Second year performance report for the grant:

HEALTH MONITORING OF COMPOSITE MATERIAL STRUCTURES USING A VIBROMETRY TECHNIQUE

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by

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1. INTRODUCTION

Non-destructive evaluation (NDE) methods for quantifying and locating damage are essential for inspecting structures to ensure safety and reliability. Transmittance function monitoring is a potentially new NDE technique being tested as a tool to detect, quantify, and locate damage on flexible structures. The technique has a large spatial range that is practical for detecting damage on large composite material structures such as a reusable launch vehicle. The Transmittance Function (TF) theory is based on structural dynamics principles that define how vibration at one point in a structure is related to a force at another point. This relationship is called the Frequency Response Function (FRF). A Transmittance Function (TF) is derived as the ratio of FRFs, and can detect damage because the FRFs change due to damage. If one excitation is used for the testing, the force does not need to be measured to compute the TF. In the damage detection procedure, the structure is subjected to wide-band vibration and TFs are computed between different accelerometers to detect changes in the structure, presumably due to damage.

In the first year of the project the TF method was tested on a bolted panel, a curved panel, and beams, all made of fiberglass. It was shown that damage could be detected using low frequency vibration, 250 to 1,250 Hz. The technique is sensitive to damage, but it requires storage of historical or pre-damage TFs for the healthy structure. This would become a large data storage requirement for large structures. Thus one objective for the second year of the project was to eliminate the need to store historical data. The second year report gives details of how storage of historical data was eliminated. Further results of testing panel structures are also given.

2. DAMAGE DETECTION THEORY

A schematic illustrating the Transmittance Function (TF) method is shown in Figure 1.

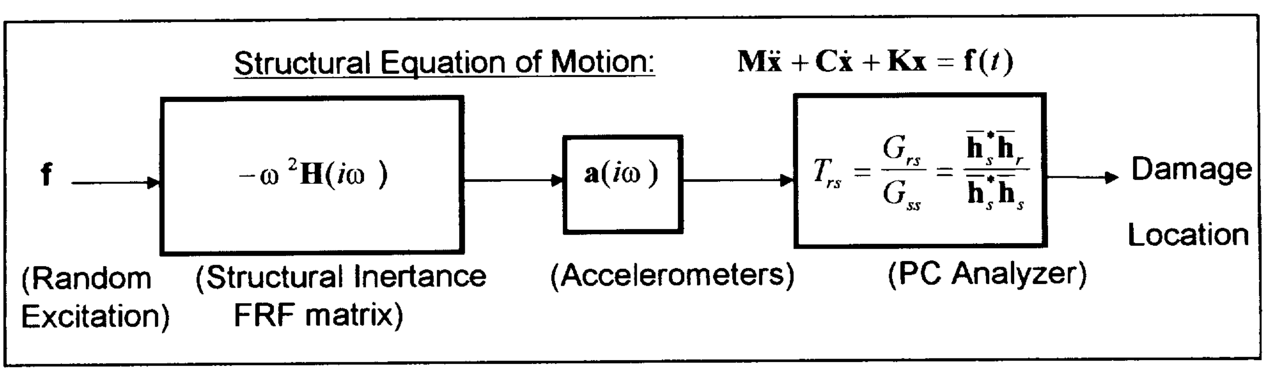

Figure 1. Schematic of the Transmittance Function Monitoring system

In practice, the TF is computed as:

$$T_{rs} = \frac{G_{rs}}{G_{ss}}. \tag{1}$$

The TF matrix is written as (n is the number of accelerometers on the structure):

$$\mathbf{T}=\begin{bmatrix} 1 & T_{12} & \cdots & T_{1n} \\ T_{21} & 1 & & T_{2n} \\ \vdots & & \ddots & \vdots \\ T_{n1} & T_{n2} & \cdots & 1 \end{bmatrix} \tag{2}$$

Either the first row or first upper diagonal of the **T** matrix is used to detect damage. Damage is determined using a normalized damage matrix defined as:

$$\mathbf{D} = \int_{f1}^{f2} |\mathbf{T}^h - \mathbf{T}^d| / |\mathbf{T}^h| \, df \tag{3}$$

For symmetric structures, it is possible to detect damage without using historical data by monitoring TFs that approximately equal one in the undamaged condition. This is done by clipping the TFs to make them closer to one for a symmetric excitation and structure. The clipping also removes bad data due to round-off errors at the anti-resonant points of the FRFs.

A variance damage indicator has been derived for use with the clipping algorithm. The variance damage indicator is defined as:

$$D_v = \frac{\int_{f1}^{f2} \left|T^d - \mu^d\right|^2 df}{\int_{f1}^{f2} \left|T^h - \mu^h\right|^2 df} - 1 \tag{4}$$

where μ is the mean value of the TF. The variance damage indicator does not need to store the historical data or healthy TFs versus frequency. This damage indicator requires storing only one number per healthy TF. The down side is that the damage indicator (4) will have somewhat reduced sensitivity to that given in (3).

The variance damage indicator with clipping actually can be used on non-symmetric structures also as long as the variance values are known for the healthy structure.

