# Application of Constrained Layer Damping to the F/A-18 Horizontal Tail

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**Abstract** - At high angle of attack the F/A-18 empennage is subjected to intense dynamic loads caused by buffeting flow generated by the wing leading edge extension (LEX). At angles of attack of approximately 20 degrees the stabilator and the engine mounts both exhibit high dynamic response. Flight test data show that the engine mounts have a very strong response at approximately 45 Hz, while ground tests show that the stabilator has two resonant frequencies in this frequency range. Also, the stabilator response and the engine mount response have a very high degree of correlation as measured during flight test. Therefore, it was postulated that (a) the stabilator resonant modes drive the engine mounts and, (b) if the stabilator response could be reduced, the engine mount response could also be reduced.

A combined analytical and experimental study was under taken to determine if the stabilator response could be reduced by using contained layer viscoelastic treatment. The goal was to cut the stabilator response in half, and, in order to do this, the level of damping in the system would have to be doubled. Since damping measured in flight for the modes of interest was about ten percent, the goal was to obtain ten percent damping in these modes on the ground. If the results of the analytical study and experiment proved positive, a flight test program to determine the effect of stabilator damping on engine mount loads under buffet flight conditions was to be carried out.

**Explanation of the Problem** - Modern high performance fighter aircraft are required to have a high degree of maneuverability as well as high speed. On the F/A-18 aircraft the ability to fly to high angles of attack is achieved by the added lift created by the leading edge extension (LEX) which acts like a low aspect ratio delta wing at high angles of attack. Under this condition, lift is generated by a vortex that forms off the LEX. In order to maintain stability at high angles of attack, the vortex flow is used to entrain air over the empennage surfaces, thus maintaining their effectiveness and hence aircraft stability. The F/A-18 at a high angle of attack flight condition is shown in Figure 1. Under conditions of high humidity, the vortex from the LEX and from the wing tip can be seen. Associated with the LEX vortex is high energy turbulent flow. When this flow impinges on an empennage surface, a high dynamic response condition results; a condition which has led to structural damage to the aerodynamic surface and to other parts of the aircraft.

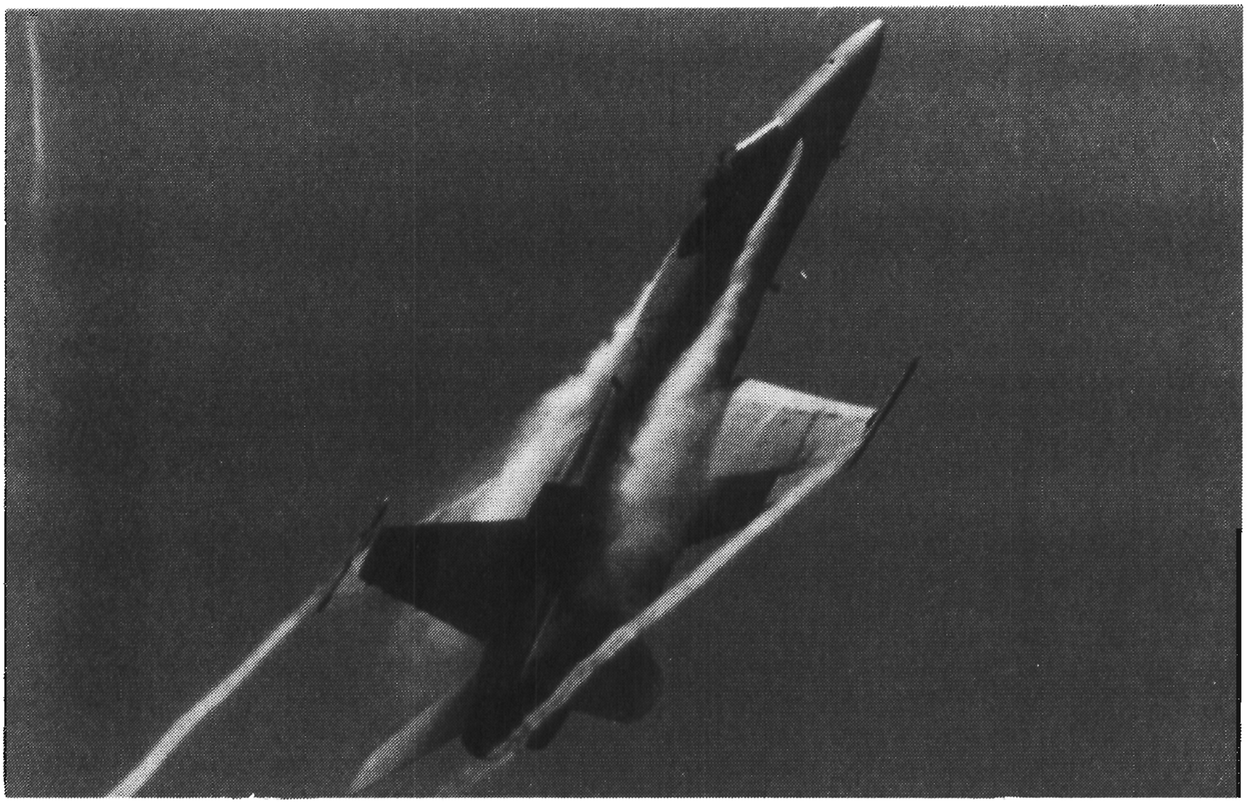

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**Figure 1. F/A-18 Aircraft at High Angle-of-Attack Showing Vortex From the Leading Edge Extension and Wing Tips**

For the case of interest here, the engine mounts were being damaged. From flight test data it was determined that the engine mounts experience high dynamic loads at the same time as the stabilator is being excited by the buffeting flow. It was theorized that the loads from the stabilator were being transmitted from the stabilator into the fuselage and then into the engine mounts. This premise was supported by the fact that both the stabilator and the engine mounts have resonances in the 45 Hz range, and it is at these resonant frequencies that most of the engine mount response is observed. In addition, flight test data showed a very high correlation between engine mount response and stabilator response. Thus, based on these assumptions, it was postulated that a reduction of stabilator response would reduce engine mount response.

