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Design, Analysis and Testing of High Frequency Passively Damped Struts

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The work presented here was performed under the SPICE Investigation of Critical Technology for the Active Control Subtask. It is a collaborative effort of a team of engineers from LMSC, Honeywell, CSA and the Phillips Lab.

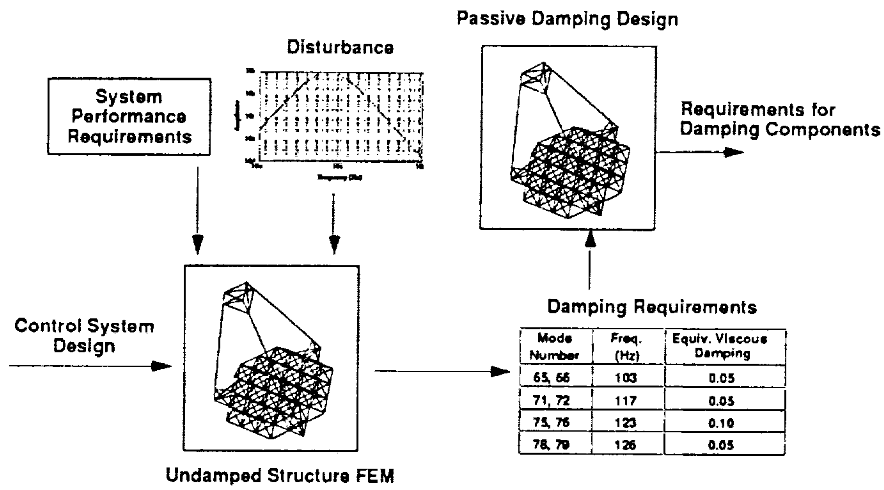
Objectives

- Develop design requirements for damped struts to stabilize control system in the high frequency cross-over and spill-over range
- Design, fabricate and test
  - viscously damped strut
  - viscoelastically damped strut
- Verify accuracy of design and analysis methodology of damped struts
- Design and build test apparatus, and develop data reduction algorithm to measure strut complex stiffness

In order to meet the stringent performance requirements of the SPICE experiment, the active control system is used to suppress the dynamic responses of the low order structural modes. However, the control system also inadvertently drives some of the higher order modes unstable in the cross-over and spill-over frequency range. Passive damping is a reliable and effective way to provide damping to stabilize the control system. It also improves the robustness of the control system. Damping is designed into the SPICE testbed as an integral part of the control-structure technology.

Precision highly damped struts operating at high frequency are essential to the success of the SPICE experiment. The performance and precision of these struts have never been demonstrated. The objectives of this subtask are to design, fabricate, and test two damped struts based on two damping mechanisms: viscous fluid and viscoelastic material. The methodologies of design and analysis will be verified scientifically to ensure future design can be readily achieved. A test apparatus was also designed and built to accurately measure the complex stiffness of these struts.

System Level Damping Design



Mode Number	Freq. (Hz)	Equiv. Viscous Damping
65, 66	103	0.05
71, 72	117	0.05
75, 76	123	0.10
78, 79	126	0.05

The preliminary control system design was based on a baseline finite element model with nominal structural damping. Equivalent viscous damping ratios for a set of high order modes were specified for a stable control system. High damping ratios, 0.05 to 0.10, are required for these target modes. It is technically challenging to design high damping in high order modes. Based on this damping schedule, a system level passive damping design was performed. As a result of this design, the requirements for passive damping components are established.

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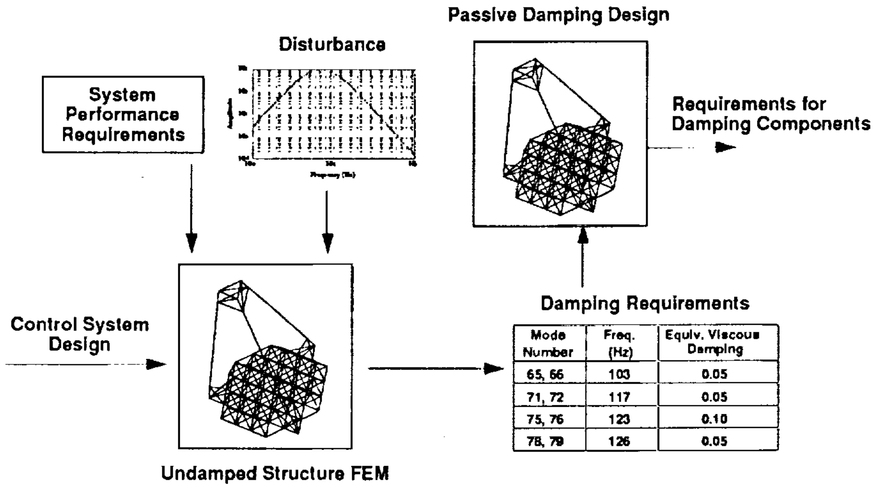