3. EXPERIMENTATION

Damage detection testing was performed on a bolted composite plate using accelerometers, a curved composite panel using a laser vibrometer, and on a composite debris shield using PZT patches. These experiments are described below.

3.1 Delamination Detection

This experiment uses two fiberglass panels with dimensions 48 inches by 48 inches by

¼ inch. Steel bolts that are ¼ inch diameter are used to hold the panels together (144 inside bolts and 52 boundary bolts) thus creating one panel that is ½ inch thick that is the horizontal top of a table, as shown in Figure 2. Screws can be loosened to simulate different sizes and locations of reversible delamination damage. The panel is bolted along all edges to a horizontal steel frame to simulate fixed BC's. Four piezoceramic accelerometers are attached to the panel. A piezoceramic inertial actuator is used to excite the plate in the center. Signal processing is done using four channels of a 16-channel DP-420 FFT analyzer board inside a PC.

The Normalized error of Auto Power Spectra (APS) and Cross Power Spectra (CPS) are used to calculate the TFs. The error is minimized (≈0.1%) by taking 100 averages. "Healthy" TFs are calculated from the undamaged panel. Delamination in the mid-thickness of the panel is simulated by loosening successive bolt groups to 5 lb.-in torque, and the "damaged" TFs are calculated.

The Coherence [1] between the accelerometers and the actuator is a measure of how much of the response is due to the input. The Coherence between the force (y) and accelerometer (x) is:

$$C_{xy} = \left|G_{xy} * G_{yx}\right|^2 / \left(G_{xx} * G_{yy}\right) \tag{5}$$

and ranges from 0 to 1. Coherence decreases at frequency values where the FRFs approach zero. Also, the TFs become large at these frequency values due to near zero APS values or ratios of CPS values to lower APS values. Clip levels can be determined for the APS and CPS to limit fluctuation in the TFs due to low coherence. Clipping can be APS only, or APS and CPS. Maximum values of the damage matrix (4) are shown in Table 1 for individual APS & CPS clipping, and in Table 1 for one clip value for all APS & CPS using TF variance (4) as damage.

The results in Table 1 show that in the composite panel, 3% to 12% delamination was detected by the TF technique. Coherence based clipping made the TFs behave more symmetric. Ideally, the TF in the healthy condition would equal one when the structure and loading are symmetric. Symmetry based clipping is done by choosing a clip level to make the TF at symmetric locations be close to one. This reduces the amount of historical data to one matrix of TF variance values. Sensitivity to damage is decreased with both clipping types. The damage is detected in all experiments, but could not be located using only four sensors. Higher frequency input might be required to locate the damage. In Figure 3, a symmetry clipped TF (APS & CPS) is shown. The large variations from one indicate damage. Symmetry of the structure and loading simplifies the technique, but the technique also works for non-symmetric cases as long as the variance value in the healthy condition is used for reference.

