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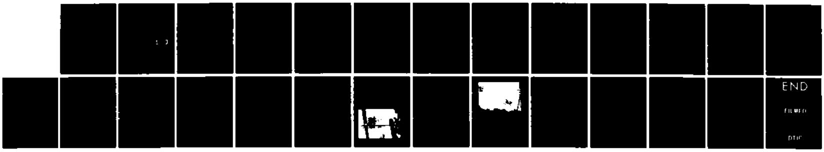

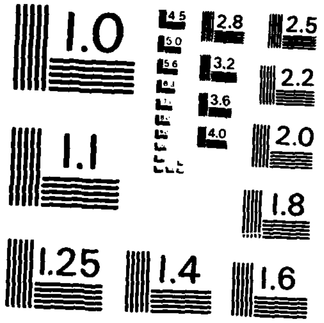

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VIBRATION CONTROL
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FOUR MODE CONTROLLER
MODAL-SPACE CONTROL
THEORETICAL PREDICTIONS
EXPERIMENTAL MEASUREMENTS

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Active vibration control was implemented on two laboratory structures having some important dynamic characteristics of large space structures: a dynamically uncomplicated beam-cable structure and a dynamically complicated plane grid structure. The control techniques used are direct-velocity-

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feedback control, with a single colocated sensor-actuator pair, and modal-space control, with a single sensor and several actuators. Experimental measurements and corresponding theoretical calculations were completed. The most challenging control task attempted was modal-space control of five low frequency modes of the plane grid structure, including a closely spaced pair. But interference between the two close modes produced a mild instability of the structure-control system. Subsequently, a stable four mode controller was produced by simply disabling the control of the mode which had driven the unstable motion. Satisfactory agreement between theoretical predictions and experimental measurements was achieved in this research. However, the nature of the inevitable differences observed suggests in general that any active vibration control technique implemented on a dynamically complicated large space structure should be insensitive to errors in the structure model used to design the control, because that model is unlikely to predict accurately the parameters of all modes affected by the control.

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FINAL SCIENTIFIC REPORT
TO THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
FOR THE PERIOD MARCH 15, 1982 TO AUGUST 31, 1983

GRANT NO. AFOSR-82-0217

EXPERIMENTAL STUDY OF ACTIVE VIBRATION CONTROL*

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Virginia Polytechnic Institute and State University
October 27, 1983

I. INTRODUCTION

This was an experimental-theoretical study of active vibration control. The research was intended to contribute to our understanding of the dynamics and control of large space structures. Control techniques were implemented on specially designed laboratory structures, and theoretical-numerical simulations of the experiments were developed. The general objective was to achieve satisfactory agreement between experiment and theory, thus either validating the control techniques under study for practical application or determining the factors which prevent them from being successful in practice.

The techniques investigated are the relatively simple direct-velocity-feedback control and the more involved modal-space control. The former provides viscous damping at individual degrees of freedom of the vibrating structure, while the latter essentially provides viscous damping of specific individual modes of vibration, which are referred to as controlled modes. These control techniques were implemented in analog form, with the use of

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* Dr. Anthony Amos is the AFOSR Program Manager. This research is continuing with AFOSR sponsorship under Contract F49620-83-C-0158.

standard analog circuitry. To simplify actuator dynamics, the actuators were mechanically grounded, not structure-borne, devices.

A subcontractor, HR Textron, assisted with numerical aspects of the experimental-theoretical research and also independently performed studies of two topics relevant to active vibration control of large space structures.

II. RESEARCH OBJECTIVES

II.A. INITIAL ACTIVE VIBRATION CONTROL EXPERIMENTS ON A BEAM-CABLE STRUCTURE

It was necessary to develop suitable laboratory structures and all of the hardware required to implement feedback control on the structures. Neither the structures nor any of the control hardware were available commercially at prices within the budget of this project. The control hardware which had to be designed, fabricated, calibrated, and proof-tested includes control circuits, sensors, and actuators. It was decided, therefore, that the work should proceed in a deliberate manner, beginning with relatively simple tasks and progressing to the more challenging ultimate objectives only after experience with equipment and methods was accumulated from the simpler tasks.

The first task was to implement the simplest control technique, direct-velocity-feedback control, with the use of a single colocated sensor-actuator pair controlling a relatively uncomplicated structure, a cable-supported vertical beam. The first several vibration modes of this beam-cable structure can be predicted quite accurately with a rather low order finite element model. There are no closely spaced modes or very-low-frequency modes to present unusual difficulties for a control system. The second task was to implement modal-space control on the beam-cable structure, with only the three lowest modes being controlled by a single sensor and three actuators. These experiments on the beam-cable structure were intended to provide operational testing of the control hardware and to give the researchers experience with laboratory implementation of active vibration control without presenting extremely challenging control problems such as a multiplicity of closely spaced modes.

II.B. PLANE GRID STRUCTURE FOR ACTIVE VIBRATION CONTROL EXPERIMENTS

A more complicated structure than the beam-cable structure was needed to provide a demanding test for modal-space control. It was required that the structure be reasonably small to fit in the limited space available, that it be relatively easy to build, and that it be capable of exhibiting pathologies such as closely spaced modes and, somewhat less importantly, rigid body (or nearly so) modes. It was decided to attempt to achieve these characteristics with a plane grid structure which has variable geometry and hangs in a vertical plane such that, under the influence of gravity, it has a low frequency pendulum mode. Before this plane grid structure could be used in active vibration control experiments, it would be necessary to develop a finite element model of the structure sufficiently representative to give reasonably accurate natural frequencies and mode shapes for the first dozen or so vibration modes.

II.C. ACTIVE VIBRATION CONTROL EXPERIMENTS ON THE PLANE GRID STRUCTURE

Once the control hardware was developed and proved in operation on the beam-cable structure, the stage would be set for much more challenging control experiments on the plane grid structure. The principal objectives of these experiments would be to control five modes by application of modal-space control with a single control sensor and five control actuators. Different configurations of sensor and actuator locations and different combinations of controlled modes would be examined.

II.D. SUBCONTRACTOR HR TEXTRON TASKS

HR Textron contracted to perform three tasks. The first was to assist VPI in development of the finite element model of the plane grid structure. The second task was to conduct a theoretical-numerical study of the technique known as component cost analysis relative to the issues of which modes would be most desirable to control and which locations on the structure would be best for control sensors and actuators. The third task was to conduct a preliminary study of criteria which should be considered in addressing the question of ground-based versus on-orbit active vibration control experiments.

