Control of the UltraLITE Precision Deployable Test Article Using Adaptive Spatio-Temporal Filtering Based Control

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ABSTRACT

Experimental results are presented for active vibration control of the Air Force Research Laboratory's UltraLITE Precision Deployable Optical Structure (PDOS), a ground based model of a sparse array, large aperture, deployable optical space telescope. The primary vibration suppression technique employs spatio-temporal filtering, in which a small number of sensors are used to produce modal coordinates for the structural modes to be controlled. The spatio-temporal filtering technique is well suited for the control of complex, real-world structures because it requires little model information, automatically adapts to sensor and actuator failures, is computationally efficient, and can be easily configured to account for time-varying system dynamics. While controller development for PDOS continues, the results obtained thus far indicate the need for an integrated optical/structural control system.

Keywords: vibration, suppression, sparse, optical, array, space, telescope, modal

1. INTRODUCTION

The Air Force Research Laboratory (AFRL) Space Vehicles Directorate, located at Kirtland Air Force Base in Albuquerque, NM, is developing advanced concepts and innovative supporting component technologies for large aperture imaging systems [1]. These include lightweight mirrors, precision deployable composite structures, positioning control systems for phasing large optics, and structural control. Since January 1996, numerous ground test beds have been constructed at AFRL, which will culminate in the construction of the Deployable Optical Telescope (DOT), slated for completion in January 2000. The Deployable Optical Telescope is a 1.7 meter diameter deployable, large-aperture, sparse array (37% fill fraction) optical telescope that will demonstrate many of the capabilities required for a deployable space telescope. The main objective of DOT is to demonstrate autonomous deployment, phase capture, and maintenance of three 60 centimeter diameter primary mirrors in a simulated operational environment.

Sheet Dynamics, Ltd. (SDL) is currently working with AFRL under an SBIR Phase II contract to develop innovative structural control concepts for both the ground based Deployable Optical Telescope and the future deployable space telescope. This paper describes the application of SDL's proprietary spatio-temporal filtering algorithms to the Precision Deployable Optical Structure, a precursor to the more complicated Deployable Optical Telescope system. The organization of the paper is as follows. Section 2 presents a description of the Precision Deployable Optical Structure test facility. Section 3 describes the objectives of the optical and structural control systems. Section 4 describes the adaptive spatio-temporal filter based control algorithm. Section 5 discusses the closed loop control results. Finally, Section 6 contains a discussion of the results and conclusions.

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2. PDOS DESCRIPTION

The Precision Deployable Optical Structure (PDOS) was designed to address the issues associated with the deployment of a precision structure and the active control of a sub-aperture element to optical tolerances. The scale and control requirements have been designed with traceability to large (10m class) deployable optical systems [1]. PDOS, which is pictured in Figure 1, consists of an aluminum honeycomb Mirror Mass Simulator attached to a composite Reaction Plate structure using three Physik Instrumente P-842.20 PZT-stack actuators. The Reaction Plate is attached to a Backup Structure through two hinges and a latch, and the Backup Structure is bolted to a 66,000 lb granite table. There are four air-bag isolators between the laboratory floor and the granite table. A passive zero-gravity suspension device from CSA Engineering provides gravity offload for the lightweight structures and mechanisms, and is mounted directly to the laboratory ceiling [2]. With a resolution of 10 nanometers, a Hewlett-Packard interferometer system measures the displacement between the granite table and three locations on the Mirror Mass Simulator nearly collocated with the PZT-stack actuators.

