Optimum Design of Intelligent Truss Structures

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Abstract

An integrated structures/active vibration suppression design optimization procedure for intelligent truss structures is presented. The intelligent truss structures consist of inert trusses augmented with active members. The active members contain piezoelectric sensors and actuators embedded within a composite layup and local vibration suppression loops. A two stage optimization procedure is described which breaks a complex implicit combinatoric optimization problem into a heuristic subproblem for active member placement and a formal subproblem for sizing the inert truss members and the active truss members. By designing the local loops around the active members simultaneously with the structural parameters of the inert and active members, damping in the lower modes can be obtained without destabilizing the higher modes. Solution to the optimum design problem is found in relatively few iterations by employing approximation concepts.

Introduction

The development of "intelligent" structures promises to change the way that space systems are conceptualized, designed, and implemented. By utilizing active members, composite members with embedded sensors and actuators, intelligence can be designed into space structures so as to enhance the potential for mission success and to adaptively change on-orbit the characteristics of the structure to meet changing environmental and mission specifications. New design and analysis techniques are required in order to maximally exploit the flexibility of the structures' intelligence.

Recent theoretical and experimental work [1,2] has demonstrated the potential use of active members for structural vibration suppression with minimal mass, complexity, and power consumption impact. In order to utilize the active members to their full potential, integrated design procedures are needed in which the active members are designed into the structure early in the design process. Integrated design procedures show promise for yielding more efficient system designs than do sequential design procedures.

Integrated structure/control design methods using active members have been reported on in the recent literature. An integrated optimization methodology was developed by Lust and Schmit [3] for active members using direct output feedback. Their work pointed out the synergy which exists between the structures and controls disciplines and showed the benefits of using an integrated, rather than sequential, structures/controls design procedure. Dynamic stability constraints were added to the previous work by Thomas and Schmit [4]. The stability constraints become increasingly important as one attempts to open up the design space by allowing noncolocated sensors and actuators and by allowing negative feedback gains. Direct output feedback was used in both of the previous studies without including a compensator between the sensors and the actuators. McLaren and Slater [5] demonstrated the effect of including a compensator in an integrated optimization procedure. Figures 4 and 8 in Reference 5 show that increasing the order of the compensator from 0 (for direct feedback) to 2-5 yields significantly improved designs.

This work builds on the the results demonstrated by Manning [6] where both active and passive members were used in an integrated design optimization procedure. The design problem is posed as a combinatoric optimization problem in which active member placement, active and inert member cross sectional dimensions, and compensator parameters are treated as design variables. By designing the compensator parameters simultaneously with the structural parameters, better performance can be obtained while meeting stability constraints than for direct output feedback. The integrated design procedure is applied to a system representative of complex structures where purely structural solutions (such as mass and stiffness redistribution) have little potential for meeting the stringent performance requirements.

System Description

This work is concerned with the optimum design of truss structures augmented with active or intelligent members. A block diagram for such systems is shown in Figure 1. The inert structure takes externally-applied loads and produces physical responses based on the dynamics of the structure and the location and magnitude of the applied load (i.e., box A in Figure 1) yielding

$$\dot{Z} = A_s Z + B_s u + B_s R \tag{1}$$

where the state vector Z is the vector of stacked physical displacements and velocities

$$Z = \left\{ \begin{array}{c} z \\ \dot{z} \end{array} \right\} \tag{2}$$

For a purely inert structure with no active members, the $B_s u$ term would be zero. The addition of active members yields a set of sensor measurements based on the physical response of the structure (box B in Figure 1)

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$$y = C_s Z + D_s u \quad (3)$$

and a set of control forces to be applied to the structure (box C). Feeding the sensor measurements directly to the actuators would give a direct output feedback control law. However, in order to prevent the destabilization of higher modes (when trying to damp the lower modes) it makes sense to roll-off the control law. This roll-off allows one to damp the lower modes the most while leaving the higher modes untouched. Roll-off is accomplished by placing a compensator of order 1 or greater (box D in Figure 1) between the sensor measurements and the actuator forces. Thus, compensator voltage degrees-of-freedom can be written as

$$\dot{V} = A_c V + B_c y \quad (4)$$

The intuitive need for a roll-off in the compensator was verified in Reference 5 where increasing the order of the compensator yielded improved optimum designs. For this work, both Strain Rate Feedback (SRF) and Positive Position Feedback (PPF) compensators were implemented. The SRF compensator was implemented using a second order roll-off filter and a differentiating filter. The PPF compensator was implemented using either two or three second order roll-off filters connected in parallel. The resulting fourth through sixth order filters should yield improved designs when compared with the results reported in Reference 6 where a second order Positive Position Feedback compensator was used. Finally, feedforward between the actuators and sensors is shown in box E and given by the $D_s u$ term in equation(3). The feedforward is the voltage produced by the sensors due to the forces generated by the actuators.