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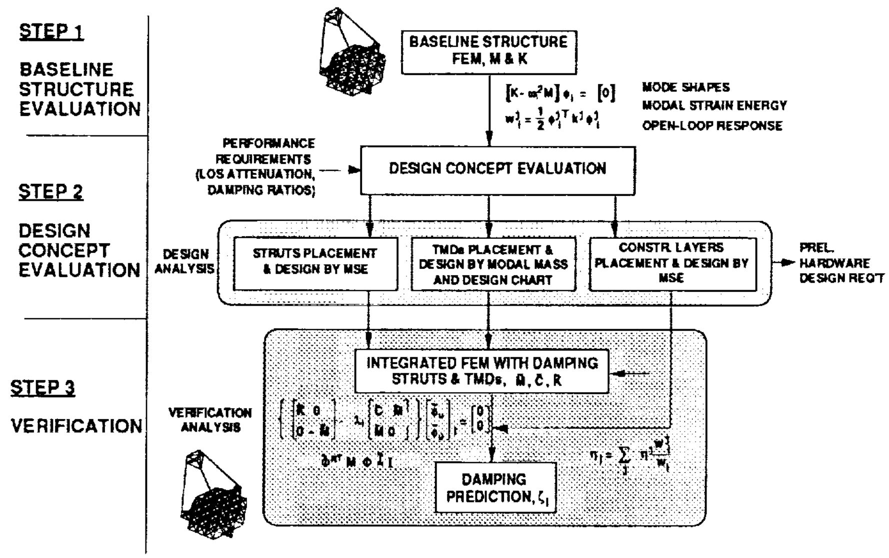
Passive Damping Design Synthesis



The passive damping design synthesis is a three-step process: baseline structure evaluation, design concept evaluation and verification analysis.

The modal characteristics of the baseline finite element model were first analyzed for each target mode: mode shape, modal strain energy distribution and open-loop response.

Three types of damping devices were considered to provide passive damping: constrained layer treatments, damped struts and tuned mass dampers. For each target mode, the applicability of these devices was studied. The device which can most effectively provide the necessary damping was selected.

The finite element model was updated to incorporate these damping devices, and a system level analysis was then performed to ensure that the integrated damping design will meet the system level requirements.

Strut Design Requirements

- SPICE experiment requires struts having
  - high damping at frequency of high order modes
  - high stiffness
  - high load capacity

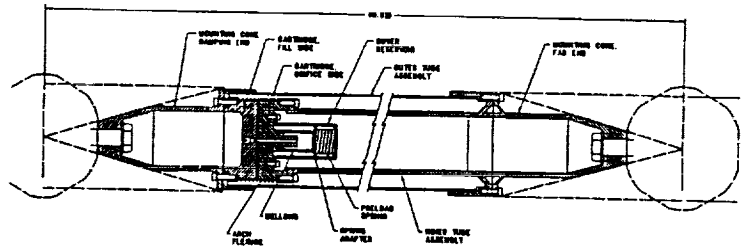
Description		Requirement
Physical Dimensions	Length	40.615" between centers of node balls
	Diameter	Not interfere with other struts
Interface	Joint	Compatible with existing node balls
Loads	Yield	± 3150 lb
	Ultimate	± 5250 lb
Stiffness	Static	$k(f=0\ \text{Hz}) \geq 80{,}000$ lb/in
	Dynamic	$k(f=100\ \text{Hz}) = 160{,}000\ (\pm 10\%)$ lb/in
Damping		loss factor ≥ 0.4, 70 Hz $\leq$ freq $\leq$ 130 Hz
Temperature	Operation	65°F $\leq T \leq$ 85°F
	Storage	20°F $\leq T \leq$ 120°F
Weight		Minimize
Materials		Space compatible
Life		10 years
Linearity		Maximize

The design requirements for the damped strut were then formulated. The damped struts will be used to replace existing struts. The damped strut must be compatible with the existing structural configuration and meet the strength requirements.

