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Smart structures and their applications on active vibration control: Studies in the Department of Aerospace Engineering, METU

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Abstract This work presents the theoretical and experimental studies conducted in Aerospace Engineering Department of Middle East Technical University on smart structures with particular attention given to the structural modelling characteristics and active suppression of in-vacuo vibrations. The smart structures considered in these analyses are finite and flat aluminium cantilever beam-like (called as smart beam) and plate-like (called as smart fin) structures with surface bonded lead–zirconate–titanate patches. Finite element models of smart beam and smart fin are obtained. Then the experimental studies regarding open loop behaviour of the structures are performed by using strain gauges and laser displacement sensor to determine the system models. Further studies are carried out to obtain H_∞ and μ-synthesis controllers which are intended to be used in the suppression of free and forced vibrations of the smart structures. It is observed that satisfactory attenuation levels are achieved and robust performance of the systems in the presence of uncertainties is ensured. In that respect a comparative study involving H_∞ and sliding mode controls is also conducted. Recently, the studies involving aerodynamic loading are also gathering pace.

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1 Introduction

The developments in piezoelectric materials have motivated many researchers to work in the field of smart structures. A smart structure can be defined as the structure that can sense external disturbance and respond to that with active control in real time to maintain the mission requirements. Smart structures consist of highly distributed active devices which are primarily sensors and actuators either embedded or attached to an existing passive structure with integrated processor networks. Depending on the characteristics of the smart structures involved and the expected operating conditions, the selection of sensors and actuators vary considerably. The typical smart structure sensors used in discrete or distributed locations to measure the performance of the system comprise fibre optics, piezoelectric ceramics and piezoelectric polymers. The actuators used in the smart materials technologies include applications of piezoelectric ceramics, piezoelectric polymers, electrostrictive, magnetostrictive materials and piezofibres. Their reliability, nearly linear response with applied voltage, showing excellent response to the applied electric field over very large range of frequencies and their low cost make piezoelectric materials [lead–zirconate–titanate (PZT)] the most widely preferred one as collocated sensor and actuator pair. Therefore our work mainly considers the application of PZT patches to smart beam-like and smart plate-like structures for the purpose of active vibration control. Structural models and controller models so far developed and implemented were for in-vacuo vibrations where the effects of aerodynamics were neglected. Current studies are intended to use the smart structures in the active control of aeroelastic problems which are frequently encountered in aeronautical applications.

2 Modelling of smart structures

The theoretical studies regarding modelling and the design of smart structures [1] are performed by using the finite element method which is shown to be a very effective tool for the analysis of piezoelectric materials as the method offers fully coupled thermo-mechanical-electrical analysis of structures. Our studies, for in-vacuo vibrations, use the commercial software ANSYS® (v.5.6) [2] as a finite element tool and focus on parametric design capabilities regarding the effects of the piezoelectric patches on the response of the smart structures, influences of the actuator size, placement and the maximum admissible piezoelectric actuation value to secure the integrity of the piezoelectric patches.

2.1 Smart beam

The beam-like structure considered in the studies is composed of an aluminum strip (507×51×2 mm) modelled in cantilevered configuration with eight surface bonded piezoelectric patches (25×20×0.5 mm, BM500 type [3]). These identically polarised piezoelectric patches are symmetrically bonded on top and bottom surfaces of the passive portion of the structure in order to provide bimorph configuration. This beam-like structure is generally referred as smart beam. After extensive studies and verifications with the experimental results [4], the prismatic elements (SOLID5) are used for the modelling of active portion (i.e. PZTs) and linear prismatic elements (SOLID45) are used to model the passive portions. Finite element method is shown to be especially advantageous in handling the multiple design parameters of piezoelectric patches. By enabling the parametric design features of the finite element modeling and analysis technique, the influences of the piezoelectric patch placement and size on the responses of the smart beam are obtained. It is observed that as the patches move closer to clamped-end and increase in the size, the response of the smart beam increases. The finite element method also allows determination of the maximum admissible actuation value, hence effectively gives the actuator limits. It is also observed that the presence of the patches shifts the natural frequencies of the passive structure to higher frequencies [5]. From finite element model of the smart beam, strain values are obtained by performing modal analysis in order to determine the most suitable location for the strain gauge sensor pair. This corresponds to the location where the strain values attain their highest value for the first two modes of vibrations.