**Analytical Studies** - Since this is a dynamic response problem, damping is one of the factors that control the amplitude and thus, if it can be introduced, can be a solution. Constrained layer viscoelastic material will introduce damping. A procedure that can be used to compute the modal damping from the properties of the viscoelastic materials is the modal strain energy method (Reference 1). This method was used for all of the damping calculations. It requires the calculation of the ratio of the strain energy in the viscoelastic material to the total strain energy in the structure on a mode by mode basis. This ratio is an approximation to the modal damping assuming a material loss factor of 1.0 for the viscoelastic material. This calculation is shown in the following equation.

$$\eta = \frac{1/2\ \phi^T K_V\ \phi}{1/2\ \phi^T K\ \phi} = \frac{S_V}{S}$$

where: $\phi$ = eigenvector

$K$ = stiffness matrix

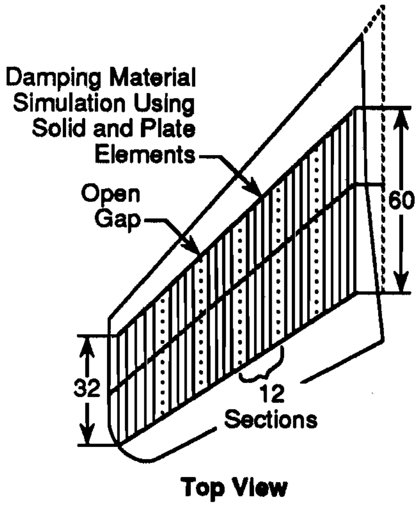
$K_v$ = stiffness matrix for viscoelastic only

$S$ = strain energy

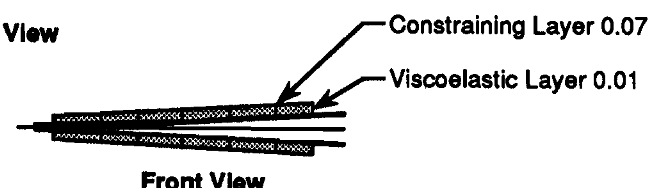
$S_v$ = strain energy for viscoelastic

In order to carry out this computation, a vibration model of the structure to be treated with viscoelastic material is required. A NASTRAN beam-rod vibration model of the stabilator had been developed for use in flutter studies and that model was modified for the present studies. These modifications included the addition of RBAR elements from the beam that defined the elastic axis to the surface where the viscoelastic elements were to be attached. The viscoelastic material was modeled using NASTRAN HEXA elements and the constraining layer was modeled using NASTRAN CQUAD elements. For the initial studies, the shear modulus of the viscoelastic material was assumed to be 1000 psi and the damping treatment was assumed to be applied in six sections of equal width. The stabilator with the viscoelastic material and constraining layer is shown in schematic form in Figure 2. The material properties of the damping treatment are indicated as well.

Vibration studies with this model were run to determine the strain energy in the viscoelastic elements. The damping levels determined from the strain energy ratio, as well as the modal frequencies, are shown in Figure 3. Data for the first four modes are shown. The two modes of interest here are the pitch/torsion mode and the second bending mode which have frequencies of 41.7 Hz and 47.8 Hz respectively. The engine mounts show maximum response at approximately 45 Hz. The other modal frequencies fall outside of the range of interest. The predicted level of damping in the pitch/torsion mode is relatively low. This is because there is very little strain energy in the structure, rather most of the energy is in the actuator since the motion is largely pitch about the spindle. This mode is not a candidate for viscoelastic damping applied to the surface. The second bending mode, however, has a very high level of predicted damping. Thus, if excitation from this mode were the source of the high engine mount loads, damping could be very effective in reducing them.




| Damping Treatment Properties | | | | | |
|---|---|---|---|---|---|
| Layer | Thickness in. | Weight lbs. | E psi | ʋ | Density lb/in.$^3$ |
| Viscoelastic | 0.01 | 3.25 | 1000 | 0.49 | 0.05 |
| Constrained Layer | 0.07 | 22.75 | 22.E06 | 0.33 | 0.05 |




Note: All dimensions given in inches.

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**Figure 2. F/A-18 Horizontal Tail Constrained Layer Damping Treatment**

| Mode Number | Loss Factor, η | Frequency (Hz) |
|---|---|---|
| 1 (1st Bending) | 0.072 | 12.68 |
| 2 (Pitch/Torsion) | 0.041 | 41.74 |
| 3 (2nd Bending) | 0.191 | 47.78 |
| 4 (2nd Torsion) | 0.102 | 87.53 |

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**Figure 3. F-18 Horizontal Tail Constrained Layer Damping Treatment**

In order to investigate the effectiveness of damping to control the stabilator response during buffeting flow conditions, additional analytical studies were run. Using the predicted levels of damping as calculated above, buffet response calculations were made. Unsteady pressures during buffet conditions were measured during a wind tunnel program described in Reference 2. These pressures were scaled to aircraft size and were used as the forcing function in the response calculation. The method to accomplish the scaling and for carrying out the calculation itself is also described in Reference 2. The results of these calculations are shown in Figure 4. The data are presented in the form of bending and torsion moment PSD's for a root station and a 70 percent span station. Data for the base line stabilator with only aerodynamic damping present is compared to that computed with the damping from the viscoelastic treatment included (damping levels from Figure 3). For the root, where the loads would be directly transferred into the fuselage, the response in the critical 45 Hz range is reduced by a factor of two. Thus, even though only one mode is effectively being controlled, the reduction in response is still significant.

