DAMPING TREATMENT FOR JITTER REDUCTION ON A HIGH POWER OPTICAL BENCH

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ABSTRACT

As part of a High Energy Laser program, a large optical laser system is required to meet a stringent RMS specification for residual jitter. Using MSC/NASTRAN, the optical jitter due to ground and coolant-flow excitations was predicted as a combination of the dynamic motions of several optics. The modal strain energy method was used both in identifying the best candidate locations for damping treatments as well as predicting damping levels. The final solution incorporated constrained layer damping treatments on an interface component between the mirrors and their mounts and link dampers between selected locations on the optical bench.

1. Introduction and Objectives

A proposed high power laser system modification requires an optical bench and associated optics and their mounts. Some of these optics require coolant flows to maintain proper mirror figure. The coolant flowing through the high power mirrors generates substantial optical jitter. This jitter degrades the quality of the propagated laser beam. One of the primary priorities of the optical bench design was to minimize optical jitter.

Jitter reduction techniques applied to this high power optical bench (HPOB) can be summarized in three categories: 1) reduce the disturbance energy input from the coolant flow and the surrounding excitation environment, 2) improve the structural design to enhance its rigidity, and 3) provide a good passive damping treatment design to minimize mirror vibration response. This paper presents the technique, approach, and results of the passive damping treatment on the HPOB.

Six optics are in the primary beam path of the HPOB. Three of these are cooled mirrors. All mirrors are kinematically mounted on three-tab tangent flanges. The tangent flange, in turn, is mounted on a relatively rigid and heavy ball-mount. All mounting connections are jointed by spherical washers and bolts. The ball-mounts are bolted on their respective supporting plates, which are 3/4-inch-thick steel plates, welded to the bench members. The HPOB is designed as a three-dimensional space frame structure. Its overall dimensions are 44 inches wide, 180 inches long, and 81 inches high. The main frame members are 6x6x1/2 inch rectangular steel tubes. The bench's diagonal bracings are W6x25 steel I-beams.

2. Damping Design Analysis

This project was split into several phases of work: Phase I was a study of the feasibility of reducing residual beam jitter by adding passive damping to the HPOB, and Phases II and III were concerned with the design of the passive damping treatments. The residual jitter is calculated as a function of the angular displacements (rotations) of the mirrors on the bench. NASTRAN was used to predict these rotations and evaluate the optical (ray-tracing) equations under random excitations applied at both the base of the bench and at the cooled mirrors. The residual jitter is given as a displacement power spectral density function (PSD). The overall goal of the program was to reduce the residual jitter to a normalized RMS jitter of 1.0 unit. The sources of disturbances for the optical bench were excitations from equipment and seismic effects and the coolant flowing through the cooled mirrors.

2.1 Phase I Analysis

The Phase I analysis was performed using a crude finite element model. The optical bench is modeled with BAR elements, typically one element per span of the structure. The model is crude because the optics are represented only by lumped masses and stiff bars. There are six optical components represented in the model. Figure 1 shows the Phase I finite element model and the locations of these optical components.

