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DECENTRALIZED VIBRATION CONTROL IN A LAUNCH VEHICLE PAYLOAD FAIRING

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ABSTRACT

The vibro-acoustic environment inside a launch vehicle payload fairing is extremely violent resulting in excessive development costs for satellites and other payloads. The development of smart structures and active noise and vibration control technologies promised to revolutionize the design, construction and, most importantly, the acoustic environment within these fairings. However, the early promise of these technologies has not been realized in such large-scale systems primarily because of the excessive complexity, cost and weight associated with centralized control systems. Now, recent developments in MEMS sensors and actuators, along with networked embedded processor technology, have opened new research avenues in decentralized controls based on networked embedded systems. This work describes the development and comparison of decentralized control systems that utilize this new control paradigm. The controllers are hosted on numerous nodes, possessing limited computational capability, sensors and actuators. Each of these nodes is also capable of communicating with other nodes via a wired or wireless network. The constraints associated with networked embedded systems control that the control systems be relatively simple computationally, scalable and robust to failures. Simulations were conducted that demonstrate the ability of such a control architecture to attenuate specific structural modes.

INTRODUCTION

A major factor in the cost of deploying orbital vehicles is associated with the most physically demanding aspect of its life: surviving launch. As one can easily imagine, the vibro-acoustic environment within a launch vehicle is extreme. So extreme that a tremendous amount of effort and cost is expended to ensure that the vehicles comes through the launch process cable of fulfilling its mission. Although a great deal of effort has been put into the development of passive vibro-acoustic control mechanisms for launch vehicles, this approach is limited by weight. As is well known, the best answer to acoustic attenuation is to add mass. This is a very expensive solution when one considers the expense of putting a single pound of payload into orbit. Therefore, attention has recently turned to the application of active control technologies in order to address this problem.

Work investigating active control technologies applied to launch vehicle payload fairings focuses on the use of smart-material based structural actuators[1] and acoustic actuators[2]. However, both of these investigations employed centralized control system designs. The advantage of a centralized control approach is that the controller has all sensor data available to it in order to affect its control. The disadvantages are the complexity associated with large numbers of sensors and actuators; the weight associated with communications wiring; and the fault susceptibility of the system should the centralized processor or communications system fail.

The purpose of this investigation is to establish the ability of a decentralized control system to reduce the vibration of a launch vehicle payload fairing with the ultimate goal of minimizing the interior acoustic environment. A decentralized control system is one that consists of many autonomous, or semi-autonomous, localized controllers called nodes, acting on the fairing, in order to achieve a global control objective. Each of these nodes has the following assets and limitations: 1) a computational processor with limited computational capability and limited memory, 2) oversight of a suite of sensors, actuators and the necessary signal conditioning hardware and 3) a network communications link (either wired or wireless) with neighboring or regional nodes and with limited bandwidth.

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The objective of a decentralized controller is the same as for a centralized control system: to minimize the global vibro-acoustic behavior in the presences of disturbances. However, decentralized controllers do so with each node having access to only a limited amount of the total sensor data: i.e. each node has access to only some small number of the sensor signals. The information available to each node is limited to the local sensor signal, actuator signal and any sensor or actuator signals that are shared among nodes over the network. Exactly what information is shared among nodes, and how that information is used, is the topic of this investigation.

One of the important attributes of a decentralized controls system based on networked processors is that it be scalable. Ultimately, such systems will operate on hundreds or thousands of networked processors and they must do so without overburdening the individual processors or the network communication system. Therefore, each processor will have access to only a limited amount of sensor information. The approach taken here is to arrange the individual nodes into groups consisting of a fraction of the total number of nodes in the system. By sharing data only with other nodes within a group the system will be scalable.

The field of decentralized control has been the topic of numerous investigations for over 30 years[3]. Most of these studies have considered "weakly connected" systems or architectures wherein each node only experiences a few of the degrees of freedom of the entire system while being weakly connected to other parts of the system. Robotic swarms are a good example of weakly connected systems and have been the topic of many research projects in recent years[4,5,6]. Decentralized control has been considered in a few vibration control projects for application in space structures[7,8,9]. Hierarchical decentralized approaches have also been considered for control of buckling in beams as well[10].

