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 PZT (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/or laser displacement sensor to determine the system models. Further studies are carried out to obtain the models of H_∞ and μ vibration 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. The laboratory also allows joint studies to be conducted. 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.

Keywords: smart structures, piezoelectricty, finite element method, active vibration suppression, robust performance

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 the sensors and actuators vary considerably. While typical smart structure sensors used in discrete or distributed locations to measure the performance of the system comprise fibre optics, piezoelectric ceramics and polymers, the actuators used in the smart materials technologies include applications of piezoelectric ceramics, piezoelectric polymers (PVDF), electrostrictive (ES) and magnetostrictive (MS) materials, electro-rheological (ER) and magneto-rheological (MR) fluids and piezofibres. Their reliability, near linear response with applied voltage, exhibiting excellent response to the applied electric field over very large range of frequencies and their low cost make piezoelectric materials (PZT, Lead-Zirconate-Titanate) 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.

2. Modelling of Smart Structures

The theoretical studies regarding modelling and the design of smart structures [1] are performed by using finite element method which is shown to be a very effective tool for the analysis of the piezoelectric materials as the method offers fully coupled thermo-mechanical-electrical analysis of the 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) modeled 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 to as smart beam.

After extensive studies and the verifications with the experimental results, 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. Fig.1 gives the geometry, dimensions and the finite element model of the smart beam used in the study [4].

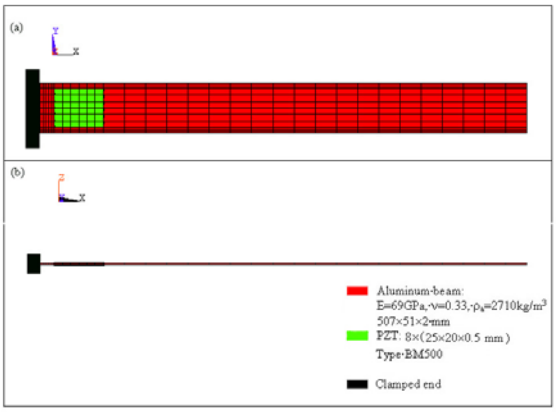


Fig.1: Finite element model of the smart beam (a) Top view (b) Side view

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 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 technique 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 modeling 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 actually 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.2.

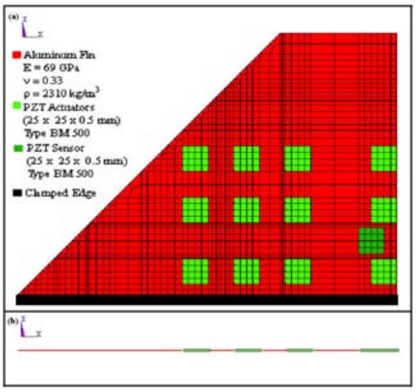


Fig.2: Finite element model of the smart fin (a) Top view (b) Side view

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 considered as sensors (Fig.2). 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. Finite element method also allows the 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 considered 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 exhibit 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 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 transfer function of the system is obtained from the relevant input output relations, then the least square curve fitting method is applied to find the approximate representation of the model (Eqn.1).

$$\frac{-0.00024\,s^8 - 0.01185\,s^7 - 128.9\,s^6 + 3552\,s^5 - 2.294*10^7\,s^4 - 9.158*10^8\,s^3 + 3.117*10^{11}\,s^2 + 6.433*10^{12}\,s + 7.224*10^{14}}{s^8 + 41.43\,s^7 + 5.648*10^5\,s^6 + 1.637*10^7\,s^5 + 3.492*10^{10}\,s^4 + 6.383*10^{11}\,s^3 + 1.262*10^{14}\,s^2 + 1.134*10^{15}\,s + 1.1*10^{17}} \qquad (1)$$

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]. The effectiveness of the technique in the modeling of the uncertainties is also presented. As a joint work, a comparative study involving H_∞ and sliding mode controls is also conducted [11]. The smart beam used in experimental studies is shown in Fig.3.