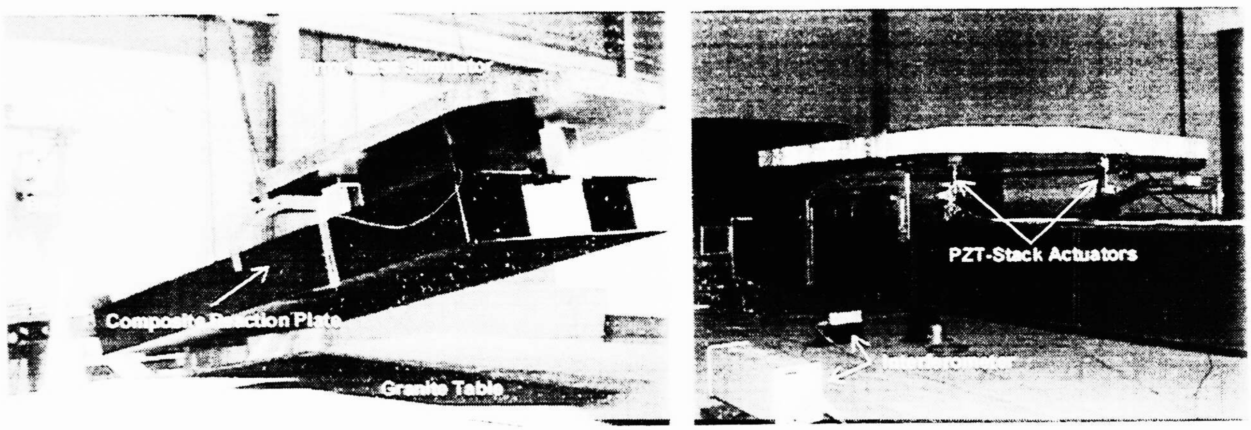

Figure 1: Two views of PDOS: during deployment (left) and in test configuration (right)

The heart of the IBM-compatible PC-based digital control system is a dSPACE, Inc. DS1003 board which includes a Texas Instruments TMS320C40 digital signal processor (DSP). In conjunction with the MATLAB/Real-Time Workshop software from The MathWorks, Inc., the Total Development Environment software from dSPACE, Inc. allows the user to automatically convert MATLAB/SIMULINK control system block diagrams into real-time executable code, thus enabling rapid implementation of controllers. TRACE and COCKPIT software from dSPACE, Inc. allow for real-time display and manipulation of control system variables [3]. The plant under consideration has 3 inputs and 3 outputs, corresponding to the 3 PZT-stack actuators and the 3 nearly collocated interferometer signals.

3. CONTROL OBJECTIVES

The objective of the control system is to maintain root-mean square (RMS) values for the interferometers at less than 30 nanometers under ambient vibration disturbances. Figure 2 shows the power spectral densities (PSD's) for the interferometers over the frequency band 0-200 Hz (computed using the MATLAB script *psd.m)* due to the ambient laboratory disturbance environment. The distances from the hinge line at the clamped end of the Reaction Plate to interferometers 1, 2 and 3 are 102, 65, and 65.5 inches, respectively. The corresponding RMS values for interferometers 1, 2 and 3 are 155.3, 98.23 and 89.05 nanometers, respectively.

It is apparent from Figure 2 that most of the energy in the system lies in the frequency band 0-15 Hz. Figure 3 shows the same PSD's as in Figure 2, however, the frequency band has been zoomed to 0-50 Hz. The vertical lines appearing in Figure 3 correspond to structural vibration modes identified from a modal test, in which band-limited random noise was input to each of the PZT-stack actuators and frequency response functions (FRF's) were computed for the interferometers. The Eigensystem Realization Algorithm (ERA) [4] was then used identify a discrete (A,B,C,D) state-space model of the plant using these FRF's. Figure 4 shows a comparison of identified model versus test frequency response functions, indicating an excellent curve-fit. The next section describes the adaptive STF algorithm which was used to control PDOS modes.

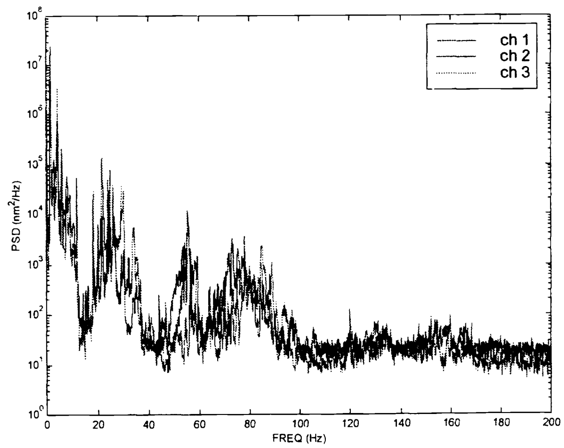

Figure 2: Interferometer Power Spectral Densities Under Ambient Conditions (0-200 Hz)