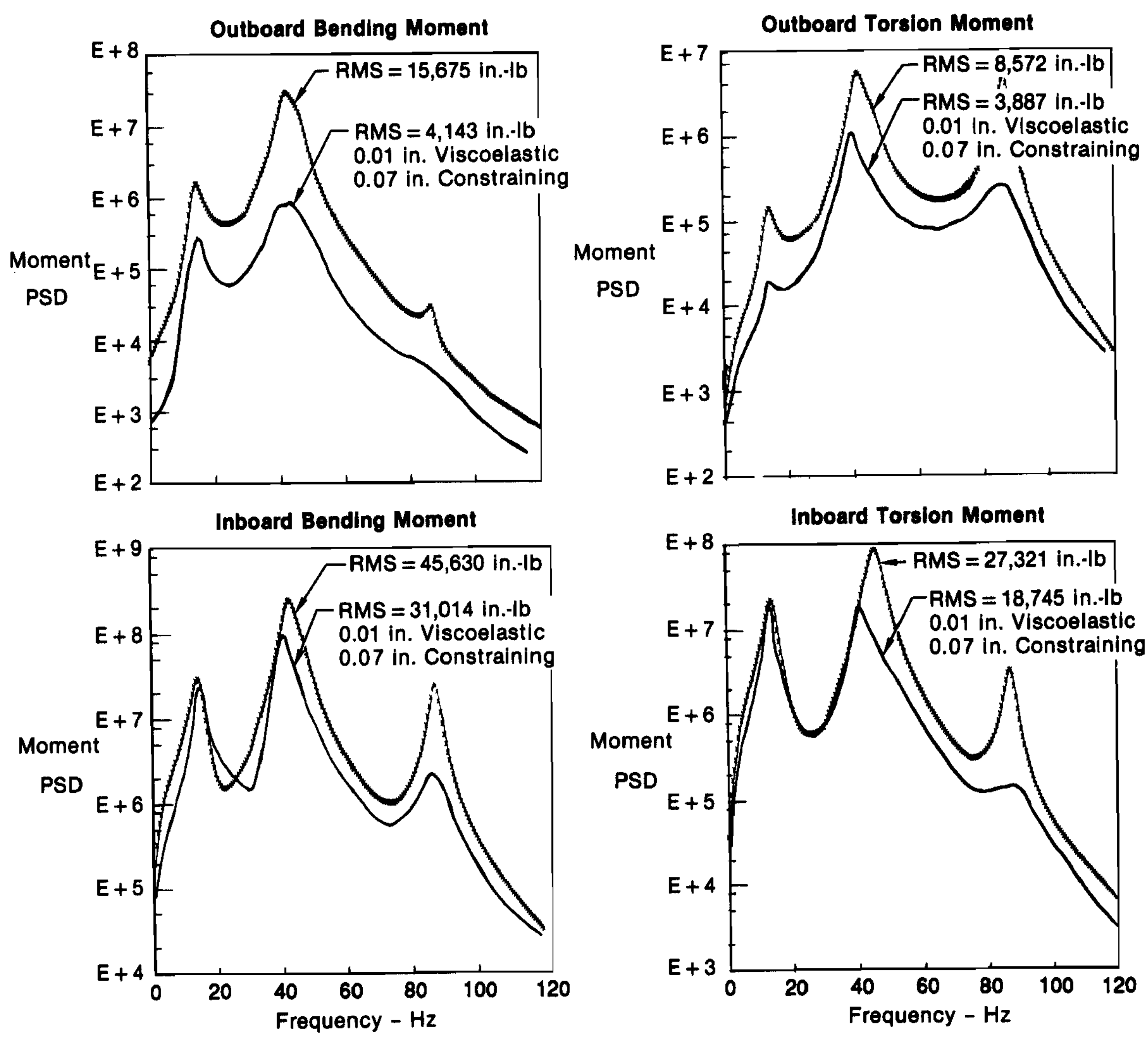



**Figure 4. F/A-18 Stabilator Buffet Response Predictions With/Without Viscoelastic Damping Treatment**

The distribution of modal strain energy in the second bending mode is shown in Figure 5. This figure shows that most of the strain energy is concentrated in three sections inboard of the tip. If only the second bending mode needs to be controlled, then it is necessary to install damping treatment only in this area. This is what was done since the other mode in the frequency range of interest, the pitch/rotation mode, could not be controlled by constrained layer viscoelastic treatment. The remaining modes have frequencies that fall outside the frequency range of interest.

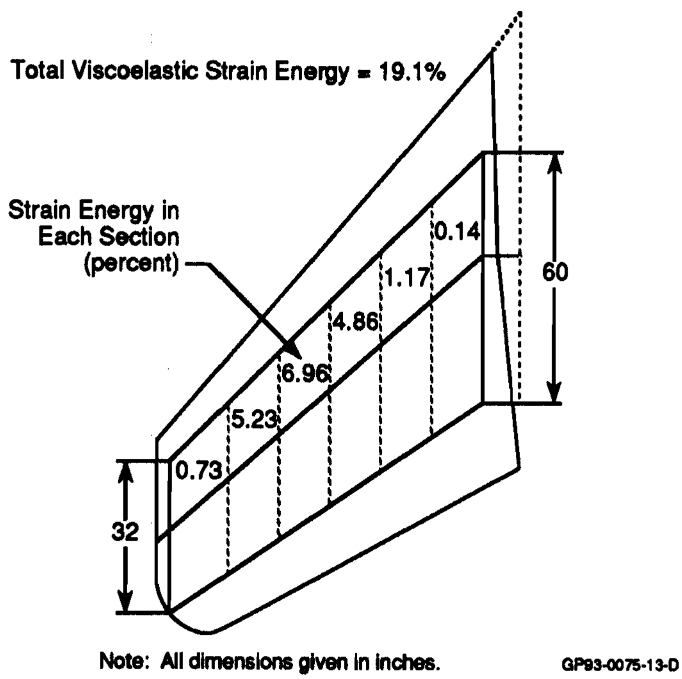
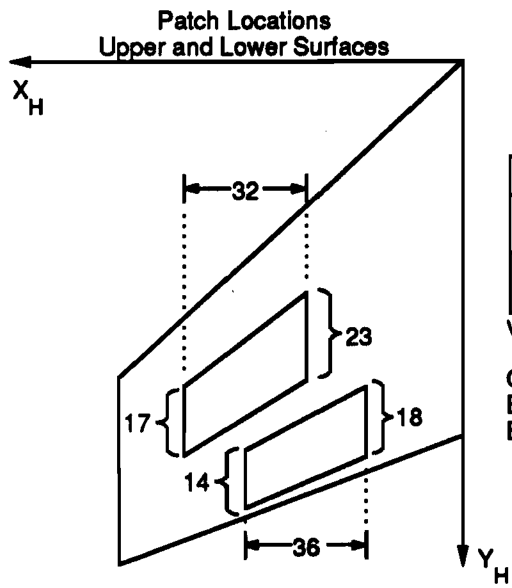



**Figure 5. F/A-18 Horizontal Tail Constrained Layer Damping Treatment**
Modal Strain Energy Distribution Mode 3
(2nd Bending)

For geometric reasons the treatment configuration shown in Figure 6 was selected as best. The treatment was broken into two pieces because in the area where the treatment is required, the composite skin has several ply drop-offs. This makes the surface very irregular and, since the constraining layers are very stiff, they would be difficult to manufacture if they had to run across the ply drop-offs. The material properties for the viscoelastic and constraint material are also shown in Figure 6. The ISD-113 viscoelastic material was selected primarily because it was available at the time the test had to be run. The constraint material was carbon epoxy. A composite constraining layer was selected to maximize the stiffness to weight ratio and an orthotropic ply lay-up was selected to maximize the stiffness in the direction of maximum bending. In general, the stiffer the constraining layer is, the higher the damping.




| Damping Treatment Properties | | | |
|---|---|---|---|
| Layer | Thickness in. | Weight lbs. | Density lb/in$^3$ |
| Viscoelastic | 0.020 | 2.9 | 0.050 |
| Constraint | 0.094 | 12.6 | 0.057 |

Viscoelastic Material Are Temperature Dependent.

Constraint Layer Material Properties Are Orthotropic:
E = 18.7E6 Along Elastic Axis
E = 2.5E6 Perpendicular to Elastic Axis

Note: All dimensions given in inches.