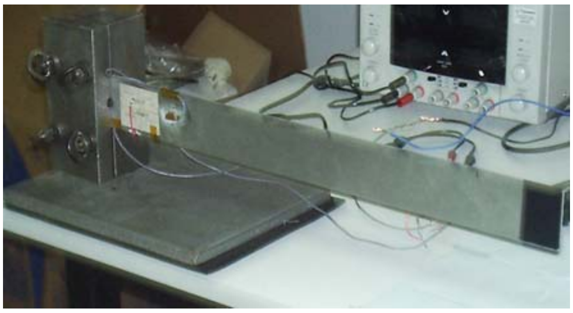
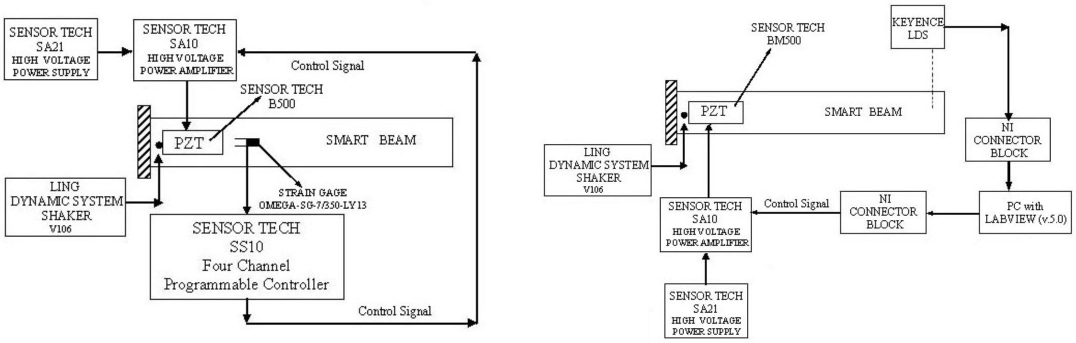


Fig.3: The Smart Beam used in the study

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 application, the system model of the smart beam is obtained by considering the piezoelectric actuator voltage as an input and the beam tip flexural displacement as an 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. Fig.4 (a) and (b) show experimental setups for controller implementation of the smart beam based on strain and displacement measurements respectively. Some open loop experiments are also performed on the smart beam for the determination of the structural characteristics and for the verification of the theoretical results.

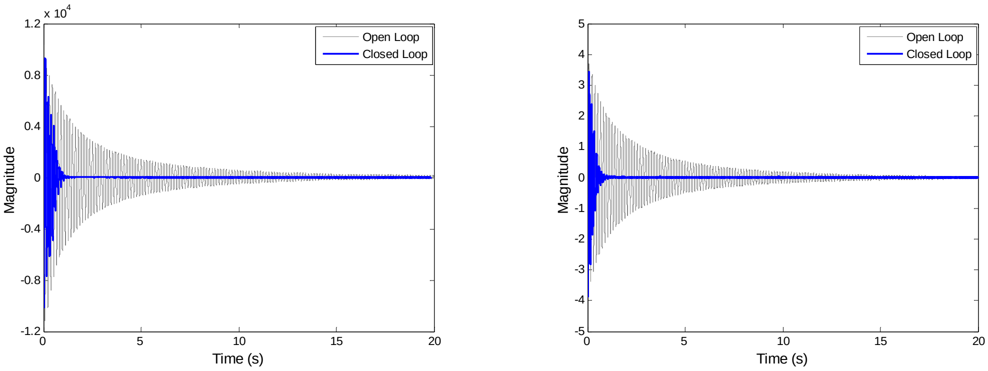


(a) (b)

Fig.4: Experimental Setup for Controller Implementation of the Smart Beam for
(a) Strain Measurement (b) Displacement Measurement

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.5 (a) and (b) for strain and displacement measurements respectively. It is observed that while the smart beam continues to vibrate even at 20 seconds in the open loop case, significant vibration suppressions are achieved in less than 1.3 seconds for the closed loop case based on both strain [12,13] and displacement measurements [12].