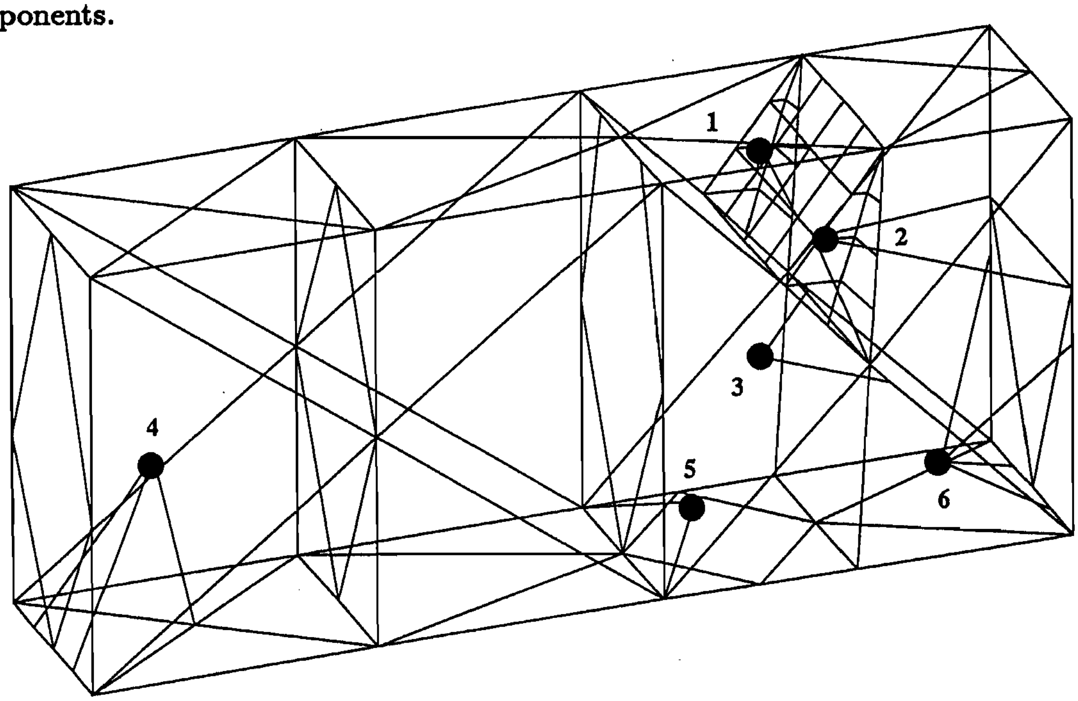

Figure 1. Baseline Phase I finite element model

A random response analysis was performed using the Phase I finite element model with the given excitations and the residual jitter predicted. Approximately 91% of the total residual jitter was due to only four modes between 87 and 245 Hz. The suppression of these modes was the criteria for the effectiveness of the Phase I damping study.

Three different approaches to damping were considered: constrained layer damping, damped links, and tuned-mass dampers. All three have certain types of situations in which they work best.

Constrained layer treatments work by placing a viscoelastic material (VEM) layer between the structure and a constraining layer. As the structure is deformed, the constraining layer opposes the motion and causes shear in the VEM. Strain in the VEM is the mechanism for energy dissipation. The treatments are mode shape dependent and work best for frequencies that were targeted by the design, but their effectiveness may spill over to all modes in which the particular member participates. Several diagonal I-beams were chosen to receive a constrained layer treatment. These I-beams were modeled in detail in order to predict the strain energy in the viscoelastic material accurately. A 0.050-inch-thick layer of Soundcoat's DYAD 606 was chosen as the VEM, with a 0.50-inch-thick steel constraining layer. The predicted RMS of the residual jitter was reduced by 56% using this treatment.

Damped links dissipate energy by connecting pairs of points on the structure that have high relative displacements with a viscoelastic spring. These dampers, like constrained layer treatments, are not explicitly frequency dependent. They will work to some degree for any mode that has relative displacements between the endpoints. Four damped links were incorporated into the Phase I model and shown to be effective in reducing the jitter.

Tuned-mass dampers (TMD's) are a way of damping a single mode only. They work by attaching a damped spring-mass device to the structure at a location of high displacement. TMD's are inherently frequency dependent. They need to be tuned, usually by varying the mass, to a specific frequency just below the target frequency. The potential for damping is very high, but the tuning must be precise. By combining damping links and TMD's, a 64% reduction of residual jitter was predicted.

It was shown during the Phase I analysis that, using either the constrained layer treatments or a combination of link dampers and TMD's, the predicted RMS residual jitter could be reduced by over 50%. The Phase I analysis showed that by successfully identifying the modes causing jitter, passive damping treatments on a relatively small portion of the structure could be used to reduce the residual jitter on a relatively heavy and stiff steel bench.

The Phase I model was used to ascertain if passive damping was a viable method of reducing the jitter. However, the detail of this model was insufficient to actually design the passive damping treatments. Also, the relatively flexible optical components were not modeled. With the incorporation of these optical components, it was known that the problem modes could be altered and the overall jitter could be expected to increase substantially.

2.2 Phase II Analysis

The finite element model used for the Phase II analysis (see Figure 2) contained more detailed models of some of the optical components and their support structures, but was otherwise similar in resolution to the Phase I model. The actual mirrors were still modeled as concentrated masses attached to the outer housing through a tangent flange. The finite element model of the Phase II mirror tangent flange is shown in Figure 3.

