broadly, tests will be made to extend its application to situations where there is interaction between the analytically and experimentally derived parameters.

PUBLISHED PAPERS

Akylas, T.R. and Toplosky, N., **The Sound Field of Tollmien-Schlichting Wave,** Physical Fluids, Vol. 29, no. 3, March 1986, pp. 685-689.

An asymptotic theory is presented for predicting the sound field generated by small-amplitude instability waves in low speed, boundary-layer flows. A Tollmien-Schlichting wave of fixed frequency, which evolves spatially in a Blasius boundary layer, is considered, and the associated far-field acoustic radiation is calculated. It is found that the directional dependence of the radiation intensity is of the dipole type. This result is discussed in connection with the superdirective acoustic fields caused by instability waves, which were recently observed in low Mach number jets.

Akylas, T.R. and Benney, D.J., **Direct Resonance in Nonlinear Wave Systems,** Studies in Applied Mathematics, Vol. 63, 1980, pp. 209-226.

In certain wave systems it is possible for the amplitudes associated with special wave numbers to be larger than expected. Such may be the case if two frequencies are close together. Direct resonances of this type are studied and some possible applications are discussed.

Baggeroer, A.B., Kuperman, W.A. and Schmidt, H., **Matched Field Processing: Source Localization in Correlated Noise as an Optimum Parameter Estimation Problem,** J. Acoustical Society of America, Vol. 83 (2), February 1988, pp. 571-587.

Matched field processing is a parameter estimation technique for localizing the range, depth, and bearing of a point source from the signal field propagating in an acoustic waveguide. The signal is observed at an array in the presence of additive, spatially correlated noise that also propagates in the same ocean environment as the signal. In a weak signal-to-noise situation this parameter estimation requires the maximum exploitation of the physics of both the signal and noise structure that then must be coupled to optimum methods for the signal processing. We study the physics of this processing by modeling the ocean environment as a waveguide that is horizontally stratified with an arbitrary sound-speed profile in the vertical. Thus, the wave equation describes the underlying structure of the signal and noise, and the signal processing via the generation of the replica fields. Two methods of array processing are examined: (i) the linear cross correlator (Bartlett) and (ii) the maximum likelihood method (MLM), for the parameter estimation procedure.

Dubowsky, S. and Morris, T.L., **An Analytical and Experimental Study of the Acoustic Noise Produced by Machine Links,** Journal of Mechanical Design, ASME Trans., July 1983, Vol. 105, pp. 393-401.

Noise from high-speed machine systems is an important engineering design problem. This study investigates a recently developed analytical technique for calculating the noise generated by linkage-type machines based both on recently developed analytical methods for modeling the dynamic response of machines and on classical acoustical theory. This acoustical-dynamic modeling method is applied to an experimental system with elastic elements and clearance connections; the analytically predicted acoustical fields are compared to the measured noise. The results show excellent correlation between the experimental and analytical noise fields and support the validity of this modeling method.

Dubowsky, S. and Perreira, N.D., **Noise and Vibration Generated by Impacts in Linkage Systems: with Application to Engines,** Proceedings of the International Symposium on Engine Noise: Excitation, Vibration and Radiation, General Motors Research Lab., Warren, OH, October 1981.

The noise of machine systems is an important consideration in their design. To reduce noise, engineers require accurate analytical methods to predict the acoustic behavior of machine systems. Such models would also facilitate the use of noise signatures as a diagnostic tool for detecting and locating mechanical problems.

Analytical techniques in acoustics have been combined to develop procedures for predicting the noise produced by linked machine systems in a free field. These methods are briefly described. Experimental results show good correlation with the predicted values, verifying both the dynamic and acoustic models. The last part of this paper introduces a finite element model for flexible machines that is being employed in current research. This model may be of use when linkages radiate in a non-free field, as, for example, where a linkage is mounted in a tight-fitting enclosure, in an engine.

Dubowsky, S. and Oppenhiemer, C.H., **An Acoustic Modeling Method for the Design of Machine System Enclosures, with Experimental Verification,** The Twentieth Biennial ASME Mechanisms Conference, Orlando, FL, September 1988.

