An Optimum Design Methodology for Passively Damped Truss Structures

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ABSTRACT

Many of the complex space structures proposed for future space missions will utilize enhanced damping to meet stringent performance requirements. The enhanced damping is necessary to prevent excessive slew/settle times, unacceptable jitter levels, and harmful controls/structures interactions. There are currently no documented integrated design methodologies for designing damping into complex structures early in the design process.

In this paper, an optimum design methodology is presented for truss structures augmented with constrained layer viscoelastically damped members. The methodology is presented as a two stage procedure. In the first stage, efficient locations for the passive members are found heuristically, thus avoiding a computationally burdensome combinatoric optimization problem. In the second stage, a formal optimization procedure is used to simultaneously size both the truss members and the passive members. Values for the design variables at the optimum design are found by solving a sequence of approximate problems. Each approximate problem is constructed using design sensitivity information in conjunction with first order Taylor series expansions. The sizing-type design variables treated in the optimum design procedure are inert structural member cross sectional dimensions, passive member cross sectional dimensions, passive member viscoelastic layer and constraining layer thicknesses.

The complex space structure design problem is posed as a nonlinear mathematical programming problem in which an objective function critical to adequate mission performance (e.g., line-of-sight errors or settling time following slew) is to be minimized. Limitations considered during the design procedure include an upper bound weight cap, dynamic response constraints (which represent additional mission requirements), and side constraints on the design variables.

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INTRODUCTION

Stringent performance goals for future space missions will require minimum levels of "designed-in" damping. The necessary levels of damping can be added through either active or passive means. Active damping requires sensors and actuators, a source of power, and a compensator (control law) which gives good performance and remains stable in the wake of structural parameter uncertainty and change. Passive damping requires high loss viscoelastic or fluid materials and thermal control. For some space systems, the lack of adequate power margins and the potential for gross structural parameter perturbations suggest that passive damping methods are the method of choice.

Recent developments in analysis and fabrication techniques have led to the consideration of constrained layer viscoelastically damped members for vibration suppression. Bronowicki et al. [1] derived a special purpose finite element for use in analyzing such members. In addition, Reference 1 is notable for the fabrication and hardware verification of the passive members. Hedgepeth [2] derived simplified design equations for use with segmented constraining layer VEM damped members. His results yielded expressions for the real and complex stiffness of these members when loaded axially (i.e., when used as truss members). In order to utilize passive members on complex space structures, automated design procedures are needed which employ these analysis methods.

The approach used in the current work was to start at the element level and develop a design-oriented procedure for passively damped structures. Other approaches, Gibson and Johnson [3], for example, have developed system level optimization capability utilizing a prepackaged finite element code such as NASTRAN in conjunction with the ADS [4] optimizer. Because a prepackaged finite element code was used, the viscoelastic damping treatment had to be modeled using standard elements, such as the QUAD4, HEXA, and/or PENTA elements, and sensitivities had to be computed numerically. Starting at the element level allows the calculation of element design sensitivities in closed form for use with gradient-based optimization packages. The closed form element level sensitivities avoids the computational intensity of finite difference-based sensitivity information. Furthermore, the availability of inexpensive and accurate gradients gives credence to the construction of high quality approximations for use during the optimization procedure. These high quality approximations, in conjunction with a suitable nonlinear mathematical programming procedure, allows many optimum design problems to be solved in relatively few complete dynamic analyses.

In the current study, the design problem is posed as a combinatoric optimization problem in which passive member placement, inert member cross sectional dimensions, and passive member cross sectional dimensions are treated simultaneously as design variables. By designing the inert and passive members simultaneously, strain energy can be funneled into the passive members, thus yielding suitable levels of damping. The design optimization procedure is applied to a problem where purely mass and stiffness redistribution has little chance for success due to the broadband nature of the disturbance.

OPTIMUM DESIGN PROBLEM STATEMENT

The optimum design problem used for this work is

$$\min \ \mathrm{LOS}(\mathrm{d}, \mathrm{t}) \tag{1}$$

subject to

$$g(d, t) \leq 0 \tag{2}$$

along with the side constraints

$$d^l \leq d \leq d^u \tag{3}$$

where it is understood that d is the vector of design variables for the inert truss members and the passive members.

The design problem stated in equations (1) through (3) corresponds to a spacecraft design problem where maximum performance is obtained by minimizing a single specified performance index, such as a line-of-sight (LOS) pointing error. Other restrictions on the performance of the spacecraft, such as 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 for controlled structures, are specified as additional constraints, g.