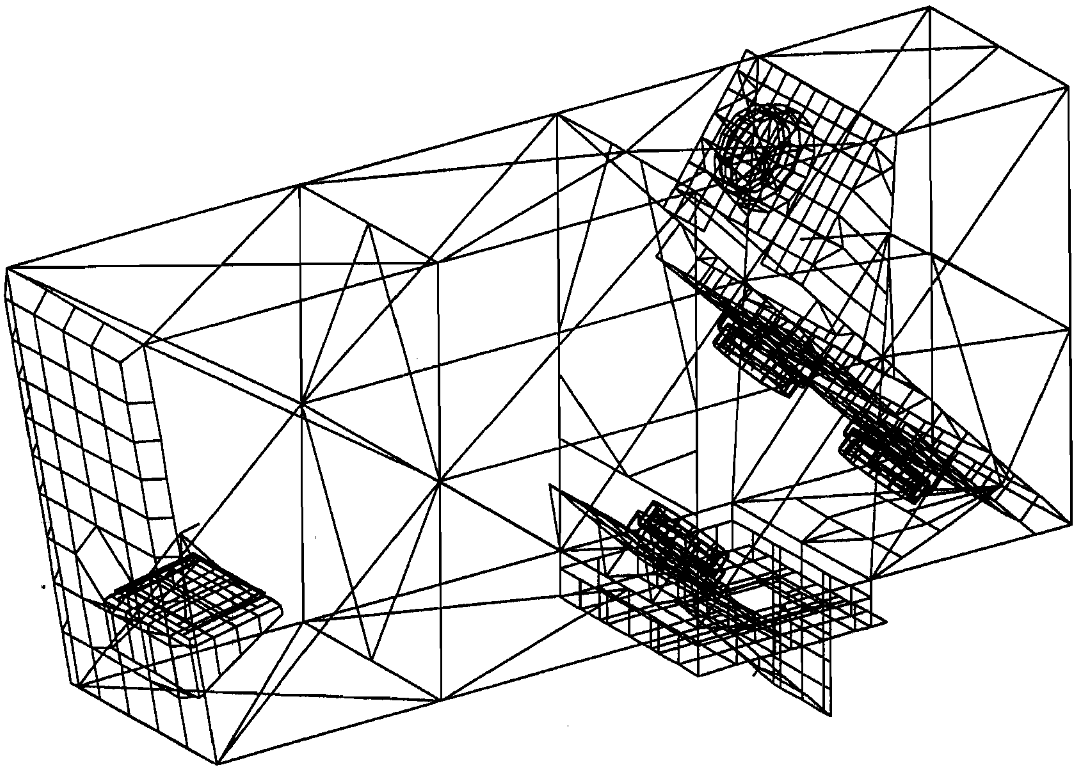

Figure 2. Baseline Phase II finite element model

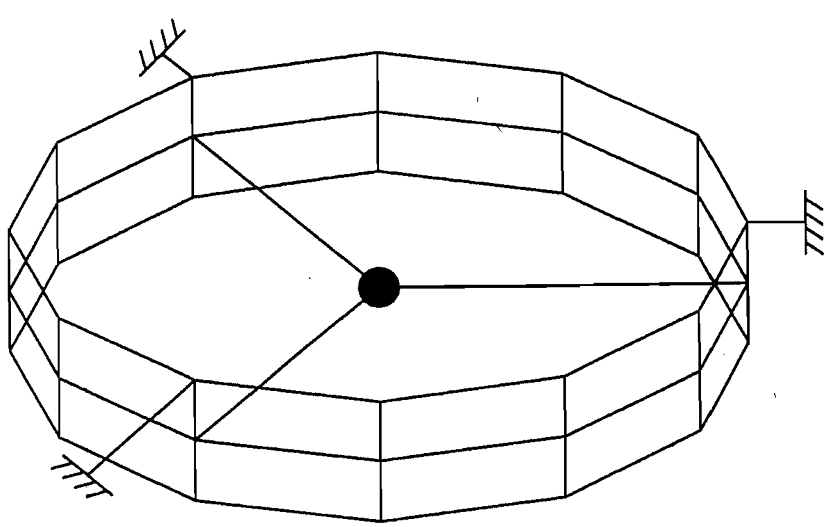

Figure 3. Phase II finite element model of mirror tangent flange

The Phase II baseline analysis showed that the highest jitter-contributing modes were now in the optical components rather than the bench. Based on the modal strain energy (MSE) distribution shown in Table 1, the best areas for damping treatments are, in order, the tangent flanges, the mirror support structures, and the frame elements. Damping on the tangent flanges was judged to be the most effective.