III. ACCOMPLISHMENTS OF THE RESEARCH

III.A. INITIAL ACTIVE VIBRATION CONTROL EXPERIMENTS ON A BEAM-CABLE STRUCTURE

The structure is described in Figures 1, with the attached sensor and three attached actuators configured for modal-space control. Natural frequencies and inherent modal damping values are listed in Table 1. Both these damping values and those for the plane grid structure (Table 2) are based on the assumptions that the inherent damping has the form of standard viscous damping and that it does not couple the normal modes of vibration.

The experimental-theoretical study of direct-velocity-feedback control was completed and described in two papers (Nos. 1 and 2, Section VII). Reasonable agreement between experimental measurements and theoretical calculations was achieved, although errors in the finite element analysis were discovered after the documentation which prevented the agreement from being even better. As was expected, direct-velocity-feedback control with a single colocated sensor-actuator pair proved to be very stable but also to have inconsistent control authority, providing high damping to some modes but almost no damping to others.

The experiments and theoretical calculations for three-mode modal-space control of the beam-cable structure were completed. The work is documented in a Master's thesis (G. R. Skidmore, Section VI), a completed paper (No. 3, Section VII), and a paper in preparation (No. 1, Section V). Satisfactory agreement between experiment and theory was achieved, as is illustrated by Figures 2. Modal-space control proved to be very effective in actively damping the three lowest modes of the beam-cable structure, without having any effect on the higher, uncontrolled modes.

III.B. PLANE GRID STRUCTURE FOR ACTIVE VIBRATION CONTROL EXPERIMENTS

The initial version of this structure is described in Figures 3. The initial experimental and theoretical analyses for vibration modes are documented in a Master's thesis (M. A. Masse, Section VI). The structure consisted of a vertical, variable-geometry grid of very flexible aluminum beams hanging from a horizontal steel beam. The steel beam was supported at each end on knife edges, so that it acted as a flexible frictionless hinge. Also attached to the steel beam were two large eccentric masses which could be positioned vertically relative to the beam so as to establish a desired pendulum frequency of the entire structure.

The lateral positions of the eccentric masses shown on Figures 3 proved to be undesirable. The large masses near the ends of flexible beams outboard of the supports produced strong, low frequency appendage modes of the steel beam eccentric mass assembly. These modes were inappropriate because the intention of the experiments was to control vibrations involving primarily the aluminum grid with the use of sensors and actuators acting direct on the grid. Therefore, the appendage modes were raised beyond the bandwidth of control by a relatively simple modification: the eccentric masses were moved inward along the beam to positions just inboard of the supports. This is the current, but not final, configuration. The knife-edge supports also have proved unsatisfactory, because their contact elasticity-plasticity evidently introduced some unpredictable degree of rotational stiffness (especially observable in the pendulum mode), and this stiffness evidently increased slightly with time, possibly due to wearing of the steel in the contact region. Therefore, the knife-edge supports will be replaced by ball-bearing supports in the near future.

The finite element analysis of the current plane grid structure has been completed satisfactorily after a considerable amount of refinement based on comparisons of theoretical calculations with experimental measurements. Factors which caused special difficulties include the effect of gravity and the presence in the same structure of both very stiff elements representing the steel beam and very flexible elements representing the aluminum grid.

Modal testing of the plane grid structure also has been completed satisfactorily but, as for the finite element modeling, only after the necessity of considerable refinement. The aluminum grid is so light and flexible (to produce low frequency modes) that even a slight air current excites it into easily visible motion. Moreover, much of the standard vibration testing equipment available early in the research performed poorly at frequencies below 10 Hz, the band which includes the lowest dozen modes of the structure. Therefore, testing techniques and nonstandard equipment evolved to accommodate the special circumstances of this research. A noteworthy accomplishment (R. N. Gehling, Section VI) was the design and construction of two essential structures: a versatile frame surrounding the plane grid structure to support sensors, actuators, and vibration exciters; and a traversing mechanism for precise positioning of a noncontacting displacement sensor used to locate nodal points of vibration mode shapes.

Experimental and theoretical natural frequencies are listed in Table 2. Most of the calculated frequencies agree to within +/-5% with the measured frequencies. However, a rather small change in detail of the finite element model could easily alter the levels of agreement, improving it for some modes and worsening it to, say, +/-10% for others. One example of such a detail is the modeling of bolted joints in the aluminum grid: should they be represented by short rigid elements and, if so, how long should the rigid elements be? In general, there a multitude of such modeling decisions that must be made for any practical structure, because no theory can exactly represent the structure. It is therefore the author's opinion that +/-5% accurate theoretical predictions for the first several natural frequencies is about as good as can be expected for any practical structure, with generally poorer predictions to be expected for the higher frequencies.

Figures 4 and 5 are examples of comparable experimental and theoretical frequency response functions of the structure itself without the control system (the open loop configuration). The modal inherent damping values listed in Table 2 were chosen to make the theoretical curves resemble as closely as possible the experimental data. It is somewhat surprising that the four lowest modes were so heavily damped. Measurements of the fundamental (pendulum) mode, both with and without the aluminum grid attached to the steel beam-eccentric mass assembly, strongly suggested that the fundamental mode's high damping is attributable to aerodynamic drag on the aluminum beams. It is likely that aerodynamic drag contributed significantly also to inherent damping of modes 2-4.

In the author's opinion, the successful development of the plane grid structure and its theoretical model constitutes a significant achievement; it was certainly far more difficult than was anticipated when this project was proposed. It is planned, therefore, that a technical paper describing the structure alone, exclusive of the control issues, will be submitted for publication (No. 2, Section V).

III.C. ACTIVE VIBRATION CONTROL EXPERIMENTS ON THE PLANE GRID STRUCTURE

The modal-space controller was designed to provide active damping of modes 2-6 with the use of five actuators. The criterion used in selection of sensor and actuator locations was to avoid as much as possible nodal points of the controlled modes. One set of locations appeared to be the best, and the control gains were computed on the basis of this set.

The controlled modes included a closely spaced pair, modes 4 and 5 near 3.5 Hz, as can be seen in Table 2. This pair is also quite evident in the frequency response functions of Figures 4 and 5. The reader may note that the theoretical results for modes 4 and 5 fit the experimental data less well than any other of the controlled modes. This suggests that the simple inherent damping model used may be inadequate for those closely spaced modes, and that the actual damping might, in fact, couple them.