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**Figure 6. F/A-18 Horizontal Tail Constrained Layer Damping Treatment**

For the viscoelastic treatment geometry shown in Figure 6, analytical studies were conducted to determine the sensitivity of damping to various geometric parameters. For example, shown in Figure 7 is a plot of modal damping as a function of shear modulus of the viscoelastic material for three different thicknesses of the viscoelastic material. It is interesting that while the peak damping changes by a small amount as the thickness changes, it also tunes to a different shear modulus. This data can be used, along with the material data shown in Figure 8 for ISD-113, to plot damping as a function of temperature. This conversion was carried out and the result is shown in Figure 9. This data is interesting in that the thickness parameter shows the ability to tune the peak damping to a given temperature in the same way that it was able to tune peak damping to a given shear modulus. Also, for the range of thicknesses studied here, the thickest material does show the highest damping. Since both the material loss factor and the shear modulus of the viscoelastic material are temperature dependent, both must be considered. However, the shear modulus accounts for most of the trend shown in Figure 9.

A second study was run to determine the effect of treatment length on modal damping. Shown in Figure 10 is a plot of modal damping as a function of viscoelastic material shear modulus for three different treatment lengths. It can be seen that the effect of changing treatment length is to tune the peak damping value to a different shear modulus, as well as to change the level of peak damping. The level of peak damping changes from about 11 percent to about 13 percent. The data from Figure 10 plotted as a function of temperature is shown in Figure 11 for the ISD-113 material. Now it can be seen that the effect of increasing treatment length is to increase the peak level of damping and also to tune it to a higher temperature.

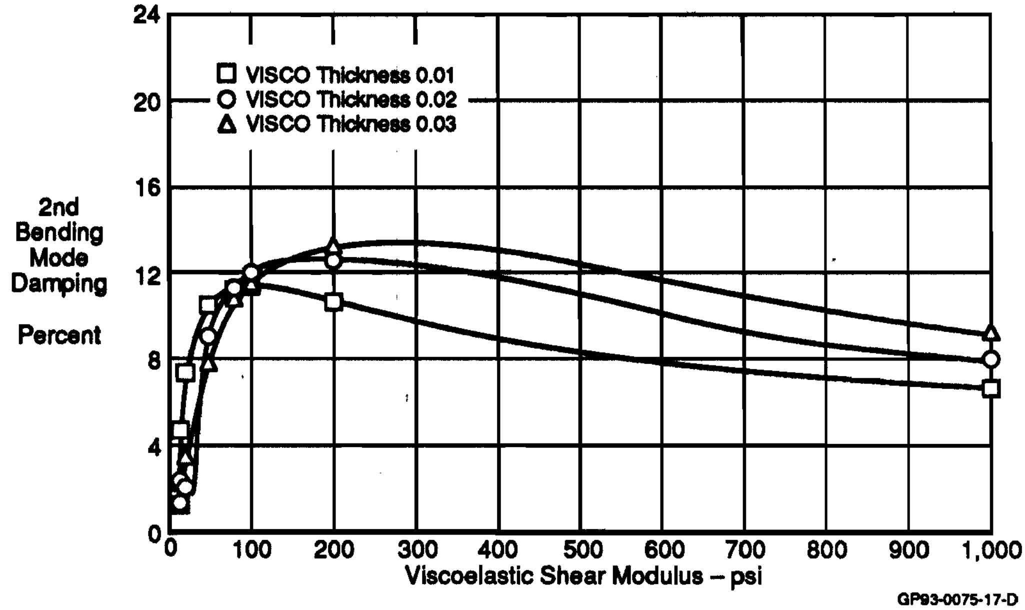


**Figure 7. F/A-18 Horizontal Tail Constrained Layer Damping Treatment**
Damping Sensitivity to Viscoelastic Thickness Patch Length 32 In.