	% of Total Jitter from this Mode	Percent of modal strain energy		
		Tangent Flanges	Mirror Support	Frame Members
Mode 11	59%	74%	17%	4%
Mode 13	7%	89%	5%	1.6%
Mode 22	15%	8%	59%	24%
Mode 33	7%	6%	72%	13%

Table 1. Critical modes predicted by the Phase II model with their contributions to the total residual jitter

The frame members themselves do not contribute much of the MSE to any of the troublesome jitter modes. However, the motion of the frame cannot be neglected if the final jitter goal is to be met. The Phase I analysis produced two possible approaches to damp frame modes: constrained layer damping and link dampers. Considering all factors, the link dampers were selected for the frame damping treatment.

The modal strain energy distribution in the modes of interest showed strain energies in many of the bench members. From a large number of candidate pairs of end points, eight locations were chosen. The endpoints were chosen based on the highest relative displacements along the lines between them.

The link dampers were designed so that they could be fabricated from commercially available materials. The damped link is essentially a pipe that spans between two points on the structure and contains a viscoelastic joint inserted along its length. Figure 4 shows a schematic drawing of the link along with the end fittings.

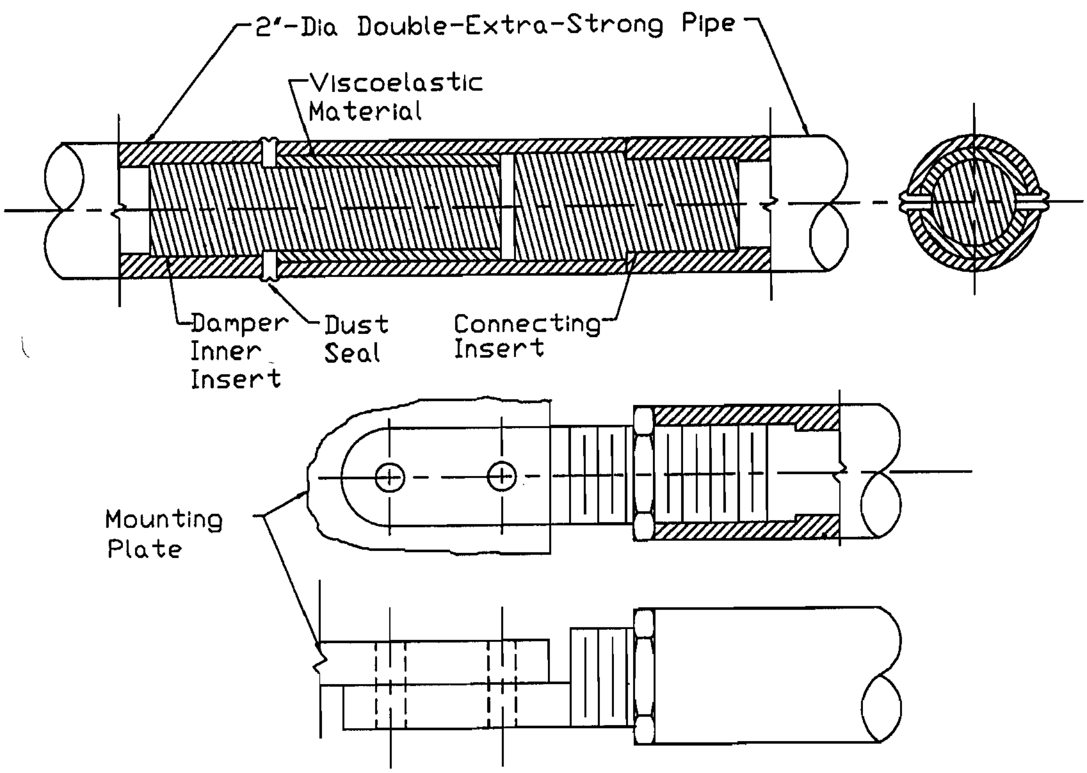

Figure 4. Schematic drawing of the damped link and its end fittings

2.3 Phase III Analysis

The finite element model of the tangent flange used in Phases I and II was coarse and neglected some structural details that turned out to be important, most notably the rim used for attachment to the ball-mount and the three "tabs" used to attach the mirror to the tangent flange. The goal of Phase III was to verify the damping design and analysis of this most critical jitter component. A detailed finite element model of the mirror and tangent flange was created and the frequencies and mode shapes were verified using results from a modal test. The model was then used in designing an optimal damping treatment under the known restrictions. Figure 5 depicts the updated tangent flange finite element model.

