Life cycle testing of viscoelastic material for Hubble Space Telescope Solar Array 3 Damper

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ABSTRACT

During the March 2002 Servicing Mission by Space Shuttle (STS 109), the Hubble Space Telescope (HST) was refurbished with two new solar arrays that now provide all of its power. These arrays were built with viscoelastic/titanium dampers, integral to the supporting masts, which reduce the interaction of the wing bending modes with the Telescope. Damping of over 3% of critical was achieved. [1]

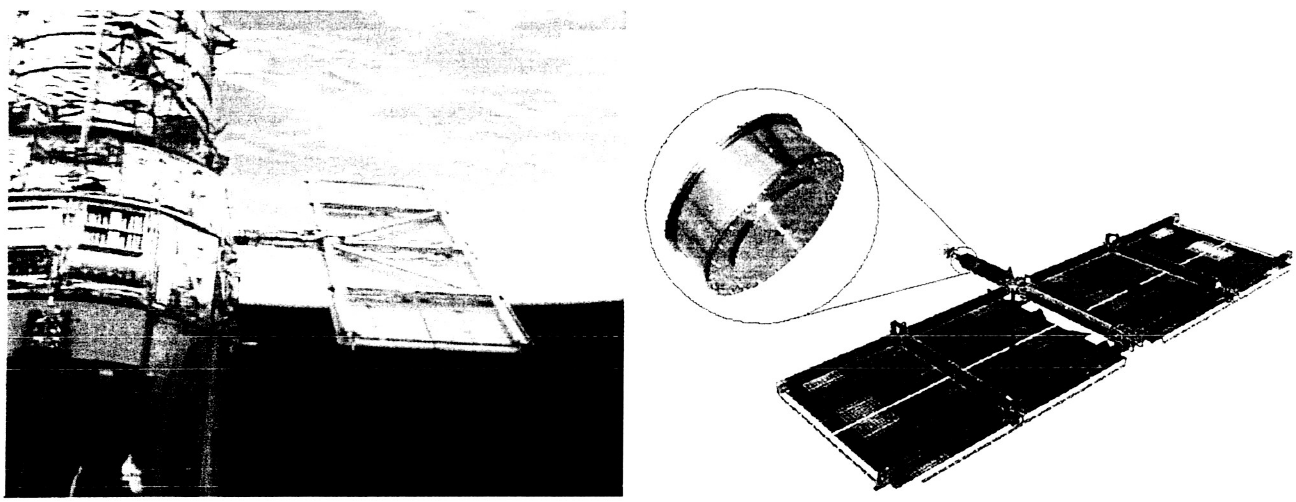

Figure 1. HST with Solar Array 3 (SA3) on orbit and SA3 finite element model showing damper location

To assess the damper's ability to maintain nominal performance over the 10-year on-orbit design goal, material specimens were subjected to an accelerated life test. The test matrix consisted of scheduled events to expose the specimens to pre-determined combinations of temperatures, frequencies, displacement levels, and numbers of cycles. These exposure events were designed to replicate the life environment of the damper from fabrication through testing to launch and life on-orbit. To determine whether material degradation occurred during the exposure sequence, material performance was evaluated before and after the accelerated aging with complex stiffness measurements. Based on comparison of pre- and post-life-cycle measurements, the material is expected to maintain nominal performance through end of life on-orbit. Recent telemetry from the Telescope indicates that the dampers are performing nominally.

Keywords: viscoelastic material, passive damping, complex stiffness, direct complex stiffness test, life cycling, accelerated life testing, Hubble Space Telescope

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1. INTRODUCTION

The Hubble Space Telescope (HST) is an observatory that conducts astronomical observations from low earth orbit. Due to its orbital track and velocity, it circles the earth approximately 18 times a day. Each circumnavigation keeps the telescope in direct sun light for roughly half the time and in the shadow of the earth the other half. When crossing the shadow boundary (penumbra), exposure to solar radiation causes all exposed surfaces of HST to heat up rapidly, at a rate which largely depends on the materials' thermal-optical properties. Unfortunately this effect caused the original solar arrays (SA1), which were on HST during deployment (1990), to bow, or flap like a bird's wing. This bowing induced jitter into the main structure of the telescope that violated the strict pointing requirements for scientific observations. Eventually the jitter would decay, and the remainder of the 45-minute half orbit could be used for science, prior to the next penumbra. Needless to say, pausing data collection 36 times a day is not the preferred way to operate a telescope.