Figure 1 contains schematics of the inert truss design elements and the passive member 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 passive members, the design variables are the inside diameter of the base tube and it's wall thickness, the thickness of the viscoelastic material, and the thickness of the constraining layer. Optimization variables for the passive members are the reciprocal of the area of the tube, the viscoelastic material, and the constraining layer. A 100% mass penalty was applied to each passive member to account for thermal control hardware.

The system optimization problem posed in equations (1) through (3) is an implicit combinatoric optimization problem. The task of placing the passive members on the structure for maximum effectiveness gives rise to the combinatoric nature of the problem. Furthermore, both the objective function and the constraints are complicated implicit functions of the design variables. A limited number of solution methods exist for this class of problems, all of which are computationally burdensome.

SOLUTION METHODOLOGY

An alternative solution methodology is to separate the combinatoric and implicit aspects of the problem and attack each subproblem individually. A flow diagram for such a procedure is shown in Figure 2. Placing the passive members at efficient locations on the structure involves solving a heuristic subproblem. One solution to the heuristic subproblem is to place the passive members in regions of high strain energy for the modes that are to be damped. Optimum values for the design variables are then found using a formal optimization procedure with the locations of the passive members fixed. The formal subproblem replaces the implicit problem posed in equations (1) through (3) with the explicit approximate problem [5]

$$\min\ \tilde{\mathrm{LOS}}(\mathrm{d},\mathrm{t}) \tag{4}$$

subject to

$$\tilde{g}(d,t) \leq 0 \tag{5}$$

along with the side constraints

$$d^l \leq d \leq d^u \tag{6}$$

where both the objective function and the constraints have been replaced by the explicit hybrid [6] first order Taylor series, $\tilde{LOS}$ and $\tilde{g}$, respectively.

Solution of the implicit optimum design problem posed in equations (1) through (3) proceeds by solving a sequence of heuristic and formal subproblems. Each formal subproblem involves solving a sequence of approximate problems (stated in equations (4) through (6)). A pictorial description of the complete solution sequence to the original optimum design problem is shown in Figure 2.

SYSTEM DESCRIPTION

The structural dynamic equations of motion for the class of problems dealt with here, namely truss structures augmented with passive members, can be written as

$$M\ddot{Z} + (K_s + K_p)Z = R \tag{7}$$

where R is the vector of externally applied loads, M is the mass matrix, K_s is the real portion of the structural stiffness matrix, and K_p is the complex portion of the stiffness matrix. The complex portion of the stiffness matrix arises due to the complex material properties of the viscoelastic material. Using the undamped normal modes of the structure, namely,

$$Z = \phi q \tag{8}$$

equation (7) can be cast in reduced size first order form as

$$\dot{X} = AX + BR \tag{9}$$

where the system plant matrix is given by

$$A = \begin{bmatrix} 0 & I \\ -\omega^2 & -\phi^T K_p \phi \end{bmatrix} \tag{10}$$

the state X is the vector of stacked modal displacements and velocities

$$X = \begin{Bmatrix} q \\ \dot{q} \end{Bmatrix} \tag{11}$$

and the input matrix is

$$B = \begin{bmatrix} 0 \\ \phi^T R \end{bmatrix} \tag{12}$$

The M and K_s matrices are computed for the truss elements in the usual finite element manner. The K_s and K_p matrices are computed for the segmented constrained layer passive members using the analysis methodology presented in Reference 2. The effective stiffness of the passive member can be written in terms of the stiffness of the tube wall, k_w, and the stiffness of the constraining layer, k_c, as

$$k_{eff} = \frac{k_w + k_c}{1 + \frac{k_c}{k_w} \frac{\tanh(Dl)}{D}} \tag{13}$$

The D parameter is related to the shear lag length τ by

$$D = \frac{l}{2\tau} \tag{14}$$

The shear lag length, which is used for determining the lengths of the segments of the constraining layer, is given by

$$\tau = \sqrt{\frac{E_c t_c t_{vem}}{G_{vem}} \frac{1}{1 + \frac{E_c t_c}{E_w t_w}}} \tag{15}$$

where G_{vem} is the complex shear stiffness of the VEM. Sensitivity information at the element level is found by taking the derivative of the effective stiffness of the passive member with respect to the design variables.

Solution of equation (9) for the system response due to external loads is accomplished by computing the complex modes of the system plant A and solving the resulting uncoupled equations in the frequency domain.

EXAMPLE PROBLEM

The structure shown in Figure 3 will be used to demonstrate the benefits of the previously-described optimization procedure. The structure is a scaled version of a proposed Space Based Interferometer [7]. Two 13 meter arms run out from the sides of the interferometer and hold light-collecting telescopes at the tips. The 11 meter tower contains a telescope running down its center while laser metrology equipment is mounted at the end of an additional 11 meter truss. In an undeformed, perfectly-aligned state, the two 13 meter arms give an optical path length (baseline) of 26 meters.