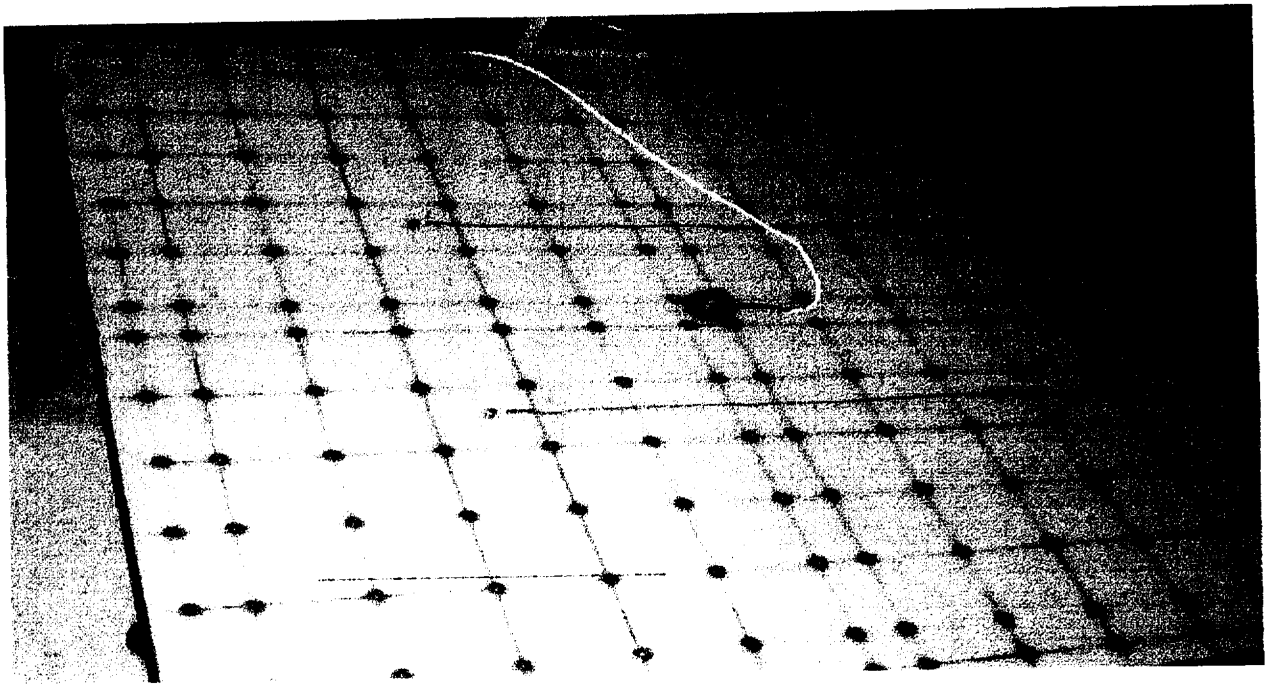

Figure 2. Composite panels bolted together

Table 1. Maximum D Matrix values (TFs for coherence clipping, variance for symmetry clipping)

	Coherence Clipping			Symmetry Clipping	
Damage Level	No Clipping	APS Clipping	APS & CPS Clipping	APS Clipping	APS & CPS Clipping
none	0.0208	0.0561	0.0392	0.0205	0.0729
4-bolts	0.3978	0.3104	0.1935	0.2158	0.5843
9-bolts	0.5931	0.4144	0.3435	0.3578	0.8145
13-bolts	0.6567	0.5570	0.4734	0.3856	1.1867
18-bolts	0.7979	0.6210	0.5140	0.4583	1.3592

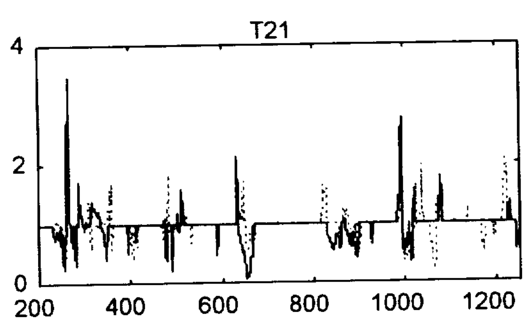

Figure 3. Symmetry clipped TF (APS & CPS), healthy=dash line, damaged=solid line

Summarizing these results, in the composite panel 3% to 12% delamination was simulated, and then detected by the TFM technique. Coherence based clipping made the TFs behave more symmetric. Symmetry based clipping reduced the amount of historical data to one matrix of TF variance values. Sensitivity to damage was decreased with both clipping types. While damage could always be detected, it could not always be located. This means that more sensors are needed to get a better spatial resolution of damage, or higher frequency input might be required to locate the damage. Elimination of the need to store the frequency dependent data from the healthy structure is a significant improvement in the technique.

3.2 Damage Detection on a Curved Panel

A curved fiberglass panel 1/4 in by 48 inch by 48 inch is used with piezoceramic PZT patch actuators and a Scanning Laser Doppler Vibrometer (SLDV) to detect damage, as shown in Figure 4. Damage is simulated as a 2-inch saw cut at the top of the panel. The SLDV is used to measure FRFs at closely spaced points. Reflective tape is used at some points to minimize laser signal dropout

The results of the testing show that adjacent FRFs away from damage (Figure 5) have similar amplitudes. On the other hand, adjacent FRFs near the cut (Figure 6) have different amplitudes at certain frequencies. Thus differences in paired FRFs at symmetrically located points can identify moderate to large damage to structures. The next step in the laser testing is to develop utility software to download the laser data to MATLAB and then to compute transmittance functions using the algorithm for sequential data derived for this use. The theory of computing TFs from sequential data is given in the first year report.