Testing of the five mode control system revealed a mild instability at about 3.5 Hz. Several diagnostic tests were run in the investigation of this instability. It was first determined that all equipment was functioning properly. Next, a specific source of the instability was sought. The controller design allowed the control for each individual mode to be disarmed without affecting the control of any other of the controlled modes. With the use of this feature, it was determined that the control for mode 5 was causing the instability; in particular, it appeared that the mode 5 control was driving mode 4 unstable. This situation is quite plausible physically since the half power bandwidths of the control filters for modes 4 and 5 were 0.3 Hz; thus, each of those modes could contribute significant error signals to the input of the other mode's control system. Theoretical investigation of the instability requires calculation of the complex roots of the complete structure-control system. A computer program to perform this calculation is nearly completed.

Even without the roots calculation program, it proved possible to establish the validity of the theoretical model of the structure-control system by comparison of frequency response measurements and calculations. Frequency response of an unstable system is physically meaningless, so it was necessary to consider a stable system. This was achieved by simply disarming the control for mode 5 and leaving the controls for modes 2-4 and 6 intact. Thus, four modes were controlled by five actuators. Figures 6 and 7 are examples of comparable experimental and theoretical frequency response functions for the plane grid structure with the four mode control system (closed loop configuration). The agreement between experimental measurements and theoretical calculations is, in the author's opinion, as good as can be expected in practice for a dynamically complicated structure.

A report of the work summarized in this section will, if accepted, be presented soon at a conference (No. 4, Section VII), and a paper will be submitted for publication (No. 3, Section V).

III.D. SUBCONTRACTOR HR TEXTRON TASKS

HR Textron assisted VPI in preparation of the finite element model of the plane grid structure and independently performed studies of two topics related to active vibration control of large space structures. These studies are documented in two formal reports (W. E. Davis, Section VI). One study examined the application of component cost analysis and a related technique, internal balancing theory. Calculations were performed using a twelve-degree-of-freedom finite element model of a tetrahedral truss. The numerical results reported are quite reasonable physically, but they are somewhat inconclusive because the structure model used was too small and too stiff to be representative of a highly flexible large space structure. The report from the other study is, in essence, a preliminary proposal for development of a comprehensive *proof of design procedure for large space* structures. Important issues associated with this development, including the role of on-orbit experiments, are defined and discussed.

IV. CONCLUDING REMARKS

The objective of producing satisfactory agreement between experiment and theory has been achieved. The small study of direct-velocity-feedback control substantiated what other researchers have predicted: it is stable but not necessarily effective in actively damping all modes. The extensive study of modal-space control demonstrated that it functions substantially as predicted by the theory on the two laboratory structures tested. However, the instability observed experimentally in the five mode control of the plane grid structure has not yet been reproduced theoretically. It is important that this issue be resolved. If the present theoretical model does demonstrate the observed instability, then the validity of the model will be further substantiated. If, on the other hand, the present model fails to demonstrate the instability, then it might be necessary to conclude that modal-space control is susceptible to subtle factors which are difficult to predict or sometimes even to measure in dynamically complicated structures. Such factors might include closely spaced modes, coupling damping, and slight nonlinearities.

Comparison of open loop (structure alone) experimental and theoretical results of this research suggests a practical lesson: it is difficult if not impossible to predict theoretically in all detail the structural dynamic characteristics which might be required for control system design. For example, the theoretical model of even the simple beam-cable structure is imperfect: note in Figures 2 for the open loop configuration that while the frequencies of sharp peaks (poles) are predicted accurately, there are substantial errors in the calculated frequencies of sharp valleys (zeros). It might be argued that system identification can provide accurate structural dynamic characteristics. But it seems very unlikely to the author that this will be feasible for the first generation of large space structures, and possibly even for later generations. Modal testing and system identification have been areas of active research for over 30 years now, but to the author's knowledge they have not yet been refined to the extent that reliable results can be achieved consistently even for rather well behaved earthbound structures.

This all leads the author to conclude that vibration control systems for large space structures will have to be very forgiving of errors in the structure models used to design the controls.

V. PUBLICATIONS ANTICIPATED

1. G. R. Skidmore and W. L. Hallauer Jr., "Modal-space active damping of a beam-cable structure: theory and experiment," to be submitted to the *Journal of Sound and Vibration.*

2. R. N. Gehling, W. L. Hallauer Jr., M. A. Masse, and G. R. Skidmore, "A plane grid for structural dynamics experiments: theory, design, testing," to be submitted to the *Journal of Guidance, Control, and Dynamics.*

3. W. L. Hallauer Jr., G. R. Skidmore, and R. N. Gehling, "Modal-space active damping of a plane grid structure: theory and experiment," to be submitted to the *Journal of Guidance, Control, and Dynamics.*

VI. PROFESSIONAL PERSONNEL

VPI Principal Investigator: William L. Hallauer Jr.

VPI Graduate Research Assistants:

Michael A. Masse, "A plane *grillage model for* structural dynamics experiments: design, theoretical analysis, and experimental testing," Master of Science Thesis, VPI & SU, February 1983.

Gary R. Skidmore, "A study of modal-space control on a beam-cable structure: experiments and theory," Master of Science Thesis, VPI & SU, May 1983.

Russell N. Gehling, "A plane grid for structural dynamics experiments: theory, design, testing," Master of Science Thesis, VPI & SU, to be completed in March 1984.

HR Textron Project Engineer: William E. Davis
HR Textron reports dated April, 6 1983: "Development of component cost analysis and design tools," and "Preliminary investigation of on-orbit experimental study of active vibration control."

VII. CONFERENCE PAPERS

1. G. R. Skidmore and M. A. Masse, "Active vibration control of a flexible beam-cable structure," International Astronautical Federation Paper 82-ST-02, 33rd International Astronautical Congress, Paris, France, Sept. 27-Oct. 2, 1982.

2. W. L. Hallauer Jr., G. R. Skidmore, and L. C. Mesquita, "Experimental-theoretical study of active vibration control," 1st International Modal Analysis Conference, Orlando, Florida, Nov. 8-10, 1982; *Proceedings*, pp. 39-45.

3. G. R. Skidmore, W. L. Hallauer Jr., and R. N. Gehling, "Experimental-theoretical study of modal-space control," 2nd International Modal Analysis Conference, Orlando, Florida, February 6-9, 1984; submitted for publication in the *Proceedings*.