The verified and tuned finite element models of the mirror assemblies were then integrated into the Phase III system model together with several other structural updates, such as increasing the thickness of the ball-mount supporting plates and adjusting the supporting brackets. Figure 6 presents the Phase III system finite element model of the High Power Optical Bench.

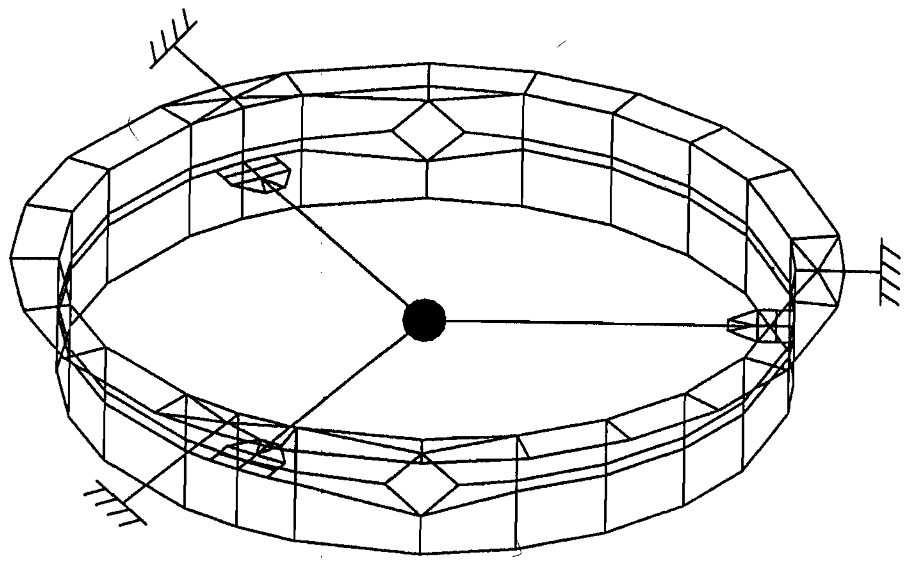

Figure 5. Phase III finite element model of mirror tangent flange

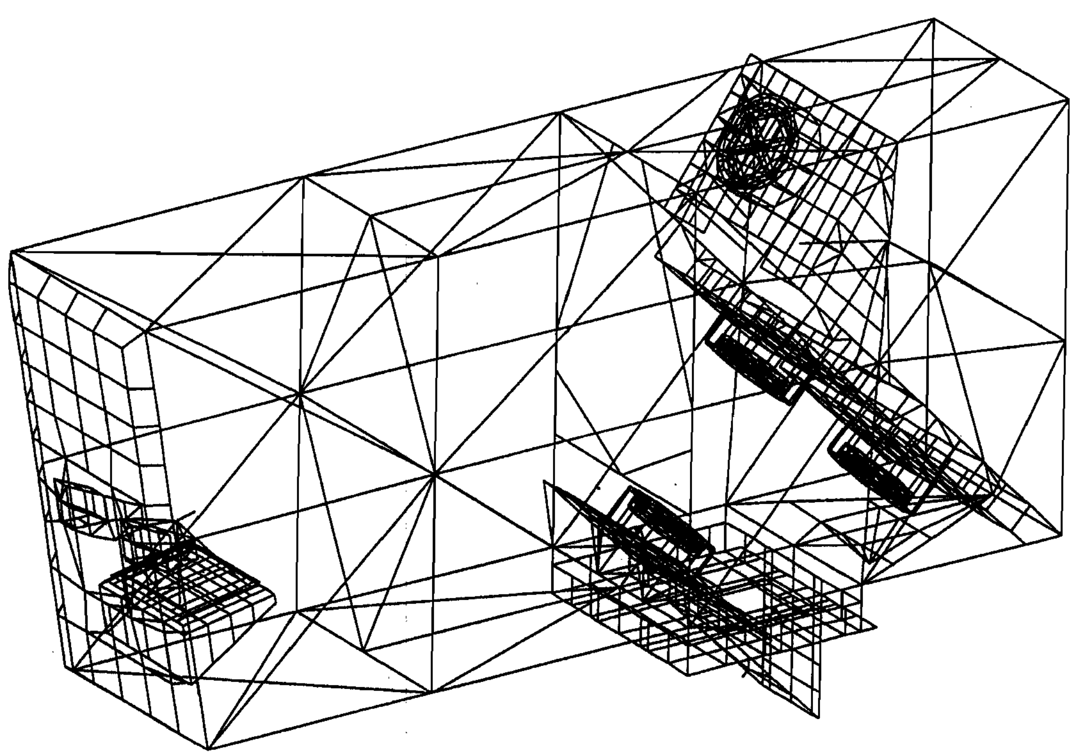

Figure 6. Baseline Phase III finite element model

2.3.1 Residual Jitter of the Baseline System

Dynamic analysis of the complete Phase III model was executed, the system modal strain energy distributions were recalculated, and residual jitter for the undamped baseline structure was determined. An inherent damping level of 0.4% structural (Q=250) was assumed for the "undamped" analysis and was also added to the predicted damping for the damped analysis. Table 2 gives the approximate percentage contributions of the major jitter modes. Additionally, the percentage of the modal strain energy for each mode is given for the tangent flanges as a group, the support plates as a group, and the space frame. The last row of the table gives a weighted average of the contributions of the three groups. This average is the sum of the percentage of the MSE for each group multiplied by the percentage RMS contributions for each mode. It is only a rough indicator of the relative contribution of each group to the overall residual jitter.

This table shows that four modes contribute over seventy percent of the RMS jitter. The tangent flange components are still the top area requiring vibration suppression. The supporting structures rank second, and the space frame contributes less than 20 % to the RMS jitter.