The noise generated from machine enclosures is an important design issue. In this paper a technique that combines Finite Element Method (FEM) dynamic models with an acoustic Boundary Element Method (BEM) is used to predict the noise generated by machine enclosures. The technique is applied to a relatively simple system, and the numerical results are compared to experimentally measured noise levels. The technique appears to be a promising tool for design purposes.

Haj-Hariri, H. and Akylas, T.R., **Sound Radiation by Instability Wavepackets in a Boundary Layer,** Studies in Applied Mathematics, Vol. 75, 1986, pp. 57-76.

Sound radiation by instability wavepackets evolving from general initial conditions in a low Mach number, slightly unstable boundary layer, is studied. The formulation can be viewed as an exact instance of Lighthill's acoustic analogy. The original disturbance may be line or point centered with an infinitesimal amplitude. The sound field is confined within an expanding sphere. The directivity of sound is beamed and points upstream. This "superdirectivity" is slowly enhanced in time whereas the sound level is slowly attenuated. Nonlinear processes, once they come into play, reverse the temporal behavior of the sound level and sound directivity. For the boundary-layer profiles studied, nonlinearity causes a "burst," in a finite time, of the sound field in the form of a dipole.

Haj-Hariri, H. and Akylas, T.R., **The Wall Shear-Stress Contribution to Boundary-Layer Noise,** Physical Fluids, Vol. 28, no. 9, September 1985, pp. 2727-2729.

The effect of viscosity on the wall-pressure spectrum of a slightly compressible, turbulent boundary layer is studied. Apart from resolving the singularities of the inviscid spectrum, the viscous shear-stress dipole sources also partake in sound generation. The dominant viscous contribution to the low wave number part of the spectrum is evaluated in terms of the flow Mach and Reynolds numbers. It is concluded that, in typical applications, the viscous contribution is small compared with the inviscid one.

Miller, D.W. and von Flotow, A.H., **A Travelling Wave Approach to Power Flow in Structural Networks**, J. of Sound and Vibration, Vol. 128 (1), 1989, pp. 145-162.

A structural network is an assemblage of slender one-dimensional members. Each member is demarcated, by definition, by two junctions. A junction may involve only one member (a termination) or may be an interconnection of many members. In this paper, computationally and theoretically, the dynamics of such networks are investigated. The focus of the analysis is on elastic disturbance propagation and power flow in the networks. Spatially local models are assembled into a global, frequency domain description. This global description of the response is then investigated for local global power flow. The procedure serves to identify disturbance transmission paths and to choose and evaluate control procedures, both active and passive. The techniques are demonstrated by application to several samples.

Miller, D.W., Hall, S.R. and von Flotow, A.H., **Optimal Control of Power Flow at Structural Junctions**, J. of Sound Vibration, October 1989.

This paper describes several techniques for deriving optimal feedback compensators for structural waveguides at junctions. A frequency dependent cost functional, composed of power flow and control effort, is minimized. Control of power flow, by modifying junction reflection and transmission properties, enables selective absorption of incoming vibrational power. Noncausal, causal fixed form and Weiner-Hopf feedback solutions are derived. These solutions, including a positive real approximation to the Weiner-Hopf solution, are illustrated through an extensive example for the free end of a dispersive Bernoulli-Euler-beam.

Oppenheimer, C.H. **An Acoustic Modeling Method for the Design of Machine System Noise Enclosures, with Experimental Verification**, Proceedings of the ASME Design Technical Conferences (Trends and Developments in Mechanisms, Machine and Robotics), ASME Pub. DE-Vol. 15-2, Orlando FL 25-28, 1988.

Ota, K., Kagawa, K. and Honda, I., **Analysis of Fluid-Structural Vibration Using Boundary Element Method and Model Analysis Technique**, ASME Fluid Structure Dynamics, PVP-Vol. 98-7, Book No. H00327.

Ota, K., Honda, I., Kagawa, T. and Yanagi, K., **Studies on Fluid-Structural Vibration Using Boundary Element Method**, Mitsubishi Technical Bulletin, No. 172, 1986.

Pines, D.J. and von Flotow, A.H., **Active Control of Bending Wave Propagation at Acoustic Frequencies**, J. of Sound Vibration, October 1989.