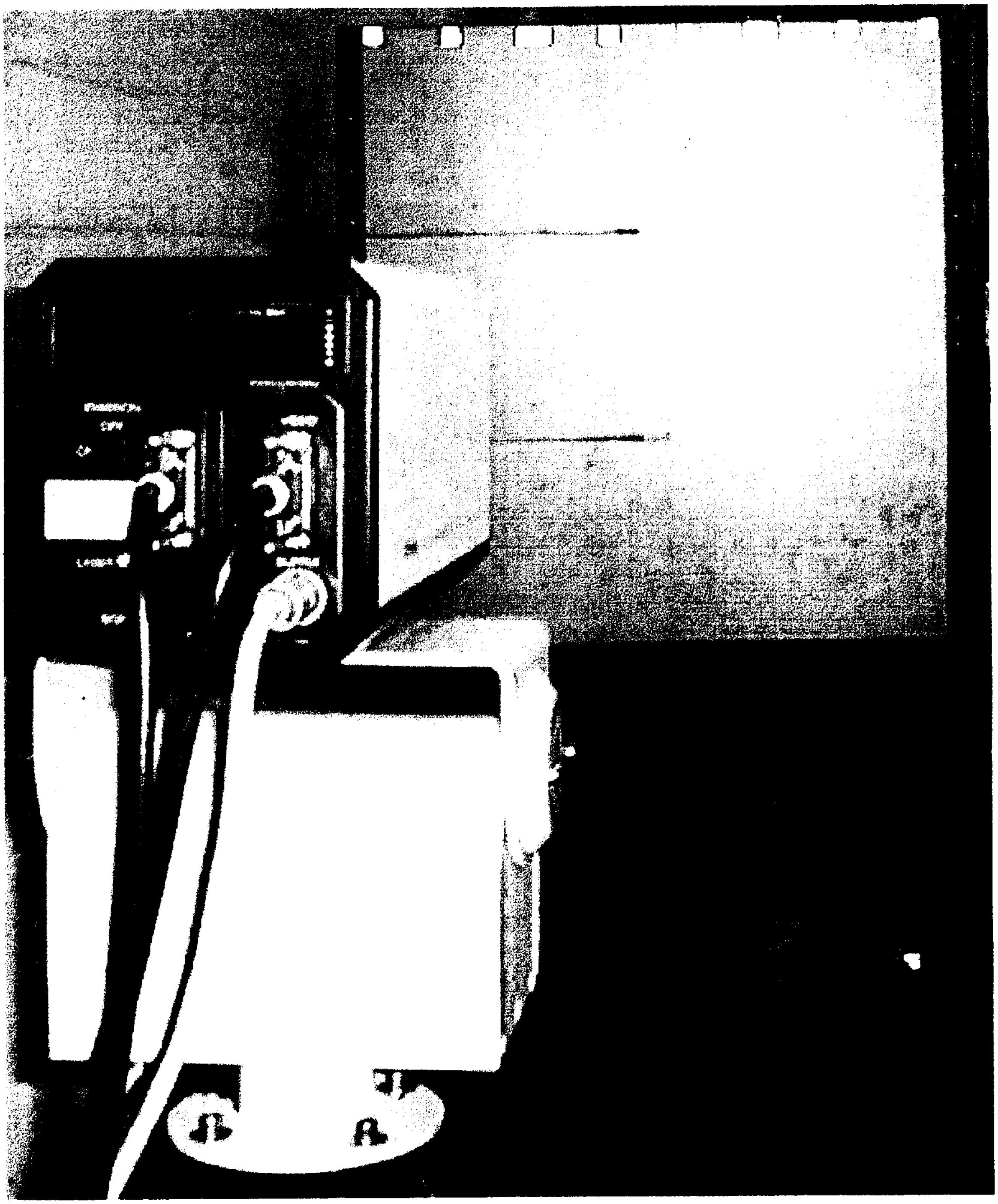

Figure 4. Curved fiberglass panel and SLDV

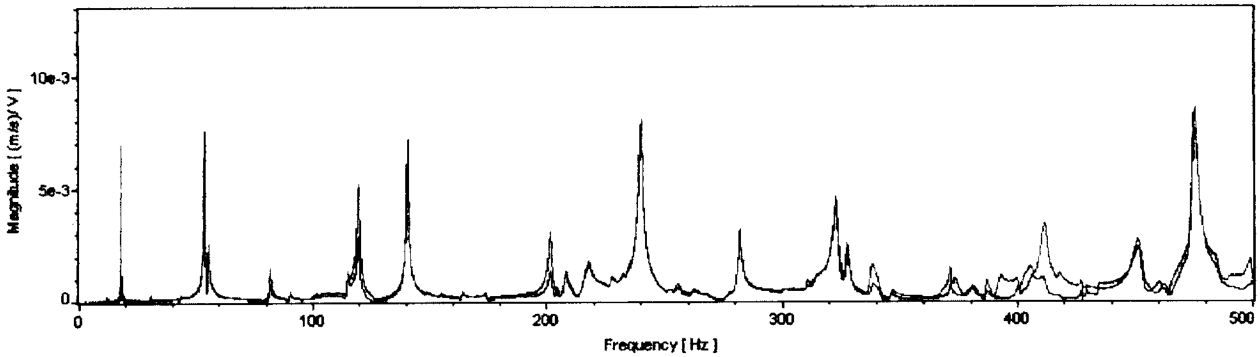

Figure 5. FRFs at adjacent points on undamaged section of panel

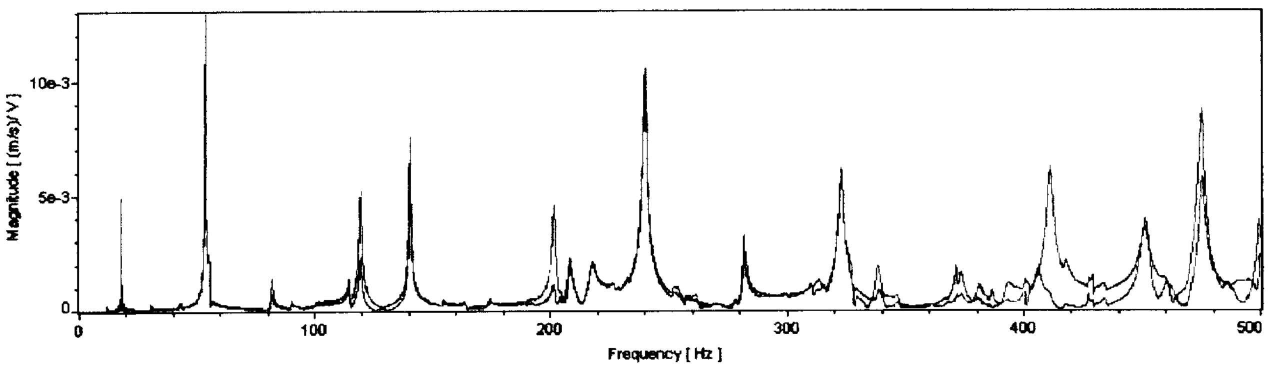

Figure 6. FRFs at adjacent sides of cut on panel

3.3 Damage Detection in a Graphite-Epoxy Debris Shield

Previously fiberglass has been used in the damage detection testing due to its low cost and availability. However, the technical monitor of this grant, Mr. Chuck Wilkerson of NASA Marshall Space Flight Center, was able to donate a graphite–epoxy debris shield to test for damage detection. The shield is shown in Figures 7 and 8.

The test is set up to detect damage to the shield using four PZT patches on the inside surface of the panel (Fig. 8). The PZTs are ACX type QP10N, which are nominally 2"X1"x0.01". The PZTs are used alternatively as sensors and actuators.

