Active Vibration Control of Composite Plate

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***Abstract*- A finite element modelling of composite plate with integrated piezoelectric layers, acting as sensor/actuator, for active vibration control is presented in this paper. The displacement feedback (DF) and direct velocity feedback (DVF) controls are integrated into the FE software ANSYS to perform closed loop analysis for vibration control. A smart laminated composite beam with different layup configurations under free and forced vibration condition is studied and the results shows suppression of vibration achieved successfully in both DF and DVF controls.**

***Keywords*- Active Vibration, Composites, Piezoelectric, Modes, ANSYS**

I. INTRODUCTION

Vibration control is an important and rapidly developing field for lightweight flexible structures. Those structures may get damaged or become ineffective under the undesired vibrational loads they constantly experience. Hence, they require effective control mechanism to attenuate the vibration levels in order to preserve the structural integrity. The inherent damping of these structures to suppress vibration response is very small. Hence, active vibration control methods are very useful to control the vibration. After the emergence of smart materials, researchers found smarter way of reducing the vibration that is called as active vibration control using piezoelectric materials. Piezoelectric materials are able to exhibit a strong coupling between the mechanical degrees of freedom and the electrical degrees of freedom. These materials have the unusual capability of converting mechanical strain energy into electrical energy and vice versa. This is the unique property which made researchers to turn their head towards these materials. Piezoelectric materials are preferred because of their unique coupling nature.

Investigations on active vibration control of smart/intelligent shells with a distributed piezoelectric sensor and actuator layer bonded on to the top and bottom surfaces of the structures are available in a number of literatures [1]. Numerical investigation to analyse the free edge effect in laminated piezoelectric plates using finite element method was presented by J. Artel et al. [2]. Two different cross-ply and one angle-ply laminates have been investigated and the results for uncoupled and coupled analysis have been compared. It was found that the interlaminar stresses at the free edge were significantly higher in the coupled case for cross-ply laminates, whereas the coupling effect for the symmetric angle-ply laminate was of lower significance. Pinto Correia et al. [3] developed a semi-analytical axisymmetric shell finite element model with embedded or surface bonded piezoelectric ring actuators or sensors for active damping vibration control of the structure. Feedback control algorithm was used to achieve a mechanism of active control. Based on Kirchoff classical theory Jose M. Simoes Moita et al.[4] presented the finite element formulation for active control of composite structures covered with piezoelectric layers. Levent Malgaca et al.[5] outlined the vibration control problems which can be directly and systematically solved using finite element programs. They also studied the active vibration control of forced and free vibration in laminated composite structures with different lay-ups.

In present study, Finite element modelling of composite beam with piezoelectric material for active vibration control is presented. Displacement feedback (DF) and direct velocity feedback (DVF) controls are studied for vibration control of composite with different lay-up configurations under free and forced vibration modes.

II. METHOD AND METHODOLOGY

The finite element method has become a powerful tool for the numerical solution of a wide range of engineering problems. Finite element method in general and commercial software in particular implemented on a computer offers a universal procedure for engineering analysis. The focus of this work is on use of ANSYS software for simulation of Vibration control in a piezoelectric composite beam.

A cantilever beam made of laminated Glass-epoxy composite material bonded with piezoelectric sensor/actuator is considered in the present work. Finite element model of the beam developed using ANSYS software is presented. The model is validated using benchmark. Two configurations viz., $[0/90]_s$ and $[45/-45]_s$ are considered for the laminates. Vibration control of the composite beam using PZT actuator is studied with DF and DVF control for Free vibration and Forced vibration modes.

A. Finite Element Modelling

Finite element modelling is defined here is analyst's choice of material models, finite elements (type, shape, and order), meshes, constraint equations, analysis procedures, governing differential equations and their solution methods, specific pre-processing and post-processing options implemented in

ANSYS for coupled field analysis. A smart cantilever beam is considered for validation of FE model. The geometric dimensions and material properties are given in table 1. Finite element model of the composite beam is as shown in figure 2. SOLID185 and SOLID5[7] elements are considered to model beam and actuator respectively. Modal analysis of the composite beam is performed to obtain the natural frequencies using the Block Lanczos solver. The obtained natural frequencies are listed in table 2. The comparison of frequency response with experimental study is as shown in Fig 3.