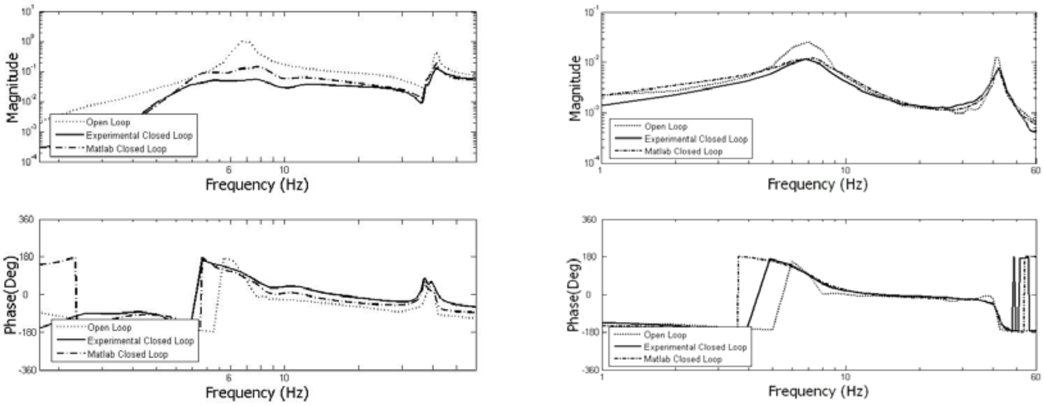


(a) (b)

Fig.5: Open Loop and Closed Loop Time Responses of the Smart Beam 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 Hz- 60 Hz frequency range) is applied through a Ling Dynamic Systems LDS V106 shaker located near the root 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.6 (a) and (b).



(a) (b)

Fig.6: Open Loop and Closed Loop Frequency Responses of the Smart Beam for
(a) Strain Measurement (b) Displacement Measurement

Fig.6 reveals that a significant reduction in the response levels of the first two modes is achieved for both strain and displacement measurements [12].

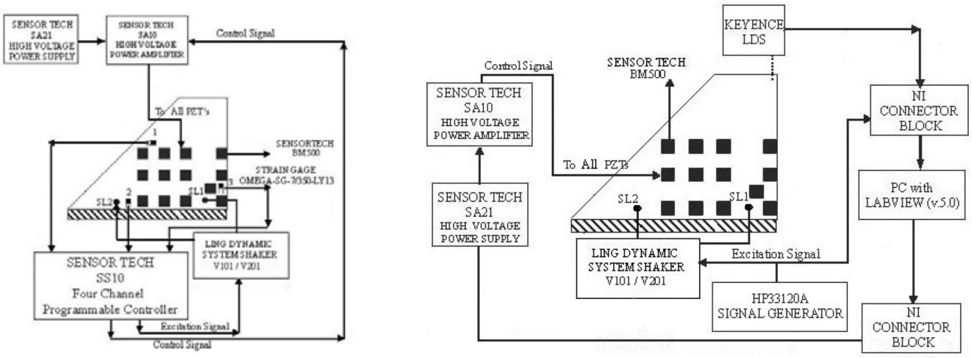
3.2 Control of Smart Fin

The work performed in the area of control of plate-like structures starts with active vibration control of a smart rectangular aluminium plate [14]. Further studies concentrate on active vibration control of a smart fin (Fig.7). 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. The order of the resultant model can vary, the following equation (Eqn 2) describes the 6th order model.

$$\frac{0.0001179\,s^6 - 0.02197\,s^5 + 162.4\,s^4 - 1302\,s^3 + 2.339*10^7\,s^2 + 6.697*10^7\,s + 5.913*10^{11}}{s^6 + 46.71\,s^5 + 2.758*10^5\,s^4 + 7.644*10^6\,s^3 + 1.748*10^{10}\,s^2 + 1.623*10^{11}\,s + 1.179*10^{14}} \tag{2}$$

An experimentally identified model is utilised in the design of H_∞ controller which suppresses in-vacuo vibrations of the smart fin due to its first two modes [6]. Experimental setups for controller implementation of the fin based on strain and displacement measurements are displayed in Fig.8 (a) and (b) respectively. A different controller developed through μ-synthesis is also designed in order to suppress the vibrations of the smart fin due to these three modes [15,16]. It is observed that the controllers guaranty the robust performance of the system in the presence of uncertainties.