Modes 16, 17, and 19 contribute over sixty percent of the total RMS jitter. These fall in the frequency range of the primary modes of the tangent flanges. However, in contrast to the Phase II analyses, only between one-half and two-thirds of the modal strain energy of these modes is attributable to the tangent flanges: the rest is divided between the support plates and the frame elements. The conclusion from these results is that the tangent flanges as a group still contribute more to the residual jitter than any other areas of the structure, but not by as much as previously predicted. This does not eliminate the need to damp the tangent flanges, but it does de-emphasize it slightly. It is likely that any additional significant increases in damping will have to come from damping treatments for the mirror support structures and the space frame.

The support plates contribute the next largest amount to the residual jitter. The percentages listed in the Table give the total modal strain energy in all of the parts of the support plates, i.e., base plate, grout plate, grout, stiffeners, etc.

The modal strain energy in the frame is the sum of the main frame members. It gives a rough idea of the potential for damping through link dampers and constrained layer treatments on frame members. The latter concept was investigated during Phase I, but found to be too inefficient to justify the cost in design and application.

	% of total jitter from this Mode	Percent of modal strain energy		
		Tangent Flanges	Mirror Supports	Frame Members
Mode 16 134 Hz	47.4%	42.1%	27.6%	19.5%
Mode 17 137 Hz	4.3%	36.6%	7.3%	40.9%
Mode 19 142 Hz	10.5%	49.6%	16.3%	16.8%
Mode 22 148 Hz	2.5%	43.3%	7.9%	39.3%
Mode 36 199 Hz	5.1%	25.7%	43.9%	16.7%
Mode 39 224 Hz	7.6%	23.3%	58.7%	9.7 %
Mode 47 280 Hz	3.0%	35.5%	30.8%	22.3 %
Weighted Contribution		33.5%	26.8%	17.2%

Table 2. Major modes for residual jitter in the undamped Phase III baseline model along with their contribution and composition

2.4 Residual Jitter of the Damped System

During Phase II, link dampers were found to be an effective way of introducing damping into frame-dominated modes. As a result of damping design analysis performed during Phase III, three additional links were proposed for the frame. The locations of the damped links are shown in Figure 7.