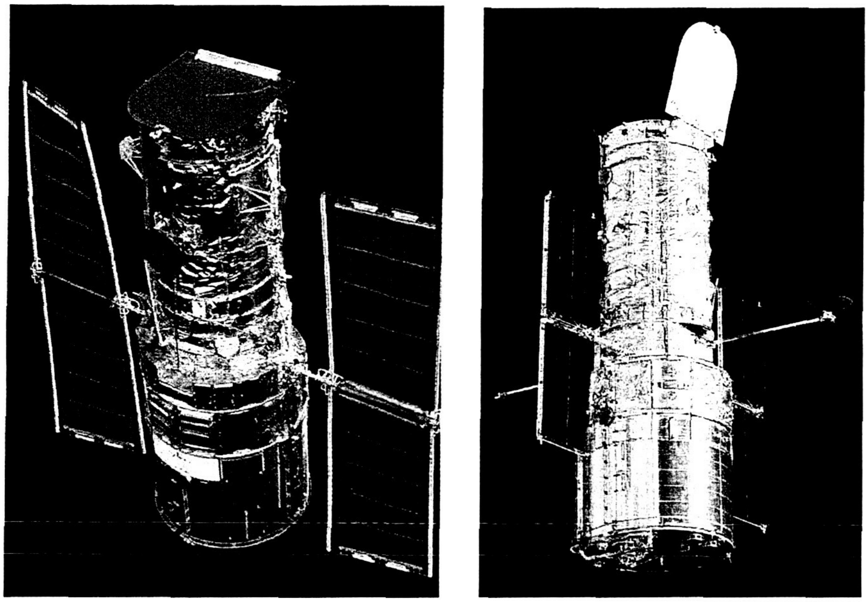

Figure 2. HST with Solar Array 2 (SA2), on left, and HST with SA3, on right

Astronauts installed a second set of arrays (SA2) onto HST during the first servicing mission (SM1) in 1993. The addition of a thermal shield improved the arrays such that science could be taken continuously, but these arrays were not a permanent fix. Damage to individual cells on the arrays, coupled with the telescope's "appetite" for more power, led to the decision to replace the arrays a second time with a more efficient set. These new arrays, SA3, are 31% smaller in area, yet produce 15% more power, than SA2. Furthermore, SA1 and SA2 were (mechanically) fundamentally different than SA3 in that the two former arrays were flexible blankets, populated with cells, which deployed (unrolled) upon installation on orbit, whereas SA3 is a rigid array (Figure 2).[1] Each "wing" of SA3 consists of two flat panels, 3.7 meters by 2.4 meters by 40 mm each, which are hinged to a mast The two panels were opened like a book by the SM3B astronauts, and each mast was attached to a socket vacated by SA2 on the main body of the telescope. Preflight analysis showed dynamic interactions which could influence the pointing control authority. Therefore, the array design was modified to include passive damping. Based on system-level requirements for mode frequencies and damping, CSA Engineering in conjunction with the NASA team, designed, built, and tested viscoelastic/titanium dampers which were integrated into the array masts. The objective of these dampers was to reduce the interaction of the wing bending modes with the Telescope.

The damper configuration is shown in Figure 3. The flanges of the titanium spool support quarter-cylindrical "shear-lap sandwiches" (titanium-viscoelastic-titanium); one of these shear laps is removed in the Figure for clarity. The

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[1] The SA3 arrays are not rigid in the traditional mechanical sense, as the primary modes of these arrays are around 1 Hz. But SA3 is considered rigid compared to SA2; the primary modes of SA2 were about 0.1 Hz.

materials for these sandwiches are titanium alloy (Ti 6Al4V) and 3M® ISD142R acrylic pressure-sensitive adhesive. The outer titanium portion of the sandwich is bolted to one flange, and the inner titanium portion is bolted to the other flange. Therefore, bending of the solar array masts (in-plane at 1.2 Hz and out-of-plane at 1.5 Hz) forces the viscoelastic material into shear, thereby dissipating mechanical energy.

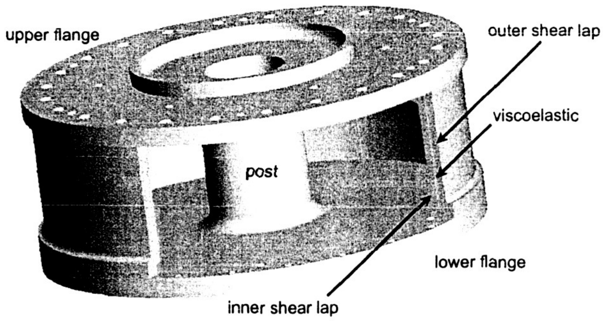


Figure 3. Solid model of SA3, with one shear lap section removed, showing significant features of damper

To mitigate the risk of damper performance decreasing below acceptable limits before the end of the design life of the arrays (10 years on orbit), an accelerated life test was developed.

2. LIFE TEST DESIGN

The accelerated life test for the SA3 viscoelastic material consisted of the following sequence:

1. making coupons which represented (as closely as possible) the flight damper design,
2. measuring baseline mechanical performance (complex stiffness) of the coupons,
3. subjecting the coupons to a simulated environment, both mechanical and thermal, derived based on the expected environment that the flight damper material would see prior to launch and on orbit, [2] then
4. re-measuring mechanical performance.

The life test was also designed to verify that the viscoelastic material was not susceptible to progressive growth of pre-existing voids, if such voids were to exist. The length of time required to simulate the thermal history the damper will have seen by end of life ended up being almost 5 months, partly due to the relatively large thermal mass of each coupon and partly due to the number of thermal cycles that the dampers will see during ten years on orbit (approximately 56,000 cycles). Furthermore, if there was a flaw in the damper design that the life testing was going to uncover, HST Project management wanted as much time as possible for redesign. Therefore, it was decided to subject a subset of coupons (4) to mechanical cycling only, hunting for showstoppers so to speak.

Evaluation of the material's capability to maintain its mechanical performance after the simulated aging environment was based on comparison of complex stiffness measurements before and after the simulated aging. Complex stiffness is the key mechanical property of the material with regard to its structural performance. The damper was designed using finite element analysis and measured viscoelastic material properties, [3] [4] and the damper performance requires that these properties are maintained throughout its life. Complex stiffness was measured and plotted in terms of two functions of frequency, real stiffness and loss factor, in the frequency range for which the damper was designed. Viscoelastic mechanical properties are temperature-dependent as well as frequency-dependent, so each specimen was characterized at two distinct temperatures near the operating range of the dampers on orbit.

3. MECHANICAL CYCLING, ULTRASONIC INSPECTION, AND COMPLEX STIFFNESS MEASUREMENT CONFIGURATIONS

Figure 4 shows a test specimen mounted in the configuration that was used to apply the vibratory excitation for the accelerated aging environment. The test setup was designed to cycle the material with components of shear and dilatation (peel). Fixturing was configured to bolt the 1.5-by-2-inch coupons in the test rig, at a 20° angle. This angle between the shear direction and the excitation direction was determined from the deformation pattern of the viscoelastic material in the damper finite element model.