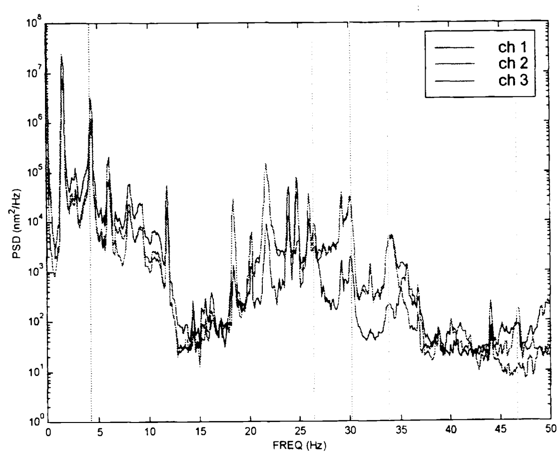

Figure 3: Interferometer Power Spectral Densities Under Ambient Conditions (0-50 Hz)
(Vertical Lines Represent Structural Vibration Modes)

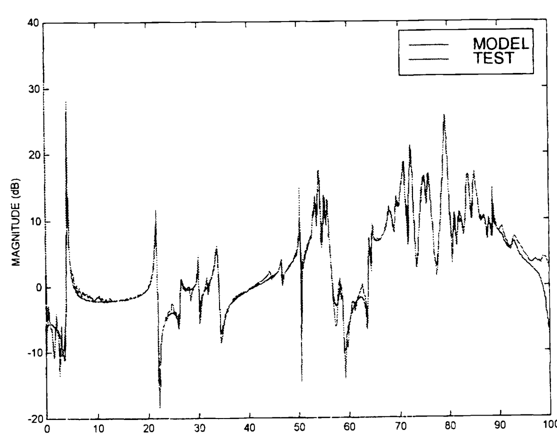

Figure 4: Model versus Test Frequency Response Function for Interferometer 1 over PZT-Stack Actuator 2

4. ADAPTIVE SPATIO-TEMPORAL FILTERING THEORY

In this section, the origins of spatio-temporal filtering (STF) are discussed, STF theory and its application to structural vibration control is reviewed, and a reference model approach to adaptively calculating and updating STF coefficients is presented.

1. STF BACKGROUND

STF is an extension of modal, or spatial, filtering which has been investigated by the authors and other researchers for some time [5-11]. Modal filtering utilizes the characteristic that the dynamic response of any real structure is composed of a sum of individual modal responses, each behaving as a single-degree-of-freedom (SDOF) system and each having a particular response shape or eigenvector. The modal filter approach applies sets of scalar, spatial weighting coefficients to responses measured by each element of a sensor array to extract these individual canonical modal responses from the global response of the structure. Note the modal filter is **NOT** related to a conventional bandpass filter. Each channel of the modal filter has output across the entire frequency band, however, it is the output associated with just a single mode (see Figure 5).