The closed loop equations of motion can be derived by substituting equations (3) and (4) into (1) to give

$$\dot{X} = AX + Bu + BR \quad (5)$$

where the state vector X is the stacked vector of physical displacements and velocities and compensator voltages

$$X = \left\{ \begin{array}{c} z \\ \dot{z} \\ v \end{array} \right\} \quad (6)$$

and R is the disturbance. The overall system plant matrix A is given by

$$A = \left[\begin{array}{cc} A_s & -B_s C_c \\ B_c C_s & A_c - B_c D_s C_c \end{array} \right] \quad (7)$$

and the input matrix B, for distributing the active control forces on the structure, is given by

$$B = \left\{ \begin{array}{c} B_s \\ B_c D_s \end{array} \right\} \quad (8)$$

A set of observations y is available from the sensors and can be expressed as

$$Y = CX + Du \quad (9)$$

where the observation matrix C consists of

$$C = \left[\begin{array}{cc} C_s & -D_s C_c \end{array} \right] \quad (10)$$

and the feedforward relation is

$$D = [D_s] \quad (11)$$

Solution of the state space form of the equations of motion given in (5) and (9) is accomplished by computing the complex modes for the overall plant matrix A and solving the resulting uncoupled equations in the frequency domain.

Optimum Design Problem Statement

The optimum design problem used for this work is

$$\min \ \mathrm{LOS}(d,t) \quad (12)$$

subject to

$$g(d,t) \leq 0 \quad (13)$$

along with the side constraints

$$d^l \leq d \leq d^u \quad (14)$$

where it is understood that d is the vector of design variables for the inert truss members, active members, and the compensators. This design problem corresponds to those missions where a single performance index, such as a line-of-sight (LOS) pointing error, is critical for mission success. Additional constraints, g, must be imposed on the design to insure that a space-based functional design is obtained. Some of the possible restrictions that are used in forming these additional constraints are an upper bound mass cap, limits on the travel of key optical or sensor components, limits on the loads induced in fragile sensor/electrical assemblies, and dynamic stability margins.

Figure 2 contains schematics of the inert truss design elements, the active member design elements, and the compensator design elements. For the inert truss design elements, the inside diameter and wall thickness of the member are the design variables whereas the reciprocal of the cross sectional area is used as the optimization variables. For the active members, the design variables are the inside dimension of the square member and it's wall thickness. Optimization variables for the active members are the reciprocal of the area of the member. Design variables (and optimization variables) for the compensator include the roll-off frequencies and damping ratios, the differentiator break frequency, and the overall gain of the compensator. In addition, a 200% weight penalty was attached to each active member to represent the weight of associated electronics and power supply hardware.

The control augmented system optimization problem posed in equations (12) through (14) is an implicit combinatoric optimization problem. In general, both the objective function and the constraints are complicated implicit functions of the design variables. The combinatoric nature of the problem arises due to the task of placing the active members on the structure. Methods for the solution of this class of problem exist, but are computationally burdensome.

Solution Methodology

A more tractable solution methodology, rather than solving a combinatoric optimization problem, is to break the problem down into heuristic and formal subproblems as shown in Figure 3. The heuristic subproblem is concerned with determining efficient locations for the active members. One way to find efficient locations is to place the active members in regions of high strain energy for the modes that are to be controlled. Following the placement of the active members, the formal subproblem, concerned with finding optimum values for the design variables, is solved. The formal subproblem replaces the implicit problem posed in equations (12) through (14) with the explicit approximate problem [3]

$$\min\ \tilde{\mathrm{LOS}}(\mathrm{d},\mathrm{t}) \tag{15}$$

subject to

$$\tilde{g}(d,t) \leq 0 \tag{16}$$

along with the side constraints

$$d^l \leq d \leq d^u \tag{17}$$

where both the objective function and the constraints have been replaced by the explicit hybrid [7] first order Taylor series, $\tilde{LOS}$ and $\tilde{g}$, respectively.