This work specifically addresses the decentralized control of vibration in a launch vehicle payload fairing. The fairing consists of a conically shaped composite shell. The function of a fairing is to contain and protect a payload during launch. The work is developed based on a finite element model which includes 100 uniformly spaced, collocated displacement sensors and point force actuators. Since the ultimate purpose is to minimize the interior acoustic environment, the objective of the decentralized control system will be to minimize those structural fairing vibration modes that are most responsible for the interior acoustic radiation. Decentralized compensators are designed which interact with each other by sharing sensor and actuator information. The performance of these decentralized control approaches are evaluated by comparing their performance with a centralized control system that uses the same sensors and actuators and that expends an equal amount of control energy. The discussion begins with a general discussion of decentralized control. This is followed by the development of a specific example; namely a simply supported beam. This includes beam modeling, control design methodology and hierarchical organization. Finally, results are presented which demonstrate the effectiveness of various hierarchies in active vibration control.

FAIRING MODEL

The fairing consists of a conically shaped shell that is 3 meters high and 1.5 m across. A picture of the fairing is shown

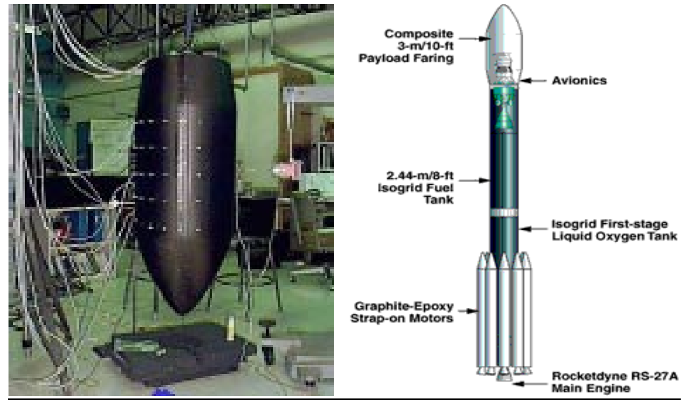

Figure 1 Picture of an experimental fairing in the laboratory (left) and of a Delta launch vehicle (photos

in Figure 1. A finite element model has been developed using a proprietary software package. The model consisted of 300 elements however the final modal has been truncated to include the lowest 40 structural modes. This was done in order to expedite the design process and since the modes to be target for control are below the 20th. The final model was cast in state variable form such that

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(\mathbf{t}) + \mathbf{B}\begin{Bmatrix} \mathbf{u}_d(\mathbf{t}) \\ \mathbf{u}_c(\mathbf{t}) \end{Bmatrix}$$
$$\mathbf{y}(\mathbf{t}) = \mathbf{C}\mathbf{x}(\mathbf{t})$$

where the state vector x(t), is populated with the modal displacements and velocities, $u_d(t)$ is the disturbance input and $u_c(t)$ are the control inputs. The output vector y(t) contains all of the displacement sensor signals.

CONTROL SYSTEM ARCHITECTURE AND DESIGN

One of the most critical constraints associated with embedded systems control is that of communication bandwidth. Only a limited amount of information can be exchanged between nodes. Therefore, the most important question addressed in this investigation is exactly what information should be exchanged in order to achieve the best result. It is important that any control architecture be scalable. That is to say, it should have the ability to scale up to a system possessing hundreds or thousands of nodes without undue growth in the computation and communications. In order to fit within the constraints of the control system architecture studied here is based on "groups". The primary objective of this group-based architecture will be to target those structural modes that are the dominant acoustic radiators.

Group Architecture

A group is defined as a collection of nodes that are associated with each other by the exchange of sensor signals. All nodes within a group receive the instantaneous sensor signals of all other members in the group. Then, each node calculates it's own local control signal based on it's own sensor signal plus all sensor signals from fellow group members. Therefore, each local control algorithm is a multi-input, single output control system. Various size groups will be compared, however, the size of each group is set such that it is a fraction of the total number of nodes in the system (on the order of 5 to

15 nodes per group). Since the number of members in each group is finite the architecture is scalable and we can expect that it will perform reasonably well on much larger scale systems.

Two types of groups will be considered here: groups based on structural modal sensitivity and groups based on geography. Groups based on modal sensitivity contain a fixed number of nodes that posses the highest sensitivity to 4 selected structural modes. In this case the controllers target modes numbered 8, 9, 13 and 14. Modes 8 and 9 have a resonance of 220Hz while modes 13 and 14 resonate at 290 Hz. These modes were selected for attenuation because they are the dominant acoustic radiating modes. The number of nodes in each modal group is varied from 10 to 50. Four examples of modal based groups are shown in Figure 2. This figure shows all nodes on the fairing in an "unwrapped" view. The top (with fewer nodes per ring) corresponds to the conical peak of the fairing. Note that the black nodes belong to the indicated modal group.