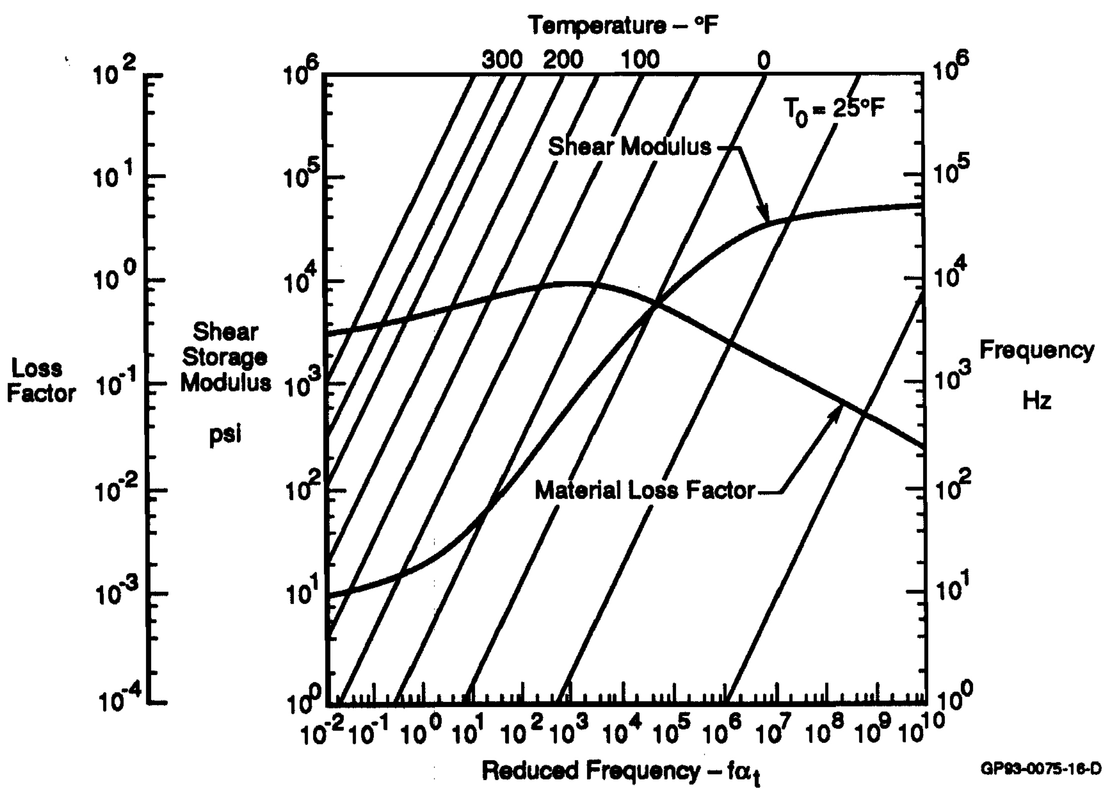


**Figure 8. Viscoelastic Material Properties ISD – 113**

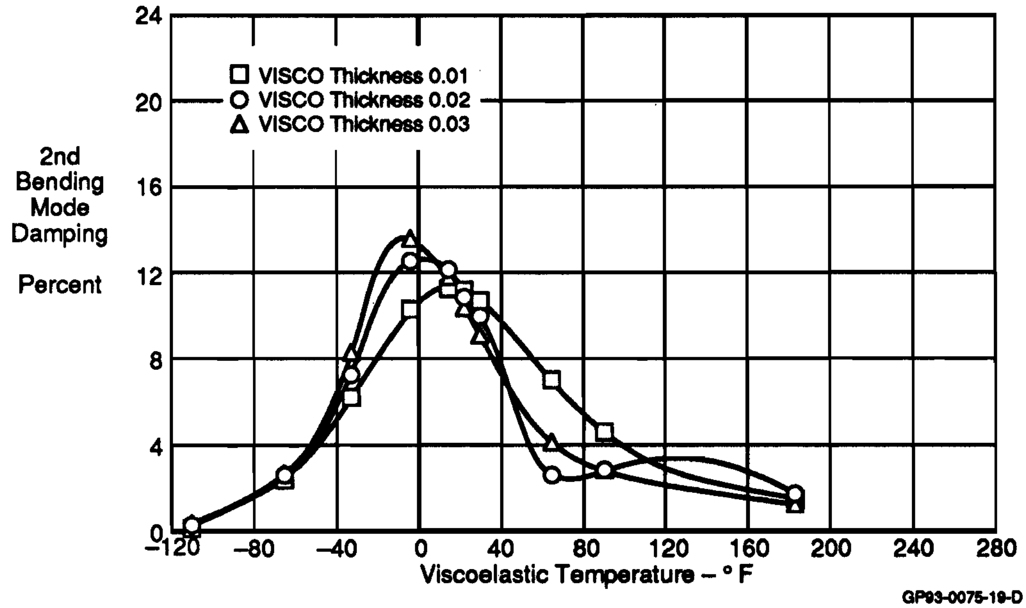


**Figure 9. F/A-18 Horizontal Tail Constrained Layer Damping Treatment**
Damping Sensitivity to Viscoelastic Thickness Patch Length 32 In.

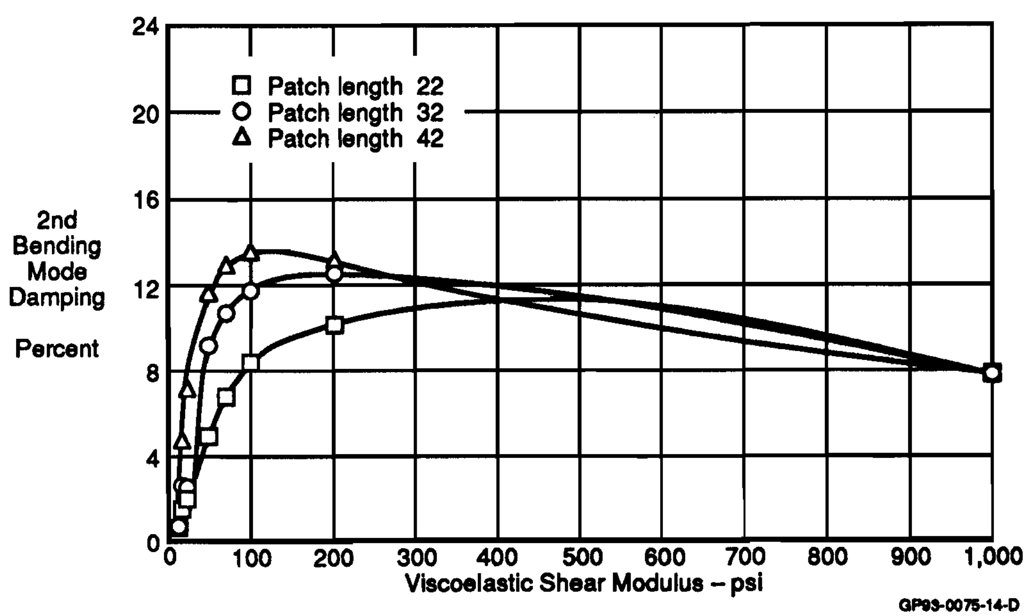


**Figure 10. F/A-18 Horizontal Tail Constrained Layer Damping Treatment**
Damping Sensitivity to Patch Length Visco Thickness 0.02 In.

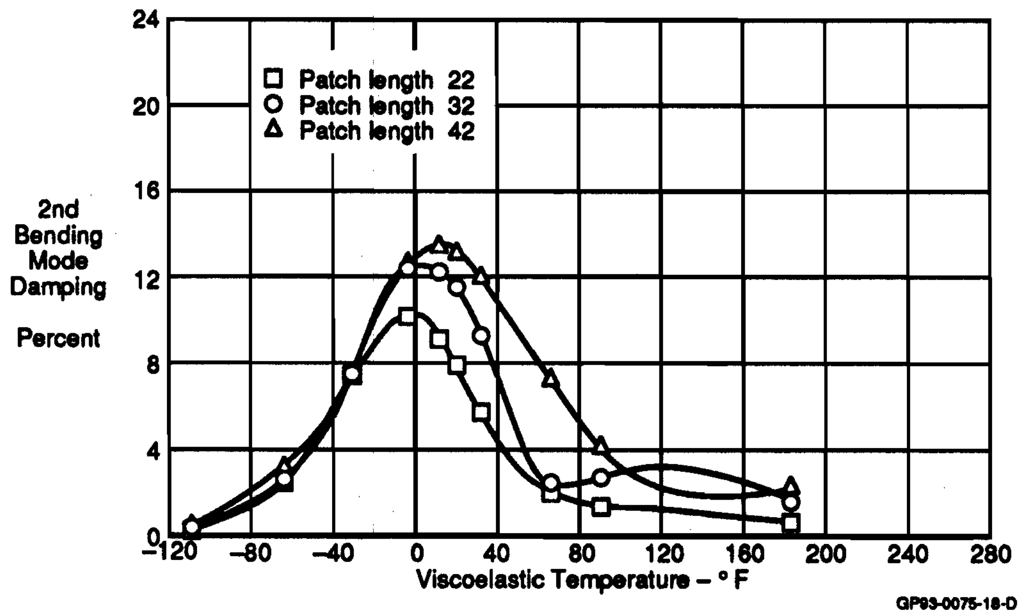


**Figure 11. F/A-18 Horizontal Tail Constrained Layer Damping Treatment**
Damping Sensitivity to Patch Length Visco Thickness 0.02 In.