The experimental setup is comprised of a DP420 signal processor, a random noise generator, and an amplifier to drive the patches. Two patches are actuated at one time and the other two act as sensors. There are six possible combinations of sensor/actuator pairs. With each combination taken, a full Transmittance Function Matrix can be assembled. The first experiments were taken during different time intervals; therefore the data presented herein is of separate transmittance function pairs.

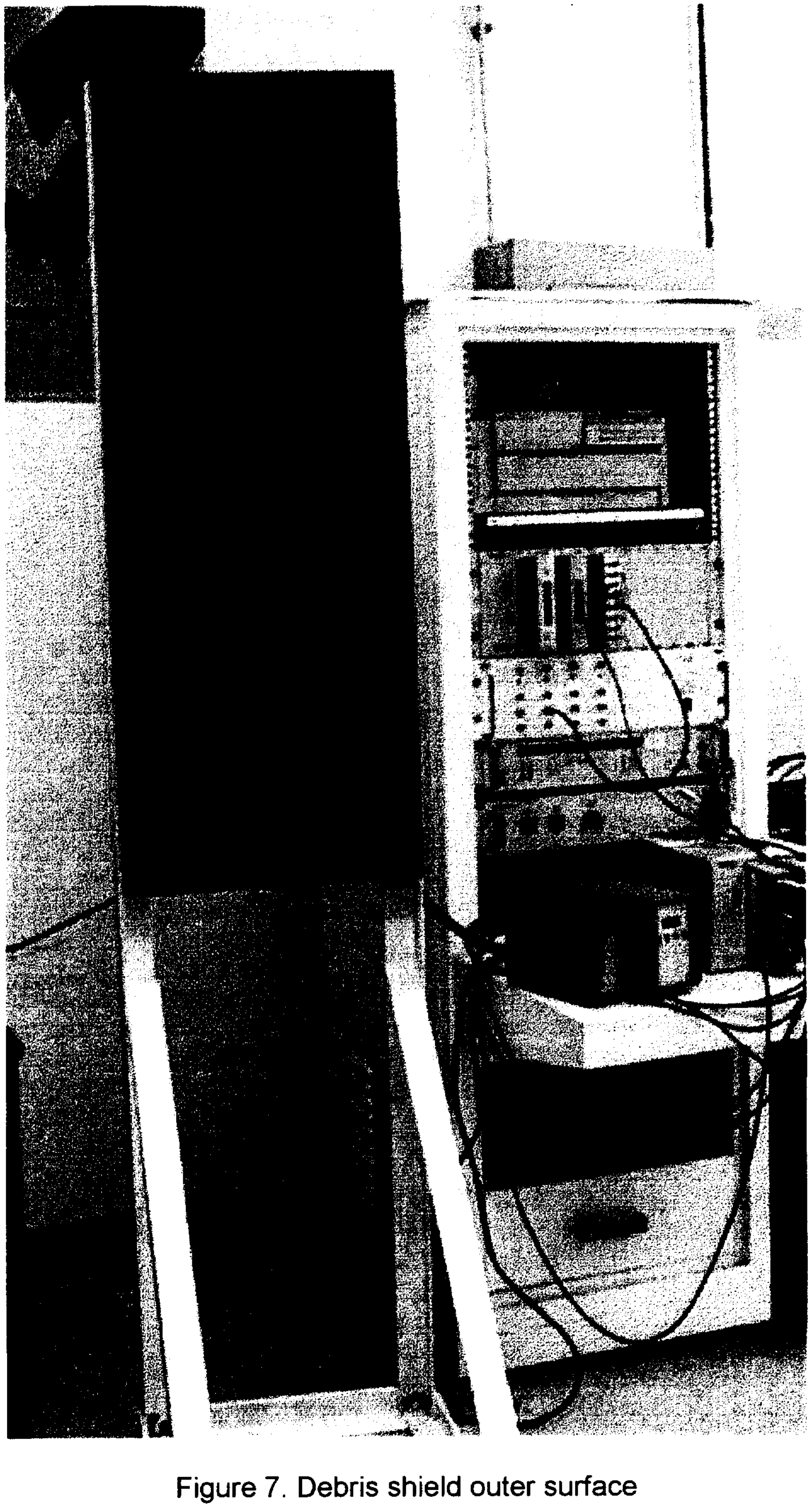
Figure 7. Debris shield outer surface

Figure 8. Debris shield inner surface showing four PZT patches

With no damage, the typical noise level for healthy-healthy comparisons using the damage formula (3), was 0.05 ~ 0.10. Each experimental run produces a two by two Transmittance Function matrix, according to whichever patches are being used as sensors. For example, if patches 1 and 2 are actuators, then the TF matrix will contain T34 and T43 (note: analytically T33 and T44 are equal to unity).