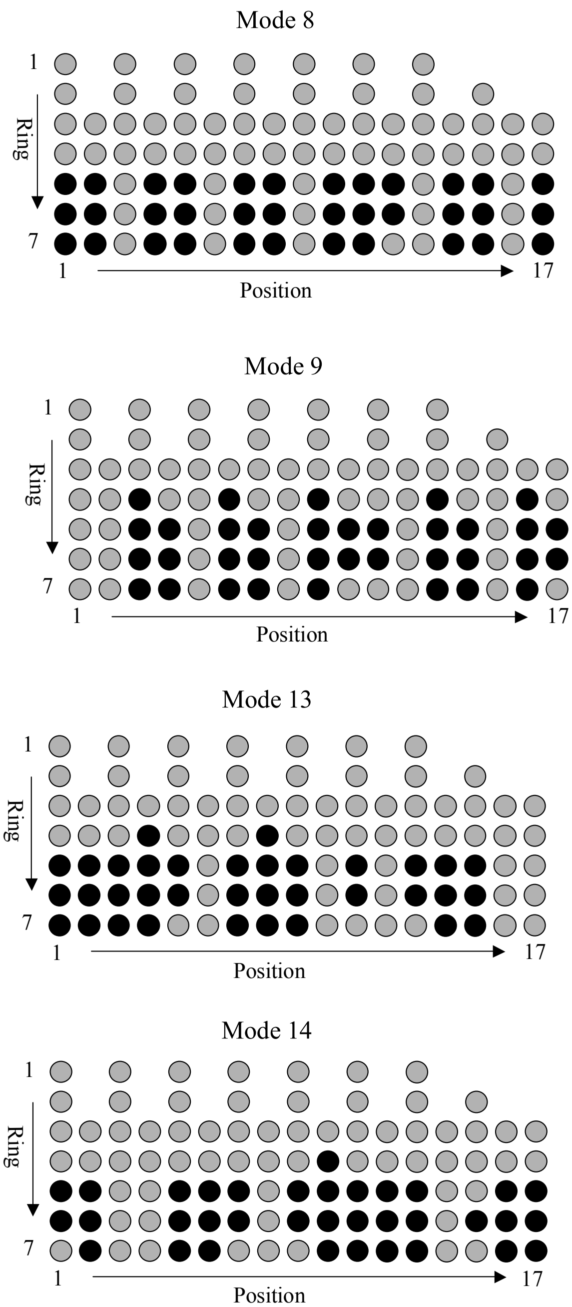

Figure 2 Membership of the modal sensitivity groups with 35 members.

Geographically based groups are created by taking all sensor signals from nodes within a certain number of steps from the node being considered. The "reach" of a group is defined as the number of steps away from the central node from which sensor signals are collected. This is shown in Figure 3 which shows an unwrapped view of all nodes on the fairing. The central node has strips while all nodes within a particular reach are shown in gray. In this way, group based compensators were designed for each node by using all sensor signals within a nodes reach as inputs.

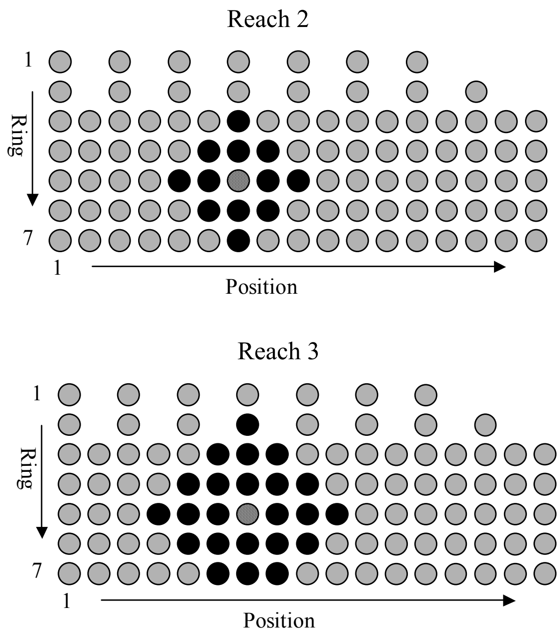

Figure 3 Membership of the geographic groups with a reach of 2 and 3.