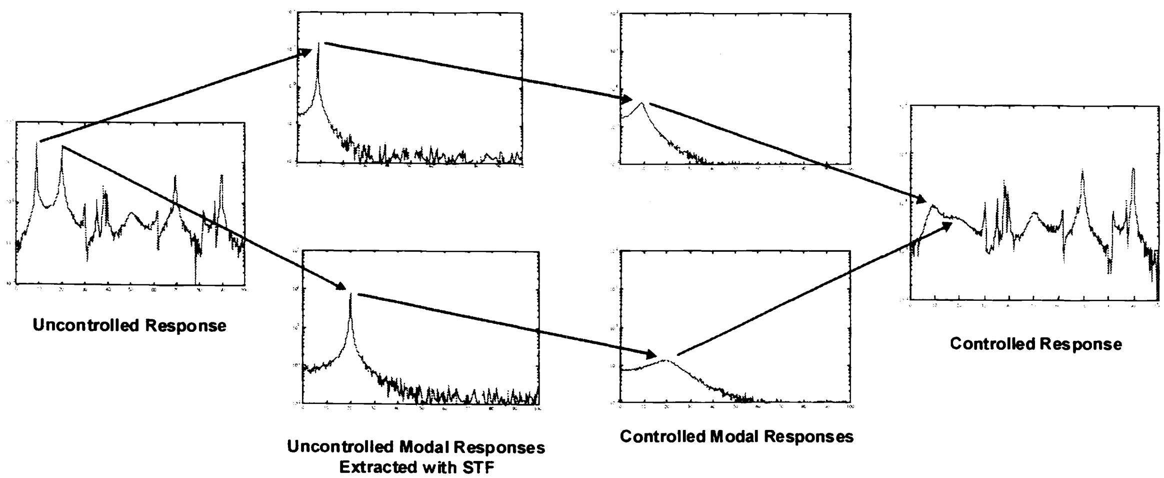

Figure 5: STF Based Vibration Control

The basis for modal filtering is the standard modal coordinate transformation that is utilized to simplify the solution, understanding, and analysis of systems of linear differential equations. For simplicity consider the undamped, structural case where the common discrete system model consists of a second order linear differential equation with N by N matrix coefficients of mass and stiffness terms

$$M\ddot{x} + Kx = f \qquad 1$$

Equation 1 may be solved for N linearly independent eigenvectors ϕ_r. Since the eigenvectors are linearly independent the system response, x, may be represented as a linear combination of the eigenvectors weighted by the canonical degrees of freedom, called modal coordinates, $\eta_r(t)$.

$$\begin{aligned} x(t) &= \sum_{r=1}^{N}\left[\phi_r \eta_r(t)\right] \\ &= \Phi\eta(t) \end{aligned} \qquad 2$$

For the physical case, where control and monitoring are being conducted on a structure, the response vector, $x(t)$, is measured with sensors located at corresponding physical locations and measurement directions. A modal filter is applied to the measured response data, $x(t)$, to extract the modal coordinate response(s), $\eta_i(t)$, of interest. To extract the modal coordinate response for the $i'th$ mode, a vector of spatial weighting coefficients, ψ_i, is sought which has the following characteristics

$$\begin{aligned} \psi_i^T \phi_r &= 0 \quad i \neq r \\ &= 1 \quad i = r \end{aligned} \qquad 3$$

The inner product between the modal filter vector, ψ_i, and response vector, $x(t)$, is formed which is equivalent to forming a weighted average of the response signals measured at different locations on the structure.

$$\begin{aligned} \psi_i^T x(t) &= \psi_i^T \sum_{r=1}^{N} \left[\phi_r \eta_r(t) \right] \\ &= \psi_i^T \phi_i \eta_i(t) \\ &= \eta_i(t) \end{aligned} \qquad 4$$

The resulting scalar quantity is the modal coordinate response, $\eta_i(t)$, for the $i'th$ mode and the vector, ψ_i, is the associated modal filter vector. The above discussion holds for the damped case as well, both proportional and non-proportional [7].

2. Spatio-Temporal Filtering

The spatio-temporal filter is a generalization of the spatial or modal filter which extends the capabilities by utilizing temporal information: two dimensional filtering in the space and time dimensions. This reduces the number of sensors required, allows dissimilar sensors to be integrated, and accommodates sensor dynamics. In order to extract the modal coordinate response of interest with modal filters, the modal vectors, as sampled at the sensor locations, must be linearly independent [7]. This dictates that at least as many sensors as there are independent modes contributing to the measured response are required. Even with modern low cost sensors and DSP electronics this may be viewed as a disadvantage in some applications.

The modal filter estimates the modal coordinate response at time k by forming a weighted summation of sensor signals measured at different spatial locations at time k

$$\hat{\eta}_k = \psi^T x_k \qquad 5$$

An N_t 'th order spatio-temporal filter also utilizes N_t past samples of the response information

$$\hat{\eta}_k = \psi^T \begin{Bmatrix} x_k \\ x_{k-1} \\ \vdots \\ x_{k-Nt} \end{Bmatrix} \qquad 6$$

This introduces a different N_t 'th order finite impulse response (FIR) or all-zero filter on each sensor channel. The FIR filters perform different functions depending on the specific implementation: pole-zero cancellation if spatial resolution alone is insufficient to separate modes, accommodating the relative phase between sensors caused by complex (non-proportional damping) modes, selective differentiation if a non-homogeneous sensor array is used, and correction for some sensor dynamics. Most likely a combination of the above characteristics will be manifested in the temporal filter component of the STF.