Bonding a thin 2-in. square metal plate near sensor 3, as shown in Figure 9 simulated damage to the shield.

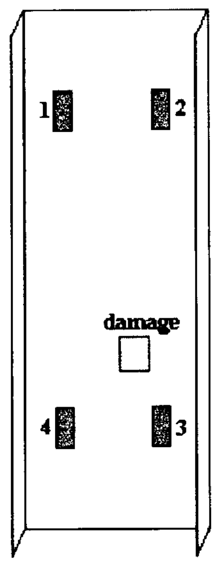

Figure 9. Schematic of debris shield with PZTs and damage

Each Transmittance function pair showed an increase in damage due to the plate. Graphically, The damage is more noticeable between sensor pair 2 and 3, than the other sensor pairs. With this simulated damage, the typical ratio between the damaged values and the healthy values was approximately 4.2. The healthy-healthy comparison and damage-healthy comparisons are shown in Figures 10-16. A summary of the damage values is given in Table 2.

Further testing of the debris shield will be at higher frequency to improve sensitivity, and using the variance TF to eliminate the need to store historical data.

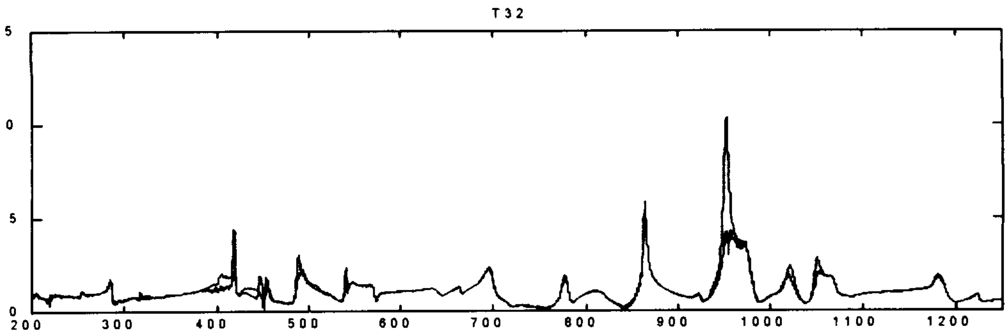

Figure 10. T32 healthy-healthy, blue = healthy1, red = healthy2

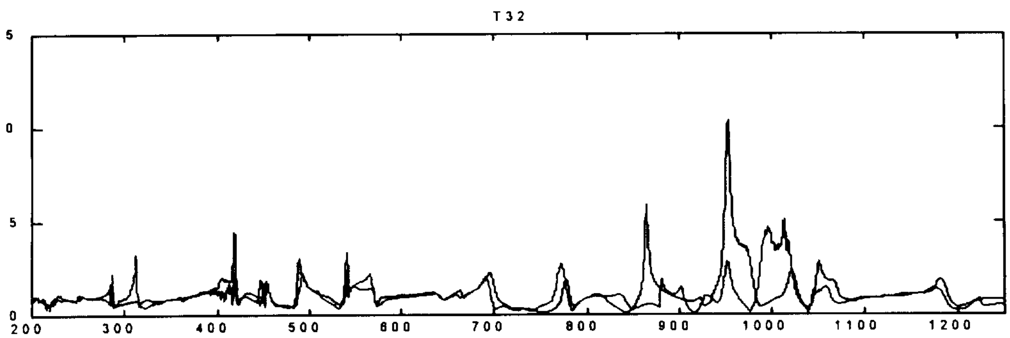

Figure 11. T32 healthy-damaged, blue = healthy, red = damaged

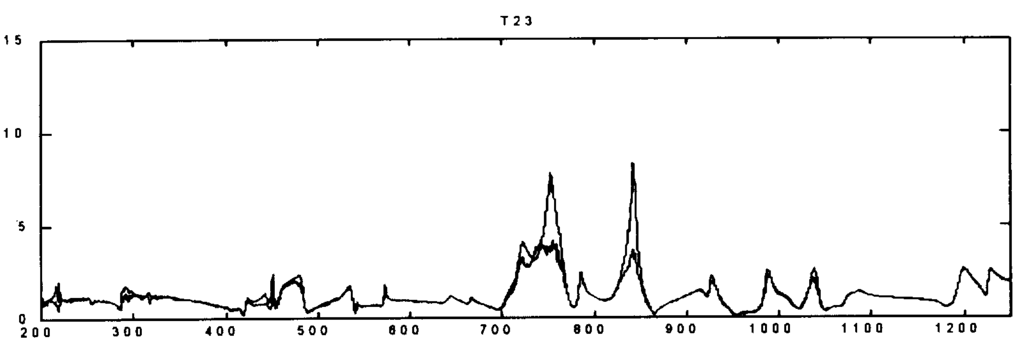

Figure 12. T23 healthy-healthy, blue = healthy1, red = healthy2

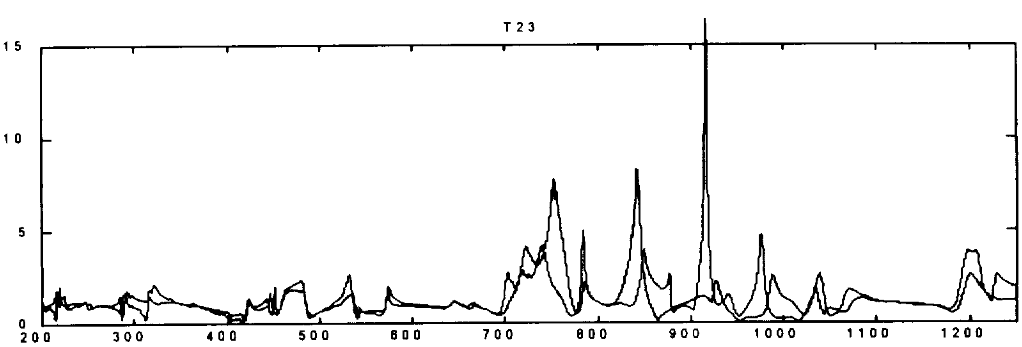

Figure 13. T23 healthy-damaged, blue = healthy, red = damaged

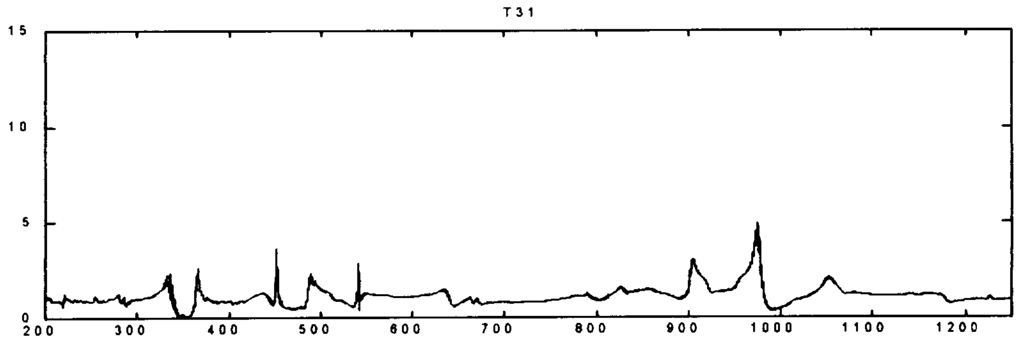

Figure 14. T31 healthy- healthy, blue = healthy1, red = healthy2

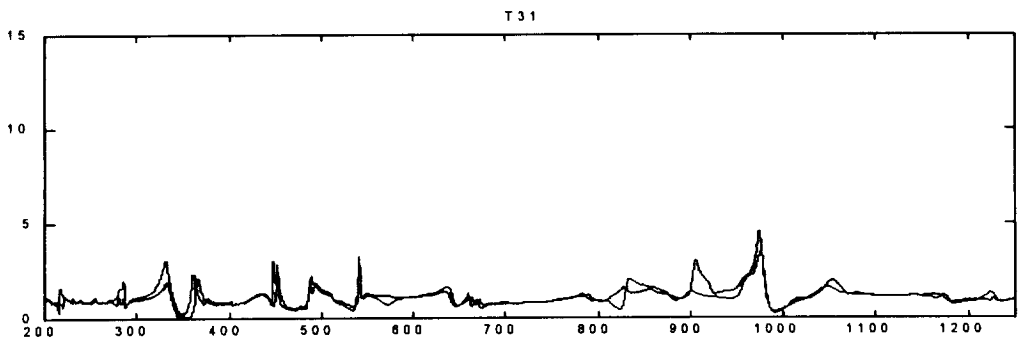

Figure 15. T31 healthy-damaged, blue = healthy, red = damaged

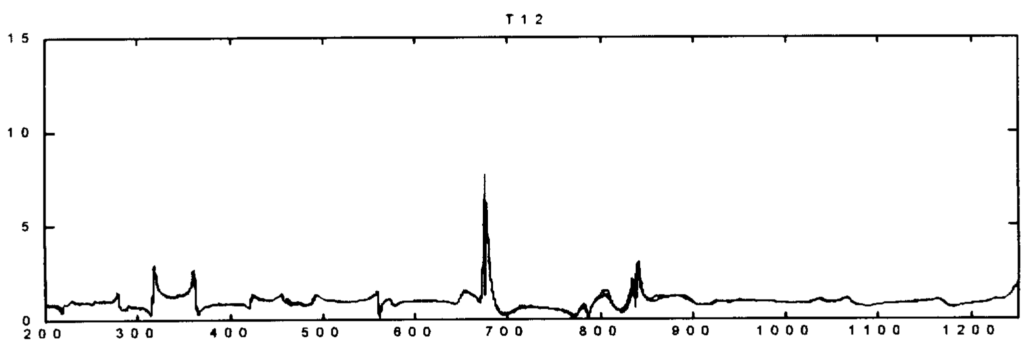

Figure 16. T12 healthy-healthy, blue = healthy1, red = healthy2

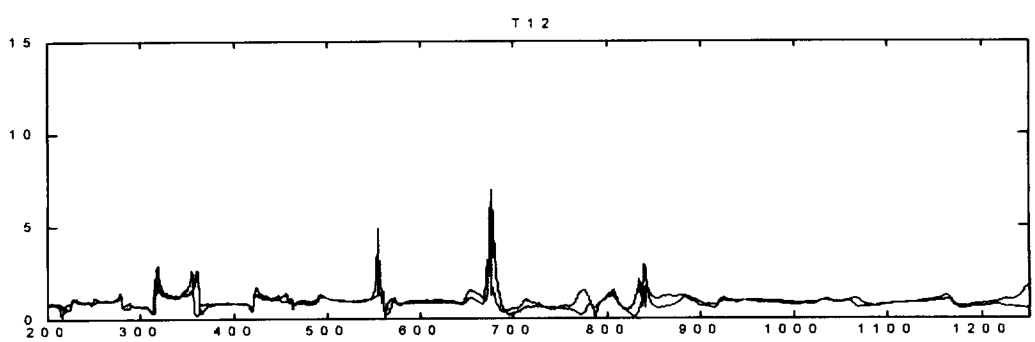

Figure 17. T12 healthy-damaged, blue = healthy, red = damaged

Table 2. Transmittance function values for debris shield

Transmittance Function Pair	Damage Matrix Value **no damage**	Damage Matrix Value **damage**
T34 **T43**	0.0742 0.0586	0.2221 0.2777
