APPLICATION OF H_∞ ACTIVE VIBRATION CONTROL STRATEGY IN SMART STRUCTURES

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ABSTRACT

In this study, H_∞ controllers were designed and implemented on a smart beam. The smart beam consisted of an aluminum beam modeled in cantilevered configuration with eight surface bonded piezoelectric lead-zirconate-titanate (PZT) patches. The study used ANSYS® (v5.6) for the structural modeling of the smart beam. The system models were obtained through the system identification made on the experimental beam data. The H_∞ active vibration controllers, which effectively suppressed the sinusoidally excited, in-vacuo forced vibrations of the smart beam due to its first two flexural modes, were then designed by using MATLAB® tool-boxes and implemented. During the experiments both the strain gauge and laser displacement sensor were used as vibration sensors. The theoretical and experimental characteristics were compared to verify the developed models. The effects of the higher beam vibrational modes and the damping were included in the system model as uncertainties. It was shown that H_∞ active vibration controllers were very effective in suppressing the sinusoidally excited, in-vacuo forced vibrations of the smart beam. Some preliminary studies on the modelling and verification of a smart fin were also presented.

KEYWORDS : Smart Structures, Active Vibration Control, System Identification, H_∞ Control

1. INTRODUCTION

A smart structure can be defined as a structure that can sense an external disturbance and respond to that with active control in real time to maintain the mission requirements. Smart structures with discrete piezoelectric actuators were shown to be applicable for the vibration suppression of one dimensional structures by Crawley and de Luis [1]. The vibrations of thin, flat plates by using piezoelectric patches were also analyzed by Dimitridis and Fuller [2]. The recent improvements in finite element codes, like ANSYS®, made the fully coupled thermo-mechanical-electrical analysis of the smart structures possible. The coupling allowed the prediction of the reciprocal relations between the piezoelectric sensors and actuators. By using this allowance, Prasad *et al.* [3] developed the closed loop controller for active vibration control. In one of the recent studies, Suleman *et al.* [4] showed the effectiveness of the piezoceramic sensors and actuators on the suppression of vibrations on an experimental wing due to the gust loading.

Yaman *et. al*. worked on various smart structures. The structures were aluminum passive structures with surface bonded piezoceramic patches (PZTs). By using ANSYS® (v5.6) the fully coupled structural models of a smart beam, a smart rectangular plate and fin shaped plate called smart fin were obtained. The system models of those smart structures were identified from the relevant experimental data. Based on those models H_∞ controllers, which effectively suppress the free, in-vacuo vibrations of those smart structures due to their first two flexural modes, were designed [5,6,7,8]. In those studies, the suitability of the H_∞ design technique in the modeling of uncertainties and the evaluation of the robust performance of the system were also demonstrated.

This study extends those previously developed models for the suppression of sinusoidally excited, in-vacuo forced vibrations of the smart beam. Two different experimental set-ups are used. The first one uses strain gauges as sensor and the Sensortech SS-10 Controller, which is specifically designed for the smart structures applications, for the active vibration control. The second one uses a Laser Displacement Sensor and LabVIEW based programs for the active vibration control. In both set-ups the PZTs are used as actuators to suppress the vibrations.

2. THE SMART BEAM

Figure 1 gives the smart beam used in this study. 8 (20×25×0.61 mm) Sensortech BM500 type PZT actuators are glued in bimorph configuration on a 507×51×2 mm aluminum beam. The structural model of the smart beam is modeled with hybrid solid-solid approach. SOLID5 elements of ANSYS® (v5.6) are used for the modeling of the active portion (piezoelectric patches) and compatible solid elements, SOLID45, are used for the modeling of the passive portion (aluminum beam).

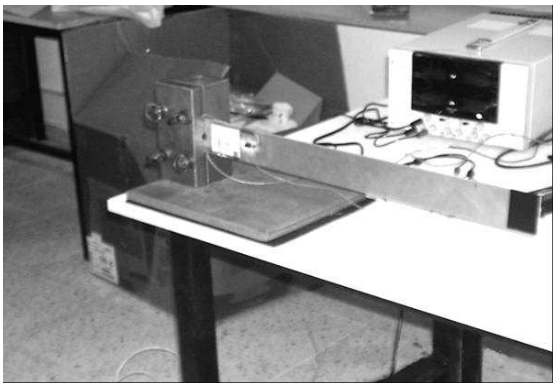

Figure 1. The Smart Beam Used in the Study

Table 1 gives the theoretically determined (FEM) and experimentally obtained resonance frequencies of the smart beam. Table 1 also gives the experimentally obtained damping values of the smart beam [8]