2.2 Smart fin

Based on the finite element modelling technique presented for the beam-like structure, the finite element model of the smart fin is obtained and analyses are performed. The smart fin is a cantilevered plate with symmetrically placed piezoelectric patches and modelled according to the plate theory. Since its shape looks like the typical vertical tail of an aircraft, it is called smart fin. The finite element model developed in the study is shown in Fig. 1.

The same element types mentioned in the modelling of the smart beam are also used to model both active and passive portions of the smart fin. By using the modal analysis results, which are obtained from the finite element model, 24×(25×25×0.5 mm) BM500 type patches are placed on the fin at the determined locations. The patches are bonded symmetrically on top and bottom surfaces of the fin and an additional pair of symmetrically placed piezoelectric BM500 patches is also used as sensors (Fig. 1). Then the effects of the patch location on the first and second natural frequencies of the smart fin are investigated. As the patches are moved away from the root both the flexural stiffness and the natural frequencies decrease by keeping the first frequency of the smart fin almost unaffected. Conversely, as the patches get close to the trailing edge the torsional stiffness significantly increases giving rise to an increased second frequency. Based on these analyses the best locations of the actuators are found. The finite element method also allows determination of the suitable locations of the sensors for vibration sensing. These locations can be determined from mode shapes of the smart fin by using the modal strain distribution at its first two modes. Three locations where the strain components reach their maximum values are determined and these locations are then used for attachment of the strain gauge sensors to sense the vibrations of the smart fin. The influences of the piezoelectric actuation voltage variation on the responses at the three strain gauge sensor locations are also calculated for both bending and twisting piezoelectric actuations [6].

3 Active vibration control of smart structures

The active vibration control of smart aerospace structures that inherently have flexibility becomes more important when the designers attempt to push with the state of the art, faster and lighter structures for aerospace applications [7]. Generally, two steps are necessary for the control of flexible smart structures. First a precise mathematical model, which is capable of handling the electromechanical coupling effects, must be developed. Second, a robust controller that