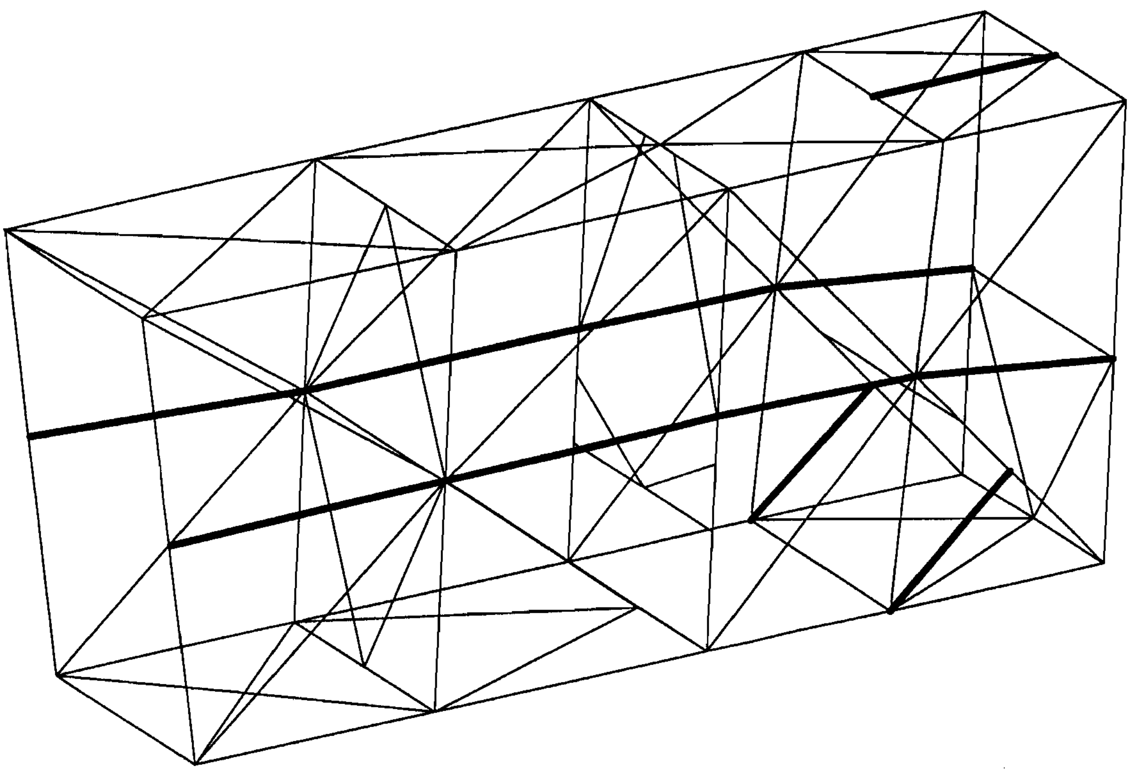

Figure 7. Proposed locations of link dampers for the HPOB

Due to design constraints, the Phase II damping concept for the tangent flanges was determined to be the best type of treatment. The optimal treatment uses a constraining layer separated into two pieces. The treatment consists of a two-piece, 40-mil-thick stainless steel constraining layer with 5 mils of ISD 110 VEM.

Before the residual jitter of the damped system was calculated, the stiffness due to the link and tangent flange damping treatments was added to the model. The models of the tangent flanges were tuned so that their frequencies matched closely those of the damped tangent flange model. The damped links were included using ROD elements.

The damping was predicted by the modal strain energy (MSE) method using the strain energies predicted by the model of the damped system. The MSE method states that the damping is the product of the VEM's modal strain energy and loss factor. However, the sheer size of the system model and detail needed to model the VEM meant that the amount of VEM strain energy had to be inferred from the isolated detailed model of the damped tangent flange. The damped links were included in the model as rod elements whose properties give it an axial stiffness equivalent to that of the actual damping link. The modal strain energy of each group (tangent flanges and links) was multiplied by the loss factor of the VEM and again by a *participation* factor. This participation factor is an estimate of the percentage of the strain energy that the VEM would see if it were in the model. For example, the participation factor for the damped links is 0.9 since calculations show that 90% of the links' strain energy will go into the VEM. However, only about 5% of the system strain energy in the tangent flanges can be considered to be VEM strain energy.

After all of the updates to the system finite element model, a random response analysis was performed. Figure 8 shows the damped residual jitter and RMS plotted over the undamped baseline. Most of the modes have shifted upwards in frequency due to the stiffness added to the system by the damping treatments.