Thus, both treatment length and thickness of the viscoelastic material can be used to tune peak damping to a given temperature. Because of this, the geometric properties of the damping treatment, as well as the visco-elastic material, must be selected such that peak damping occurs at a temperature that matches the temperature where structural response is a maximum. For the case at hand a length of 32 inches was fixed by the geometric considerations already mentioned. It will be shown that a longer length would have been a better choice. The thickness of the viscoelastic material was selected as 0.02 inches. This selection was based on material availability and the thought that a thicker material would help to fill local voids. A viscoelastic material thickness of 0.01 inches would have been a better choice as will be shown next.

The modal damping from the analytical study for the material and geometric properties that were selected, and also a non-dimensional damage curve for the engine mounts are plotted in Figure 12 as a function of temperature. The non-dimensional damage curve was determined from aircraft usage data. Initially, the maneuver data was compiled as a function of altitude and Mach number. This data was then converted to temperature based on statistical data for aircraft usage for standard day, hot day, and cold day conditions. Each data point represents a delta temperature range of 20 degrees. Thus, for the peak damage temperature, 30 percent of the damage occurs between 20 and 40 degrees. Failure occurs when the total damage reaches 100 percent. The predicted loss factor has a peak at about zero degrees F whereas the damage curve has its peak at about 30 degrees F. Thus, the viscoelastic treatment is not optimum for the problem that it was intended to control. The temperature where peak loss factor occurs could have been tuned by reducing the thickness of the viscoelastic material or by increasing the length of the treatment. Unfortunately, the constraints mentioned previously, rendered this impossible.

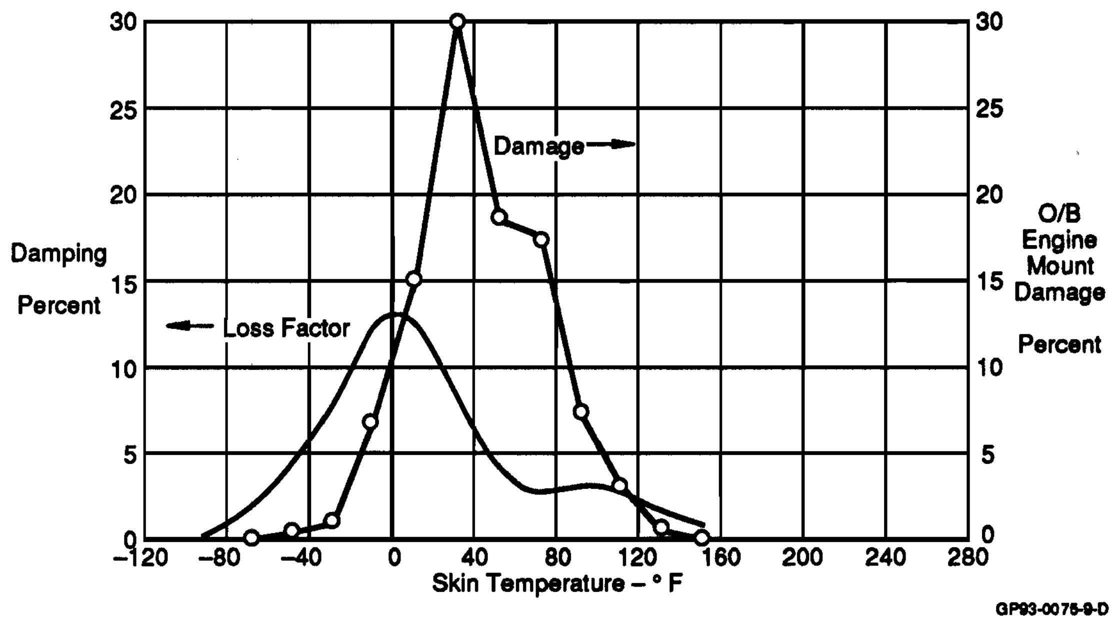


**Figure 12. F/A-18 Horizontal Tail Constrained Layer Damping Treatment**
Comparison of Mode 3 Damping and Analytical Damage Versus Skin Temperature

**Experimental Investigation** - The damping treatment described in the previous section was fabricated and installed on a pair of F/A-18 horizontal tails. The treatment installation is shown in Figure 13. The constraint layer was constructed from a high modulus composite material that was laid up such that most of the fibers were orientated in the span-wise direction. Very little strain occurs in the chordwise direction and therefore no stiffness is required in that direction. The viscoelastic material was attached to the constraint layers and any air bubbles were eliminated. As a safety of flight item, a thin line of sealer was added to the leading edge and to the trailing edge of the constraint layers. This was done to ensure that the constraint layers would not peel off in flight. The backing paper was next removed from the viscoelastic material and the constraint layer/viscoelastic material combination was attached to the stabilator. The procedure used was to stick one end of the constraint layer to the stabilator using the viscoelastic material as the adhesive, and then to push down the constraining layer in order to work the bond toward the other end. This procedure was intended to remove trapped air. Once the damping treatment was attached, the stabilator was put in a vacuum bag and then into an autoclave at 150 degrees F. This was intended to ensure that the viscoelastic material was completely attached to the stabilator and to speed curing.