Fig.7: The Smart Fin used in the study

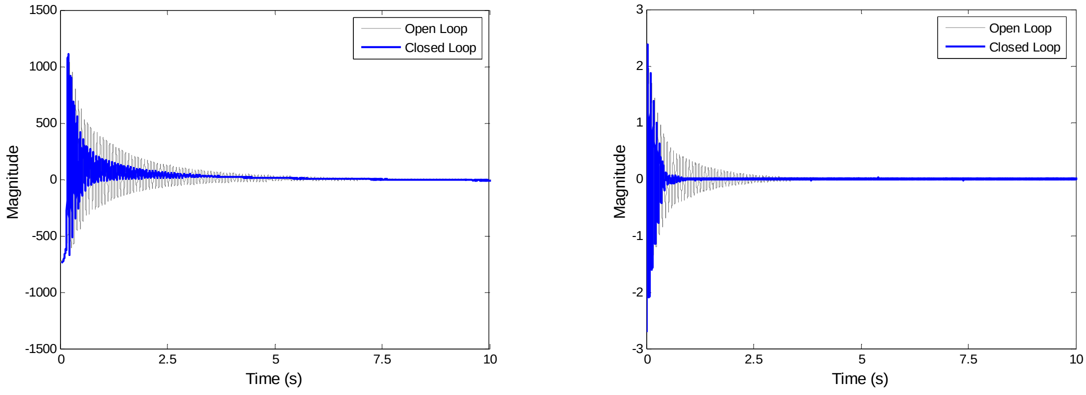


(a) (b)

Fig.8: Experimental Setup for Controller Implementation 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.9 (a) and (b) for strain and displacement measurements respectively. As it can be seen from the figures that the vibration suppression is achieved for the smart fin within one second in closed loop case [13].

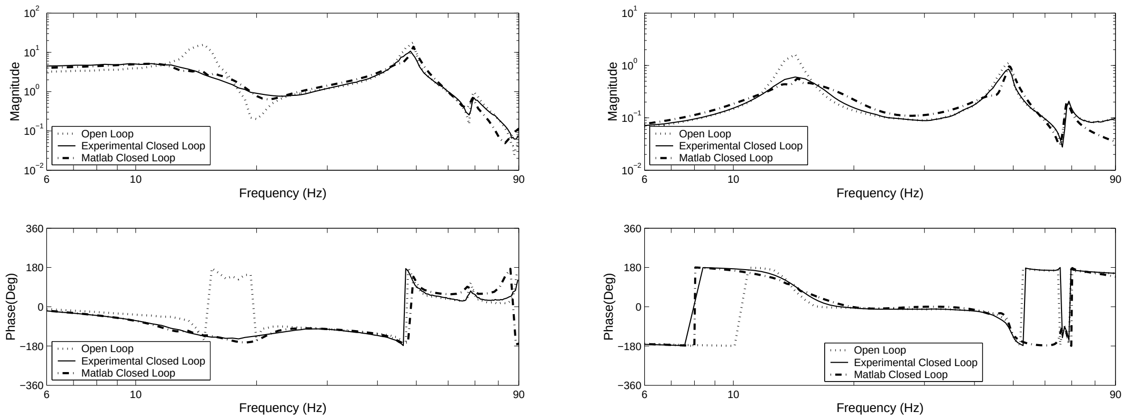


(a) (b)

Fig.9: Open Loop and Closed Loop Time Responses of the Smart Fin for
(a) Strain Measurement (b) Displacement Measurement