3. Reference Model Solution

This section introduces a reference model approach for adaptively calculating and updating the STF filter coefficients with very little a priori information. This enables the method to be applied to any arbitrarily complex real-world structure and accommodate sensor and actuator failures in a manner which is transparent to control and monitoring algorithms. The structure of the STF filter estimation problem is similar to other estimation problems in that an error is defined which is a function of the parameters (in this case STF filter vector coefficients) to be estimated. The parameters are estimated by minimizing the error. As with other estimation problems, different solution methods may be employed to minimize the error to arrive at a solution that is optimal in some sense. Also, the subscript denoting mode number on the variables is dropped. The development is applicable to any single mode. Discrete time is assumed with the subscript now indicating sample number.

For clarity, first consider a single input modal filter (no temporal information) estimation problem. An error is defined which is the difference between the true modal coordinate, η_k, and the modal coordinate estimated by the spatial filter, $\hat{\eta}_k$, at time k.

$$\begin{aligned} e_k &= \eta_k - \hat{\eta}_k \\ &= \eta_k - \psi_k^T x_k \end{aligned} \qquad 7$$

The true modal coordinate, however, is not known. Indeed, estimating η_k is the purpose of the modal filter or STF. A reference modal coordinate, $\eta_k^{(r)}$, which is highly correlated with the true modal coordinate may be generated by driving a SDOF reference system constructed from only the pole of the mode of interest. The first order, discrete time reference system is

$$\eta_{k+1}^{(r)} = z_\lambda \eta_k^{(r)} + f_k \qquad 8$$

z_λ is the Z domain pole $z_\lambda = e^{\lambda \Delta t}$. In this case the driving force, f_k, is the measured control force. The reference modal coordinate is then used in Equation 7 in place of the true modal coordinate to calculate the error. The solution problem is to minimize this error over a number of time steps to estimate ψ. The structure of this problem is illustrated in Figure 6.

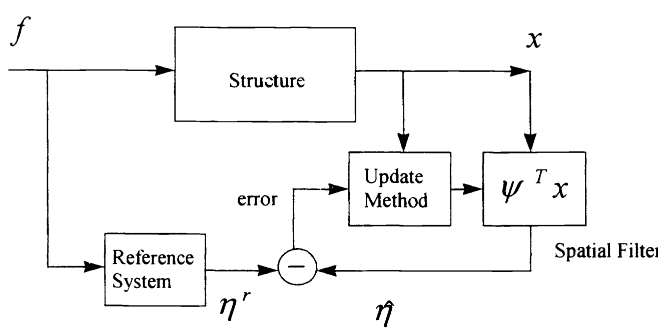

Figure 6: Structure of Modal Filter Estimation Problem

For the multi-input case, the total modal coordinate response of each mode is due to multiple input forces. The effect of each input is described by an unknown vector of, possibly, complex force appropriation coefficients, l (also called modal participation vectors) [7]. The reference model becomes

$$\eta_{k+1}^{(r)} = z_\lambda \eta_k^{(r)} + l^T f_k \qquad 9$$

where f_k is now a vector of applied forces. In this case the reference system is driven with a modal force consisting of the sum of the input forces weighted by the force appropriation vector coefficients. An equivalent reference modal coordinate may be generated by driving N_i reference models;

$$\begin{aligned} \eta_{k+1}^{(r1)} &= z_\lambda \eta_k^{(r1)} + f_k^{(1)} \\ &\vdots \\ \eta_{k+1}^{(rN_i)} &= z_\lambda \eta_k^{(rN_i)} + f_k^{(N_i)} \end{aligned} \qquad 10$$

by the unweighted N_i forces and using the force appropriation vector to form a weighted average of the Ni reference modal coordinates.

$$\begin{aligned} \eta_k^{(r)} &= l^T \begin{Bmatrix} \eta_k^{(r1)} \\ \vdots \\ \eta_k^{(rN_i)} \end{Bmatrix} \\ &= l^T \eta_k^r \end{aligned} \qquad 11$$