4. W. L. Hallauer Jr., G. R. Skidmore, and R. N. Gehling, "Modal-space active damping of a plane grid structure: theory and experiment," submitted for the AIAA Dynamics Specialists Conference, Palm Springs, California, May 17-18, 1984.

Table 1. Modal parameters of the beam-cable structure

Mode	Natural Frequency (Hz) Experimental	 Theoretical	**Inferred*** **Modal Inherent** Viscous Damping Factor
1	2.24	2.24	0.0055
2	5.25	5.27	0.0037
3	9.30	9.34	0.0037
4	15.3	15.5	0.005
5	23.8	24.6	0.005

* These values were selected by adjustment of damping in the theoretical analysis so as to achieve as much agreement as possible between theoretical and experimental frequency response functions.

Table 2. Modal parameters of the plane grid structure

Mode	Natural Frequency (Hz) Experimental	Natural Frequency (Hz) Theoretical	Inferred* Modal Inherent Viscous Damping Factor
1	0.64	0.59	0.034
2	0.97	0.95	0.027
3	1.50	1.43	0.048
4	3.46	3.41	0.016
5	3.65	3.72	0.0018
6	5.13	5.15	0.0030
7	5.68	5.53	0.0018
8	5.97	6.01	0.0016
9	6.25	6.63	0.0060
10	8.18	8.62	0.002
11	8.36	8.78	-
12	9.40	9.86	-

* These values were selected by adjustment of damping in the theoretical analysis so as to achieve as much agreement as possible between theoretical and experimental frequency response functions.

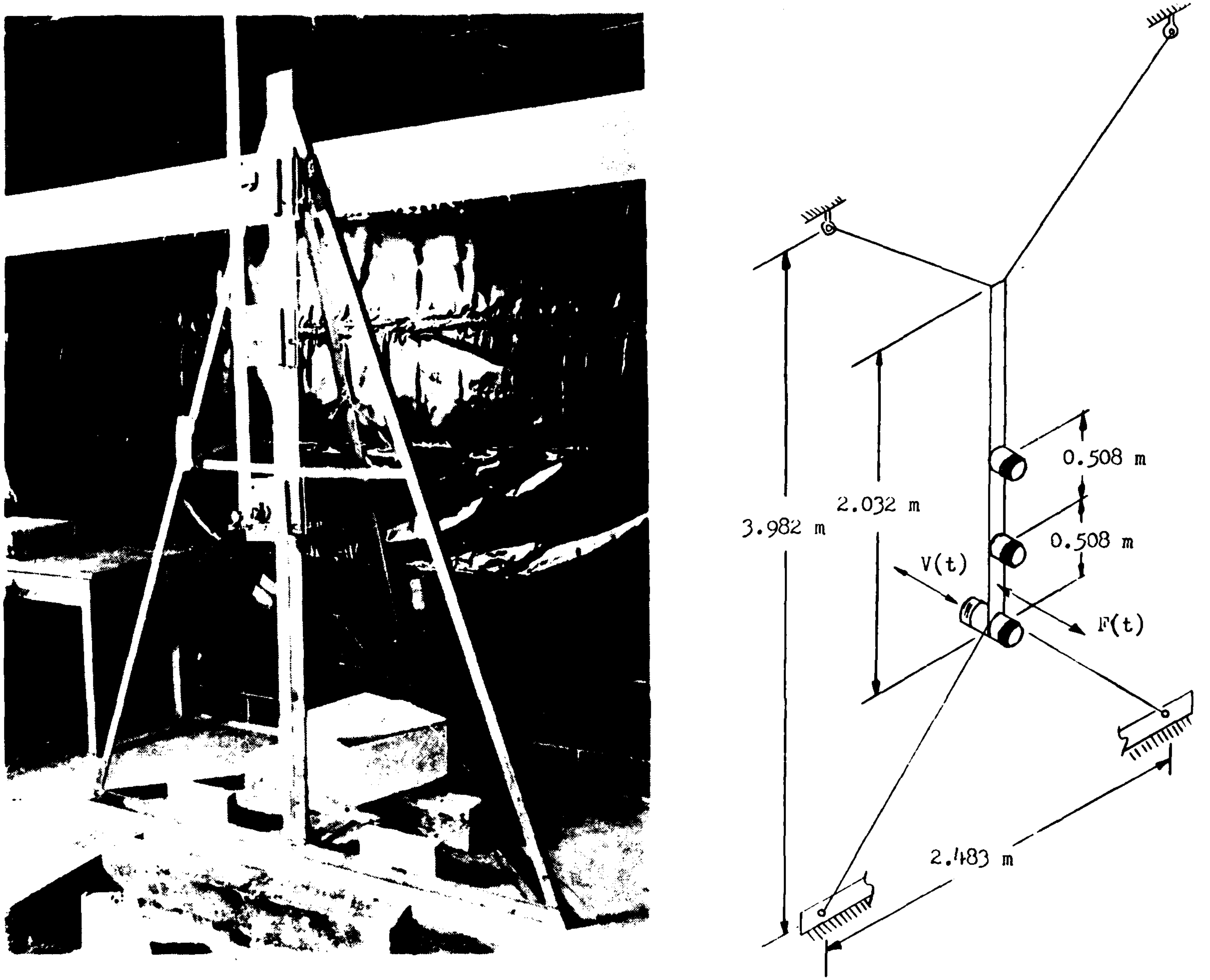
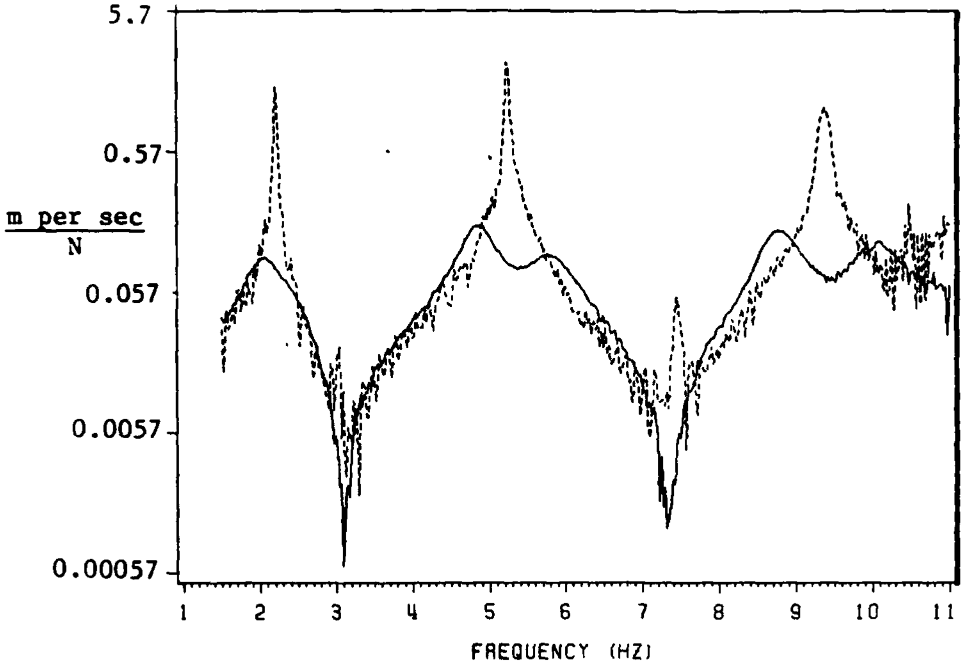
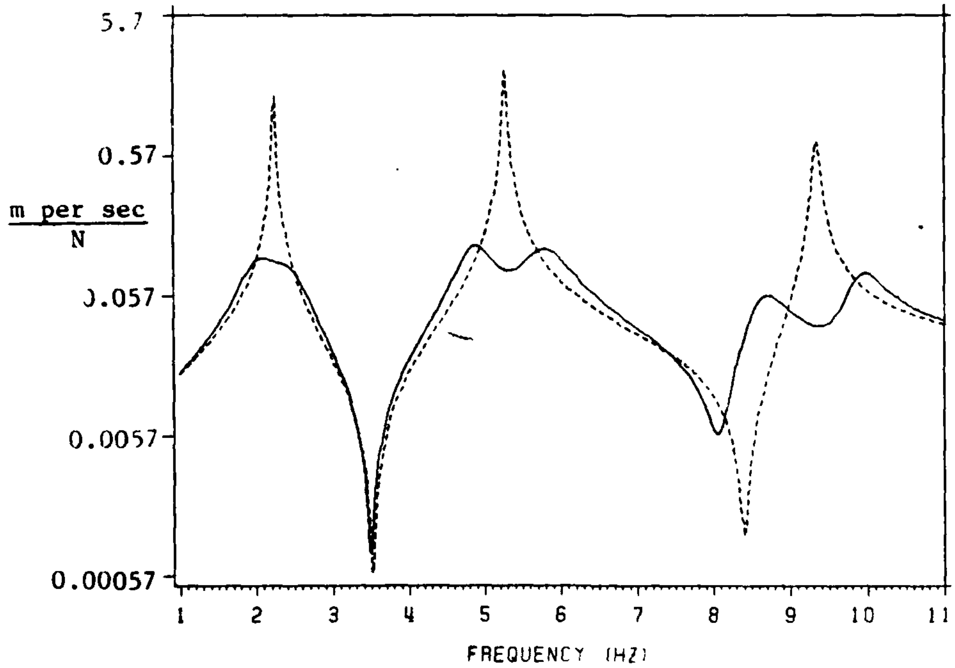