Dynamic distrubances from the attitude control system reaction wheels are fed into the structure at the central bay. The interferometer can acquire data when the relative alignment (tip and tilt) of the collecting telescopes is less than 8μrad and the optical path length does not substantially deviate from 26 meters. Therefore the design optimization problem is to minimize path length deviations from 26 meters while maintaining relative tip and tilt of the collecting telescopes within 8μrad. An upper bound mass cap of 252 kg is also imposed on the system. This cap corresponds to the preliminary design mass of the completely inert system (without passive member augmentation).

The purely inert preliminary design of the SBI was used as the point of departure for the optimum design procedure. The performance of the interferometer at the preliminary design is shown in Figure 4. Unacceptable optical lengths and relative tip and tilt motion of the collecting telescopes exceeding 8μrad were obtained. The modes at 4.4, 16.4, 19.0, 27.7, and 36.9 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 passive 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. A total of 56 passive members were added to the system.

The performance of the interferometer following optimization is shown in Figure 4. Optical length deviations have been reduced from 3.16 μm to 0.11 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 7.5 μrad and 7.8 μrad, respectively, having been reduced from 27.7 μrad and 48.3 μrad at the initial design. A comparison of damping levels at the intial design and the optimum design for each of the modes below 40 Hz are shown in Table 1. Though a large number of passive members were added, the design optimization procedure managed to meet the mass cap of 252 kgs and reduce the interferometer baseline by a factor of 28.7.

Table 1: Initial and Optimum Frequencies and Damping Ratios

	Initial Design		Optimum Design	
Mode Number	Frequency (Hz)	$\zeta(\%)$	Frequency (Hz)	$\zeta(\%)$
1-6	0.0	0.0	0.0	0.0
7	4.4	0.2	4.1	4.7
8	6.5	0.2	6.1	3.9
9	7.2	0.2	6.8	2.0
10	8.4	0.2	7.9	4.5
11	8.5	0.2	7.9	3.4
12	12.9	0.2	12.0	3.7
13	16.4	0.2	14.8	4.1
14	19.0	0.2	17.3	2.9
15	19.2	0.2	17.8	3.2
16	21.7	0.2	20.6	0.6
17	24.5	0.2	22.0	3.9
18	27.7	0.2	24.6	5.3
19	29.1	0.2	26.9	3.1
20	36.9	0.2	33.6	4.6

CONCLUDING REMARKS

An integrated inert truss/passive truss member design optimization methodology has been developed. The methodology treats both structural design variables and passive member design variables simultaneously in the optimization procedure. By employing a two stage heuristic/formal subproblem solution procedure, the computational burden associated with placing the passive members on the structure is avoided. A solution for the implicit formal subproblem is found in relatively few complete dynamic analyses by solving an explicit approximate problem. Design sensitivity information was efficiently computed by differentiating a closed form expression for the complex stiffness of the passive members. The design optimization procedure is a mission-enabling technology for future space missions with extremely stringent dynamic performance requirements where purely structural solutions fail.

REFERENCES

[1] Bronowicki, A.J. and Diaz, H.P., "Analysis, Optimization, Fabrication and Test of Composite Shells with Embedded Viscoelastic Layers", *Proceedings of Damping '89*, West Palm Beach, Florida, February 8-10, 1989, pp. GCA-1-GCA-21.

[2] Hedgepeth, J.M. and Mobren, M., "Investigation of Passive Damping of Large Space Truss Structures", *Proceedings of Damping '86*.

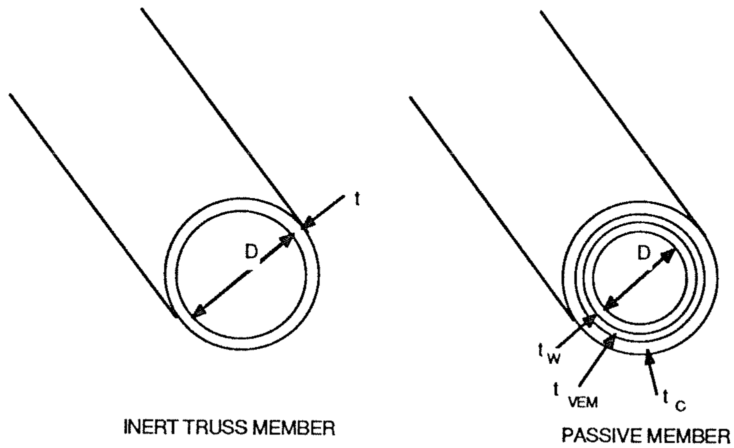

Figure 1: Inert Truss and Passive Member Design Elements

[3] Gibson, W.C. and Johnson, C.D., "Optimized Designs of Viscoelastic Damping Treatment" *Proceedings of Damping '89*, West Palm Beach, Florida, February 8-10, 1989, pp. DBD-1-DBD-23.