This paper investigates, analytically and experimentally, the possibility of actively blocking the propagation of bending waves along a uniform beam. The work takes the form of a case study; a thin brass plate beam is used, it is excited with a short duration impulse, and the resulting disturbance spreads dispersively as it travels along the beam. A short portion of the beam is used as an active block. Strain gage sensors are used to drive thin piezoceramic bending moment actuators through a dynamic compensator. The compensation is designed in the frequency domain with reference to the beam equation, but independent of boundary conditions. This paper will describe the analytical work, including the nominal design and its performance, the performance degradation due to modeling errors, and the performance degradation due to approximate implementation of the dynamic compensator. The laboratory implementation used analog electronics for the compensator and essentially verifies some of the sensitivity predictions.

Schmidt, H. and Glattetre, J., **A Fast-field Model for Three-Dimensional Wave Propagation in Stratified Environments Based on the Global Matrix Method,** J. of Acoustical Society of America, Vol. 78 (6), December 1985, pp. 2105-2114.

A three-dimensional fast field program (FFP) model based on the global matrix method will be presented. Compared to traditional propagator matrix methods, the global matrix allows for a more efficient, and, furthermore, numerically stable computation. The three-dimensional expansion does not restrict sources to be on the center axis, but allows for an arbitrary source geometry as opposed to earlier two-dimensional versions. As a consequence, the solution includes simultaneously both vertically and horizontally polarized shear waves. A mathematical description will be given and the numerical aspects will be discussed.

Sievers, L.A. and von Flotow, A.H., **Comparison of Two LQG-Based Methods for Disturbance Rejection,** Proceedings of the CDC, December 1989 (invited paper).

When the disturbances acting upon a system reflect the dynamics of the process generating them (i.e. disturbances other than white noise), this information can be exploited for the design of "disturbance rejection controllers." Two modern control approaches for designing linear disturbance rejection controllers are discussed: 1) disturbance modeling and 2) frequency shaping of cost functionals. Both methods are extensions of Linear-Quadratic-Gaussian theory. The intent of this paper is to show that although the philosophies used to develop the two control schemes are very different, there is a distinct relationship between them. This is formalized by showing that the two methods are equivalent for the single-input, single-output-case. The duality of the two methods is discussed for the multi-input, multi-output case.

Shimomura, Y. and Lyon, R.H., **Noise Reduction in a Ship Structure by a Liquid Storage Tank,** Proceedings of Inter-Noise 86, 1986.

The effect of a liquid storage tank on sound transmission through ship structures was studied. A one-tenth scale model of a fuel oil tank in a 8,000 DWT product oil carrier was built to examine the liquid loading effect of the storage tank. The vibration energy levels of the model were experimentally determined both when the tank was empty and when it was filled with water. At 2 kHz, more than 8 dB reduction of the energy level on the upper deck plate was observed by filling the tank with water. This energy reduction gradually decreased to 1 dB as the frequency increase to 20 kHz. Analysis of the vibration energy levels of the model, based on Statistical Energy Analysis (SEA), were carried out to determine the effects of liquid loading on the transmission of structure-borne sound. The main reason for the energy-level reduction is thought to be the decrease in coupling loss factors between plates of the model due to the liquid loading.

Signorelli, J. and von Flotow, A.H., **Wave Propagation, Power Flow, and Resonance in a Truss Beam,** J. of Sound and Vibration, Vol. 126 (1), November 1988, pp. 127-144.

Wave propagation in a periodic truss-work beam is investigated computationally. The analysis is based upon the transfer matrix of a single bay of the structure. The results, with members modeled as rods with pinned joints, agree well with results obtained from an equivalent continuum model of the same structure. The inclusion of bending in member models shows that both the pinned rod model and the equivalent continuum model lose fidelity above the first resonant frequency of lateral motion of the members. Modeled with beam members, the truss exhibits complicated mechanical filtering properties, which are illuminated by investigation of wave-mode power flow.

Boundary conditions are applied in wave-mode co-ordinates by reformulation in terms of reflection matrices. The phase closure principle is invoked to predict natural frequencies of a fixed-free portion of the truss. It is found that closely spaced resonant frequencies are not identified by this method. Computed results show other subtle erroneous characteristics which are attributed to computational inaccuracy.