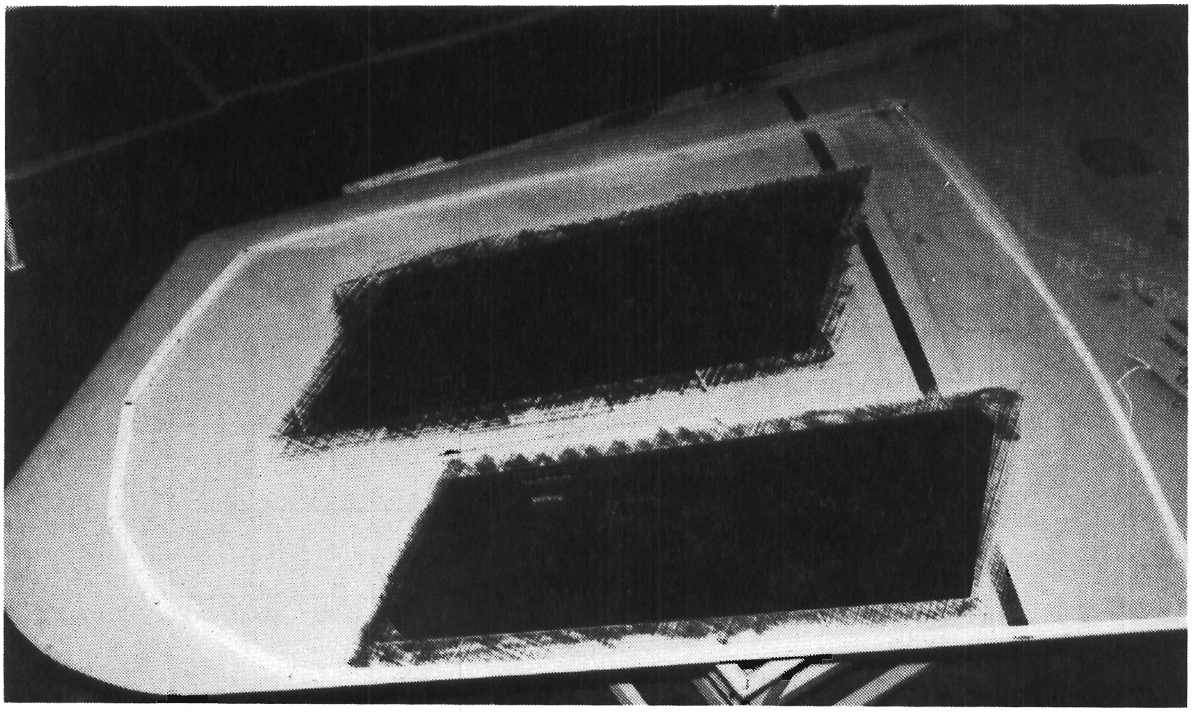

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**Figure 13. Viscoelastic Damping Treatment Installed on F/A-18 Stabilator**

These tails were installed on an F/A-18 aircraft and a ground vibration test to measure modal frequencies and damping was conducted. A complete modal survey of the stabilators was conducted at room temperature. This was done to verify that the mode shapes and frequencies were being correctly predicted by the analysis. The change in the mode shapes due to the damping treatment was predicted to be small and this is basically what was found in the test. Since it was well known that the damping generated by the visco-elastic material is temperature dependent, the modal frequencies and damping were measured over a temperature range from 0 degrees F to 80 degrees F. This was done by constructing styrofoam boxes around the horizontal tails and blowing air, cooled by liquid nitrogen heat exchangers, into them. The temperature of the viscoelastic material was monitored by thermocouples that were attached to the constraint layers. The procedure used to obtain data was to start cooling the stabilators and monitor the temperature of the thermocouples. As a temperature data point was being approached, the shakers were turned on and the resonant frequency for the second bending mode was tuned. This frequency and the transmissibility were recorded. Damping was measured by the decay method. A picture of the test set-up is shown in Figure 14. This system worked well and damping measurements over the temperature range of interest were obtained.

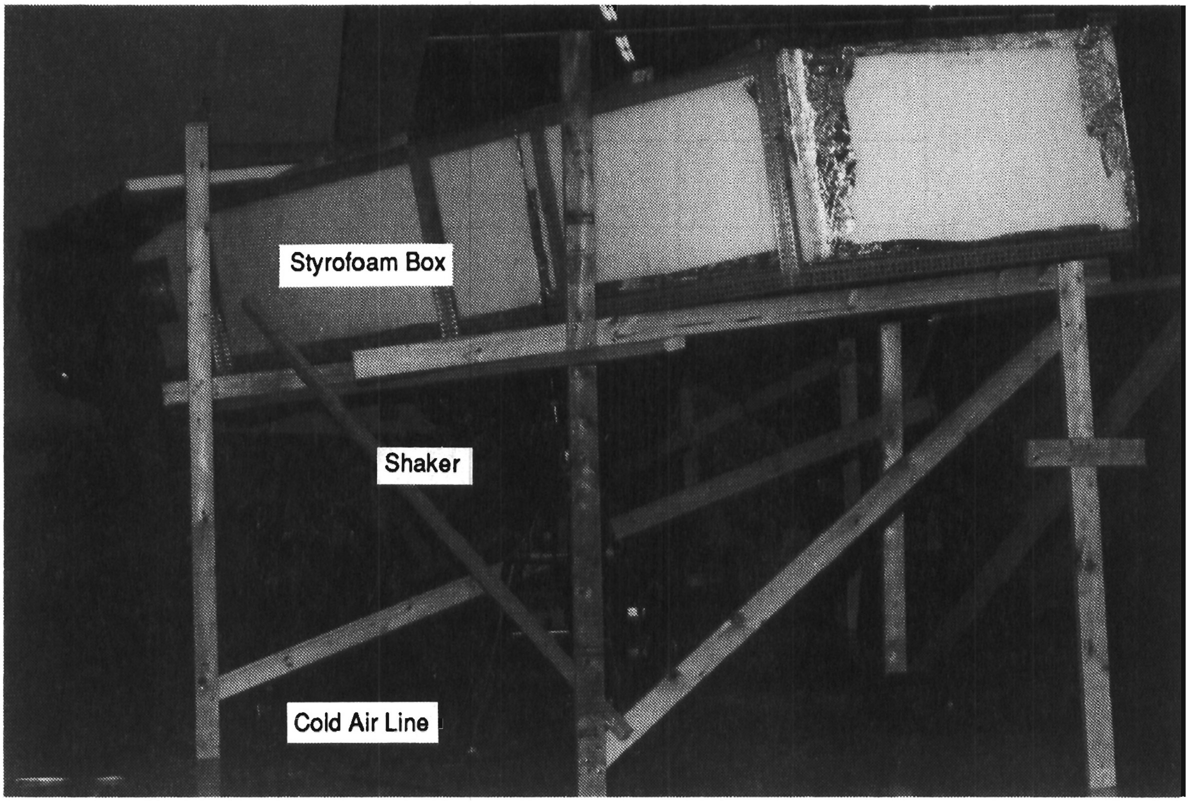


**Figure 14. Vibration Test Setup**
Stabilator Inside Styrofoam Box

Modal loss factors as a function of temperature, as predicted by analysis and as measured by the experiment, are shown in Figure 15. As can be seen from the figure, the measured damping is considerably less than predicted from the analysis. In addition, the temperature at which the peak damping occurred was about 30 degrees higher than what was predicted. The reasons for this are not fully understood. However, it was found from ultra-sonic inspection that the bond between the viscoelastic material and the primary structure was between 40 to 80 percent complete. This incomplete bonding was believed to have been caused by air bubbles trapped during the installation procedure. A second possible source for the discrepancy is that the sealant that was used on the leading edge and trailing edge of the constraining layer may have acted as an adhesive and prevented the constraining layer from forcing the viscoelastic material into shear. This possibility was checked by comparing the viscoelastic properties of the sealant to those of the ISD-113 and it was determined that this effect should have been small. A third possibility for error is in the modal strain energy calculation itself. The vibration model that was used for the stabilator was connected by root springs to ground. Thus, any strain energy in the fuselage would not be accounted for. During the vibration test a small but significant amount of fuselage motion was detected. Thus, some modal strain energy must be contained in that part of the structure. If this were true, then the denominator in the modal strain energy calculation would increase and reduce the predicted modal damping. Unfortunately, a finite element model of the fuselage and stabilator that could be used to evaluate this hypothesis was not available. Finally, it is possible that all of these factors could have contributed to the reduction in damping that was observed in the experiment.