Figure 1. Beam-cable structure: photo in laboratory and line drawing. F(t) is force excitation and V(t) is velocity response for frequency response functions in Figures 2.

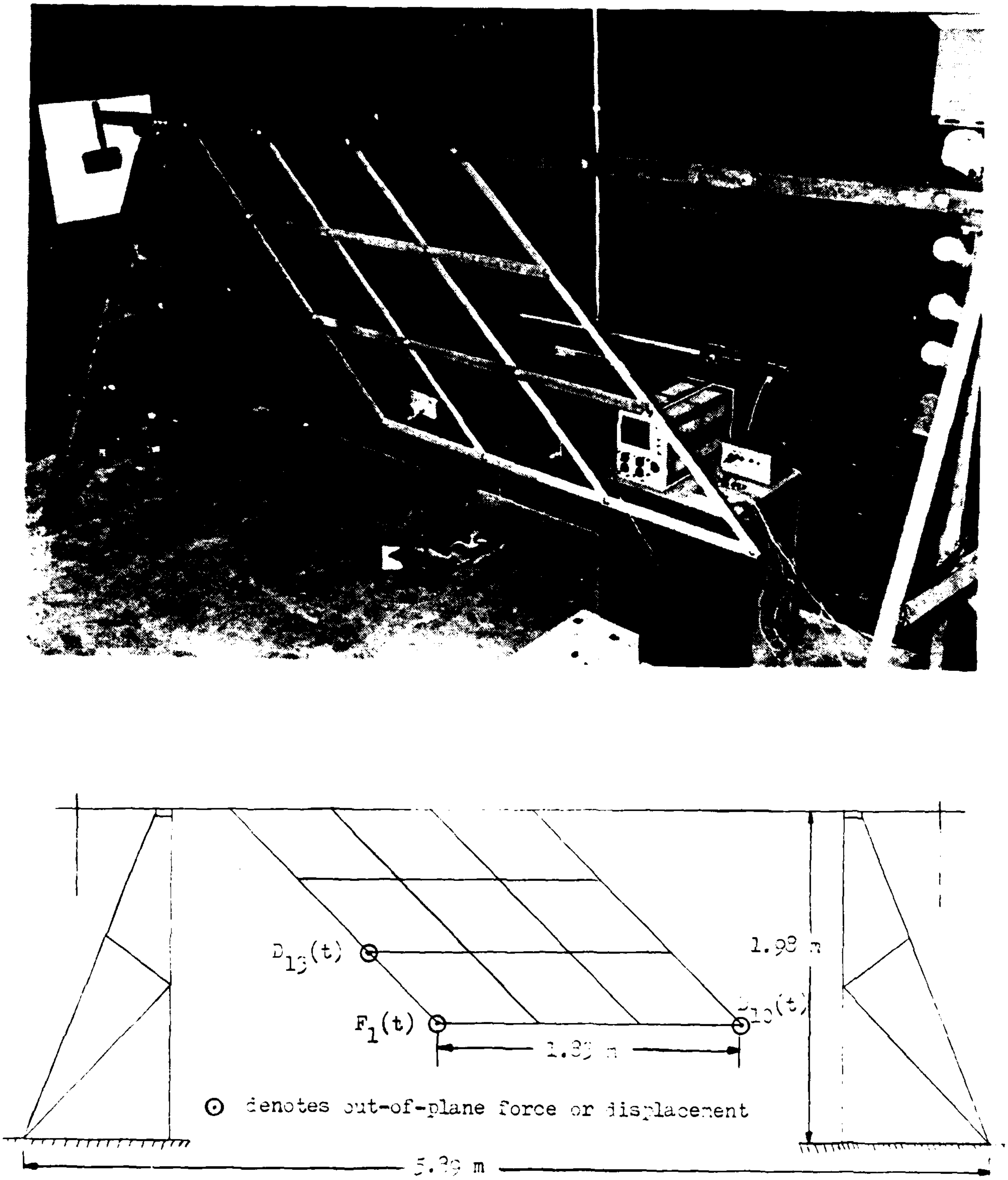


a) **Experimental measurements**

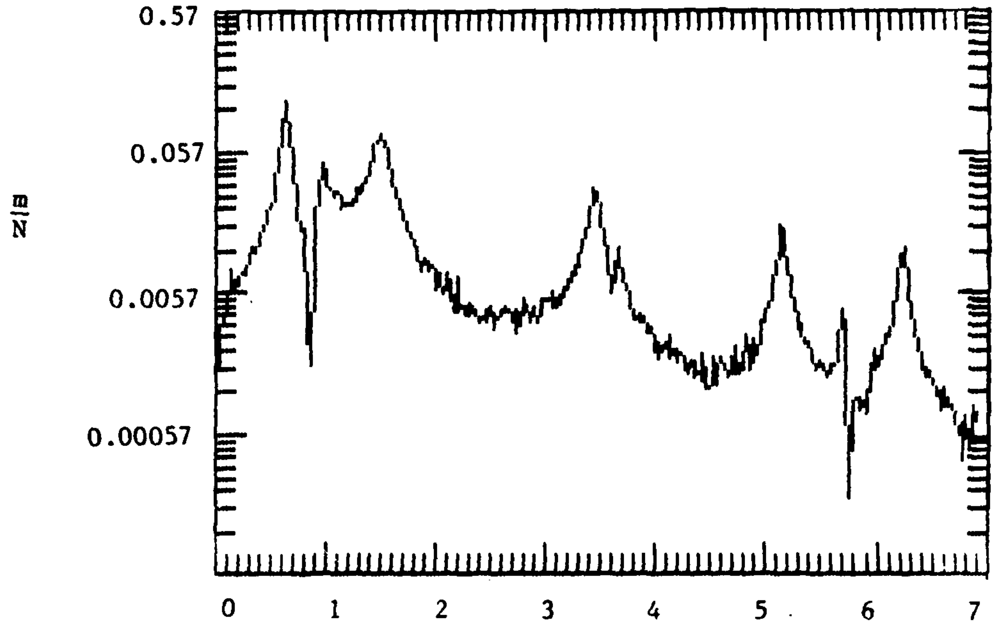


b) Theoretical calculation

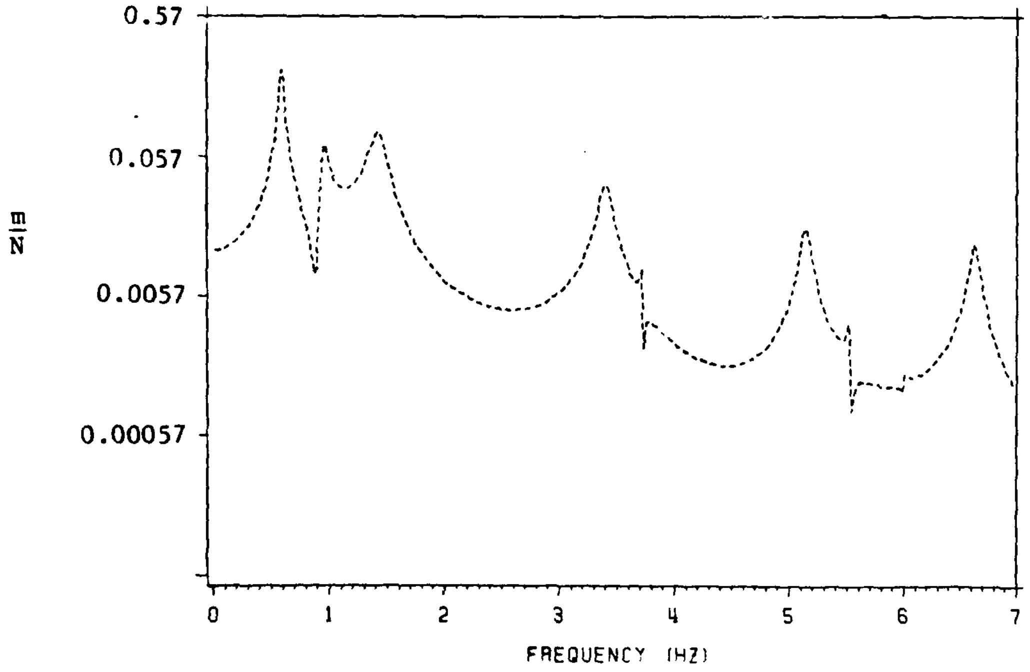
Figures 2. Velocity frequency response function magnitudes for the beam-cable structure. Dashed lines represent open loop, and solid lines represent closed loop.



Figures 3. Plane grid structure: photo in laboratory and line drawing. $F_1(t)$ is force excitation, $D_{10}(t)$ and $D_{13}(t)$ are displacement responses for frequency response functions in Figures 4-7.