Note the distinction between $\eta_k^{(r)}$ which is the scalar modal coordinate and η_k^r which is a vector of partial modal coordinate responses associated with the individual input forces. The general spatio-temporal filter error with both input and output temporal filtering is then

$$\begin{aligned} e_k &= \eta_k^{(r)} - \hat{\eta}_k \\ &= l^T \begin{Bmatrix} \eta_k^r \\ \eta_{k-1}^r \\ \vdots \\ \eta_{k-Nti}^r \end{Bmatrix} - \psi^T \begin{Bmatrix} x_k \\ x_{k-1} \\ \vdots \\ x_{k-Nto} \end{Bmatrix} \\ &= \begin{Bmatrix} \psi \\ l \end{Bmatrix}^T \begin{Bmatrix} -x_k \\ \vdots \\ -x_{k-Nto} \\ \eta_k^r \\ \vdots \\ \eta_{k-Nti}^r \end{Bmatrix} \end{aligned} \qquad 12$$

A trivial solution which must be avoided is the zero error solution where both the response STF filter vector, ψ, and force appropriation vector, l, are zero. This may be accomplished by artificially normalizing one of the coefficients to, for instance, unity. This has the draw back that, if the coefficient is physically close to zero amplitude, the problem is very ill conditioned and an inaccurate solution results. The preferable solution is to impose a norm constraint on the solution vector where, for instance, the norm of the solution vector is constrained to unity. Additional norm constraint considerations arise when the updating the STF inside a control loop. In this case the norm constraint must be applied only to the response weighting filter coefficients.

Different solution methods have been utilized for the STF filter estimation method. Of most interest are adaptive, on-line methods since they recover from sensor and actuator failure. In the event of a sensor failure the response related STF filter coefficients update to continue to optimally estimate the modal coordinate response with the remaining sensing capacity. Provided sufficient sensing capability remains to estimate the modal coordinates, a controller utilizing these outputs for feedback control would be unaffected by the sensor failure. Multiple input modal controllers apply a control force vector which is either l, the force appropriation vector component of the STF or a direct function of it. The "force" driving the reference models is generally the command to the control actuators. An actuator failure is reflected in the associated force appropriation coefficient estimated by the STF and is inherently accommodated.

To date two different real-time adaptive STF update methods have been evaluated in real-time implementation using the AFRL dSPACE data acquisition and signal processing hardware, namely, Least Mean Squares (LMS) [12] and Recursive Least Squares (RLS) [13]. Major benefits of the RLS approach are superior convergence speed and accuracy. It has a higher computational demand, however, multiple modes can be estimated with little additional computational burden. The additional computational burden to update a STF with Ns sensors and Nt time taps is approximately 2*Ns*Nt floating point multiplies and adds.

4. STF Based Control

The STF is not, in itself, a vibration controller. However, design of very effective STF based, multiple-input, multiple-output, active vibration suppression controllers generally entails selection of merely a single scalar control gain parameter for each mode to be controlled. The reference model utilized to adaptively update the STF coefficients can take the form of a position, velocity or acceleration output model. The adaptive STF will attempt to form a modal coordinate output that matches the reference model. For active vibration suppression a modal coordinate velocity output is often desired to utilize directly for rate feedback control.

In this case the control command for each mode consists of

$$f_c^{(i)} = \hat{\dot{\eta}}^{(i)} \alpha^{(i)} v^{(i)} \qquad 13$$

where $f_c^{(i)}$ is the control command (generally a force command) vector output to control the i'th mode, $\hat{\dot{\eta}}^{(i)}$ is the estimate of the modal coordinate velocity of the i'th mode generated by the STF, $\alpha^{(i)}$ is the control gain and $v^{(i)}$ is the forcing vector. The theoretical control gain required to achieve a certain level of damping can be calculated, however, in practice it is often more effective to manually adjust control gain. A number of considerations may effect the choice of forcing vector. In general the forcing vector should be chosen to project strongly on the force appropriation vector (FAV). This is desired since the resulting modal control force is the inner product of the FAV and the control force vector, $l^{(i)^T} f_c^{(i)}$. A good choice of control force vector to maximize this inner product is the FAV vector itself. Since the STF automatically generates the FAV vector it is the logical choice. For each modal controller the control force is

$$f_c^{(i)} = \hat{\dot{\eta}}^{(i)} \alpha^{(i)} l^{(i)} \qquad 14$$

Control design, then, consists of choosing the control gain, $\alpha^{(i)}$, for each controlled mode. Multiple modal controllers are run in parallel to control multiple modes. In this case the physical control force command is the sum of the individual modal control forces.