FEM	Experimental	
f_n(Hz)	f_n (Hz)	damping
7.30	7.29	7.71×10^{-2}
44.11	40.07	1.78×10^{-2}
117.28	110.62	7.06×10^{-3}

Table 1. The Comparison of the Theoretical (FEM) and Experimental Resonance Frequencies of the Smart Beam

3. H_∞ CONTROLLER DESIGNED FOR THE SMART BEAM

This section gives the H_∞ controller design on the system model of the smart beam. The goal of the controller design is to increase the modal damping ratio within the frequency range of interest, therefore reducing the settling time. In the H_∞ controller design, the aim is to minimize the H_∞ norm of the transfer function describing the relation between the inputs and the outputs of a system [9-10]. The applications of H_∞ control on the free vibrations of various smart structures with surface bonded PZTs are given in the previous studies of the authors [5-8,11]. Figure 2 gives the block diagram of H_∞ control of the smart beam.

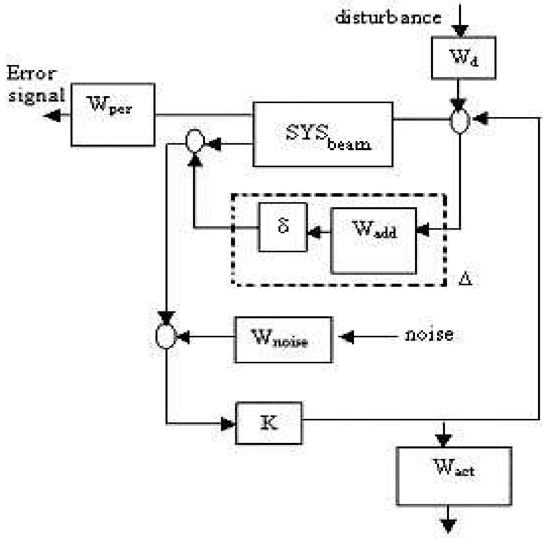

Figure 2. Block Diagram of H_∞ Control of the Smart Beam

where SYS_{beam} defines the nominal smart beam model, δ is a complex number such that $\|\delta\|<1$ and W_{add} defines the amplitude of the additive uncertainty weight included into the system model. The additive uncertainty weight W_{add} is included to account for the unmodeled or truncated high frequency modes. The interaction of the nominal transfer function SYS_{beam} with Δ which is the multiplication of W_{add} by δ defines the system model of the smart beam including the uncertainties. In the modeling, W_{per} gives the performance weight applied to the displacement measurements made on the smart beam. In the study W_d, the weight added to disturbance, is taken to be 1 indicating that the order of the disturbance acting on the system and the input signal produced by the controller is the same. Furthermore, W_{noise}, representing the noise to signal ratio is selected to be 0.01.

The goal in the controller design is to minimize the displacement signal in the low frequency range, while not exciting the unmodeled high frequency modes [12]. Figure 3 gives the comparison of the frequency response of the smart beam together with the determined W_{add} and W_{per} values for strain gauge application, whereas Figure 4 represents those for laser displacement sensor application. It can be seen from the figures that, as the frequency increases the W_{add} uncertainties increase indicating better system model at low frequencies. The comparison of W_{per} and the frequency responses of the smart beam show that the application of this weight results in the minimization of the displacement at low frequencies while making minimal changes at high frequencies. W_{act} represents the weight applied to the actuator signals in order to limit the actuator authority. The weight is chosen as 0.1 for the strain gauge application and as 0.2 for the laser displacement sensor application.