[4] Vanderplaats, G.N., "ADS - A Fortran Program for Automated Design Synthesis", Version 1.10, May 1985. Available from VMA Engineering, 5960 Mandarin Avenue, Suite F, Goleta, California, 93117.

[5] Schmit, L.A. and Miura, H., "Approximation Concepts for Efficient Structural Synthesis", NASA CR 2552, March 1976.

[6] Starnes, J.R. and Haftka, R.T., "Preliminary Design of Composite Wings for Buckling, Stress, and Displacement Constraints", *Journal of Aircraft*, Vol. 16, Aug. 1979, pp. 564-570.

[7] Laskin, R.A., "A Spaceborne Optical Interferometer: The JPL CSI Mission Focus", *Proceedings of the NASA/DoD Controls-Structures Interaction Technology Conference*, NASA CP 3041, San Diego, California, January 29-February 2, 1989, PP. 1-16.

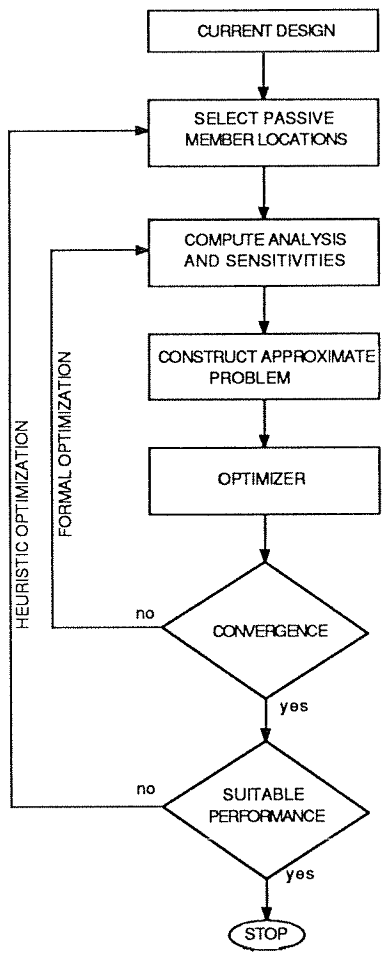

Figure 2: Optimum Design Solution Procedure

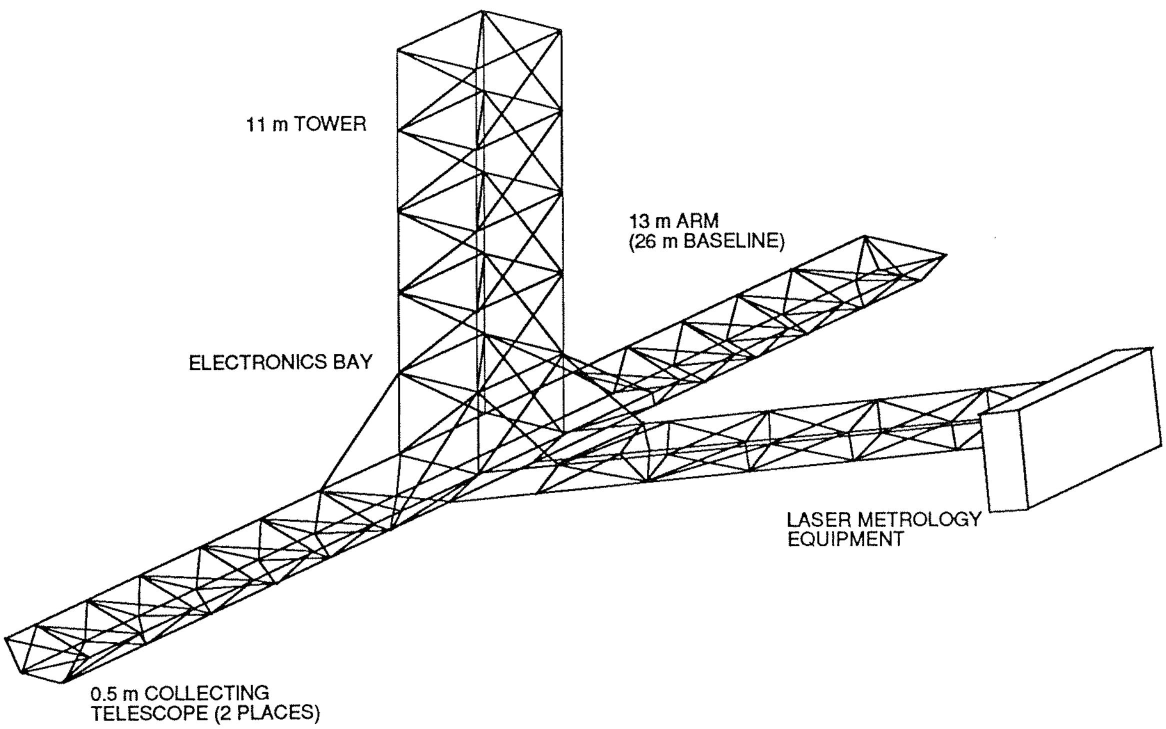

Figure 3: Space Based Interferometer

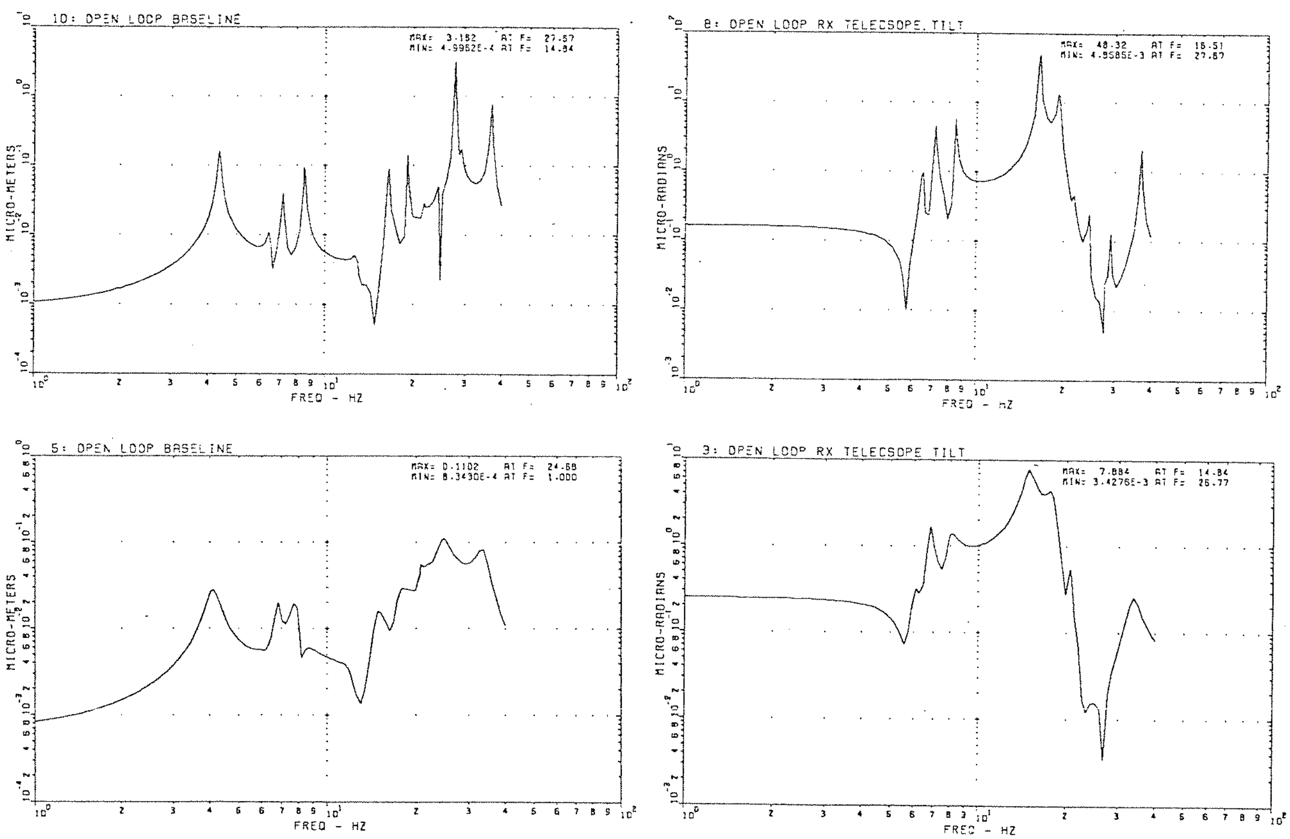

Figure 4: Initial and Optimum Design Dynamic Responses