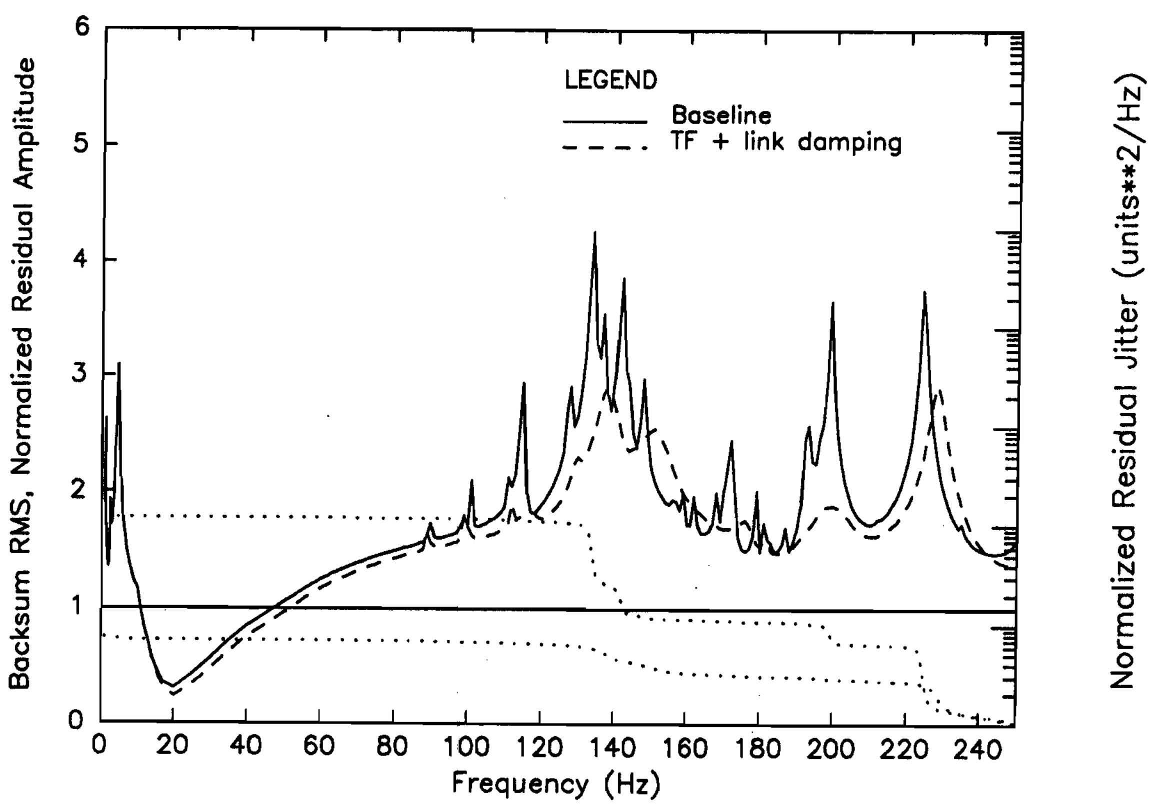

Figure 8. Residual jitter for the HPOB with link and tangent flange damping treatments

There are only three distinct jumps in the RMS curve. The modes causing these jumps and their approximate composition are listed in Table 3. The tangent flanges are still the largest contributors to the jitter, but either the frame or mirror support plates also participate strongly in each of the modes. Constraints on the tangent flange damping treatments make the prospects for greatly improved damping of the tangent flanges poor. The likely place to concentrate efforts for additional damping would be either the frame elements or the mirror support structures.

	% of total RMS from this Mode	Percent of modal strain energy		
		Tangent Flanges	Mirror Supports	Frame Members
Mode 16 138 Hz	27.5%	37.9%	27.0%	24.1%
Mode 21 151 Hz	6.1%	39.5%	8.9%	41.8%
Mode 39 228 Hz	13.2 %	24.8%	58.0%	9.2 %

Table 3. Major modes for residual jitter in the damped system along with their contribution and composition

3. Summary

The final RMS value for the residual jitter of the damped system is 0.73 units, which meets the residual jitter goal of 1.0 units. Table 4 presents in summary form the reduction of jitter predicted during each of the three Phases. The passive damping treatments on the HPOB reduced the residual jitter by 60 percent. The most effective concept for the optics' damping is a constrained layer treatment on the mirror mount tangent flange. The promising damping concept for the heavy steel optical bench is link dampers at selected bench locations.

Phase		Damping Treatment	% Jitter Reduction
I	IA	0.05" DYAD 606 VEM, 0.5" Steel Plate on 8 Diagonal Members	56
	IB	4 Link Dampers + 2 Tuned-Mass Dampers	64
II	II	5 Mils 3M ISD 110 VEM with 40-Mil Stainless Steel Plates on Tangent Flanges, 8 Link Dampers on the Bench	67
III	III	Same as Phase II, 13 Link Dampers Used	59

Table 4. Summary of residual jitter reduction