Table 1. Material and Geometric properties of smart structure

Material Properties			Geometric properties	
Glass-Epoxy Composite	Piezoelectric material[5] (BM532)	Piezoelectric material[6] (PZT-4)	Beam	Actuator
ρ =1830 kg/m^3	ρ = 7350 kg/m^3	ρ = 7500 kg/m^3	L = 345 mm	B = 25 mm
Elastic constants (N/m^2)	Elastic stiffness matrix (N/m^2)	Elastic stiffness matrix (N/m^2)	b = 20 mm	b = 20 mm
E_x=40.51 x 10^9	C_{11} =12.6 x 10^{10}	C_{11} =13.9 x 10^{10}	t_1 = 0.85 mm	t_3 = 0.5mm
E_y=13.96 x 10^9	C_{12} =7.95 x 10^{10}	C_{12} =7.78 x 10^{10}	t_2=0.02125mm	d_a = 5mm
E_z=13.96 x 10^9	C_{13} =8.41 x 10^{10}	C_{13} =7.43 x 10^{10}		
G_{xy}=3.1 x 10^9	C_{33} =11.7 x 10^{10}	C_{33} =11.53 x 10^{10}		
G_{yz}=1.55 x 10^9	C_{44}=2.33 x 10^{10}	C_{44} =2.56 x 10^{10}		
G_{xz}=3.1 x 10^9	Piezoelectric constants (C/m^2)	Piezoelectric constants (C/m^2)		
ν_{xy}= 0.22	$e_{31} = e_{32}$ = 6.5	$e_{31} = e_{32}$ = 6.5		
ν_{yz}= 0.11	$e_{24} = e_{15}$ = 17	$e_{24} = e_{15}$ = 17		
ν_{xz}= 0.22	e_{33} = 23.3	e_{33} = 23.3		
	Dielectric Constants (F/m)	Dielectric Constants (F/m)		
	$\varepsilon_{11}=\varepsilon_{22}$=1.503x10^{-8}	$\varepsilon_{11}=\varepsilon_{22}$=1.503x10^{-8}		
	ε_{33} = 1.3 $\times$10^{-8}	ε_{33} = 1.3 $\times$10^{-8}		