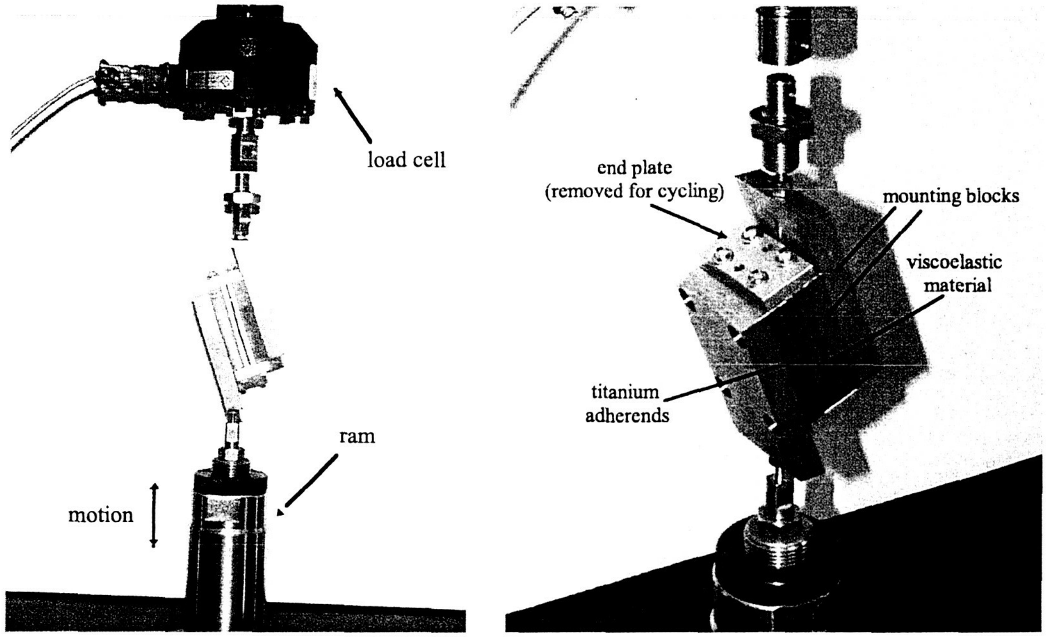


Figure 4. Mechanical cycling configuration

To assess the integrity of the adhesive bond between the viscoelastic material (VEM) and the titanium adherends, immersion ultrasonic inspection was used. The coupon fastener holes and the open edges of the coupon were taped so that the VEM would not be soaked during immersion. The inspections of the coupons were performed using a Panametrics Inc., MULTISCAN inspection system. The pulse echo inspections utilized a 10-MHz, 0.25-inch-diameter focused transducer and the data acquisition gate was set to monitor the amplitude of the signal reflected from the titanium-to-VEM bondline. A 0.01-inch step was used and all inspection parameters were based on the inspection of a standard of similar configuration which contained various size Teflon inserts at the titanium-to-VEM bondline to simulate disbonds. Interpretation of the resultant scans was not trivial due to the similar impedance mismatch between titanium and VEM and the mismatch between titanium and air.

To quantify the material performance before and after the life cycle tests, complex (shear) stiffness measurements [5] were made on one control specimen and ten cycled specimens. Two specimens are required to measure shear, so two viscoelastic specimens were installed in the test rig for each stiffness measurement. The two specimens in the rig were, as shown in Figure 5,

- a specimen under test (either a control specimen or a cycled specimen), and
- a dummy specimen.

The same dummy specimen was used for all measurements. The test rig was assembled in an environmental chamber so that ambient temperature could be controlled.

Shear stiffness was measured by applying burst random excitation, with frequency content of 0.5 Hz to 50 Hz, and simultaneously measuring force through and displacement across the specimen. Complex compliance was computed by dividing the force-to-displacement cross spectrum by the force autospectrum. For a single-input-single-output system, complex stiffness is the reciprocal of the complex compliance. Both real stiffness and loss were plotted versus frequency to 50 Hz. Real stiffness is the nomenclature used for the real (in-phase) component of the complex stiffness function, and loss is the imaginary component divided by the real component of the complex stiffness.

Measurements were made at 65°F and 75°F for each specimen. Temperature was recorded using RTDs (resistance temperature detectors) that monitored the temperature of the viscoelastic mount blocks, as shown in Figure 5. For each measurement, temperature was stabilized at the target temperature ±0.5°F for at least 30 minutes. Specimen stiffness and loss was plotted for each temperature, 65°F and 75°F, both before and after the life cycling.