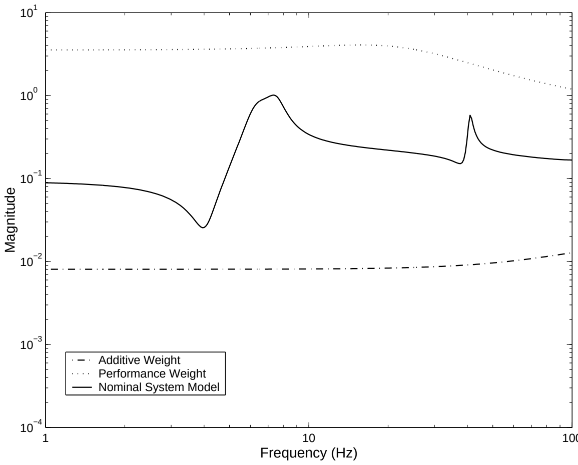

Figure 3. Performance and Uncertainty Selection Used in H_∞ control of the Smart Beam with Strain Gauge

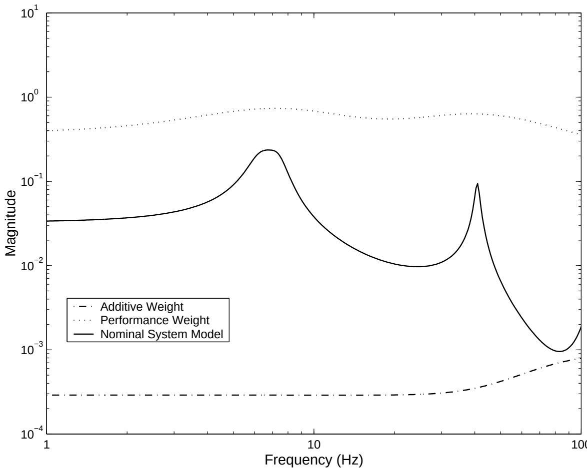

Figure 4. Performance and Uncertainty Selection Used in H_∞ control of the Smart Beam with Laser

Having designed the controller, a μ analysis is necessary for the robustness. μ is the structured singular value and the definition is given for a defined uncertainty structure Δ and closed loop system M which is obtained from lower linear fractional transformation of system model augmented with selected weights and controller model [9-10],

$$\mu_{\underline{\Delta}}(M) = \frac{1}{\min\{\overline{\sigma}(\Delta) : \Delta \in \underline{\Delta}, \det(\mathrm{I} - M\underline{\Delta}) = 0\}}$$

$$\textit{if no } \Delta \in \underline{\Delta} \text{ makes } (\mathrm{I} - M\underline{\Delta}) \text{ singular then } \mu_{\underline{\Delta}}(M) = 0$$

Figure 5 and Figure 6 give the μ analysis results for the H_∞ controllers designed for smart beam with strain gauge and laser respectively.

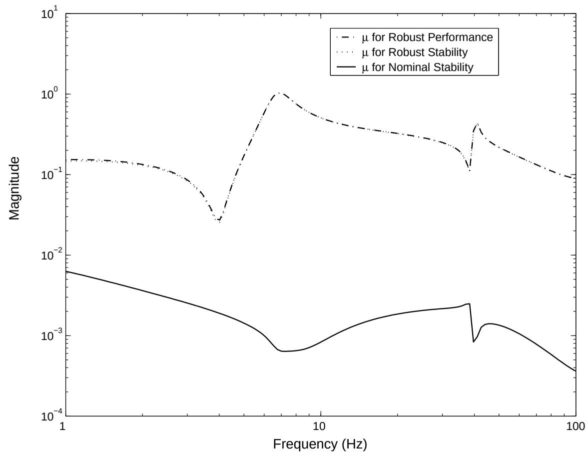

Figure 5. μ Analysis Results for the H_∞ Controller Designed for Smart Beam with Strain Gauge

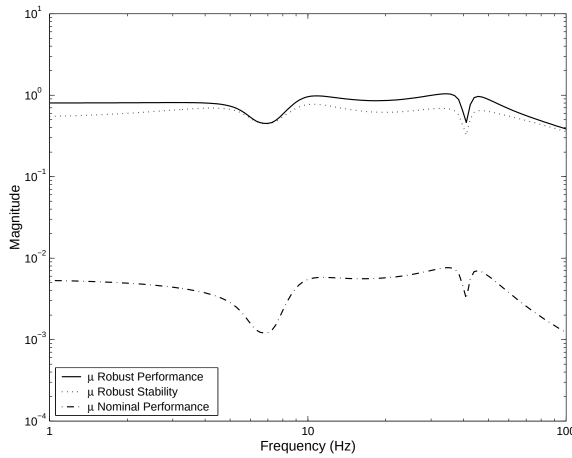

Figure 6. μ Analysis Results for the H_∞ Controller Designed for Smart Beam with Laser

4. EXPERIMENTAL STUDIES ON THE SMART BEAM

4.1. STRAIN GAUGE SENSOR APPLICATIONS

Figure 7 gives the experimental set-up used in strain gauge sensor and SS10 Controller applications. The system is excited by a chirp signal (0.1 to 60 Hz sine sweep with 10V peak to peak) through the shaker and the response of the smart beam is acquired via the strain gauge sensor. The obtained response is fed to the controller where a C code is written for the H_∞ control. The required control signal for the necessary vibration suppression is then fed to the PZTs.