Solution of the implicit optimum design problem posed in equations (12) through (14) proceeds by solving a sequence of heuristic and formal subproblems. Each formal subproblem involves solving a sequence of approximate problems (stated in equations (15) through (17)). A pictorial description of the complete solution sequence to the original optimum design problem is shown in Figure 3.

Example Problem

A scaled version of the Space Based Interferometer (SBI) [8] shown in Figure 4 will be used to demonstrate the potential payoff that can be expected using the optimum design methodology discussed herein. The interferometer consists of an 11 meter tower with a telescope running down the center of it. Two 13 meter arms are attached at the base of the tower and support collecting telescopes at their tips. The 13 meter arms yield a baseline optical path length of 26 meters. Laser metrology equipment is mounted at the end of an 11 meter truss.

The performance of the SBI is maximized when an optical path as close to 26 meters is maintained. In addition, the relative tip and tilt of the collecting telescopes at the ends of the 13 meter arms must be kept below 5μrad. The primary disturbance to the structure is a broadband disturbance from attitude control reaction wheels mounted in the center bay of the SBI. Thus the optimum design problem is to minimize optical path length excursions from 26 meters with upper bound constraints of 5μrad on the relative tip and tilt of the collecting telescopes. An upper bound mass cap of 252 kg is also imposed. This cap corresponds to the preliminary design mass of the completely inert system (without active member augmentation).

The preliminary design was used as the point of departure for the optimum design procedure. The performance of the interferometer at the preliminary design when subjected to the broadband reaction wheel disturbance is shown in Figure 5. Unacceptable optical lengths and relative tip and tilt motion of the collecting telescopes exceeding 5μrad were obtained. The modes at 4.3, 8.4, 16.4, 19.2, and 27.7 Hz needed damping augmentation to achieve the performance goals. It should be noted that purely structural methods (i.e., mass and stiffness redistribution) are doomed to failure in this case because of the wide band disturbance and the stringent performance levels required. Locations for the active members were determined by examining regions of high strain energy for the modes which needed damping augmentation. This, in effect, results in a solution to the heuristic placement subproblem. Figure 6 shows the chosen locations for the active members on the SBI.

With the locations of the active members fixed, the formal optimization subproblem was solved to give the optimum values of the structural and compensator design variables. The performance of the interferometer following optimization is shown in Figure 7. Optical length deviations have been reduced from 3.16 μm to 0.15 μm while bringing the relative tip and tilt motion of the collecting telescopes down to acceptable levels. The peak tip and tilt motions at the optimum design are 3.4 μrad and 3.6μrad, respectively, having been reduced from 21.4 μrad and 48.3 μrad at the initial design. Table 1 gives the modes and damping ratios for both the original undamped system and for the system with loops closed around the active members. Relatively broadband damping is achieved with no weight penalty and only 12 active members. The mode at 33.8 Hz is now driving the design in terms of the optical baseline response. To efficiently sense and damp this mode further, additional active members would have to be added.

Concluding Remarks

An integrated inert truss/active truss member design optimization methodology has been developed. The methodology treats both structural design variables and local compensator design variables simultaneously in the optimization procedure. By designing the local compensators for the active members simultaneously with the the inert and active member structural design parameters, damping in the lower modes can be achieved without destabilizing the higher modes. The design optimization procedure is a mission-enabling technology for future space missions with extremely stringent dynamic performance requirements where purely structural solutions fail.

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Table 1: Initial and Optimum Frequencies and Damping Ratios

	Initial Design		Optimum Design	
Mode Number	Frequency (Hz)	ζ(%)	Frequency (Hz)	ζ(%)
1-6	0.0	0.0	0.0	0.0
7	4.4	0.2	4.4	7.4
8	6.5	0.2	6.2	15.5
9	7.2	0.2	6.6	3.2
10	8.4	0.2	8.2	6.3
11	8.5	0.2	8.4	3.8
12	12.9	0.2	11.1	10.2
13	16.4	0.2	15.8	13.5
14	19.0	0.2	18.3	11.6
15	19.2	0.2	18.6	13.6
16	21.7	0.2	20.7	0.6
17	24.5	0.2	23.8	4.8
18	27.7	0.2	27.5	0.3
19	29.1	0.2	27.7	9.8
20	36.9	0.2	35.1	5.3