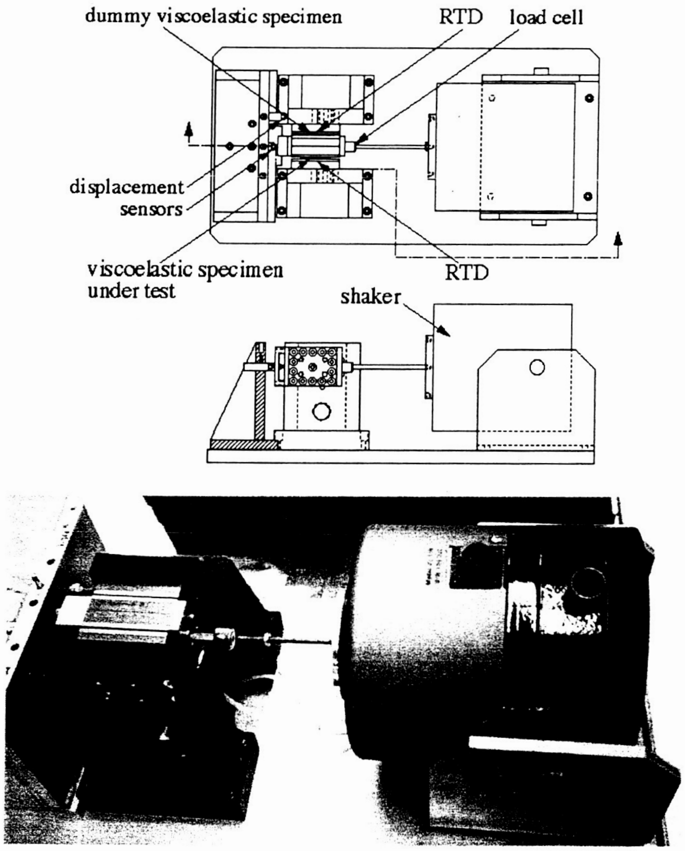


Figure 5. Test rig for measurement of complex stiffness of life cycle test specimen

4. VEM COUPON TEST SEQUENCES

Sixteen different coupons were assembled for mechanical and/or thermal cycling, or as control specimens. Three contained embedded Teflon® disks to simulate voids that could potentially occur due to air bubbles trapped during assembly. Coupon 11 was the control sample. The only loading the control samples saw was the trip back and forth between CSA Engineering in California and Goddard Space Flight Center in Maryland. The test sequence and summary for each coupon is shown in Table 1.

ID	Seeded Voids	DCS	UI	Mechanical Test Table 2 (1-18)	UI	Thermal Cycling Table 4	UI	Mechanical Test Table 3 (19-35)	UI	DCS
Q	x	x	x	x	x	x	x	x	x	x
R	x	x	x	x	x	x	x	x	x	x
S	x	x	x	x	x	x	x	x	x	x
A		x	x	x	x	x	x	x	x	x
C		x	x	x	x	x	x	x	x	x
D		x	x	x	x	x	x	x	x	x
E		x	x	x				x	x	x
F		x	x	x				x	x	x
I		x	x	x				x	x	x
J		x	x	x				x	x	x
M		x	x						x	x

Table 1. Test sequences for various coupons

Cycling sequences are listed in Table 2 through Table 4, including temperatures, cyclic frequencies, numbers of cycles, and displacements in inches.

Temperature (°C)	Frequency (Hz)	Number of Cycles	Displacement (mils)	Typical Load (lbs)
20	1	25	10	8
20	10	100	10	26
20	20	200	10	32
-12	12	2030386	0.8	66
20	12	2030386	13.0	62
20	1	9	40.0	52
20	15	3000	10.2	53
20	15	200	37.9	95
20	25	10000	17.0	59
20	25	205	35.0	78
20	43	33759	5.0	34
20	20	10058	25.0	73
20	20	200	30.0	59
20	20	600	13.0	41
20	20	600	28.0	68
20	40	8000	5.0	28
20	80	233877	2.0	24
20	80	1000	2.5	29
50	12	854800	6.0	5
50	12	1054251	19.0	15
50	12	1400	31.0	24

Table 2. Mechanical cycles derived from expected damper processing prior to on-orbit installation

Temperature (°C)		Cycle time (minutes)	Number of Cycles
min	max		
-70	50	12	100
0	25	3.75	5600

Table 3. Thermal cycles derived from expected damper life on orbit

Temperature (°C)	Frequency (Hz)	Number of Cycles	Displacement (mils)	Typical Load (lbs)
-70	2	6200	0.3	38
-12	2	8200	1.6	106
5	30	6400000	0.3	9
20	2	8200	17	33
20	20	4438	28	93
30	30	6400000	0.3	1
50	2	7052	30	12

Table 4. Mechanical cycles derived from expected damper life on orbit

5. COMPLEX STIFFNESS MEASUREMENTS AND DATA PROCESSING

Figure 6 shows two typical measurements of real stiffness and loss, at 65.2°F and 74.8°F. Both stiffness and damping vary with temperature, so, for comparison of pre- and post-life-cycle measurements, these functions were "corrected" to reference temperatures of 65°F and 75°F. This correction was made by assuming that, for temperatures near room temperature, the stiffness and damping variations per degree (of temperature) can be linearized and used to correct the data. Figure 7 shows the change in both stiffness and damping for a unit material temperature change (1°F); these functions (of frequency) were obtained by taking the difference of the two measurements shown in Figure 6, and dividing by the number of degrees between the two measurements, 9.6°F in this case. Applying these corrections to the measurements in Figure 6 results in the corrected measurements shown in Figure 8.