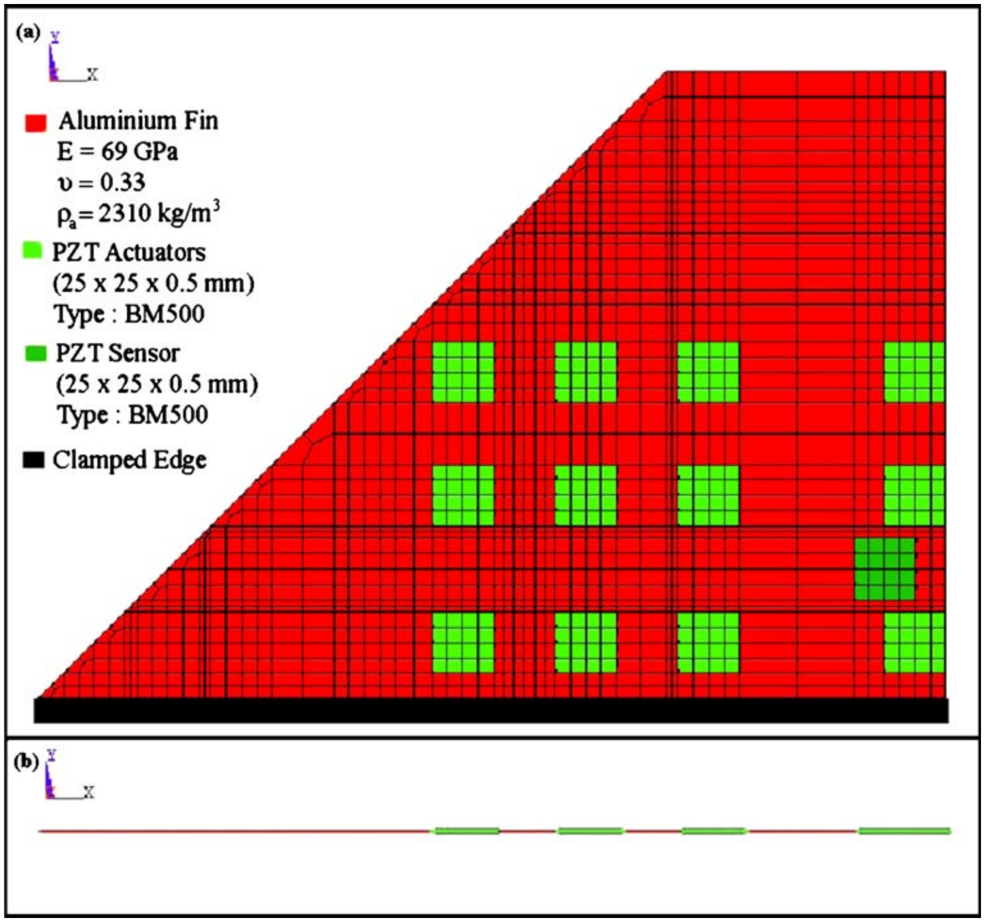

Fig. 1 Finite element model of the smart fin (**a**) top view (**b**) side view

successfully incorporates the possible modelling uncertainties must be designed.

3.1 Control of smart beam

The developed finite element model of the smart beam is reduced to a state-space form suitable for a controller design. The system model of the smart beam [5, 8, 9] is obtained from sine-wave testing, known as a frequency analysis, and provides the detailed information about a linear system in the frequency range of interest. The frequency response functions from the piezoelectric actuator to strain gage and laser displacement sensors are obtained and then the least square curve fitting method is

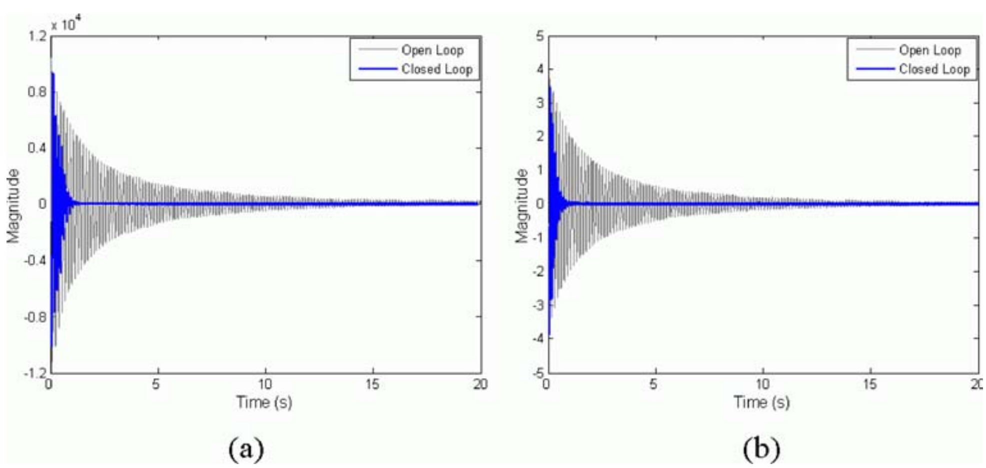

Fig. 2 Open loop and closed loop time responses of the smart beam for (**a**) strain measurement (**b**) displacement measurement