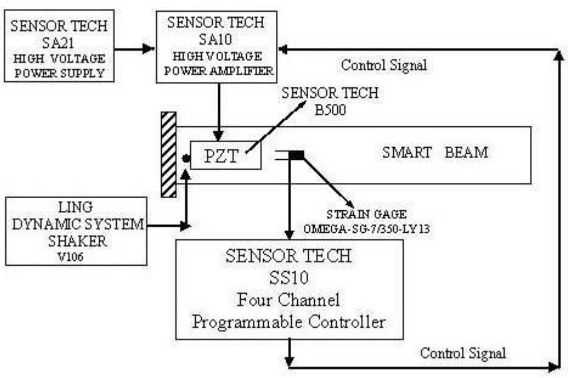

Figure 7. Experimental Setup for Strain Gauge Applications of the Smart Beam

First the effectiveness of the developed H_∞ control strategy is analyzed and verified. This is achieved for free vibrations. The smart beam is given a 5 cm tip displacement and zero tip velocity as the initial conditions and the ensuing free vibrations are recorded. The beam in this is not subjected to any control signal. This is called the open loop time response. The same initial conditions are repeated but now the controller is also set on. The time response is now called the closed loop. Figure 8 shows both of the time responses and verifies the effectiveness of the developed H_∞ controller.

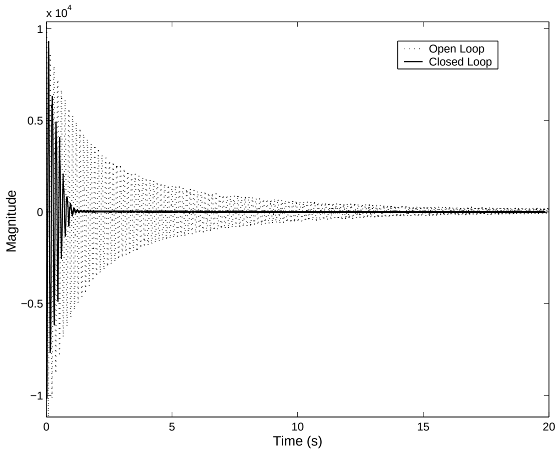

Figure 8. Open Loop and Closed Loop Time Responses of the Smart Beam with Strain Gauge

The time domain data are then processed to yield the frequency responses of the smart beam. Figure 9 shows the open loop and the closed loop frequency responses of the smart beam for sinusoidally excited, in-vacuo forced vibrations. It can be seen from Figure 9 that, though the greater efficiency is observed in the first mode, a reduction in the response levels of the both modes is achieved.

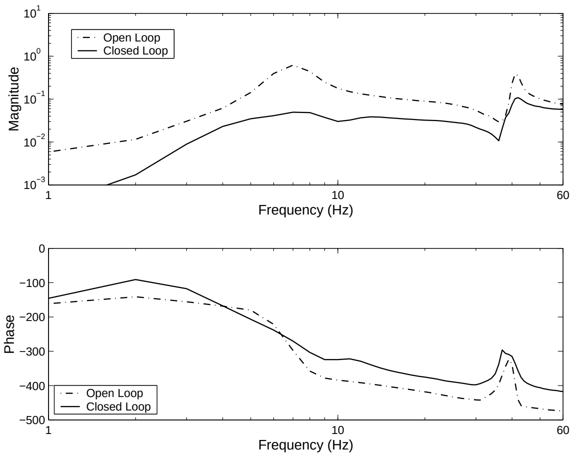

Figure 9. Open Loop and Closed Loop Frequency Responses of the Smart Beam with Strain Gauge

4.2. LASER DISPLACEMENT SENSOR APPLICATIONS

Figure 10 gives the experimental set-up used in Laser Displacement Sensor and LabVIEW (v5.0) applications. The system is again excited by a chirp signal (0.1 to 60 Hz, 10V peak to peak) through the shaker and the response of the smart beam is acquired by the Keyence LB301 laser displacement sensor. The response is fed to a PC where programs for H_∞ control involving C code are written for LabVIEW. The required signal for the necessary vibration suppression is again fed to the piezoceramic patches.