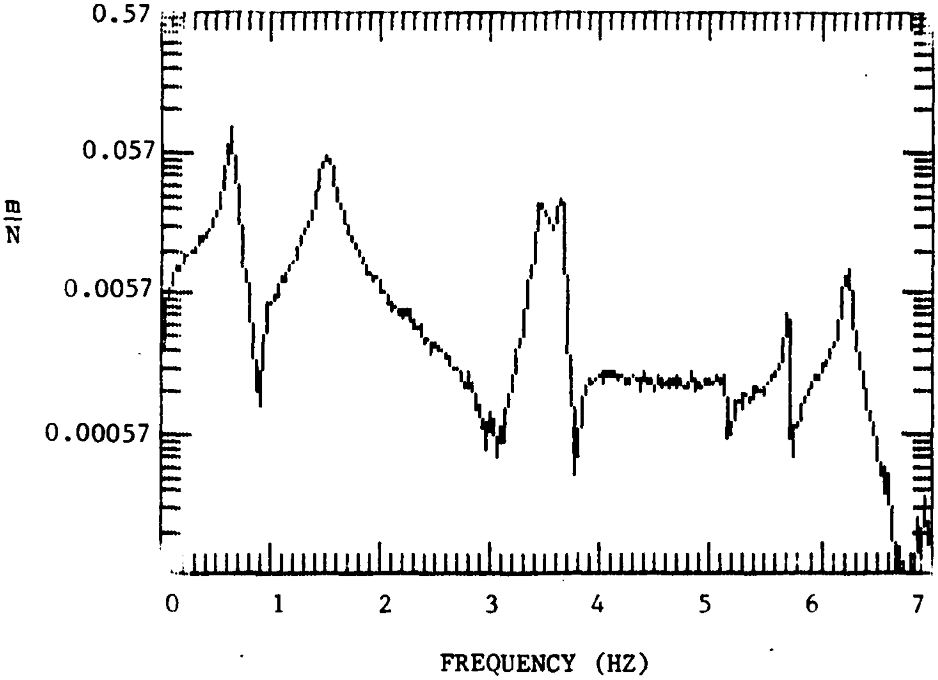


a) Experimental measurements

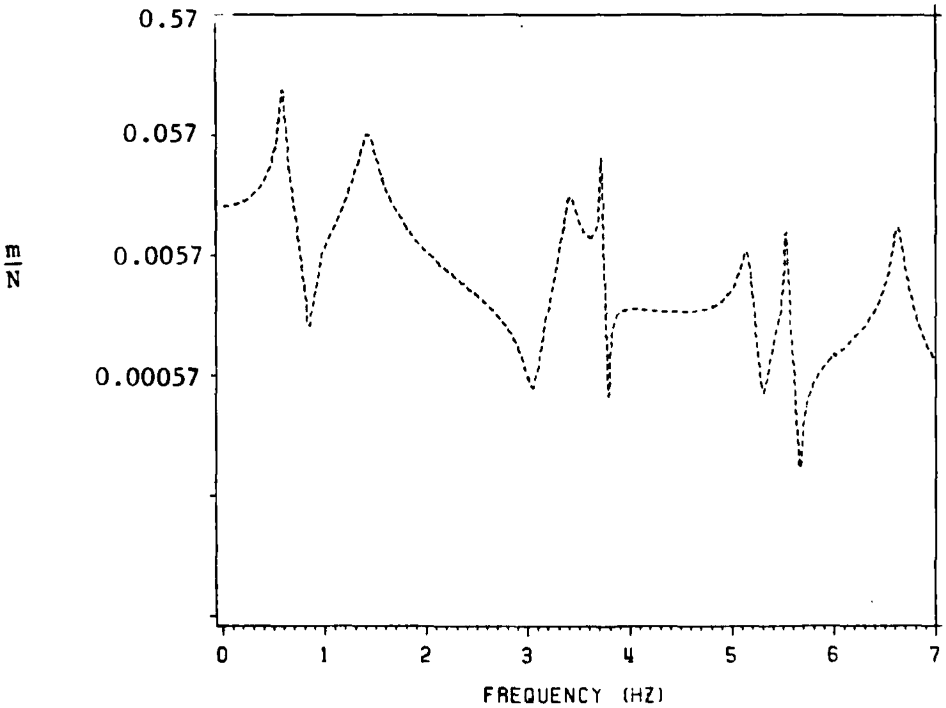


b) Theoretical calculations

Figures 4. OPEN LOOP displacement frequency response function magnitudes (10,1) for the plane grid structure.