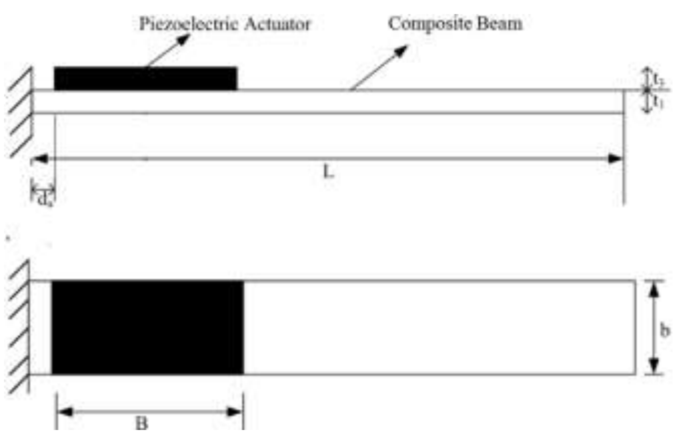


Fig. 1 Smart Cantilever Beam

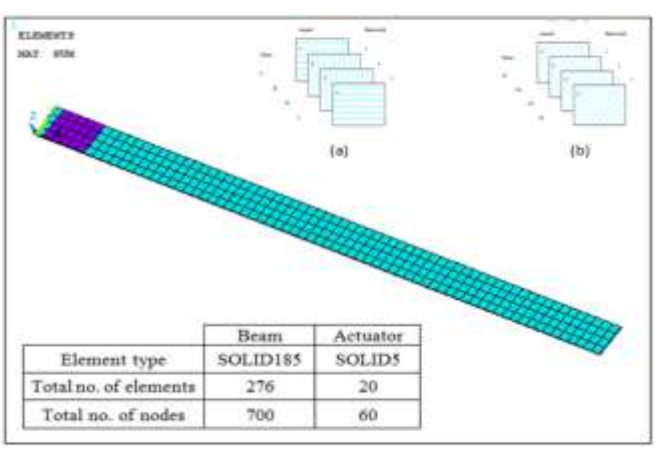
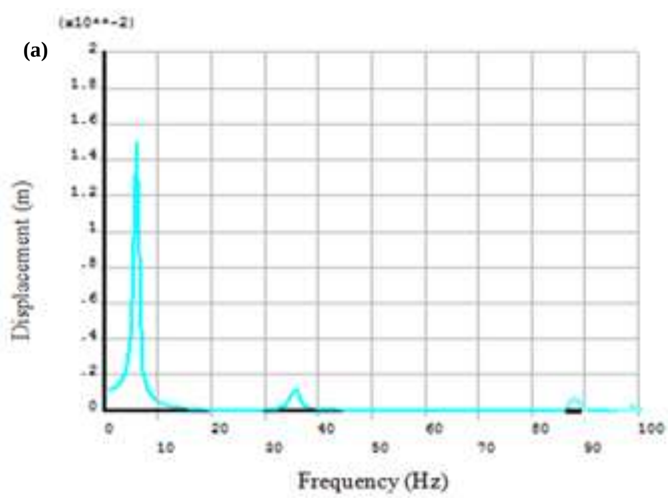


Fig. 2 FE Model of smart beam and lay-ups

Table 2 Comparison of natural frequencies

Mode	Natural frequencies (Hz)	
	Ref [5]	Present study
1	5.9678	5.7900
2	36.5700	36.0800
3	87.5280	87.3210

(a)



(b)

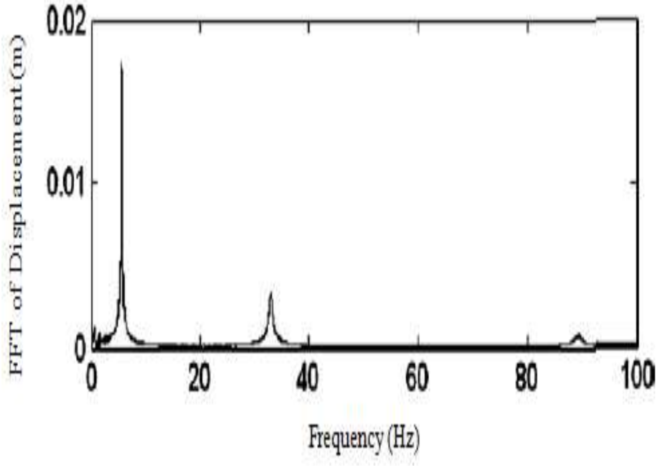


Fig. 3 Comparison of frequency response (a)Present results (b) Target results [5]

The obtained natural frequencies are in agreement with experimental results. It is observed from the results (figure 3 and table 2) that the layered element (SOLID185) and SOLID5 element can be used to model laminated composite beam with piezoelectric layers.

B. Coupled Field Analysis

The coupled field analysis is a combination of analyses from different engineering disciplines (physics fields) that interact to solve a global engineering problem. Hence, we often refer to a coupled field analysis as a multiphysics analysis. There are different types of coupled field analysis, for piezoelectric analysis ANSYS uses direct coupled field analysis. The direct method usually involves just one analysis that uses a coupled-field element type containing all necessary degrees of freedom. Coupling is handled by calculating element matrices or element load vectors that contain all necessary terms.

C. Piezoelectric Analysis

Piezoelectric analysis is the coupling of structural and electric fields. Applying a voltage to a piezoelectric material creates a displacement, and vibrating a piezoelectric material generates voltage. Possible piezoelectric analysis types, available in ANSYS Multiphysics or ANSYS Mechanical products are static, modal, pre-stressed modal, harmonic, pre-stressed harmonic, and transient. Some important points to remember are:

- For modal analysis, Block Lanczos is the recommended solver.
- For static, full harmonic and full transient analysis the sparse matrix (SPARSE) solver or the Jacobi Conjugate Gradient (JCG) solver is preferred. The sparse solver is the default for static and full transient analyses.
- For transient analyses, specify ALPHA= 0.25, DELTA = 0.5, and THETA=0.5 on the TINTP command (Main Menu> Preprocessor> Loads> Time/Frequency> Time Integration).