Smith, T.L., Rao, K. and Dyer, I., **Attenuation of Plate Flexural Waves by a Layer of Dynamic Absorbers**, Noise Control Engineering Journal, March-April 1986.

Flexural waves in a beam or plate structure can be attenuated by a distribution of masses resiliently mounted to the structure's surface. Wave attenuation and the bandwidths within which it acts are affected largely by the resistance of the resilient mounting and the attached mass, while the center frequency of the attenuation band is affected largely by the spring constant and the mass. We report experimental results obtained on a beam which show good agreement with an analytical model. The attenuation process is physically related to vibration control via dynamic absorption. Significant values of attenuation can be achieved in relatively wide bandwidths for practical combinations of attached mass and resilient mounting.

Schmidt, H., **Radiation and Scattering from Laminated Spherical Shells**, J. Acoustical Society of America, Suppl. 1, Vol. 85, Spring 1989.

von Flotow, A.H. and Pines, D.J., **Active Control of Bending Wave Propagation at Acoustic Frequencies**, J. of Sound and Vibration, October 89, in press.

This paper investigates, analytically and experimentally, the possibility of actively blocking the propagation of bending waves along a uniform beam. A short portion of the beam is used as an active block. Strain gage sensors are used to drive thin piezoceramic bending moment actuators through a dynamic compensator. The compensation is designed in the frequency domain with reference to the beam equation, but independent of boundary conditions.

This paper describes the analytical work, including the nominal design and its performance, the performance degradation due to modeling errors, and the performance degradation due to approximate implementation of the dynamic compensator. The laboratory implementation used analog electronics for the compensator and essentially verifies some of the sensitive predictions.

von Flotow, A.H., Sievers, L.A. and Scribner, K.B., **Isolation of a Vibrating Machine Mounted on a Flexible Structure**, Proceedings of the American Control Conference, Pittsburgh, PA, June 1989.

This paper considers the problem of actively isolating a vibrating machine from a flexible structure. The structural dynamic response is assumed to be known with too little fidelity to permit model-based control design. The discussion is specialized to narrow-band disturbances and to single-axis mounting. Narrow-band compensation, exploiting knowledge of the disturbance frequency, is proposed. Guaranteed properties of the structural dynamic response are exploited to derive stability and maximum performance criteria for this type of compensation.

von Flotow, A.H. and Sievers, L.A., **Active Vibration Isolation in the Presence of Unmodeled Structural Dynamic Response**, ASME Winter Meeting, San Francisco, CA, December 1989.

The problem of actively isolating a flexible machine from an adjoining flexible structure is investigated. The dynamic response of both machine and structure is assumed to be known with too little fidelity to permit model-based control design.

The discussion is specialized to narrowband disturbances with single-axis mounting. A feedback compensation scheme is proposed which ignores the system dynamics; the design uses only knowledge of the disturbance dynamics. Guaranteed properties of the structural dynamic response are exploited to derive stability and maximum performance criteria for this type of compensation. The analysis predicts that high modal overlap ensures both high performance and stability/robustness of the closed loop system.

von Flotow, A.H., **An Expository Overview of Active Control of Machinery Mounts,** Proceedings of the CDC, Austin, TX, December 1988.

This paper attempts to define and overview a class of problems; isolation of vibration originating in a comparatively compact, rigid machine. The machine can be an internal combustion engine, a turbine, compressor, transmission, etc. The machine is mounted in a structurally flexible vehicle via several machinery mounts.

A machinery mount should be capable of transmitting low frequency forces, supporting the machine against static loads due to vehicle accelerations, but incapable of transmitting high frequency, vibratory force. Past approaches have been passive, involving "soft springs" and, occasionally, dynamic effects. Advances in electronics, materials and to a lesser degree control theory, suggest the possibility of accomplishing these tasks more effectively with active or combinations of active/passive techniques. This paper attempts an overview and classification of the problem and of potential active approaches.

von Flotow, A.H. and Schafer, B., **Wave Absorbing Controllers for a Flexible Beam,** J. of Guidance Control and Dynamics, Vol. 9, no. 6, November-December 1986, pp. 673-680.