Control System Design

All control laws within each node are optimal, constant-gain, output feedback compensators and all are designed in the same manner. Since the sensor measurements are point displacement sensors, the output feedback control amounts to position feedback. Therefore, local control forces are based the following control law:

$$u_{\mathbf{c}} = -\mathbf{K}\mathbf{y}_g \tag{1}$$

where u_c is the local control force, **K** is the feedback gain matrix and $\mathbf{y_g}$ is the vector of sensor signals for all nodes in the group. The feedback gain matrix is found by minimizing the cost functional[11]

$$J = \int_{t_0}^{t_\infty} \left[\mathbf{x}^{\mathbf{T}} \mathbf{C}_m^T \mathbf{Q} \mathbf{C}_{\mathbf{m}} \mathbf{x} + \mathbf{u}_{\mathbf{c}}^{\mathbf{T}} \mathbf{R} \mathbf{u}_{\mathbf{c}} \right] dt \tag{2}$$

where **x** is the system state vector, **Q** is a semi-positive definite performance weighting, C_m is the output matrix that specifies the modes to be targeted and **R** is a positive definite control effort penalty. Details concerning the calculation of a feedback gain matrix that minimizes equation (2) can be found in Reference 11. The weighting matrix **R** was set equal to 1 in all cases (a scalar since all agents produce one output). The performance weighting matrix, **Q**, was set equal to the identity matrix of appropriate dimension multiplied by a scalar, α. This scalar was adjusted so that all cases achieved their performance with the same total control effort. This provides for a fair comparison between different cases.

The feedback gain for each node was designed independently based on the open loop plant and employing the method outlined previously. Once a local compensator was designed, all nodes were appropriately connected to the open loop plant. Then, the system was augmented such that the closed loop system control signals were contained in the output. The $\mathcal{H}_2$-norm of the system was calculated between the disturbance input and all control signal outputs. If this norm was not equal to 0.1, then the scalar multiple of the output weighting matrix, α, was adjusted. Then all compensators were redesigned and the process was repeated. This iteration was continued until an acceptable accuracy was achieved. The reason for this iteration was to ensure a fair comparison basis for different control systems. The quantity being preserved among all systems is the $\mathcal{H}_2$-norm between disturbance input and control signal output. This quantity is proportional to the total energy contained in all control signals. Therefore, if all closed loop systems have the same $\mathcal{H}_2$-norm then they will expend an equal amount of control energy[12].

RESULTS

Results are presented for 7 different control architectures. These include results of a centralized control system; three geographical group cases with a reach of 3, 1 and zero; and three modal based group cases where the groups contain 50, 35 and 10 members each.

The first result, shown in Figure 4 is for a centralized control system. This system was designed as described previously, but only a single compensator is employed and it has access to all sensors and actuators. Included in Figure 4 (and all subsequent results) are the opened and closed loop H_2 norms as well as the control effort norm. This result is provided so as to establish the effectiveness of the decentralized controllers with respect to a well-understood compensator. Note the large attenuation of the frequency response at 220 Hz and 290 Hz. These frequencies correspond to the resonances of the 8, 9, 13 and 14 modes that are targeted by the controller.

The results for geographically based group control are shown in Figures 5, 6 and 7. These plots show the performance of geographical group compensators with a reach of 3, 1 and zero respectively. A reach of zero means that there is no communication and all control is based on local sensor data only. Comparison of these three cases results in the not unexpected conclusion that having a greater reach (i.e. each compensator having more sensor information available) results in better performance. Furthermore, the performance of the reach 3 system is very similar to that of the centralized compensator of Figure 4. As the reach of the system decreases, the ability of the system to target specific modes is reduced and control effort is put toward a broadband reduction of vibration amplitude. This implies that using local controllers that make

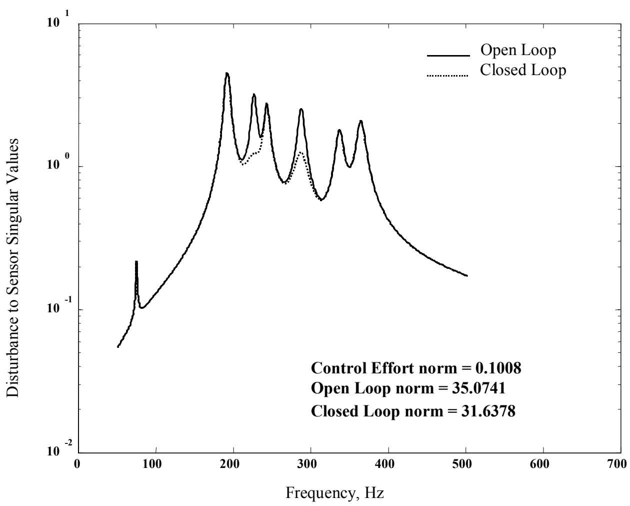

Figure 4 Performance of a centralized compensator using all sensors and actuators.