D. Governing Matrix Equations

The electromechanical constitutive equation for linear material behaviour are

$$\begin{aligned}\{T\} &= [c]\{S\} - [e]\{E\} \\ \{D\} &= [e]\{S\} + [\varepsilon]\{E\}\end{aligned} \tag{1}$$

After the application of the variational principle and finite element discretization, the equations of motion for coupled piezoelectric is,

$$\begin{bmatrix} [M] & [0] \\ [0] & [0] \end{bmatrix}\begin{Bmatrix} \ddot{u} \\ \ddot{V} \end{Bmatrix} + \begin{bmatrix} [C] & [0] \\ [0] & [0] \end{bmatrix}\begin{Bmatrix} \dot{u} \\ \dot{V} \end{Bmatrix} + \begin{bmatrix} [K] & [K^z] \\ [K^z]^T & [K^d] \end{bmatrix}\begin{Bmatrix} \{u\} \\ \{V\} \end{Bmatrix} = \begin{Bmatrix} \{F\} \\ \{L\} \end{Bmatrix} \tag{2}$$

The explanation of sub- matrices is referred in [7].

E. Solution Method

Several methods for solving the simultaneous equations of the system are available in the ANSYS program: Sparse direct solution, Preconditioned Conjugate Gradient (PCG) solution, Jacobi Conjugate Gradient (JCG) solution, Incomplete Cholesky Conjugate Gradient (ICCG) solution, automatic iterative solver option (ITER) and frontal direct solution.

The sparse direct solver is based on a direct elimination of equations, as opposed to iterative solvers, where the solution is obtained through an iterative process that successively refines an initial guess to a solution that is within an acceptable tolerance of the exact solution.

To perform closed loop analysis displacement feedback (DF) and direct velocity feedback (DVF) controls are studied. The block diagrams of DF and DVF controls are as shown in figure 4 and 5 respectively.

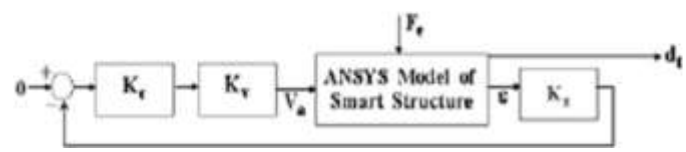


Fig. 4 Block diagram of DF control

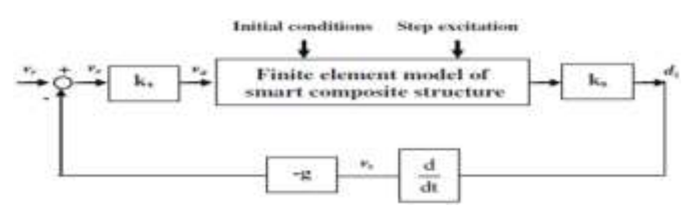


Fig. 5 Block diagram of DVF control

In DF control, the reference value is taken as zero to cancel the vibration and the displacement value from sensor is compared with reference value to determine the error value. The actuation voltage is calculated by multiplying error value with amplification factors. The actuation voltage is applied to actuator, the process continues until steady state response is reached. In DVF control, velocity feedback is calculated by dividing displacement value to dt. The error value is multiplied by K_s and K_v to find the actuation voltage. The actuation voltage is applied to actuator, the process continues until steady state response is reached.

III. ACTIVE VIBRATION CONTROL OF COMPOSITE BEAM

On validation of finite element model of composite structures, the method is used for active vibration control of cantilever beam under free and forced vibration.