T12 **T21**	0.0538 0.0605	0.2327 0.2625
T42 **T24**	0.0508 0.0564	0.2405 0.2598
T13 **T31**	0.0374 0.0414	0.1614 0.1778
T14 **T41**	0.0721 0.0765	0.3169 0.3613
T32 **T23**	0.1186 0.1357	0.4406 0.4702

4. CONCLUSION

The TF method has been improved by eliminating the need to store historical frequency dependent data. The use of a laser vibrometer to get more measurement points and give a better spatial resolution of damage is possible based on the initial testing done. Damage detection testing of a debris shield using PZT sensors/actuators is shown to also be a feasible approach to detect damage.

Two other goals in developing the damage detection technique are to eliminate the need for artificial excitation, and to verify the insensitivity of the technique to environmental changes.

5. REFERENCES

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6. PUBLICATIONS TO DATE

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6. Schulz, M.J., Brannon, G.S., Naser, A.S., and Pai, P.F., "*Structural Health Monitoring using Frequency Response Functions and Sparse Measurements*," IMAC-XVI, February 2-5, 1998, Santa Barbara, CA.
7. Schulz, M.J., Naser, A.S., Pai, P.F., and Chung, J., "*Locating Structural Damage Using Frequency Response Reference Functions and Curvatures*," International Workshop on Structural Health Monitoring," September 18-20, 1997, Stanford University, Stanford, CA.

7. STUDENT AND FACULTY PARTICIPATION

The time spent on the project by the faculty members and students for the second year is listed below. All students working on the project are from underrepresented groups.

- The PI spent one-month full time to direct the project and develop damage detection theories.
- The post-doctoral research associate working part time on this project left the university and a replacement is being hired, but this is putting spending behind schedule.