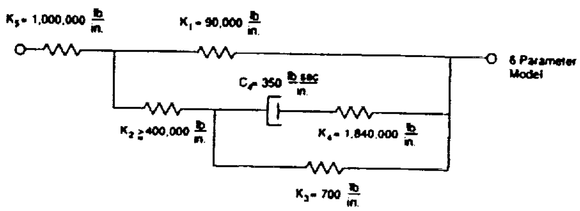
Since the control system and system level damping design is still being designed, the requirements for the damped struts were set conservatively but realistically for practically damped strut design purposes. The most important aspects of these requirements are that the required damping, frequency, stiffness and load for the damped struts are all quite high. These aspects significantly increase the challenge of the strut design.

D-strut Design

- **Damping medium - viscous fluid**



Sketch of D-strut



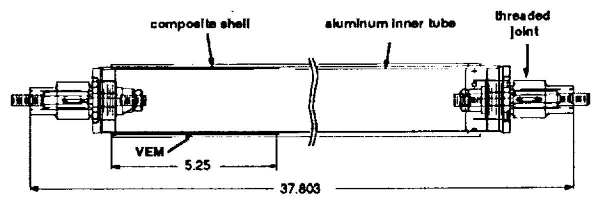
Lumped Parameter Model of D-strut

The viscous strut uses the viscous fluid flowing through an orifice as the energy dissipation mechanism. The strut comprises an outer aluminum tube and inner graphite/epoxy tube with an arched flexure/bellow assembly to contain the viscous fluid. When the strut is forced in the axial direction, the inner tube forces the fluid to flow through the orifice and dissipates mechanical energy into heat.

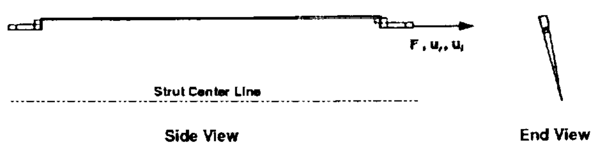
The device is modeled as a lumped parameter model with discrete springs and dashpot. The mechanical design entails the selection of proper spring and dashpot parameters to meet the strut requirements. These parameters are achieved physically by sizing of the sub-components and material selection.

V-strut Design

- **Damping medium - viscoelastic material (VEM)**



Sketch of V-strut



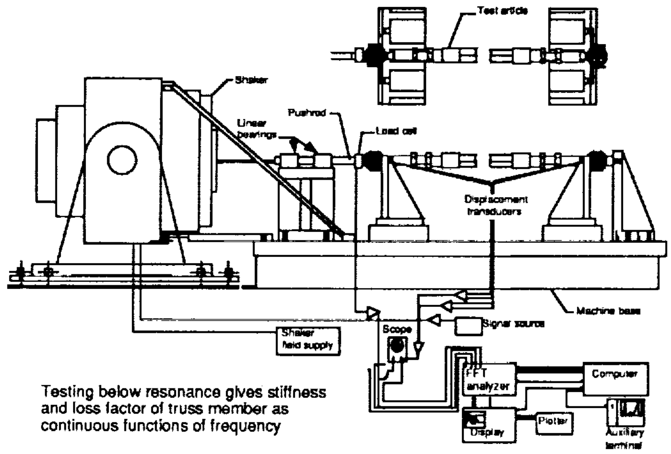
Axisymmetric Finite Element Model of V-strut

The viscoelastic strut uses the hysteretic behavior of the viscoelastic material as the energy dissipation mechanism. The strut comprises an inner aluminum tube and outer graphite/epoxy tube with viscoelastic material bonded in between. When the strut is forced in the axial direction, the viscoelastic material is subject to shear stress and dissipates mechanical energy into heat.

The device is modeled as an axisymmetric finite element model using plate and solid elements. A direct frequency response technique is used to compute the complex stiffness of the strut at selected frequency points. The mechanical design entails proper material selection and sizing of sub-components to ensure performance requirements are met.