A smart laminated composite cantilever with $[0/90]_s$ and $[45/-45]_s$ ply orientation is considered for active vibration control as shown in the figure 2. The actuator bonded to the beam is of PZT-4 material. The material and geometric properties are given in table 1. In the analysis, nodes on upper surface of the actuator are coupled to apply actuator voltage uniformly on the nodes.

Modal analysis of the beam is performed to obtain the first mode frequency and the time step (dt). Time step dt is given by $1/20f_1$, where f_1 is first natural frequency. For $[0/90]_s$ and $[45/45_s$ ply orientation the first mode frequencies are 5.79002 Hz and 3.1802 Hz respectively and the time steps are 0.0084 sec and 0.0152 sec respectively.

Transient analysis is performed to plot time history of tip deflection. Rayleigh damping coefficients used for the analysis are $\alpha = 0.00117$, $\beta = 0.000585$ for $[0/90]_s$ lay-up and $\alpha = 0.00187$, $\beta = 0.000935$ for $[45/-45]_s$ lay-up[6]. Newmark's method is used for time integration with a time step of dt. Displacement Feedback and Direct Velocity Feedback control gain theories are used for active vibration control. The power amplification value K_v is taken as 30 and sensor amplification value K_s is 250 for displacement sensor.

A. Free Vibration

Figure 6 shows the boundary condition applied before commencement of closed loop analysis. A tip displacement of 0.02m is applied in z-direction for duration dt. DF and DVF controls are studied for vibration control.

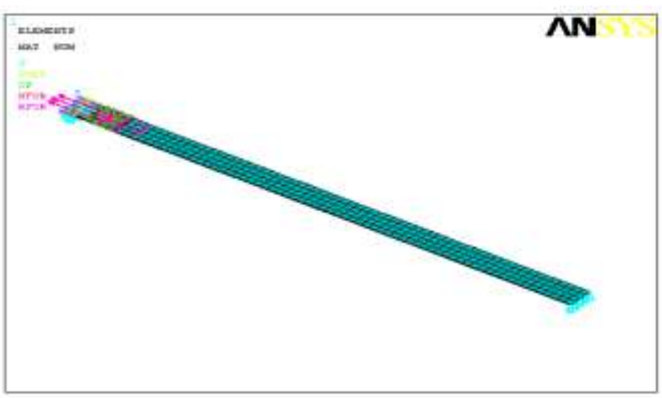


Fig. 6 FE model with boundary conditions (free vibration)

