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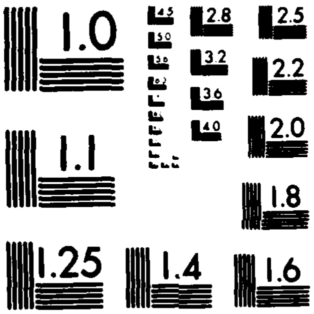

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Control system hardware, including velocity sensors, force actuators, and analog circuitry, has been designed, fabricated, calibrated, and tested in operation. Active vibration control in the forms of direct-velocity-feedback control and modal-space control has been implemented on a dynamically uncomplicated beam-cable structure, and theoretical simulations of the structure-control dynamics have been completed. Either correlation between experiment and theory has been satisfactory, or the reasons for → over

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unsatisfactory correlation have become clear so that corrections can be made in the future. A dynamically complicated, variable-geometry plane grid structure intended for control experiments has been built and analyzed experimentally and theoretically for its modes of vibration. The initial versions of both the actual structure and its theoretical model were unsatisfactory in some respects, and necessary improvements are almost completed at this writing. Finally, the tasks of subcontractor HR Textron are almost completed. They consist of a study of the techniques known as component cost analysis and modal cost analysis and a preliminary study of the issues involved in the testing of active vibration control systems of full-size satellite structures, most specifically whether testing should be conducted on the ground or in orbit.

AFOSR-TR- 83-0855

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

GRANT NO. AFOSR-82-0217

EXPERIMENTAL STUDY OF ACTIVE VIBRATION CONTROL

William L. Hallauer Jr.
Department of Aerospace and Ocean Engineering
Virginia Polytechnic Institute and State University
April 15, 1983

I. RESEARCH OBJECTIVES

This is an experimental-theoretical study of active vibration control. Control strategies are implemented on specially designed laboratory structures, and theoretical-numerical simulations of the experiments are developed. The general objective is to achieve satisfactory correlation between experiment and theory, thus validating the control strategies under study for practical application. The control techniques being 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. Modal-space control, in theory, is a high-authority control which may prove in applications to be susceptible to spillover and instability, while direct-velocity-feedback control is a low-authority control which should be robust and completely stable. It is anticipated, therefore, that modal-space control will be most suitable as a primary control technique, and that it will be supplemented by direct-velocity-feedback control. In the present study, these control strategies are implemented in analog form, with the use of standard analog circuitry. To simplify actuator dynamics, the actuators are mechanically grounded, not structure-borne, devices.

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

It has been necessary in this research 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 are available commercially at prices which are 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 much 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 analyzed quite accurately with a rather low order finite-element model. There are no closely-spaced modes or very-low-frequency modes which would present 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.

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

A more complicated structure than the beam-cable structure is required to provide a demanding test for the control strategies under study. The structure must be reasonably small to fit in the limited space available, and it must be relatively simple to build, yet it must be able to exhibit 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.

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

Once the control hardware was developed and tested in operation on the beam-cable structure, and the plane grid structure was constructed and modeled theoretically, the stage would be set for active vibration 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.

I.D. SUBCONTRACTOR HR TEXTRON TASKS

HR Textron was given three tasks. The first was to assist VPI in development of finite-element models of the laboratory structures used in the control experiments. The second task was to conduct a theoretical-numerical investigation of the technique known as component cost analysis relative to the issues of which locations on the structure would be best for control sensors and actuators and which modes would be most desirable to control. 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.

II. STATUS OF THE RESEARCH

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

The experimental-theoretical study of direct-velocity-feedback control has been completed and described in detail in Ref. 2 of Section V. To quantify control system effectiveness, frequency response was measured. Reasonable correlation between experimental measurements and theoretical calculations was achieved, although errors in the finite-element analysis were discovered after the documentation which prevented the correlation 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 numerical simulations of three-mode modal-space control on the beam-cable structure have been completed. The work is being documented in a Master's thesis which will be completed within a month of this writing (G. R. Skidmore, Section IV). For theoretical-numerical simulation of these modal-space-control experiments, a computer program written prior to the current project was used. This program is suitable for calculation of transient response to initial conditions, but not for calculation of frequency response. Accordingly, the experiments were designed to involve transient responses to known initial displacement states, but not frequency responses. The transient response temporal data, both experimental and theoretical, was transformed to the frequency domain by means of the fast Fourier transform. This process converted the original time domain data into a highly informative form somewhat similar to frequency response data. It has been much easier to compare experimental and theoretical data in the frequency domain form than in the time domain form. The correlation between experimental measurements and theoretical calculations has been adequate in a rather qualitative, order-of-magnitude sense, but has not been quantitatively satisfactory. This lack of quantitative correlation is due to a deficiency in the theoretical model of the control circuitry included in the simulation computer program. The deficiency, essentially, is that analog modal filters in the controller are represented theoretically by their frequency response functions, as if the motion were forced sinusoidal response, rather than by their exact second-order dynamics, which are coupled with the dynamics of the beam-cable structure. The experiments have clearly demonstrated that this quasi-steady-state model of the modal filters is inadequate. It is planned, therefore, that a more complete, correctly coupled model of control circuit and structure dynamics will be prepared and applied for all future experiments.