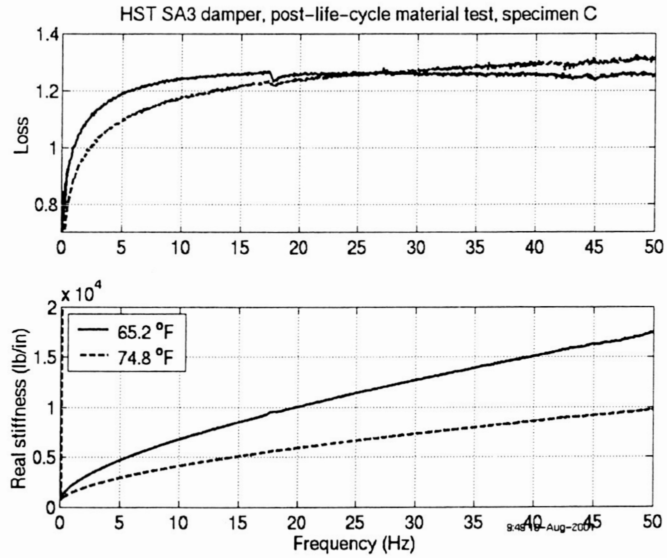


Figure 6. Typical measured stiffness and loss for life cycling test specimen

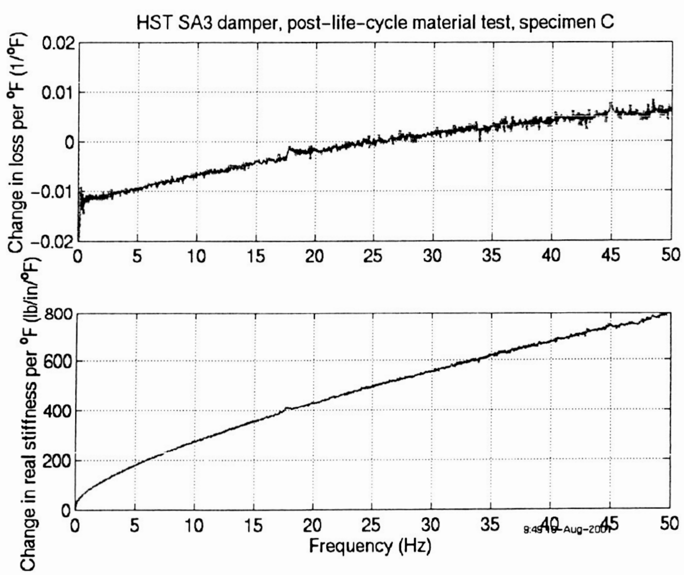


Figure 7. Typical temperature correction functions,_change in stiffness and loss per °F near room temperature

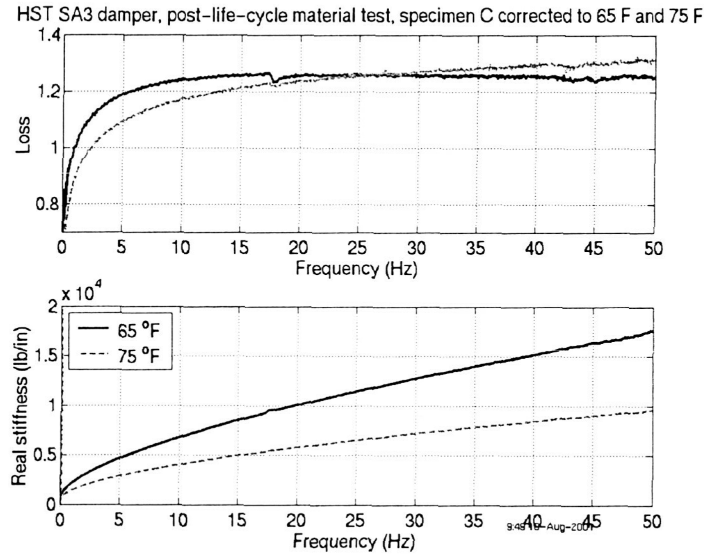


Figure 8. Typical loss and stiffness measurements with correction applied: 65.2°F measurements corrected to 65°F and 74.8°F measurements corrected to 75°F

6. PRE-LIFE-CYCLE AND POST-LIFE-CYCLE MEASUREMENTS

Ultrasonic inspection of the interfaces was used to determine if any delamination or failure of the adhesive bond between the VEM and the titanium had occurred. Two plots of the same specimen are shown below in Figure 9. The large circles of different color are Teflon® disks simulating voids of differing size. The plots show that the shape of the circular inserts became better defined after testing which suggests that the VEM adhesion actually improved due to testing.

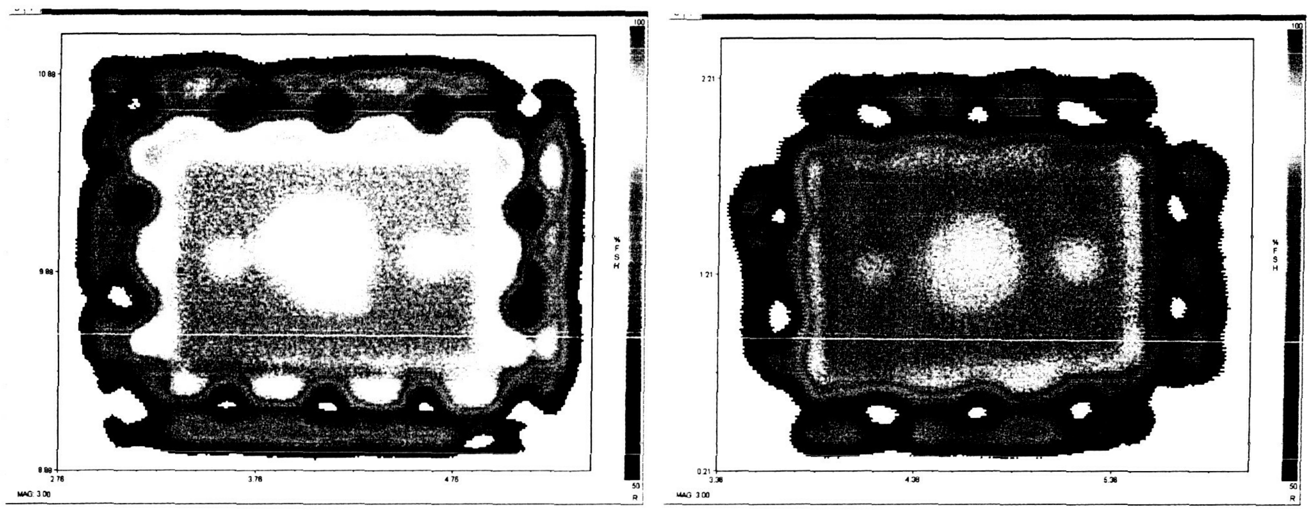


Figure 9. C-scan plots of reflection amplitude from VEM bondline for one side of a coupon taken before (on left) and after (on right) mechanical and thermal testing.