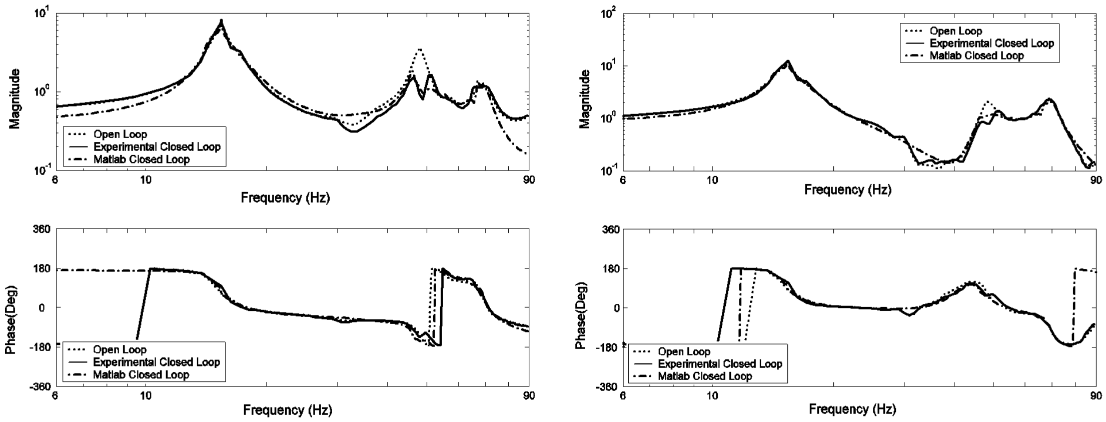
3.2.2 Forced Vibration Suppression

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 Hz – 90 Hz generated by SensorTech SS10. This frequency range covers the first flexural, first torsional and second flexural modes of vibration. Fig.10 shows open loop and closed loop frequency responses of the smart fin [15]. It can be observed from Fig.10 that for the first flexural mode controller performs satisfactorily. On the other hand, for the second mode which is predominantly torsional and the second flexural mode high attenuation levels are not achieved. With the available structural configuration the torsional mode could not be suppressed. Therefore structural model is improved by insulating the layer between PZTs [17] and the aluminium fin and by allowing PZT patches move independently from each other in order to achieve better suppression in torsional mode (Fig.11) [18].



(a) (b)

Fig.10: Open Loop and Closed Loop Frequency Responses of the Smart Fin for
(a) Strain Measurement (b) Displacement Measurement



(a) (b)

Fig.11: Open Loop and Closed Loop Frequency Responses of the Smart Fin with insulating layer for
(a) Strain Measurement (b) Displacement Measurement

4. Studies Focussing on Spatial Control

Further studies tend to suppress the vibration over 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 modelled by assumed-modes method which leads a model consisting large number of modes. Then this model is truncated to a lower order model covering the bandwidth of interest. Since truncation may perturb system zeros and cause instability, the model is corrected by adding a correction term including the effect of out of range modes [19]. 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 [20]. This data are then used in the designing and implemention of a spatial H_∞ controller for the active vibration control of the smart beam [21].

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 are supported by Turkish State Planning Organization through the project METU:AFP.03.13.DPT.98.K.122630 (1998-2002) and NATO/RTO/Applied Vehicle Technology Panel through the project T-121, “Application of Smart Materials in the Vibration control of Aeronautical Structures”. Having obtained the analytical and numerical models of aluminium beam-like and plate-like structures, the project was completed (April 2000 – March 2002) by obtaining sets of data used to verify and improve the theoretically developed control models for smart beams and plates. Studies continue with another NATO/RTO/AVT Panel project T-129 “Development of Control Strategies for the Vibration Control of Smart Aeronautical Structures”. At the end of this project, the main aim of developing of control strategies by using H_∞ and μ control techniques by using PZTs in active vibration control of smart structures and their experimental verification was achieved (April 2002 – March 2004). In these two projects the studies were largely conducted in Aerospace Engineering Department of METU. The project partners Sensor Technology Limited of Canada and Institute for Aerospace research of Canada provided experimental facilities and acted as consultants. Having extensive theoretical and experimental knowledge and a fully equipped laboratory for active vibration suppression applications, further research complimenting the previously obtained results will be focusing on more challenging subject of “Development of and Verification of Various Strategies for the Active Vibration Control of Smart Aerospace Structures subjected to Aerodynamic Loading” as NATO/RTO/AVT Panel Project T -133.

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