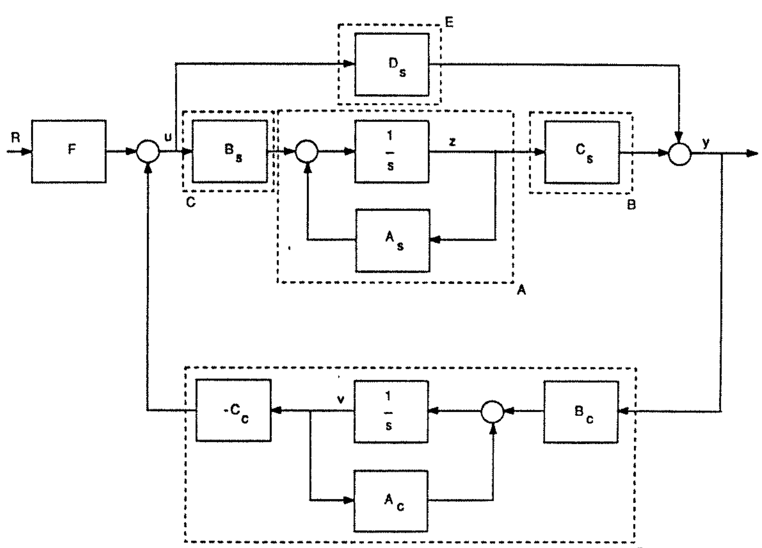

Figure 1: System Block Diagram for Intelligent Truss Structures

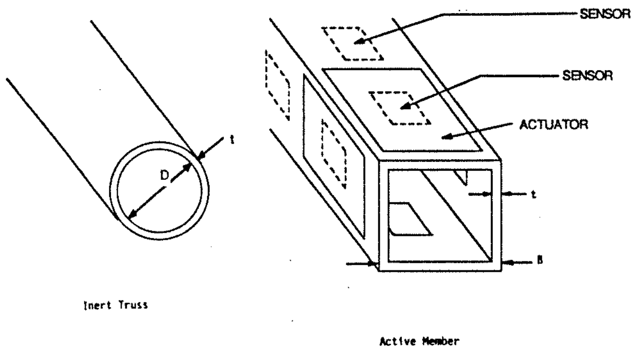

Figure 2: Inert and Active Member Design Element Schematics

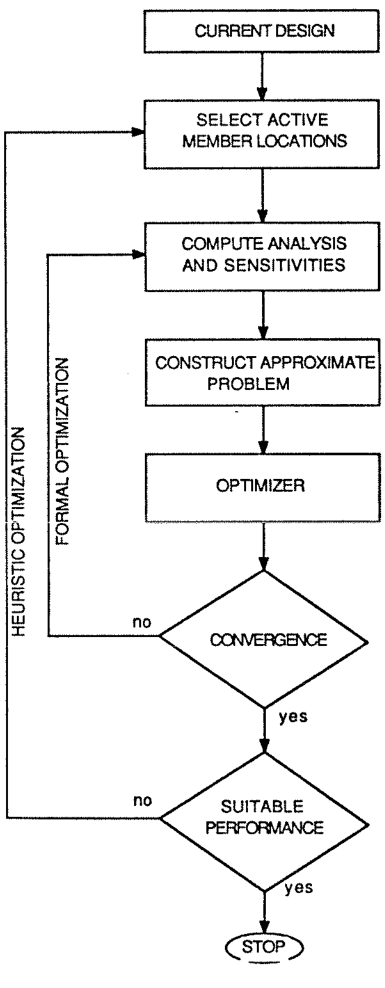

Figure 3: Optimum Design Solution Methodology

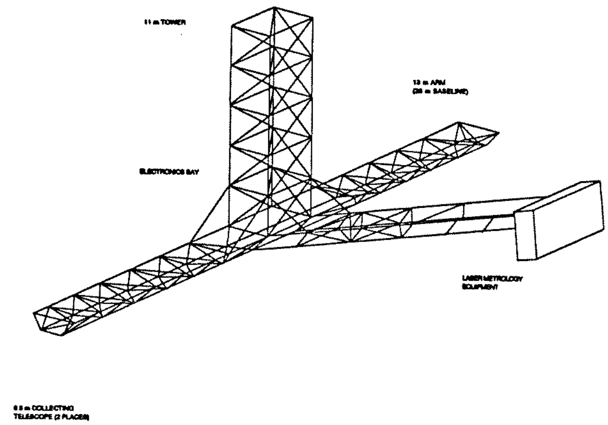