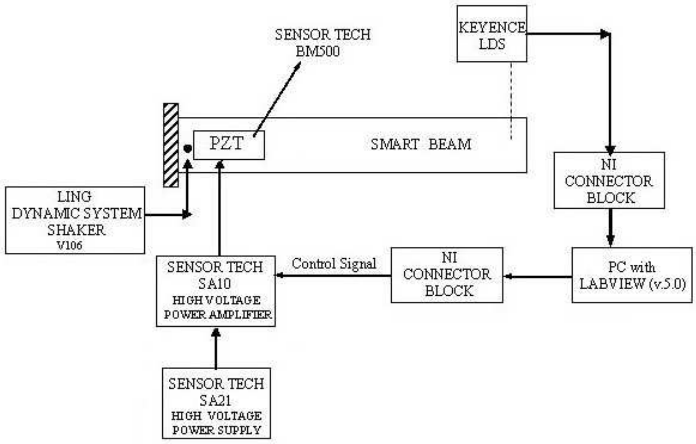

Figure 10. Experimental Setup for Laser Measurement Application of the Smart Beam

The open loop and the closed loop time responses of the smart beam for laser application are given in Figure 11. The curves are again drawn for the same initial conditions of 5 cm tip displacement and zero tip velocity for the smart beam.

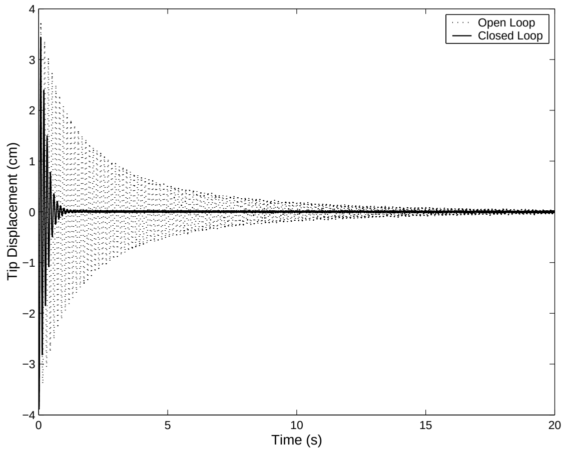

Figure 11. Open Loop and Closed Loop Time Responses of the Smart Beam with Laser

Figure 12 illustrates the open loop and the closed loop frequency response of the smart beam for laser application of sinusoidally excited, in-vacuo forced vibrations. Figure 12 also shows that a reduction in both peaks is achieved.

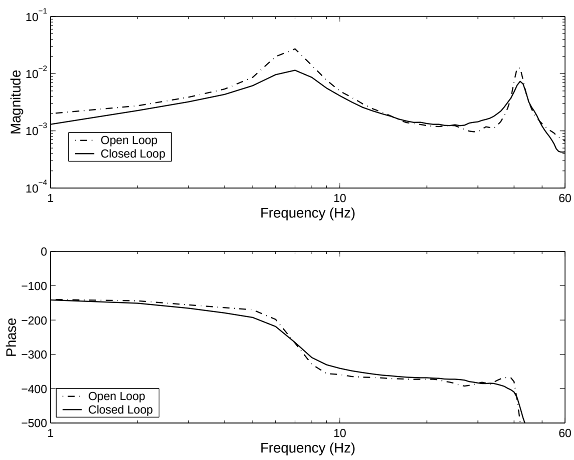

Figure 12: Open Loop and Closed Loop Frequency Responses of the Smart Beam with Laser

5. THE SMART FIN

This section gives some results of the preliminary studies conducted on a smart fin. Figure 13 gives the smart fin used in the study. 12 (25×25×0.61 mm) Sensortech BM532 type PZT actuators are glued on both sides of the passive aluminum fin-like plate. The structural model of the smart fin is modeled with hybrid solid-solid approach. SOLID5 elements of ANSYS® (v5.6) are used for the modeling of the active portion (piezoelectric patches) and compatible solid elements, SOLID45, are used for the modeling of the passive portion (aluminum fin). Table 2 gives the theoretically determined (FEM) and experimentally obtained resonance frequencies of the smart fin. Table 2 also gives the experimentally obtained damping values of the smart fin [6,8]. Figure 14 gives the open lop time response and Figure 15 shows the open loop frequency responses of the smart fin. The response is obtained by applying chirp signal to PZTs and measuring data from the strain gauge.