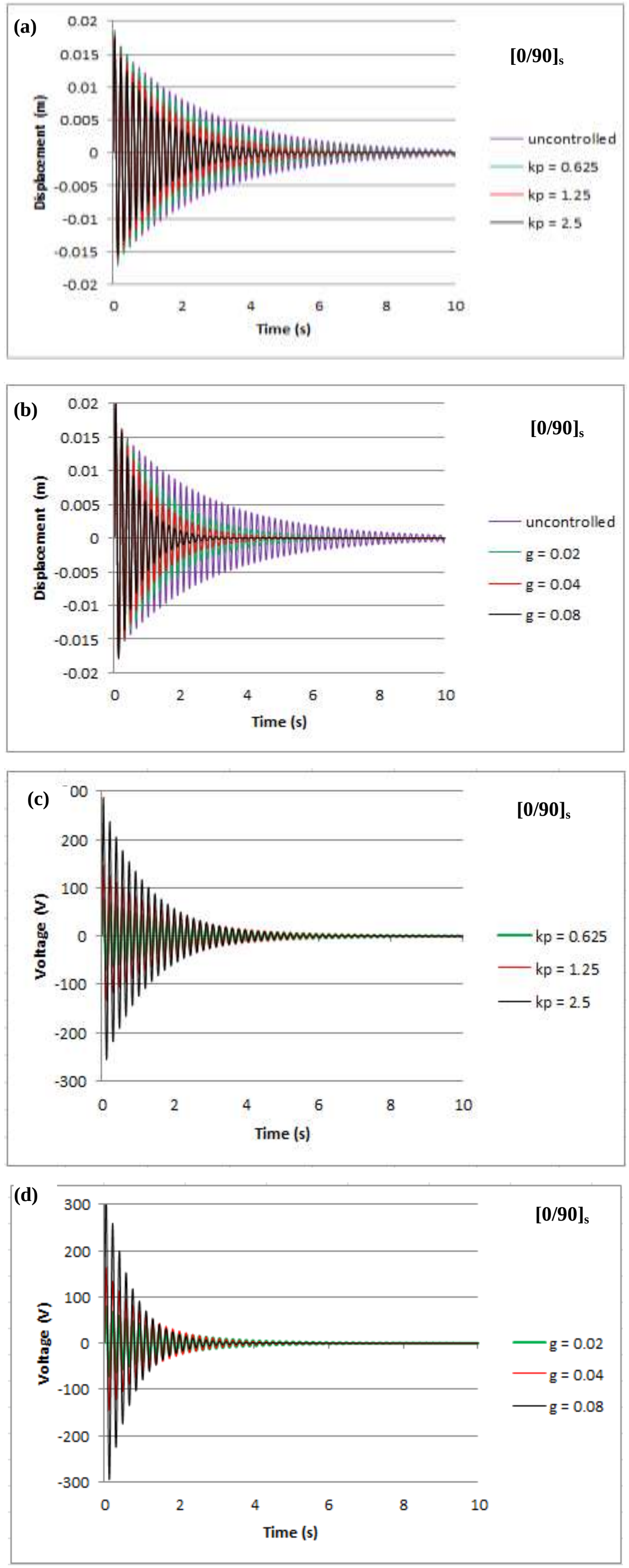


Fig. 7 Time response plots for different gain values under free vibration for $[0/90]_s$: (a) and (c) DF control, (b) and (d) DVF control