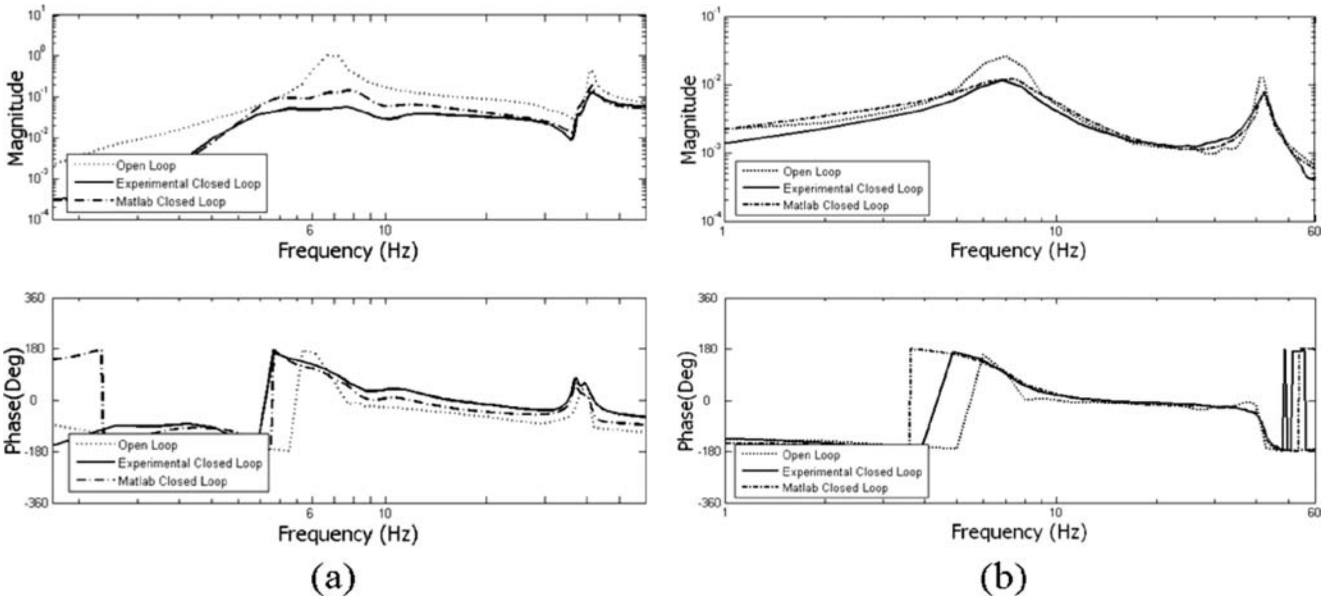

Fig. 3 Open loop and closed loop frequency responses of the smart beam for (**a**) strain measurement (**b**) displacement measurement

applied to find the approximate representation of the transfer functions. By using this reduced model, an active vibration controller which effectively suppresses the vibrations of the smart beam due to its first two flexural modes is designed. The vibration suppression is achieved by the application of H_∞ controllers [5, 9, 10]. In H_∞ control design framework the objective is to minimize the weighted H_∞ norm of the transfer function matrix from input disturbances to the output error signals. This technique allows a systematic way of introducing the model uncertainties into the design process and ensures robust stability and performance [11, 12]. As a joint work, a comparative study involving H_∞ and sliding mode controls (SMC) is also conducted [13]. SMC is a particular type of variable structure control which changes the control directions to drive the system to a specific manifold in the state space and keep the system within a neighborhood of this manifold. The main feature of SMC is its insensitivity to some class of uncertainties [14]. In order to obtain the mathematical description of the structure, two different approaches are considered. In the first approach, the system model of the smart beam is derived by considering the piezoelectric actuator voltage as an input and strain gauge result as an output of the system. For this application, the H_∞ control was performed by using a four-channel programmable controller, SensorTech SS10, which is specifically designed for smart structure applications. In the second approach, the system model of the smart beam is obtained by considering the piezoelectric actuator voltage as input and the beam tip flexural displacement as output measured by using laser displacement sensor. The H_∞ controller of this approach is designed and implemented by using a LabVIEW v5.0 based program.

3.1.1 Free vibration suppression

Free vibration analyses are performed by applying 5 cm initial tip displacement and zero initial tip velocity in order to analyze open-loop and closed-loop time responses of the smart beam. These time responses are given in Fig. 2(a, b) for strain and displacement measurements, respectively. It is observed that while the smart beam continues to vibrate even after 20 s in the open loop case, significant vibration suppressions are achieved in less than 1.3 s for the closed loop case based on both strain [15, 16] and displacement measurements [15].