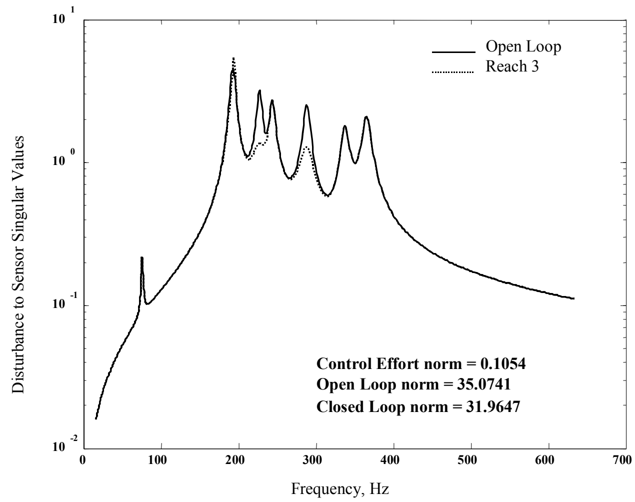

Figure 5 Performance of the geographic based groups with a reach of 3.

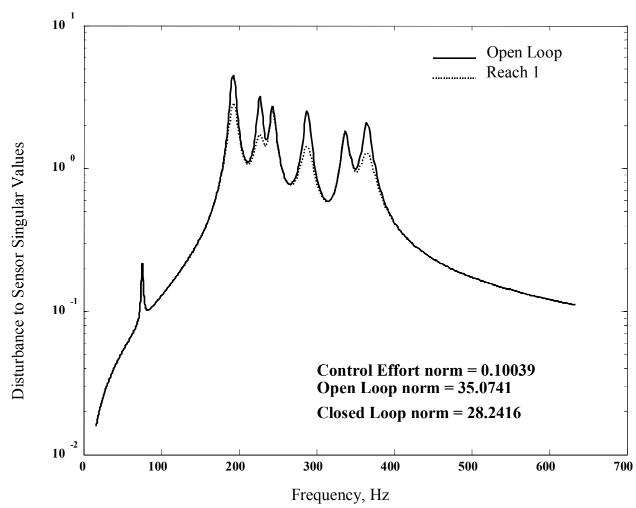

Figure 6 Performance of the geographic based groups with reach of 1.

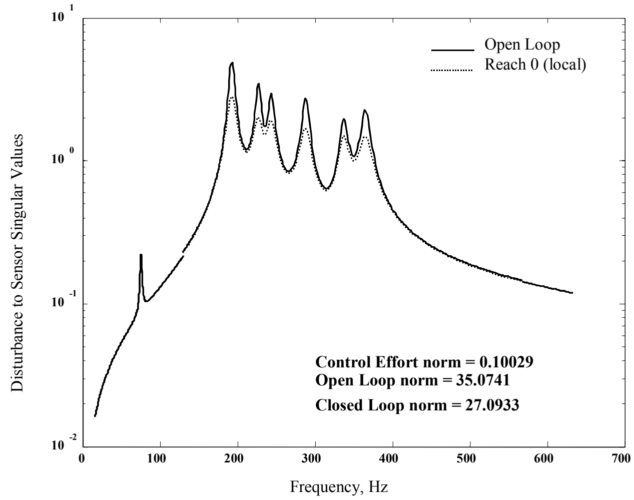

Figure 7 Performance of the geographic based groups with a reach of zero (local control).

use of a larger number of other nodes sensor data results in a control system that can more efficiently target specific dynamic degrees of freedom. This ability can be very important in structural acoustic control since not all modes are efficient acoustic radiators.