Direct Complex Stiffness Test

- **Low frequency test (1-55 Hz)**
- **Apparatus avoids resonance**
- **Random force input**
- **Complex stiffness as continuous function of frequency**



Testing below resonance gives stiffness and loss factor of truss member as continuous functions of frequency

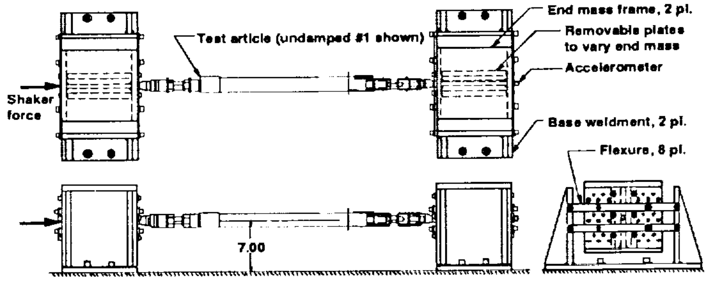
Fixture resonance is an important factor in measuring the strut stiffness and damping accurately. For measuring low frequency stiffness properties, the test fixtures were designed to be stiff and have resonance frequencies above the highest measurement frequency.

The strut will be pushed at one end and fixed at a support at the other end. A load cell measures the force level at the push rod and two transducers measure the strut end displacements. By using random force input, the damping mechanism will not be subject to excess heat due to energy dissipation.

A quick and accurate measurement over an wide frequency band (1 to 55 Hz) can be obtained. The complex stiffness of the strut can be computed from the measured data using the Fourier analyzer.

Resonant Complex Stiffness Test

- High frequency test (60-200 Hz)
- Apparatus induces resonance with simple known mode shape
- Random force input
- Complex stiffness measured in the neighborhood of resonance frequency

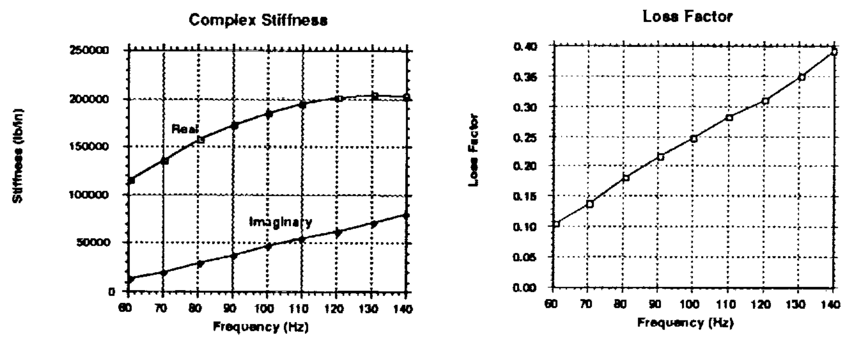


To measure the strut complex stiffness in the high frequency range, 60 to 200 Hz, a different test apparatus is required. This apparatus was designed to avoid fixture resonance in the frequency range of interest and also an accurate knowledge of the support stiffness was not required. The test apparatus simulates a free-free strut with two equal end masses. The end masses are supported by flexures. The flexures were designed to have a "free-free" resonance much lower than the resonant frequency of the strut/mass assembly.

The strut is pushed in the axial direction at one end and the accelerations of the end masses are measured. Since the apparatus is a simple two degrees-of-freedom system in the axial direction, the complex stiffness can be computed easily from the measured data. Also by varying the end masses, different resonance frequencies can be induced. This provides an accurate means of measuring the complex stiffness in the frequency band of interest.

Preliminary Test Results

- **Preliminary results from a damped strut resonant test indicate complex stiffness and loss factor can be extracted from test data over a range of frequency**



A preliminary test using the resonant test apparatus provided an opportunity to shake out the test apparatus and the design of the viscoelastic strut. The test results demonstrated that the data reduction method could provide accurate complex stiffness data in the neighborhood of the resonance frequency. It also indicated that the stiffness of the connection between two strut pieces must be increased to improve damping performance.

Work-in-progress

- V-strut
  - finalize design and permanent assembly
- D-strut
  - complete testing and parameter correlation
- Direct Complex Stiffness Test Apparatus
  - upgrade apparatus to increase maximum frequency to 55 Hz
- Resonant Complex Stiffness Test Apparatus
  - upgrade data processing to extend measurement range downward to 50 Hz
- Perform stiffness and damping test on V-strut
- Correlate V-strut finite element model with test results

Significant progress was made in understanding the important parameters to build highly damped struts in the high frequency range. More work is still in progress to complete this subtask.

The designs of the struts will be finalized. The direct complex stiffness test apparatus will be improved to increase its maximum frequency to 55 Hz. The data processing method for the resonant complex stiffness test will be upgraded to extend the measurement range down to 50 Hz. The struts will be assembled and tested for their dynamic performance. The data will be reduced and correlated to the analytical models and hence the design and analysis methods will be verified.

The findings of this subtask will be used to design the damped struts for the SPICE control-structure (active/passive) experiment.