Fig. 4 The smart fin used in the study

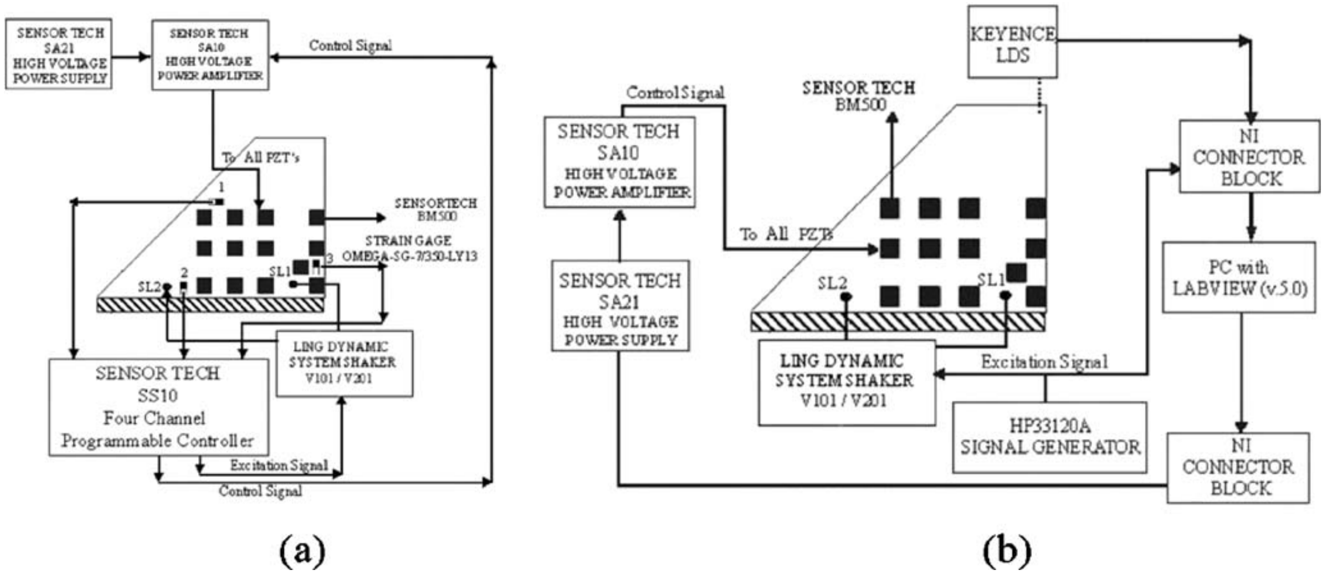

Fig. 5 Experimental setup for controller implementation of the smart fin for (**a**) strain measurement (**b**) displacement measurement

3.1.2 Forced vibration suppression

For the forced vibration analysis, a sinusoidal chirp signal (10 V peak-to-peak amplitude and 0.1–60 Hz frequency range) is applied through a Ling Dynamic Systems LDS V106 shaker located near the cantilever end next to the piezoelectric materials. Before performing experimental analyses, closed loop forced vibration responses are also simulated in MATLAB (v6.5). The open-loop and closed-loop frequency responses of the smart beam are shown in Fig. 3(a, b). Figure 3 reveals that a significant reduction in the response levels of the first two modes is achieved for both strain and displacement measurements [15].

3.2 Control of smart fin

The work performed in the area of control of plate-like structures starts with active vibration control of a smart rectangular aluminium plate [17]. Further studies concentrate on active vibration control of a smart fin (Fig. 4). The two approaches previously mentioned to drive the system model of the smart beam are also used in order to obtain the mathematical description of the fin. An experimentally identified model is utilized in the design of H_∞ controller which suppresses in-vacuo vibrations of the smart fin due to its first two flexural modes [6]. Experimental setups for controller implementation of the fin based on strain and displacement measurements are displayed in Fig. 5(a, b) respectively.

A μ-synthesis (structured singular value) controller is also designed in order to suppress the vibrations of the smart fin [18, 19]. In general, a system is built from components which themselves are uncertain with norm bounded perturbations. This results in a structure of the uncertainty representation. In H_∞ design framework this structure is ignored and the controller may be conservative depending on the type of the uncertainties. The μ-synthesis technique takes this structure into account and leads to less conservative results [20, 21].

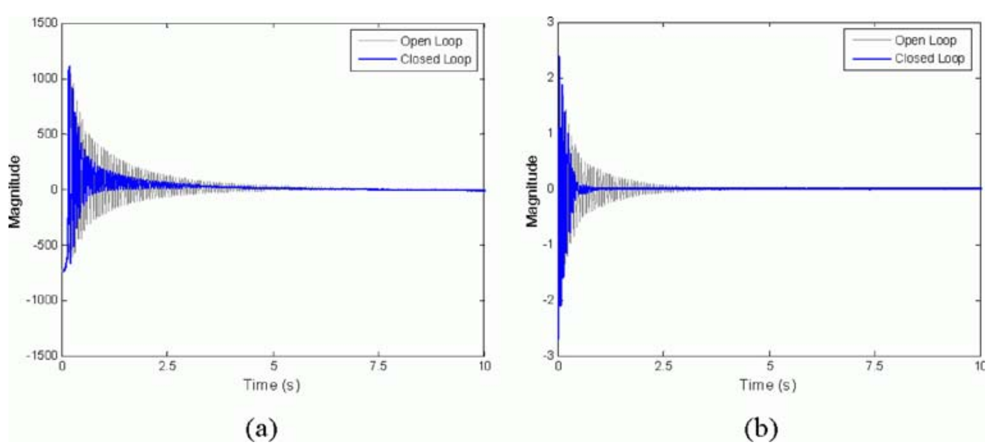

Fig. 6 Open loop and closed loop time responses of the smart fin for (**a**) strain measurement (**b**) displacement measurement