The last set of results are shown in Figures 8, 9, and 10 which show the performance of compensators employing modal groups containing 50, 35 and 10 members respectively. As expected, when the number of nodes in a specific mode group decreases, the performance of the overall system is worse. In comparison to the geographically based groups, the modal groups with 50 members do not perform as well as the reach 3 geographic system. Also, the modal groups with fewer members do not perform well at all. This is likely due to the fact that the 50, 35 and 10 member modal groups have a total of 70, 60 and 30 active nodes. The other nodes are not sensitive to the targeted modes are therefore not involved at all. However all nodes are active in the geographically based groups. Yet, the total control effort expended by each system is the same.

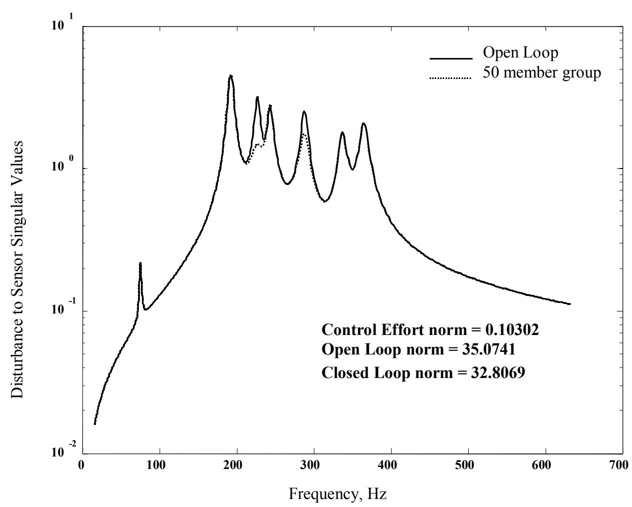

Figure 8 Performance of the modal groups with 50 members.

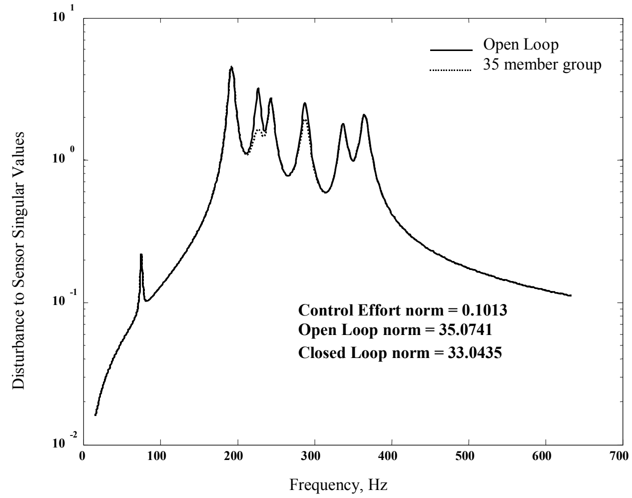

Figure 9 Performance of the modal groups with 35 members.

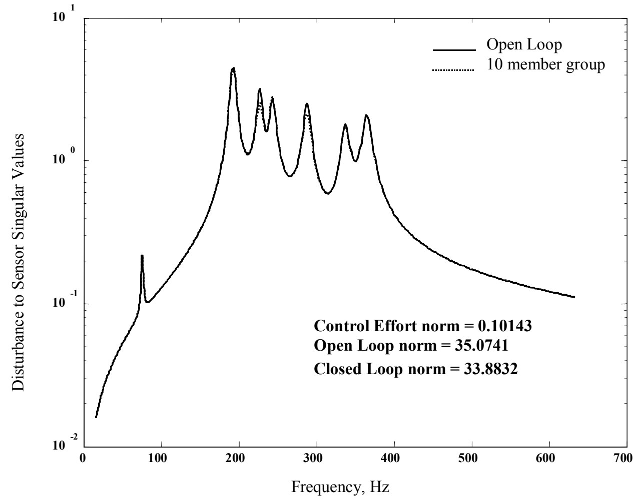

Figure 10 Performance of the modal groups with 10 members.

CONCLUSIONS

The decentralized control of vibration in a launch vehicle payload fairing has been investigated. Feedback control utilizing a network of interdependent controllers was implemented with the goal of reducing the response in specific structural modes. The individual controllers were arranged in two types of "groups": those based on modal sensitivity and those based on geographic proximity. Results were shown for several controllers of each type and with varying numbers of group members. It was demonstrated that geographically arranged groups perform at least as well, if not better than, those groups based on modal sensitivity. It was also shown that this type of control performs nearly as well as typical centralized control. It was noted that, when implemented on a networked embedded system, the geographic groups might offer a performance advantage since the required inter-node communication bandwidth will be reduced.

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