- The adjunct faculty member and a technician worked on the project two weeks each to help set-up fixtures and develop methods for attaching and protecting PZT sensors.
- One graduate student is working full time over the summer on the project and worked part-time during the semesters. He presented his research at the ICCE/5 conference.
- Two undergraduate students worked on the project during the semesters. One undergraduate student is continuing as a master's student.
- A high school senior worked on the project for six weeks in the summer. She helped the graduate student perform testing and reduce data from the experiments.

She was supported by the NASA SHARP Plus program, and not from this grant.

8. PRESENTATIONS AND CONTACTS

The following presentations have been made thus far in the project; some of the results presented involve leveraged support from different projects that the PI has on health monitoring.

a) Conference Proceedings
   - Presentations at three conferences were made on health monitoring techniques in which theresearch was partly supported by this project.

b) Contact with technical monitor
   - The PI and technical monitor have regular phone contact on progress of the project. The PI has sent the technical monitor the papers published. The technical monitor has suggested testing larger components and has sent a debris shield for testing.

9. CONTINUING RESEARCH

The damage detection technique will be improved by trying to eliminate the need for artificial excitation, and by verifying the insensitivity of the technique to environmental changes.

Further testing using the laser and with the debris shield will also be performed. Testing using different input waveforms and sizes of PZT patches will be performed to optimize the sensor system.