This paper describes theoretical and experimental work performed on the modeling and vibration control of a hanging flexible beam. The synthesis and laboratory implementation of low-authority controllers based upon feedback of local velocity to actuator force has been the subject of previous studies. This paper extends this work with the design and laboratory implementation of low-authority controllers based upon concepts of disturbance propagation and reflection. Control forces are applied to the lower end of the hanging beam. Compensators are derived which feed back local deflection and slope to control force and moment with the goal of minimizing the reflection of energy at the lower end. Several of these compensators are approximated by analog electronic filters for laboratory implementation. The performance of these wave-absorbing compensators is compared with that of velocity feedback.

von Flotow, A.H., **Disturbance Propagation in Structural Networks,** J. Sound and Vibration, Vol. 106 (3), 1986, pp. 433-450.

A structural network is taken to be an assemblage of slender structural members (beams, cables, rods) connected to each other at structural junctions. The junctions may include flexible bodies which, in this work, are restricted to those whose dynamics are described by a finite set of ordinary differential equations. Elastic disturbances in such a network are calculated in terms of propagation concepts. Members are described in the frequency domain by the propagation coefficients of their intrinsic wave-modes, junctions by frequency-dependent wave-mode reflection and transmission coefficients, grouped in the junction scattering matrix. Component impulse responses are calculated by a combination of analysis and application of the fast Fourier transform algorithm. Network time responses are synthesized by convolution of component impulse responses. A consistent analytical framework is constructed within which descriptions of various member types and junctions can be accommodated. The analysis is set up for computer implementation. Computational examples are used to demonstrate the techniques.

von Flotow, A.H., **Traveling Wave Control for Large Spacecraft Structures,** J. of Guidance Control and Dynamics, Vol. 9, No. 4, pp. 462-468.

This paper introduces the point of view that elastic deformations in large spacecraft structures may be aptly viewed in terms of propagating disturbances. Since the main topic of this paper is the control concepts, which result from such a viewpoint, the required structural dynamic description in terms of travelling disturbances is described only briefly, with reference to previously published works. The active control of these structures is approached from the point of view of actively modifying the natural disturbance propagation paths. Elastic energy is shunted into unimportant portions of the structure or is absorbed by an active "wave absorber." Several computational examples demonstrate the remarkable theoretical performance achievable by propagation-based controllers. Some discussion of practical difficulties in the implementation of such controllers is included.

RECENTLY COMPLETED THESES

Betros, R.S., **Investigations into a Non-Contacting Direct Measurement of Wavenumber Distribution for a Vibrating Surface**, August 1989.

de Luis, J., **Design and Implementation of Optimal Controllers for Intelligent Structures Using Infinite Order Structural Models**, March 1989.

Kissel, G., **Localization in Disordered Periodic Structures**, October 1987.

Kuehnle, A., **Control and Simulation of Longitudinal Wave Propagation in Structures with Lelvin-Vioigt Damping**, May 1988.

Levi, A., **Effect of Internal Fluid Containers on Sound Radiated Externally from a Surface Ship**, April 1989.

Miller, D., **Modeling and Active Modification of Wave Scattering in Structural Networks**, May 1988.

Nagem, R., **Dynamics of Distributed Lattice Structures**, February 1988.

Park, C.S., **Three Dimensional Acoustic Radiation Fields from a Spherically Layered Shell Submerged in an Infinite Fluid Medium**, August 1989.

Olivieri, L.A., **The Effect of Dynamic Absorbers on Longitudinal Wave Propagation in a Circular Rod**, September 1989.

Sievers, L.A., **Basic Relations for Actively Isolating Structures with Unmodeled Flexibility**, September 1989.

Signorelli, J., **Wave Propagation in Periodic Truss Structures**, December 1986.

BIOGRAPHIES OF PRESENTERS

Prof. Triantaphyllos R. Akylas
MIT, Department of Mechanical Engineering

Prof. Akylas joined MIT in 1981 as an assistant professor in the Department of Mechanical Engineering and in 1985 was appointed to the position of associate professor. Prof. Akylas's current research interests are in fluid flow-structure interactions and associated acoustical radiances. His areas of specialization include applied mechanics, wave propagation, vibrations, hydrodynamic stability and acoustics.