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

A first version of the plane grid structure has been constructed and analyzed experimentally and theoretically for its vibration modes. The results are presented in a recently completed Master's thesis (M. A. Masse, Section IV). The structure consists of a vertical grid of very flexible aluminum beams hanging from a much stiffer horizontal steel beam. The steel beam is supported at each end on knife edges, so that the beam acts as a frictionless horizontal hinge. Also attached to the steel beam are two large eccentric masses which can be positioned vertically relative to the beam's hinge axis so as to establish a desired pendulum frequency of the entire structure. Modes with natural frequencies under 15 Hz are of primary interest, and this structure has around a dozen of these low-frequency modes.

Unfortunately, the first versions of both the actual structure and its finite-element model proved to be unsatisfactory in some respects. One major source of difficulty was an incorrect assumption about the steel beam, namely, that it is effectively rigid in comparison with the aluminum grid. This assumption greatly reduced the complexity of the theoretical analysis, but since it is incorrect, it also led to unsatisfactory correlation between calculated and measured modes. Measurements have shown that the beam's lowest two modes, one bending and one torsion, have natural frequencies in the 5-7 Hz range, which is an important range for planned active vibration control experiments with the grid structure.

The other major source of difficulty was the analysis program chosen to perform the theoretical calculations, MCS/NASTRAN. With the assistance of subcontractor HR Textron, VPI researchers developed the MSC/NASTRAN analysis on HR Textron's CDC Cybernet account. The problems associated with using MSC/NASTRAN were: an inadequate terminal-telephone link between VPI and the CDC computer in California; a CDC operating system unfamiliar to VPI researchers; the inexperience of both VPI and HR Textron researchers with MSC/NASTRAN; probable deficiencies of MSC/NASTRAN relative to accounting simultaneously for both the effect of gravity on the structure and the presence of both very flexible elements and very stiff elements; and, finally, the absence of timely assistance from knowledgable MSC and/or CDC personnel in attempts to overcome these obstacles.

To solve the problems discussed above, changes have now been made in the actual plane grid structure, its theoretical model, and the computer program used for analysis. Firstly, the structure has been modified to reduce the number of flexible steel beam modes in the 0-15 Hz range. Secondly, the finite-element model has been expanded to include the steel beam as a flexible member. Finally, all calculations are now done with in-house Fortran programs on the VPI computer, and MSC/NASTRAN is no longer used. The vibration modes of the modified structure will be measured in the near future for comparison with the calculated modes.

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

Preparations are being made for these closed-loop experiments to follow the open-loop modal testing of the plane grid structure. All supplies have been purchased and delivered. From these supplies, two more actuators will be fabricated, and the analog control circuits will be expanded to control five rather than three modes. Fixtures for holding actuators and sensors at arbitrary positions adjacent to the structure have been completed. Highly sensitive, non-contacting displacement sensors have been acquired by loan for use in the motion measurements. Two essential instruments, a vibration monitor and an amplitude servo-controller, have been ordered and should be delivered soon. The absence previously of the capability provided by these instruments has impeded progress in vibration testing.

II.D. SUBCONTRACTOR HR TEXTRON TASKS

Two reports, entitled "Development of Component Cost Analysis and Design Tools" and "Preliminary Investigation of On-Orbit Experimental Study of Active Vibration Control," have just been delivered to VPI for approval. After examination by the Principal Investigator and completion of any necessary modifications by HR Textron, the final versions of these reports will be sent to AFOSR.

III. PUBLICATIONS ANTICIPATED

1. M. A. Masse, W. L. Hallauer Jr., and R. N. Gehling, "A Plane Grid for Structural Dynamics Experiments: Design, Theory, and Testing," technical paper to be submitted for publication in the <u>Shock and Vibration Bulletin</u>.

2. G. R. Skidmore and W. L. Hallauer Jr., "An Experimental Study of Modal-Space Control," technical note to be submitted for publication in the Journal of Guidance, Control, and Dynamics.

IV. PROFESSIONAL PERSONNEL

VPI Principal Investigator: W. L. Hallauer Jr.

VPI Graduate Research Assistants:

M. A. Masse, "A Plane Grillage Model for Structural Dynamics Experiments: Design, Theoretical Analysis, and Experimental Testing," Master of Science Thesis, Virginia Polytechnic Institute and State University, February 1983.

G. R. Skidmore, "A Study of Modal-Space Control on a Beam-Cable Structure: Experiments and Theory," Master of Science Thesis, Virginia Polytechnic Institute and State University, to be completed in May 1983.

HR Textron Project Engineer: William E. Davis

V. CONFERENCE PAPERS PRESENTED

1. G. R. Skidmore and M. A. Masse, "Active Vibration Control of a Flexible Beam-Cable Structure," presented at the 12th International Student Conference in conjunction with the 33rd International Astronautics Federation Congress in Paris, France, September 27, 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, November 8-10, 1982; Proceedings, pp. 39-45.

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