Active vibration suppression experiments were conducted on the PDOS facility at AFRL. Controllers were implemented using the dSPACE hardware hosted by a PC computer. Using MATLAB and the Real Time Workshop, controllers designed and simulated in SIMULINK were compiled, downloaded and run in the dSPACE hardware. The general structure of the controller and system is illustrated in Figure 7. Initially the system was driven (through the PZT-stack actuators) with a band-limited random excitation generated within the dSPACE system in order to adaptively identify STF filter coefficients. The same internal digital excitation signal which is output through the dSPACE digital-to-analog converters (DAC's) to drive the physical system is also used internally to drive the internal SDOF reference models. The STF is adaptively calculated such that it's output matches the output of the reference system.

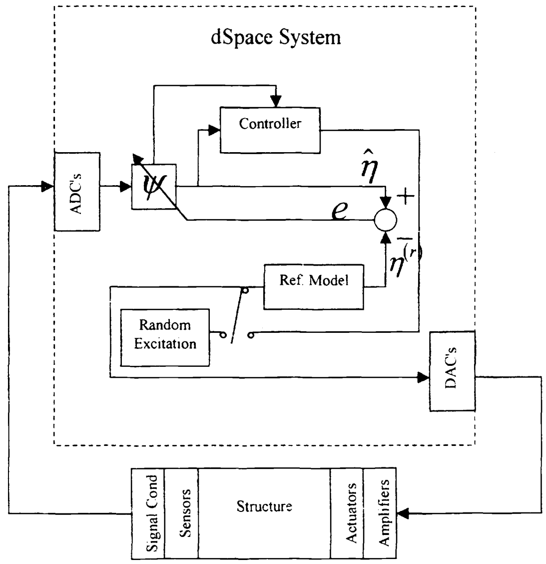

Figure 6: Structure of STF Based Controller

5. CLOSED LOOP CONTROL RESULTS

A single mode (4.6 Hz) controller was implemented on the PDOS structure utilizing the 3 piezoelectric stack actuators and 3 interferometers as control and sensing devices. Figure 7 shows open and closed loop interferometer 1 time responses due to an impulsive input applied to the Backup Structure. After control has been applied, the most dominant feature in the time response is a 1.6 Hz component, which corresponds to the uncontrollable mode of the air-bag suspension system between the floor of the laboratory and the granite table [2]. The ambient interferometer power spectral densities are shown in Figure 8, in which the peaks corresponding to the 4.6 Hz mode have been reduced by approximately 40 dB. Efforts are ongoing to implement adaptive STF controllers for all six modes in the frequency band 0-50 Hz (see Figure 3), and to implement a narrow-band disturbance rejection controller for the 1.6 Hz disturbance.