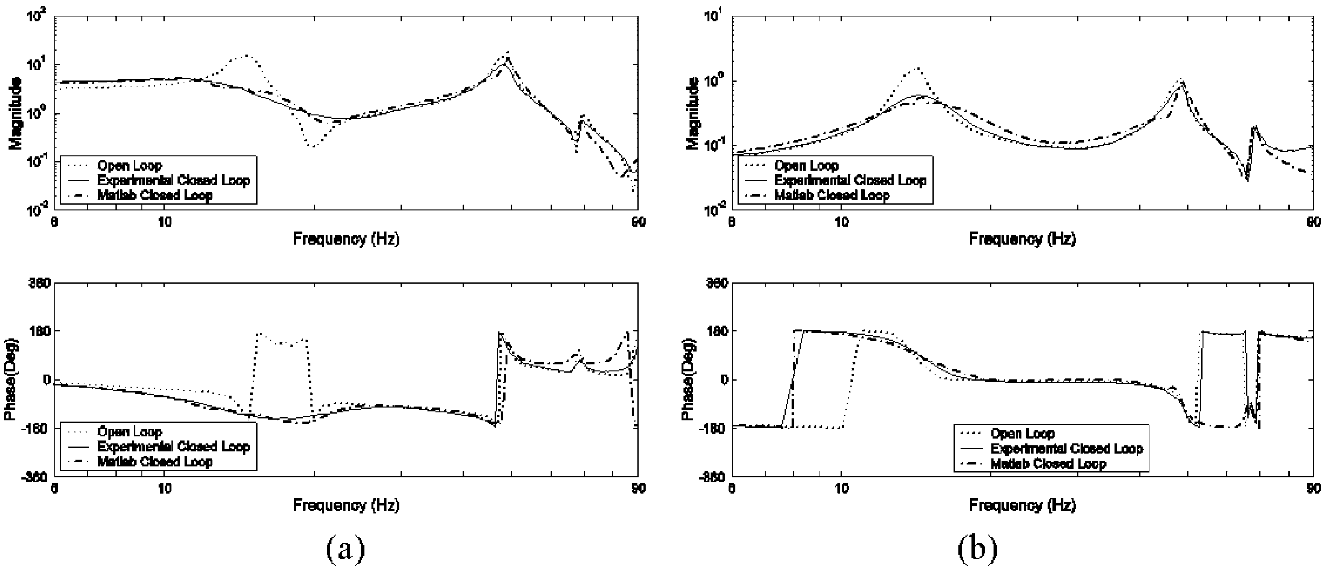

Fig. 7 Open loop and closed loop frequency responses of the smart fin for (**a**) strain measurement (**b**) displacement measurement

3.2.1 Free vibration suppression

For the free vibration analysis, an initial tip displacement of approximately 3 cm and zero tip velocity is applied to the smart fin and the open loop and closed loop characteristics of the system are recorded. These time responses are given in Fig. 6(a, b) for strain and displacement measurements respectively. As it can be seen from the figures, the vibration suppression is achieved for the smart fin within one second in closed loop case [16].

3.2.2 Forced vibration suppression

Forced vibration analyses are performed by exciting the smart fin by Ling Dynamic System shaker placed near its clamped edge via sinusoidal chirp signal of frequency 0.1–90 Hz generated by SensorTech SS10. This frequency range covers the first flexural, first torsional and second flexural modes of vibration. Figure 7 shows open loop and closed loop frequency responses of the smart fin [18]. It can be observed from Fig. 7 that for the first flexural mode the controller performs satisfactorily. On the other hand, for the second mode which is predominantly torsional and for the second flexural mode the high attenuation levels are not achieved. With the available structural configuration, the torsional mode could not be suppressed. Therefore the structural model is improved by insulating the layer between PZTs [22] and the aluminium fin and by allowing PZT patches move independently from each other in order to achieve better suppression in torsional mode. Further-