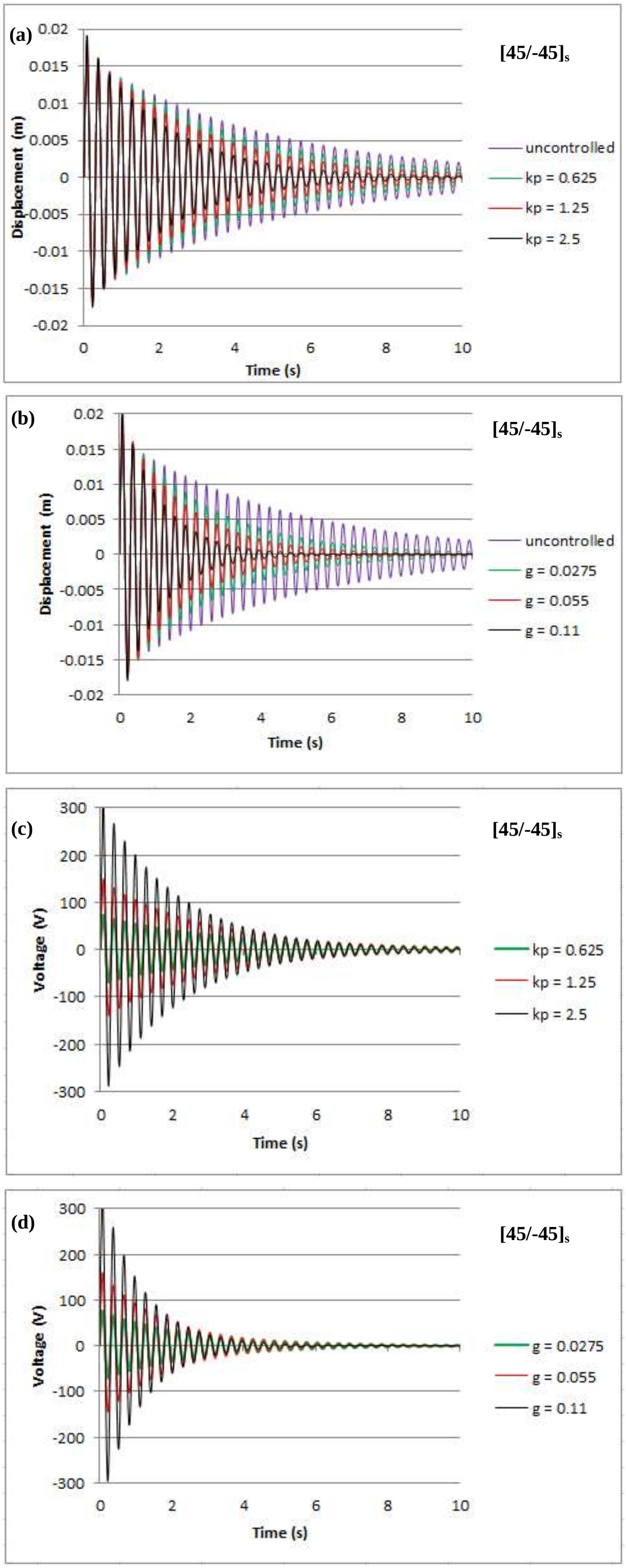


Fig. 8 Time response plots for different gain values under free vibration for [45/-45]s: (a) and (c) DF control, (b) and (d) DVF control

Figure 7 and 8 shows uncontrolled and controlled time responses and actuation voltage responses of DF and DVF controls for $[0/90]_s$ and $[45/-45]_s$ lay-ups respectively. It is observed from results that as the control gain increases the tip deflection decreases and the vibration is successfully controlled in both controls and it can be seen that the time taken to reach steady state is less in DVF control than DF control. Figure 9 shows the comparison of actuation voltage with controller gains.

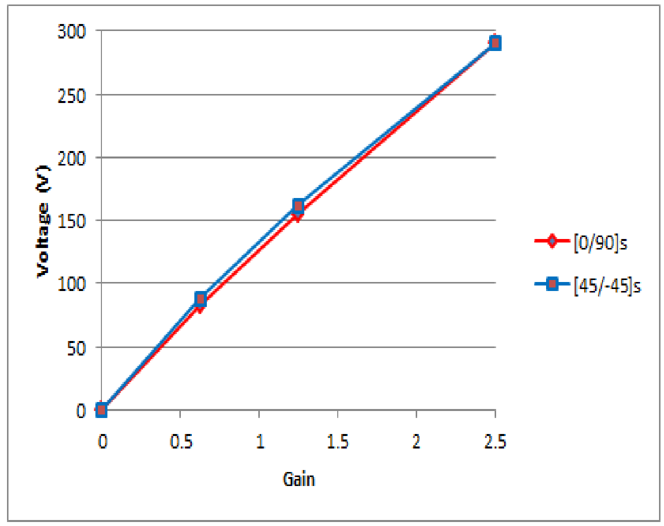


Fig. 9 Comparison of actuation voltage with gain values

B. Forced Vibration

To investigate the response under forced vibration, a step force in z-direction is applied at the tip of beam. The magnitude of step force is chosen to have 0.02 m static tip deflection. The magnitude of forces are 0.0713N and 0.0210N for $[0/90]_s$ and $[45/-45]_s$ respectively. FE model with boundary conditions and loads is shown in figure 10.

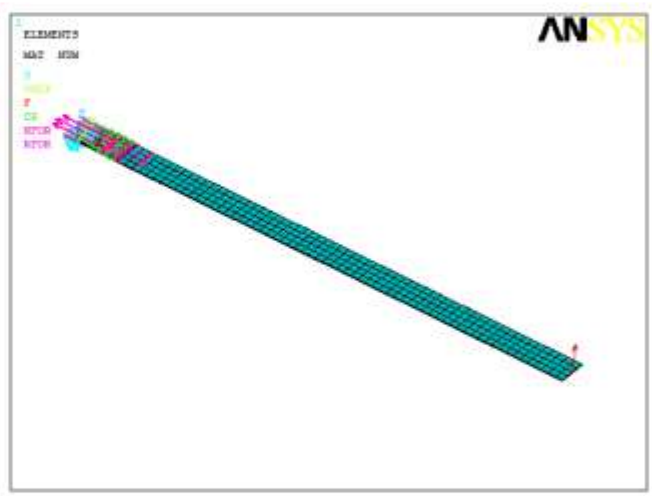


Fig. 10 FE model with boundary conditions (forced vibration)