Prof. Akylas received his B.S. in physics from the California Institute of Technology and his Ph.D. in Applied Mathematics from MIT. He is a member of ASME, APS and AMS and has also received awards while at MIT that include the NSF Presidential Young Investigator Award and the Doherty Career Development Professorship in Ocean Utilization (an award presented by the MIT Sea Grant College Program).

Prof. Arthur B. Baggeroer
MIT, Department of Ocean Engineering

Prof. Baggeroer's technical interests are the application of large, multichannel acoustical arrays for ocean acoustic and geophysical research, design of autonomous remote sensing buoys and development of high data rate underwater telemetry. Recent research has focused on acoustic propagation and ambient noise in the Arctic which has lead to determining the tectonic structure in several regions of the Arctic.

Prof. Baggeroer received his B.S. from Purdue University in electrical engineering and received his S.M. and Sc.D. in electrical engineering from MIT. He presently is a member of IEEE, AGU and is a fellow of the Acoustical Society of America.

Prof. Steven Dubowsky
MIT, Department of Mechanical Engineering

As a professor in Mechanical Engineering, Dr. Dubowsky teaches courses in control systems, kinemantics, dynamics and mechanical design. Presently, Prof. Dubowsky is associate head of the MIT Laboratory for Manufacturing and Productivity. Prof. Dubowsky is also a principal investigator on a number of research programs in the area of design for dynamics and control of mechanical and electro-mechanical systems. Past research efforts have focused on the study of three-dimensional vibrations of machine systems (finite element analysis), acoustic noise generated by high-speed systems, and the development of optimal and self-learning adaptive control procedures for rigid and flexible robotic manipulators.

Prof. Dubowsky received his B.S. in mechanical engineering from Rensselaer Polytechnical Institute and his M.S. and Ph.D. from Columbia University. A member of IEEE, Sigma Xi, Tan Beta Pi and ASME, Prof. Dubowsky is also credited with founding the Journal of Mechanisms, Transmissions and Automation in Design (a transaction of ASME) where he served as technical editor for five years.

Prof. Richard H. Lyon
MIT, Department of Mechanical Engineering

Prof. Lyon is director of the newly formed MIT-Industry Program in Structural Acoustics. Recent research of Prof. Lyon's has been concerned with the development of techniques for understanding machinery noise and the use of vibrational and acoustic signals for machinery diagnostics. His technical interests are varied and include machine diagnostics, random vibration, application of statistics to engineering analysis and the propagation of environmental noise.

Prof. Lyon received his B.A. in physics from Evansville College and a Ph.D. in physics from MIT. He is a member of the ASME, Sigma Xi and is a fellow in the Acoustical Society of America.

Kazuhide Ota
Mitsubishi Heavy Industries, Nagasaki R&D Center

In 1976, Dr. Ota joined Mitsubishi Heavy Industry's Vibration Laboratory of the Nagasaki R&D Center and eight years later, became acting manager for the Lab. Presently, Dr. Ota is a research associate in the Department of Ocean Engineering at MIT. His present research involves developing models that combine both analytical and experimental techniques to minimize both radiated and scattered sound generated from acoustical-structure interaction.