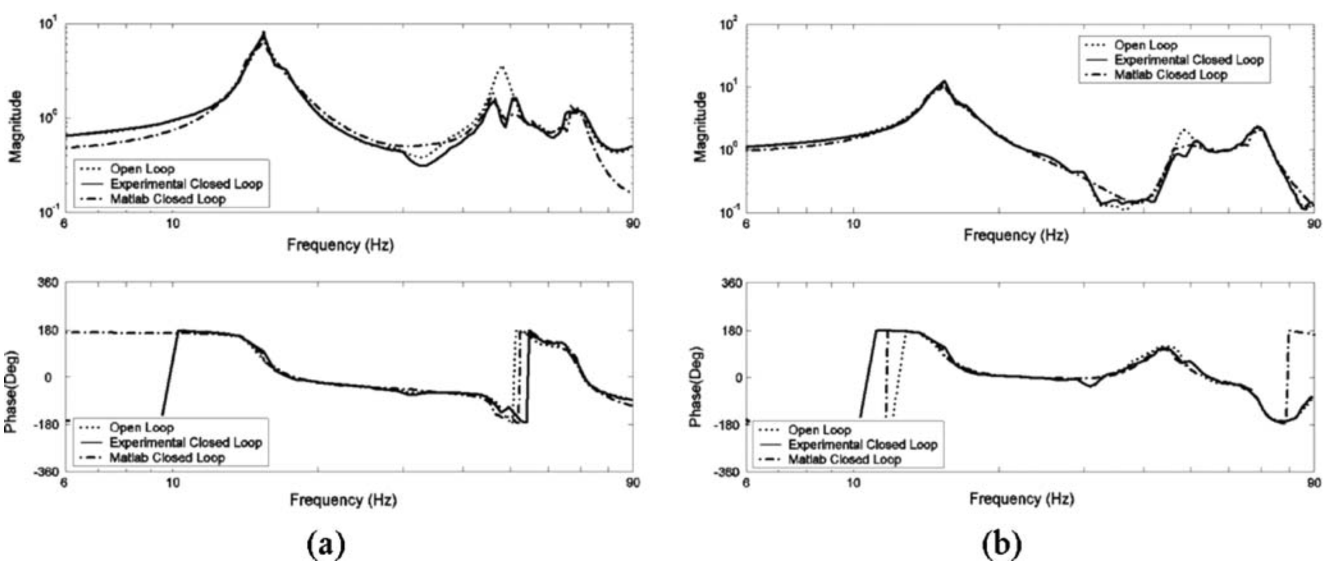

Fig. 8 Open loop and closed loop frequency responses of the smart fin with insulating layer for (**a**) strain measurement (**b**) displacement measurement

more the performance criteria in designing the controller were changed to that of the suppression of the first torsional resonance level and the controller was designed accordingly. The designed controller performed effectively on the torsional response (Fig. 8) [23]. But since the controller was aimed to suppress only the torsional characterictics, it was not very effective on suppressing the first mode around 14 Hz which is predominantly flexural.

4 Studies focusing on spatial control

Further studies tend to suppress the vibration over the entire beam by means of spatial control approach. This approach requires a system model providing spatial information of the structure. Hence, in order to perform spatial system identification of the smart beam, the beam is modeled by assumed-modes method which leads to a model consisting of large number of modes. Then this model is truncated to a lower order model covering only the bandwidth of interest. Since truncation may perturb system zeros and cause inaccuracies, the model is corrected by adding a correction term including the effects of out of range modes [24, 25]. Then analytical and experimental system models are compared and modal damping ratios are tuned till the magnitude of the analytical and experimental frequency responses at resonance frequencies match. The resonance frequencies and modal damping ratios are then determined for various points over the beam where the average values of resonance frequencies and modal damping ratios are accepted as correct ones and the standard deviations are considered as uncertainty on them [26]. These data are used in the designing and implementation of a spatial H_∞ controller for the active vibration control of the smart beam [27].

5 Conclusions

In this paper, the theoretical and experimental studies conducted in Aerospace Engineering Department of Middle East Technical University on smart structures with particular attention given to the structural modelling characteristics and active vibration suppression aspects are presented. The initial studies composed of obtaining the analytical and numerical models of aluminium beam-like and plate-like structures. Then, by obtaining sets of data used to verify and improve the theoretically developed control models for smart beams and plates, and control techniques were developed for the active vibration control of smart structures and their experimental verifications were achieved. Having theoretical and experimental knowledge and a fully equipped laboratory for active vibration suppression applications, current research, complimenting the previously obtained results, is focusing on a more challenging subject of aeroservoelastic analysis and design of aerospace engineering structures.

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