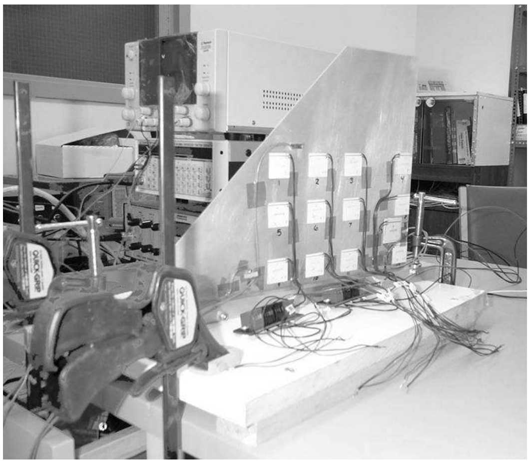

Figure 13. The smart fin used in the study

FEM	Experimental	
f_n(Hz)	f_n (Hz)	damping
14.96	14.51	4.8×10^{-2}
45.74	48.94	2.02×10^{-1}
68.25	69.43	1.79×10^{-2}

Table 2. The Comparison of the Theoretical (FEM) and Experimental Resonance Frequencies of the Smart Fin

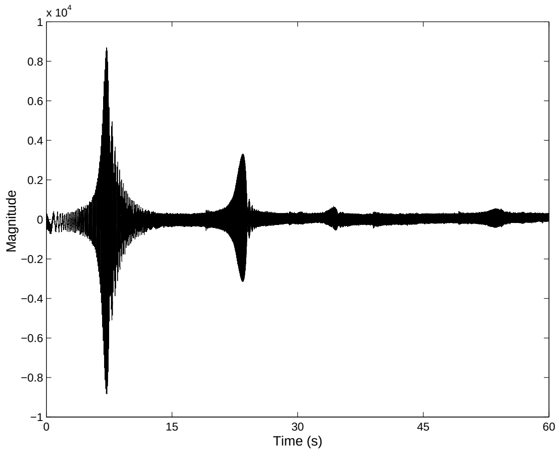

Figure 14. Open Loop Time Response of the Smart Fin

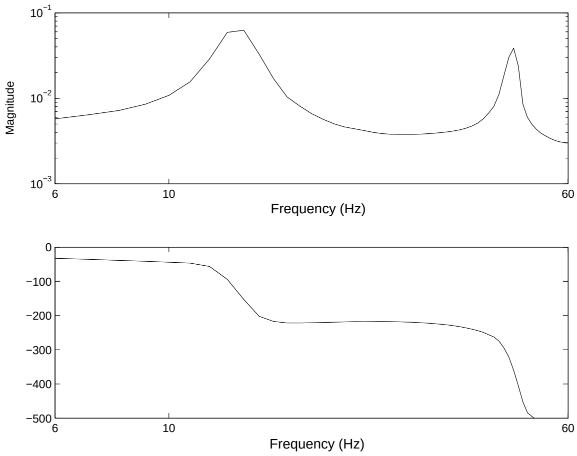

Figure 15. Open Loop Frequency Responses of the Smart Fin

6. CONCLUSIONS AND RECOMMENDATIONS

This study presented the design and implementation of an H_∞ controller which was developed for the suppression of sinusoidally excited, in-vacuo forced vibrations of a smart beam. Two different experiments were conducted where the first one used strain gauge sensor and the second one utilized a laser displacement sensor. In both set-ups the PZTs were used as actuators to suppress the vibration levels. It was shown that the developed H_∞ controller provided satisfactory results for both applications. It was also determined that, due to the available hardware, the strain measurements did not match the quality of the laser measurements. However the high sampling rate capability (4096) of the SS10 controller provided better suppression characteristics in this study.

This work only presented the preliminary open lop results for the smart fin. The studies for the design and implementation of an H_∞ controller, which will suppress the sinusoidally excited, in-vacuo forced vibrations of a smart fin, are under way.

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