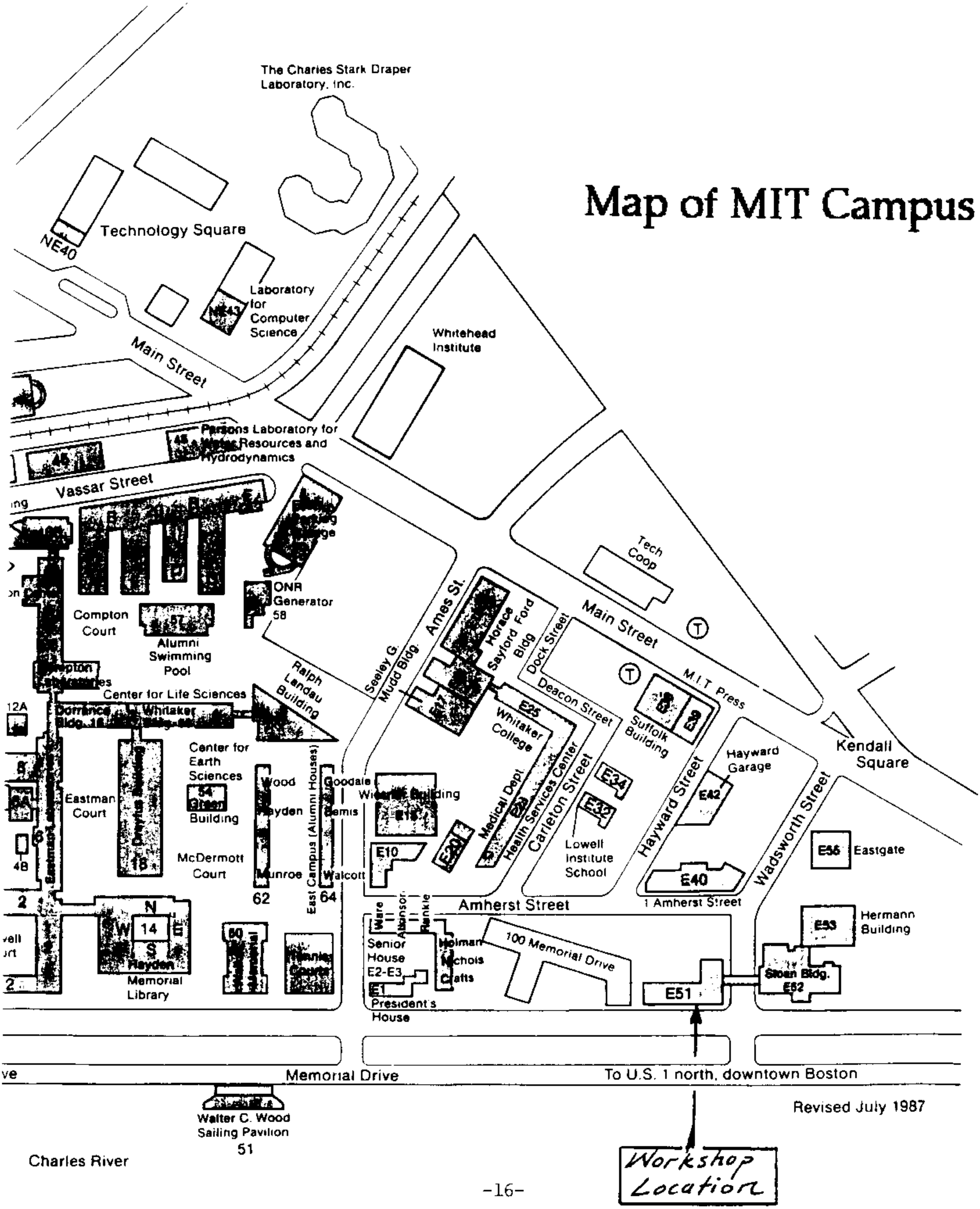
Dr. Ota received his B.S., M.S. and Ph.D. in mechanical engineering from the Tokyo Institute of Technology. He is a member of both the Japan Society of Mechanical Engineers and the Ocean Acoustic Society. An author of many papers, Dr. Ota received the ASME PVP Award in 1983 for his paper "Study on the Fluidelastic Vibration of Tube Array Using Model Analysis Technique."