Stiffness and loss of all life-cycle specimens were measured and corrected for temperature as described above. All specimens, *including the control specimen*, showed variations between measurements made before and after life cycling. Most specimens showed increased stiffness, ranging from 8% to 19%, but minimal changes in loss, ranging from 0% to 4.5%. Table 5 shows the percent changes in stiffness and loss between 1.0 and 1.6 Hz for all specimens.

The percent variation between measurements made before and after life cycling is nearly constant across the measurement bandwidth of 50 Hz.

test specimen	75°F measurements		65°F measurements	
	delta loss	delta k	delta loss	delta k
C (control)	1%	1%	2%	8%
A	2%	8.5%	3%	16%
D	4%	15%	2%	18%
E	2%	11.5%	2%	16%
F	0%	16%	0%	15.5%
I	-1%	15%	0%	15%
J	-2%	14%	-1%	14%
M	1.5%	6%	2%	9.5%
Q	-2%	-1%	-1%	5%
R	2.5%	17%	2%	19%
S	4.5%	2%	4%	4%
average (control not included)	1.2%	10.4%	1.3%	13.2%

Table 5. Percent change ("delta") in stiffness and loss, between 1.0 and 1.6 Hz

Measurements of the individual specimens, comparing the measurements before life cycling with the measurements after life cycling, were documented and studied in detail. All specimen measurements at 75°F are overplotted in Figure 10 (before life cycling) and Figure 11 (after life cycling). Plots of all specimen measurements at 65°F are shown in Figure 12 (before life cycling) and Figure 13 (after life cycling).