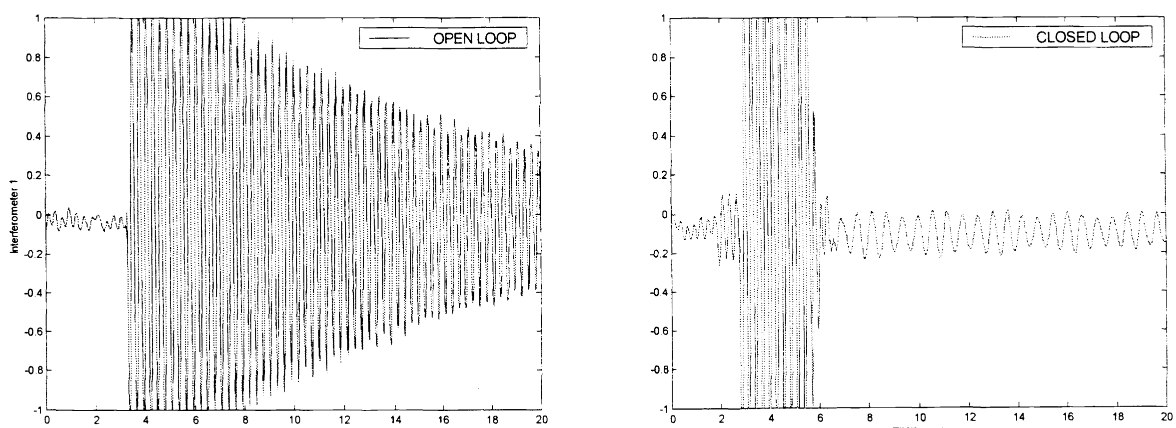

Figure 7: Open and Closed Loop Impulse Responses

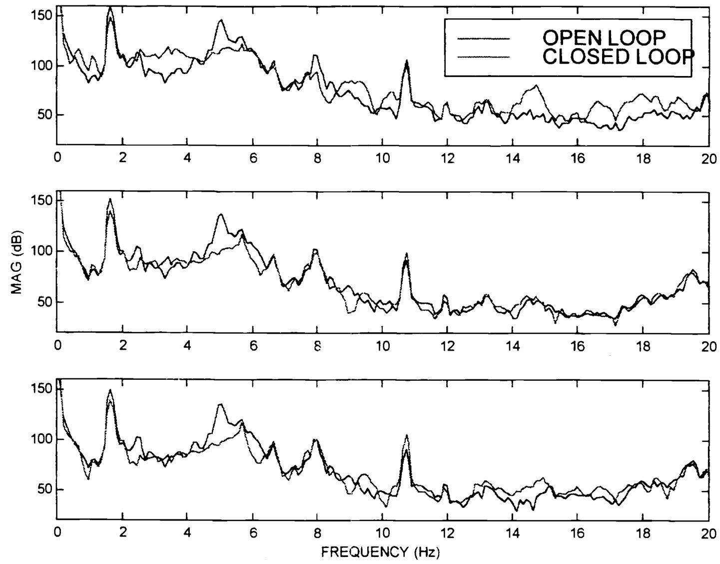

Figure 8: Open and Closed Loop Interferometer PSD's (Ch. 1 top, Ch. 2 middle, Ch. 3 bottom)

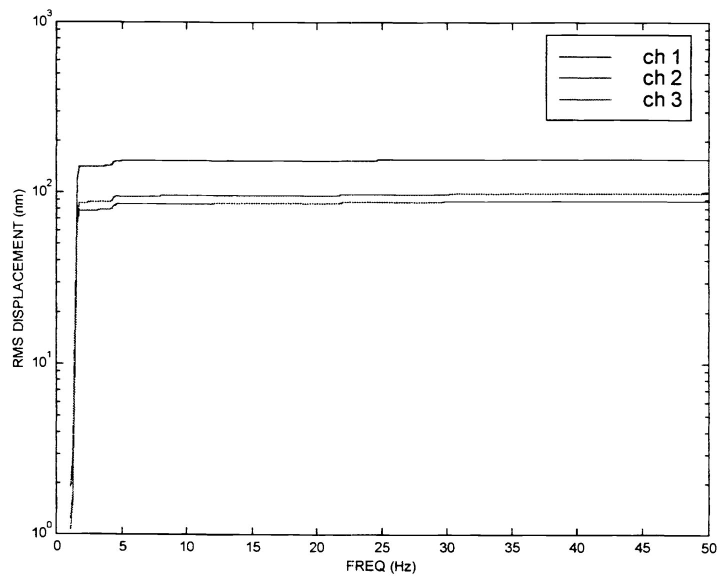

Figure 9: Interferometer RMS Value versus Frequency

6. DISCUSSION AND CONCLUSIONS

Insight into the PDOS control problem can be gained by looking at the forward sum RMS plots shown in Figure 9. This plot indicates the contribution of various frequencies to the RMS values of the interferometer time responses. In order to meet the requirement of 30 nanometers or less RMS value for the interferometers (as discussed in Section 3), it is necessary to reduce the 1.6 Hz disturbance by a factor of 10. If this can be achieved without exciting the 4.6 Hz mode, then no STF structural control is required. However, the more likely scenario is that increasing the damping of the 4.6 Hz mode using STF will be required for stability of the disturbance rejection controller. It is apparent that the solution to the PDOS control problem will involve a combination of high-bandwidth (>1 Hz) mirror position control and STF structural mode control. Work is continuing along these lines.

7. ACKNOWLEDGEMENTS

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