Figure 4: Space Based Interferometer

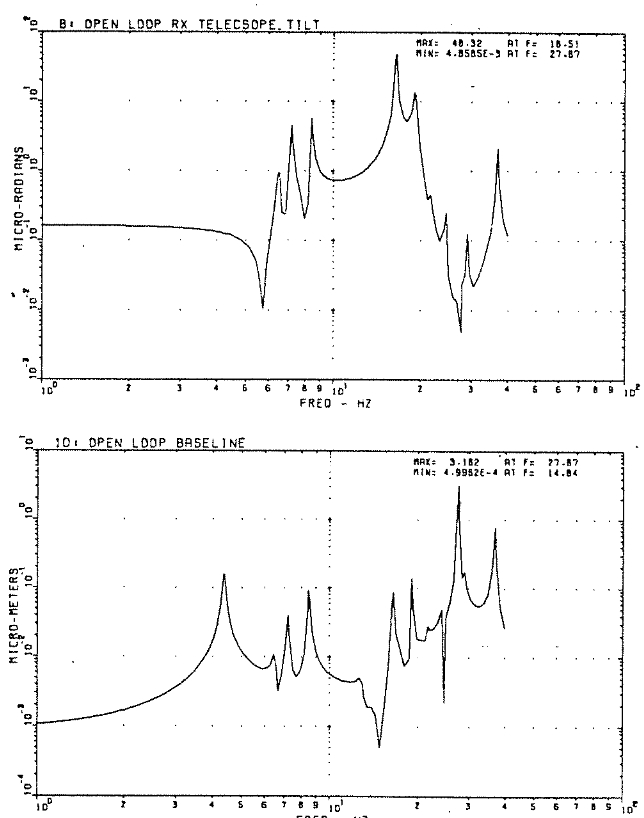

Figure 5: Inert System Preliminary Design Dynamic Response

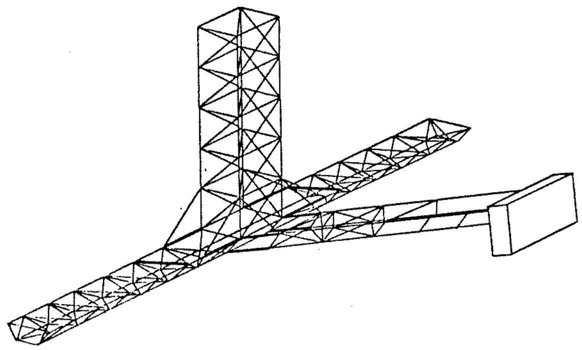

Figure 6: Locations for Active Members on the SBI

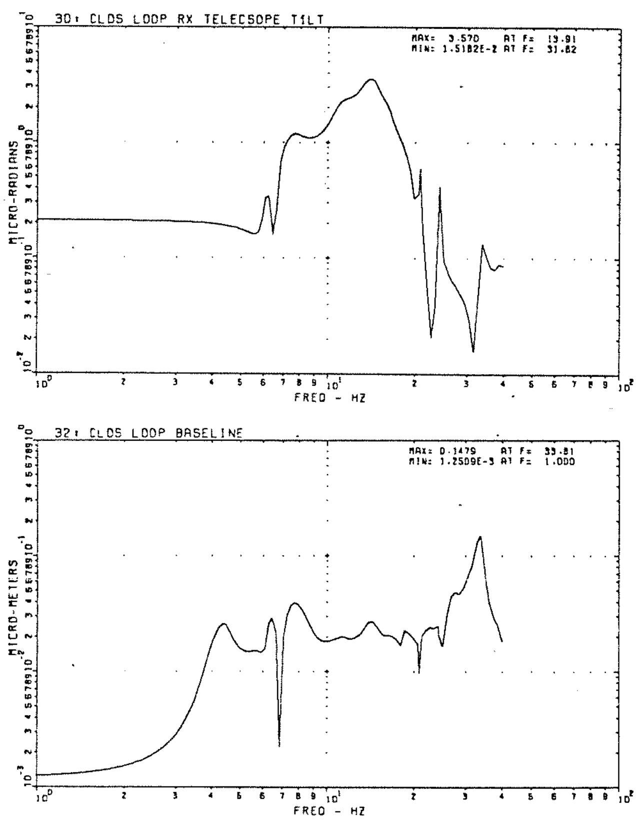

Figure 7: Optimum Design Dynamic Response