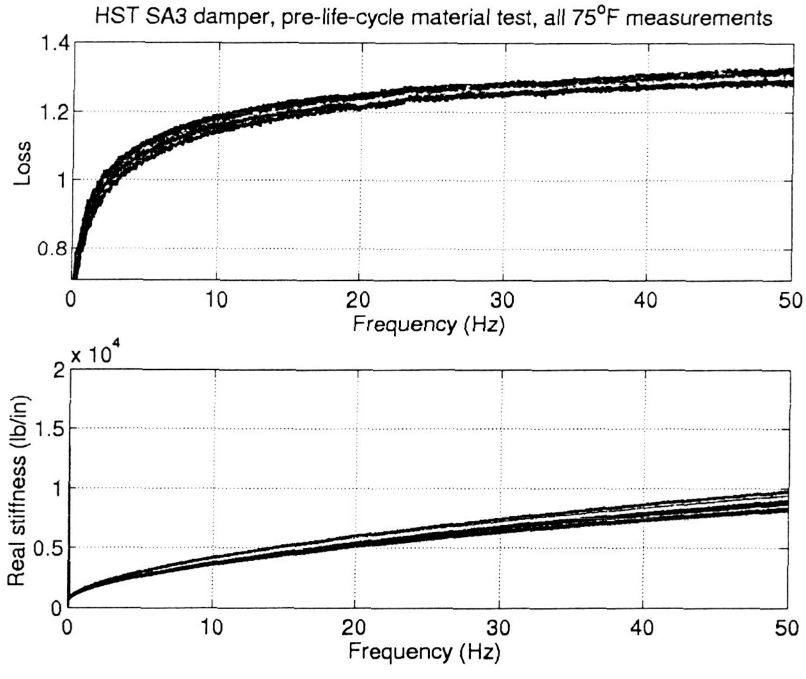


Figure 10. All complex stiffness measurements at 75°F before cycling

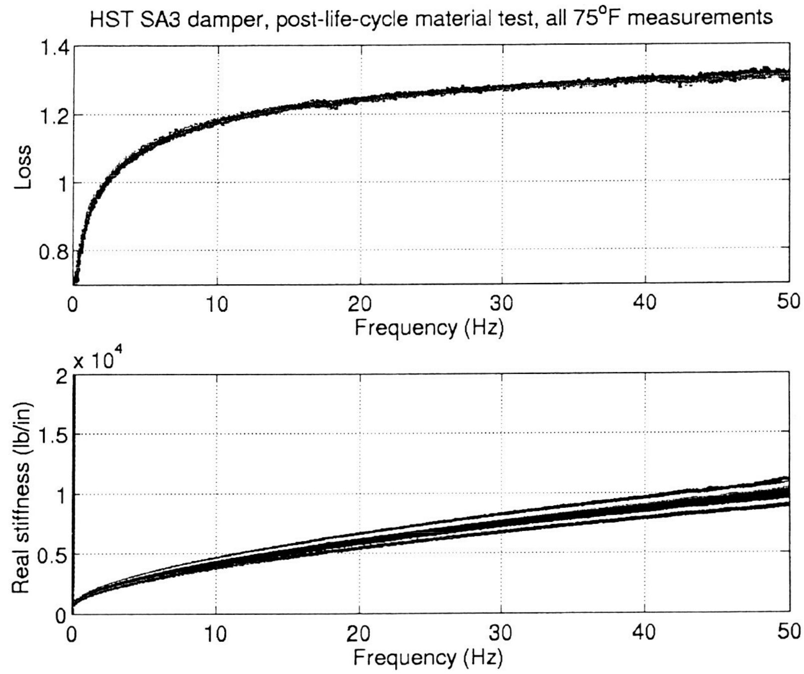


Figure 11. All complex stiffness measurements at 75°F after cycling

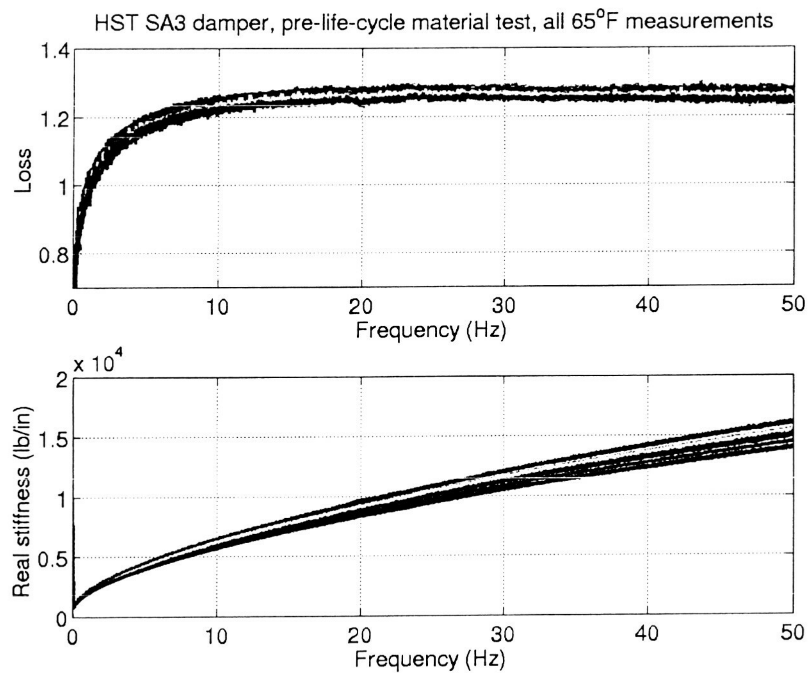


Figure 12. All complex stiffness measurements at 65°F before cycling

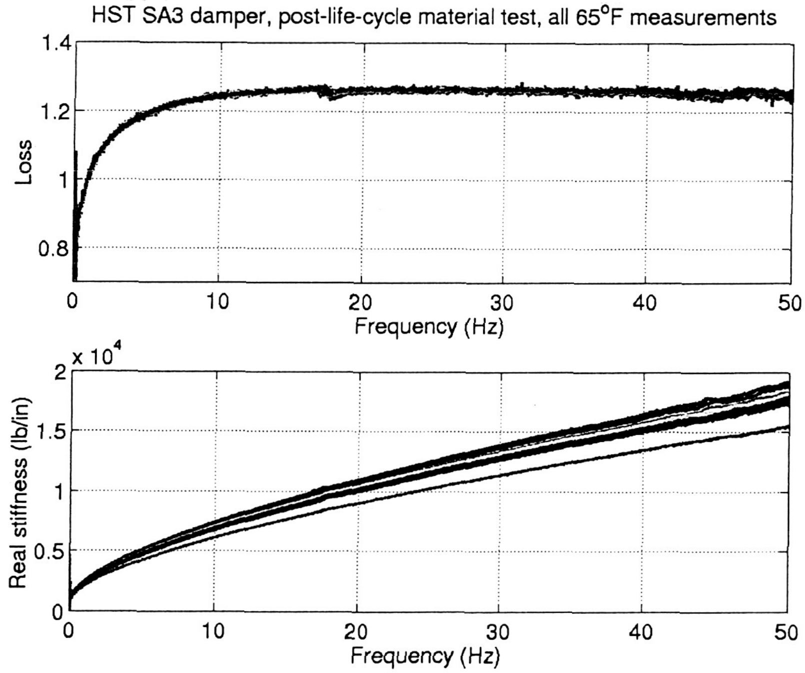


Figure 13. All complex stiffness measurements at 65°F after cycling

7. DISCUSSION OF RESULTS

Most of the test coupons showed increased stiffness, ranging from 8% to 19%, but minimal change in loss, ranging from 0% to 4.5%. Since the control specimen also showed some changes, small uncontrolled sources of measurement error were likely a factor. For example, since viscoelastic material variations in complex stiffness are extremely sensitive to temperature variation, accurate material temperature measurement could easily be a factor. Because of the configuration that was required for the life cycling, it was not feasible to install temperature sensors directly in contact with the viscoelastic material, which would have been desirable; instead RTDs were installed for temperature measurement on the surface of the titanium adherends. During the complex stiffness measurements, ambient temperature measurements were made with a NIST-calibrated glass thermometer. Temperatures recorded from this thermometer for pre-life-cycle measurements were compared with temperatures recorded for post-life-cycle measurements, and to values read by an RTD placed in air next to the thermometer. The difference in readings for tests conducted prior to life cycle testing ranged from 0.1°F to 1.6°F. The difference for tests conducted after life cycle testing ranges 0.4°F to 1.3°F.

The average specimen stiffness increase was over 10%, but the loss factor measurements on average changed by only about 1%. The stiffness increase suggests that the viscoelastic bond actually developed further with time, and this conclusion was supported by the post-cycling ultrasonic inspections. The fact that the damping did not change significantly provided confidence that the material would perform as expected over its life on orbit. The small increases in stiffness were considered acceptable, and certainly preferable to any decreases in stiffness.

At the conclusion of the testing it was noted that the exposed edges of the viscoelastic in several of the coupons appeared to be "ragged." However, the ultrasonic inspections indicated that the material was not compromised. In fact, the bond lines in general appeared to be better than before the cycling began. It is believed by the authors that this is due to the repeated mechanical cycling, which forces/allows the viscoelastic material to be worked into the microscopic pits and fissures that are enhanced during the acid etch preparation of the titanium adherends. For example, the plots in Figure 9 show that the shape of the circular inserts became better defined after testing, which suggests that the VEM adhesion actually improved due to testing.