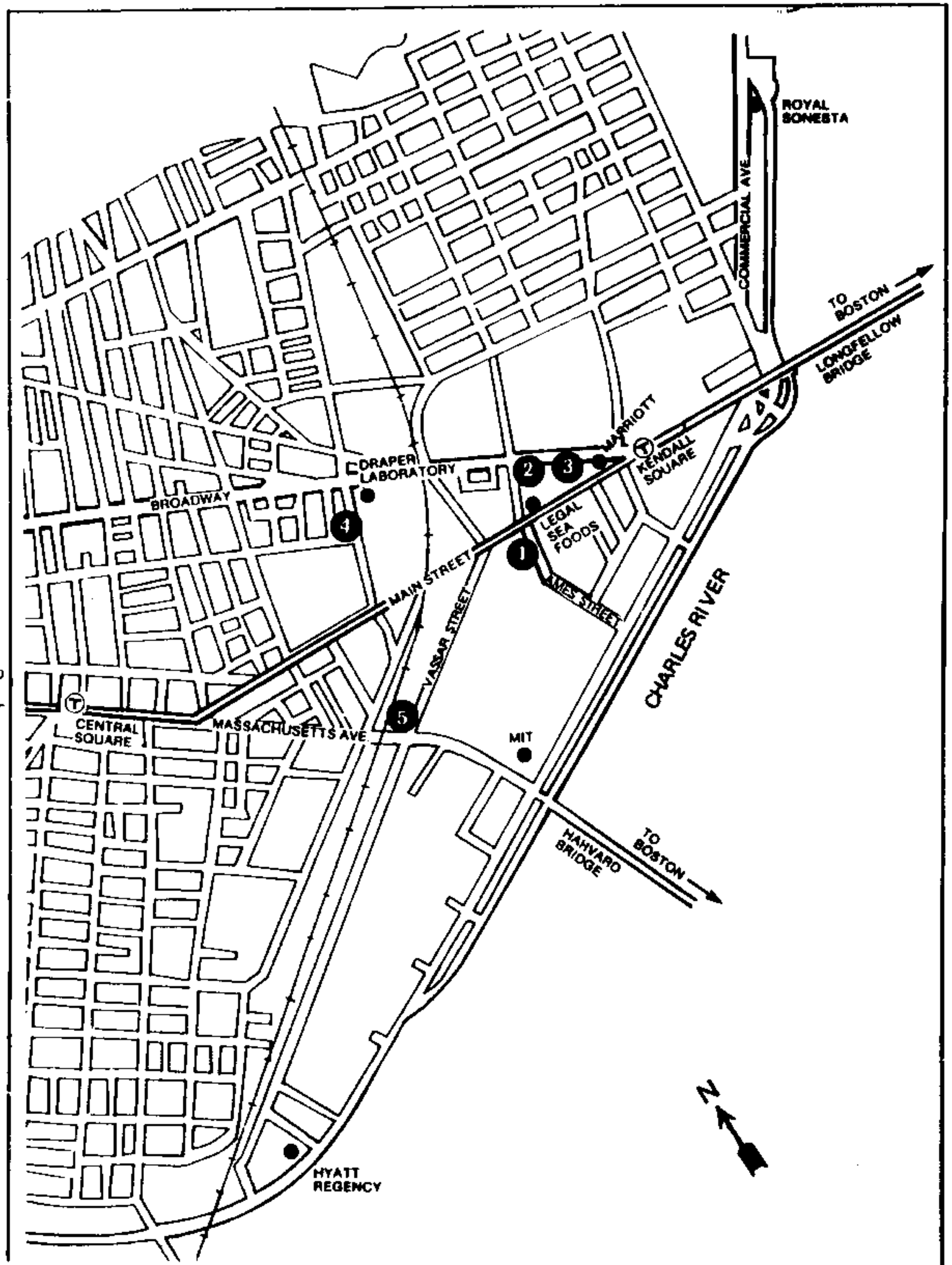
Prof. Andreas H. von Flotow
MIT, Department of Astronautics and Aeronautics

Prof. von Flotow has recently devoted his research efforts to the active control of structural acoustics, active vibration isolation and the dynamics and control of large flexible spacecraft. His technical interests lay in the fields of structural dynamics and acoustics, spacecraft dynamics and applied active control. Prior to joining MIT in 1985, Prof. von Flotow spent a year in West Germany as a visiting scientist with the DFVLR Oberpfaffenhafen on a NATO Post doctoral Fellowship award.

Prof. von Flotow received his B.S. and M.S. in aeronautical engineering from the University of Toronto, Canada, and received his Ph.D. from Stanford, where he performed research on the dynamics and control of large spacecraft structures.

Map of MIT Campus





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)

ACCOMMODATIONS*

Cambridge Marriott
2 Cambridge Center
Cambridge, MA
(617) 494-6600

Royal Sonesta Hotel
5 Cambridge Parkway
Cambridge, MA
(617) 491-3600

Hyatt Regency
Memorial Drive
Cambridge, MA
(617) 492-1234

Howard Johnson
777 Memorial Drive
Cambridge, MA
(617) 492-7777

*Listed in descending order to proximity of Workshop location.

NOTES