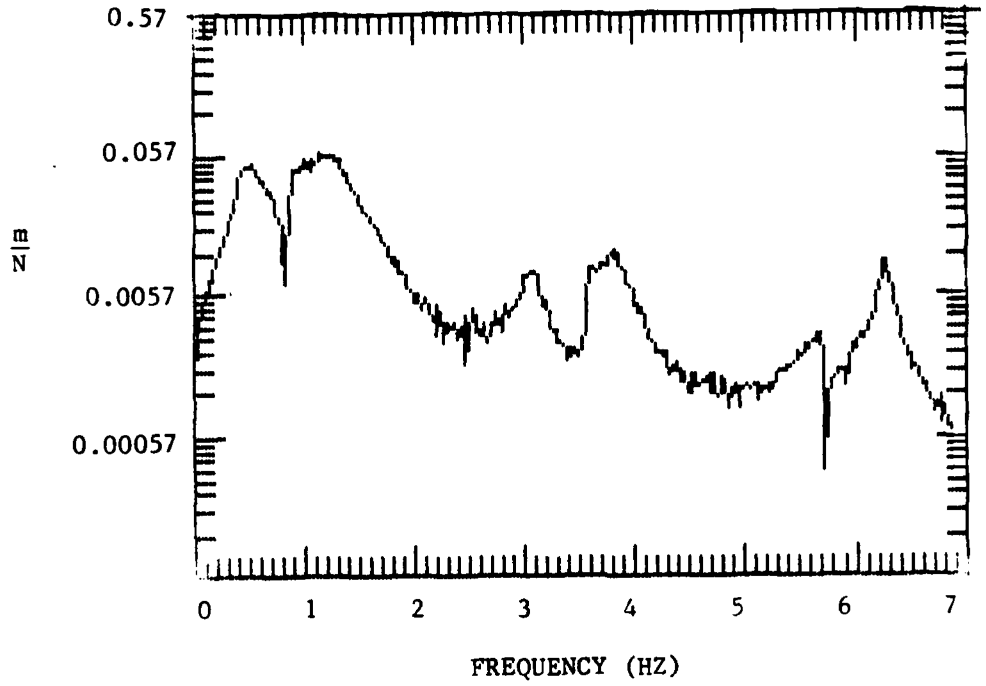


a) Experimental measurements

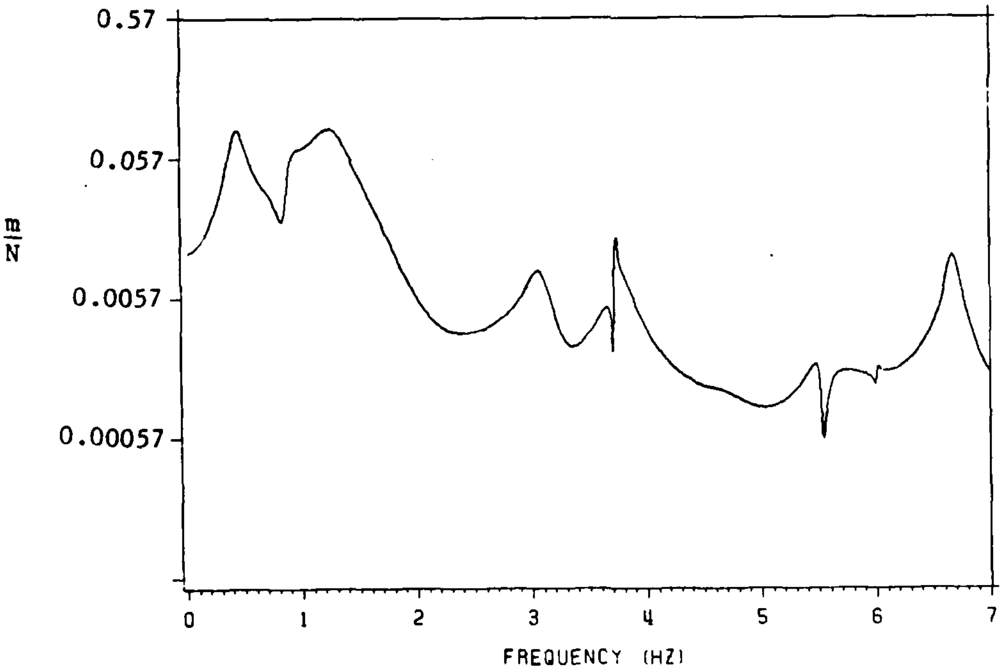


b) Theoretical calculations

Figures 5. OPEN LOOP displacement frequency response function magnitudes (13,1) for the plane grid structure.

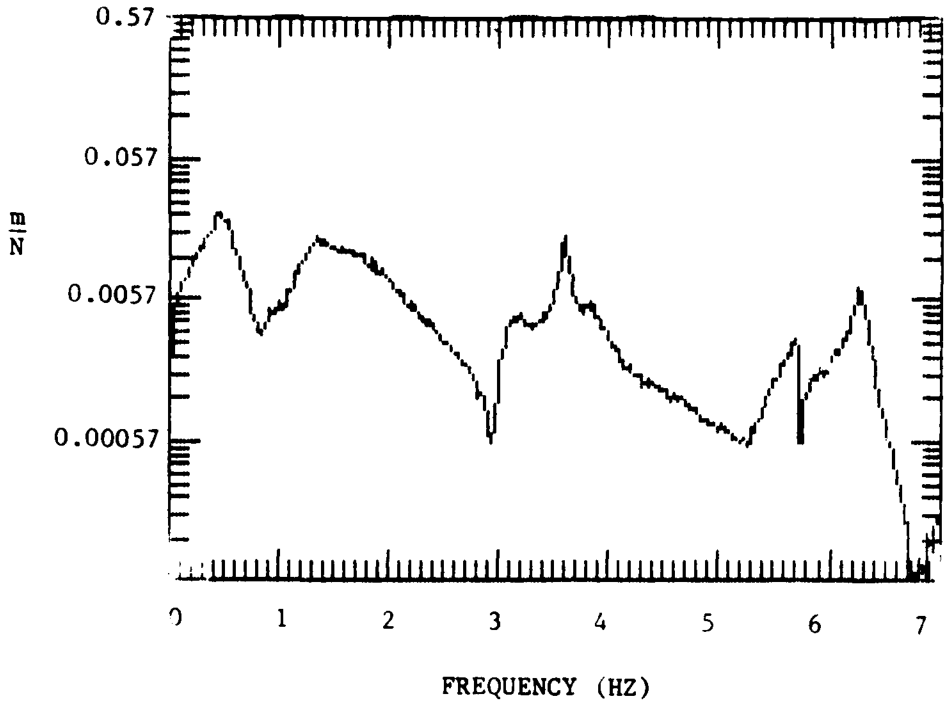


a) Experimental measurements

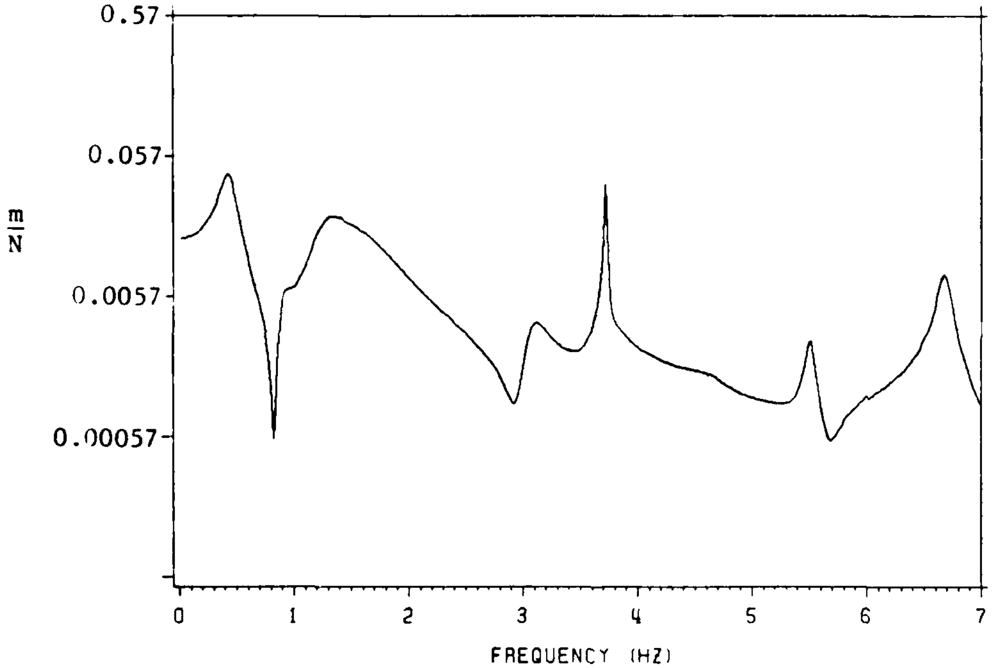


b) Theoretical calculations

Figures 6. CLOSED LOOP displacement frequency response function magnitudes (10,1) for the plane grid structure.



a) Experimental measurements



b) Theoretical calculations

Figures 7. CLOSED LOOP displacement frequency response function magnitudes (13,1) for the plane grid structure.