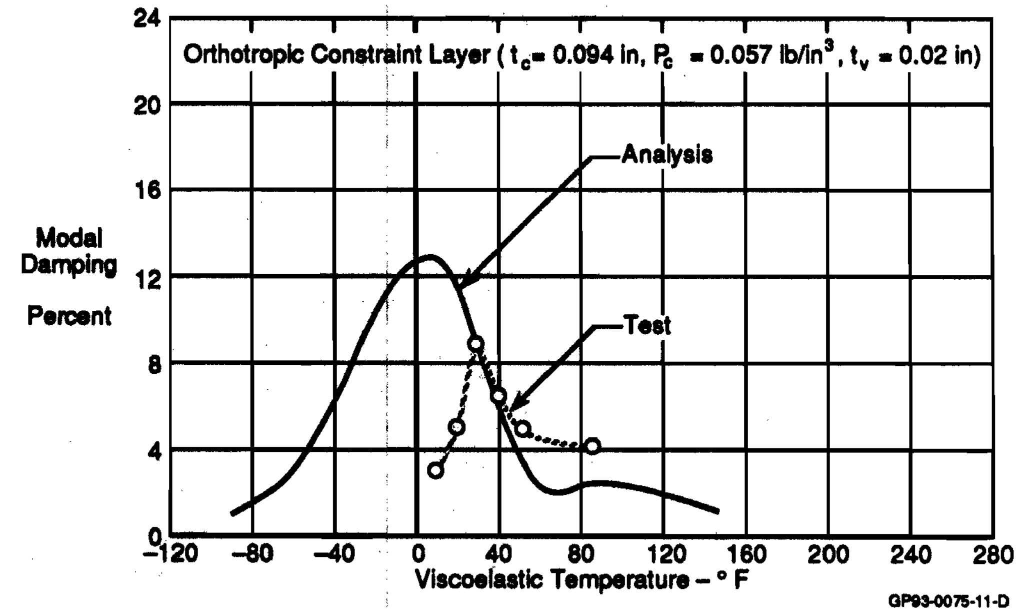


**Figure 15. F/A-18 Horizontal Tail Constrained Layer Damping Treatment Second Bending Mode**

Besides measuring modal damping as a function of temperature, modal frequency was also measured. This data is shown in Figure 16 for both the analysis and the test. What is interesting is that the delta frequency change over the temperature range of the test was predicted to be about 6 Hz and the measured result was about 4 Hz. This would suggest that the stiffness effects being introduced by the viscoelastic treatment are being modeled more accurately than are the damping effects. In fact, it would imply that 77 percent of the predicted stiffness increase is actually present.

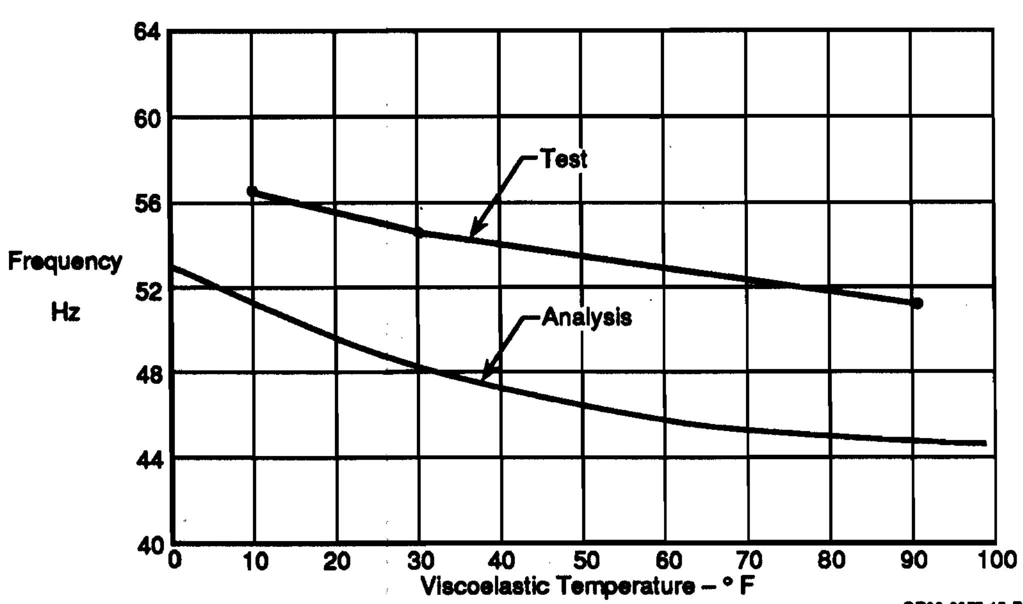


**Figure 16. F/A-18 Horizontal Tail Constrained Layer Damping Treatment**
**Shift in 2nd Bending Mode Frequency With Temperature Change**

**Conclusions** - Because the predicted levels of damping were not attained during the ground vibration test, the flight test to measure engine mount loads was canceled. Thus, the assumption that stabilator response was a factor in engine mount loads was not proved or disproved by this investigation. However, the investigation showed that additional work in both the experimental and analysis areas is required if the high level of damping required by primary aircraft surfaces is to be achieved. This is especially true with composite materials as were used in these tests.

For fundamental modes of primary aircraft structure, high levels of damping are required in order to control buffet type response because, with these surfaces, high levels of aerodynamic damping are present. In general doubling the damping will cut the response in half at the resonant frequency. Thus, levels of damping must be introduced that at least match those obtained in flight if the damping treatment is to be effective.

The vibration model that was used for these studies was entirely adequate for the purpose for which it was initially constructed, modal analysis and flutter analysis where the assumption of a root fixed to the fuselage through clock springs can be used. For the modal strain energy calculation, however, a full aircraft vibration model may be required if aircraft primary vibration modes are being investigated.

Geometric properties of the damping treatment can be used to tune peak damping as a function of temperature. However, the viscoelastic material itself is the main source for controlling damping as a function of temperature.

Even though this study was not completely successful, it should not serve as a deternent to future work in this area. What is required is a better way to install the damping treatment. If this can be found, the promise of increased structural life and reduced weight can be achieved.

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**References:**

1. Johnson, C. D., and Kienholz, D. A., "Finite Element Prediction of Damping in Structures with Constrained Viscoelastic Layers," Proc. 22nd Structures, Structural dynamics and Materials Conference, Atlanta, GA., Part 2, April 1981, pp. 17-24.

2. Zimmerman, N. H., and Ferman, M. A., "Prediction of Tail Buffet Loads for Design Application," NADC-880434-60, July 1987.

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