8. EFFECT ON SOLAR ARRAY 3 DUE TO MEASURED MATERIAL VARIATIONS

Performance of the Telescope with the new Solar Array 3 has been quantified and compared with performance during the period when SA2 was installed on HST. The increased performance is dramatic as SA3 has reduced disturbances by a factor of 25, as shown in Figure 14. The objective of the life cycle testing was to ensure that the benefits of damping built into the SA3, which is partly responsible for the improved performance, would be maintained over the life of the Telescope.

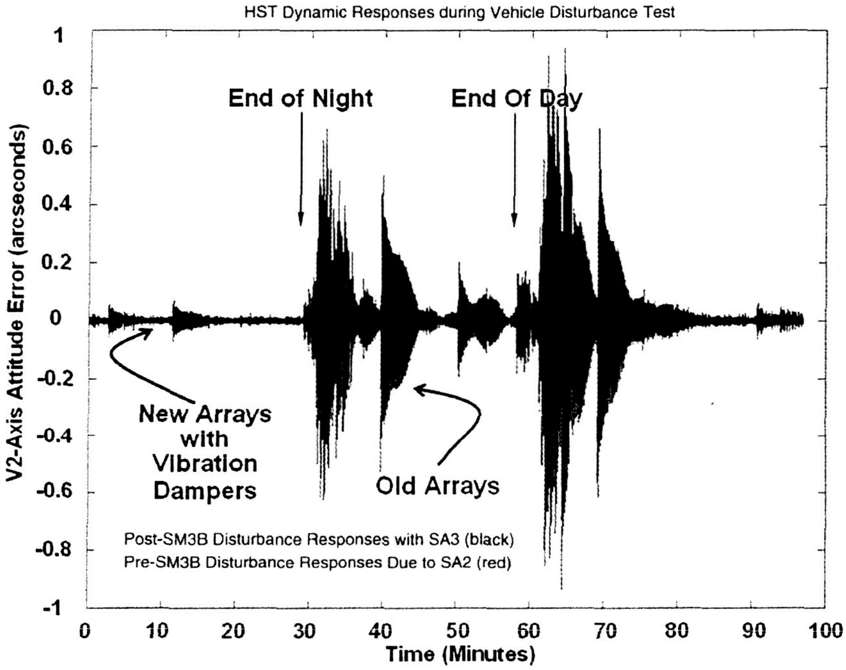


Figure 14. Measured HST attitude error with SA3 compared to SA2, during one orbit of the Telescope

The greatest variation in material stiffness from the pre-life-cycle measurements, for any of the specimens, was 19%, and the highest variation in loss was less than 5%. A stiffness increase of 19% will have a minimal effect on the bending mode frequencies of SA3, for the following reason. The viscoelastic material has less than 20% of the strain energy of the bending modes, so a 19% increase in viscoelastic stiffness will change the stiffness of the bending mode by less than 4% (20% of 19%). A 4% increase in the stiffness would raise the 1.50-Hz mode to about 1.53 Hz. With no change in loss, the damping of the mode would increase because more strain energy would go into the viscoelastic with higher stiffness. Most of the measured changes in loss increased, however, so even higher damping would be achieved.

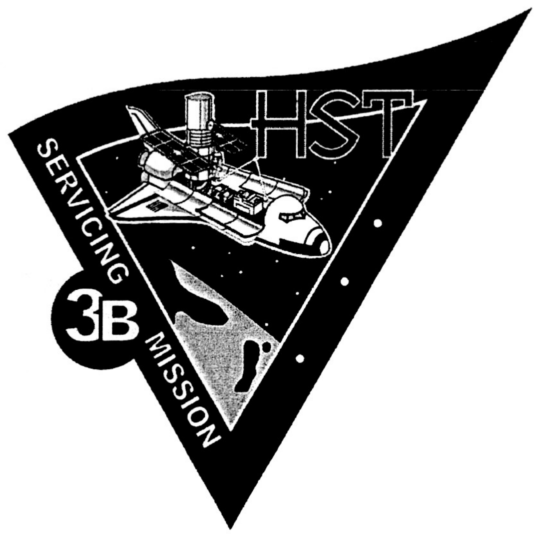
9. SUMMARY

Test specimens of the damping material for the HST SA3 damper were subjected to an accelerated aging environment. Ultrasonic inspection of the interfaces was used to determine if any delamination or failure of the adhesive bond between the viscoelastic material and the titanium had occurred. To determine whether material degradation occurred during the environment exposure, the complex stiffness of the material specimens, reported in terms of real stiffness and loss, was measured before and after the accelerated aging.

All specimens, including the control specimen, showed variations between measurements made before and after life cycling. Most specimens showed increased stiffness, ranging from 8% to 19%, but minimal changes in loss, ranging from 0% to 4.5%. Since the control specimen also showed some changes, potential sources of measurement error were considered. However, even if the material stiffness changed by 19%, the highest amount seen in these measurements, the effect on the bending mode frequencies of the SA3 will be minimal. Based on modal strain energy distribution of the

SA3 bending modes, this amount of stiffness increase will change the stiffness of the bending modes by, at most, 4%. A 4% increase in the stiffness would raise a 1.50-Hz mode to about 1.53 Hz. With no change in loss, the damping of the mode would increase slightly because more strain energy would go into the viscoelastic with higher stiffness. However, most of the measured changes in loss were increased, so higher damping would be achieved if the material changed in this manner.

Based on the pre- and post-life-cycle measurements of the 3M ISD142R material, it was judged that the material should perform as expected when subjected to the aging that will occur during testing, integration, launch, and life on-orbit.



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