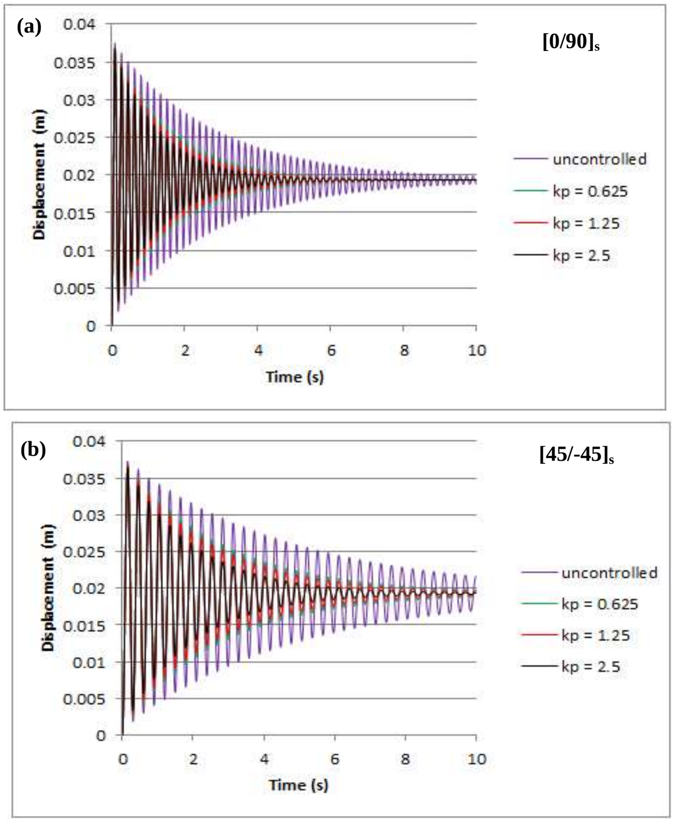


Fig. 11 Time response plots for different gain values under forced vibration using DF control (a) $[0/90]_s$, (b) $[45/-45]_s$

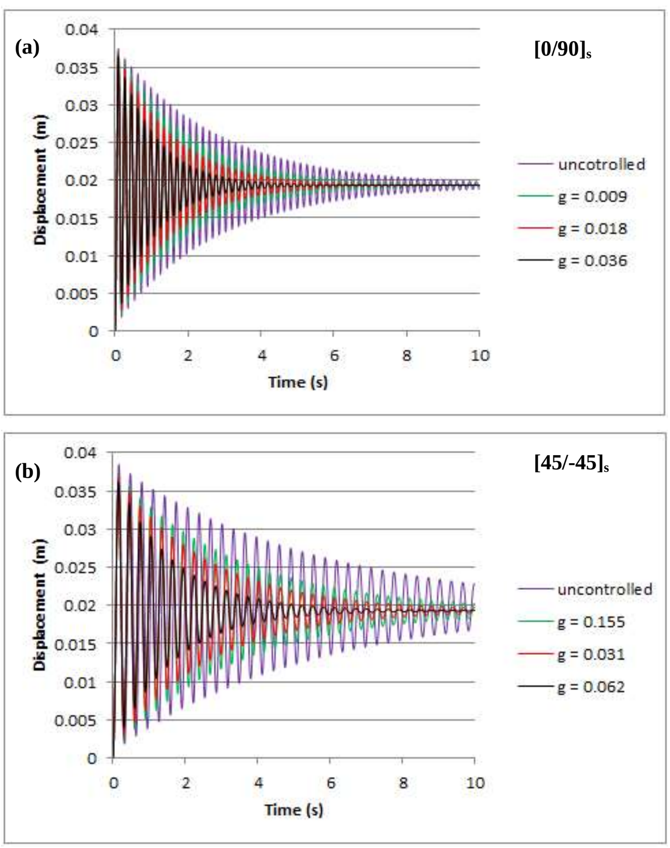


Fig. 12 Time response plots for different gain values under forced vibration using DVF control (a) $[0/90]_s$, (b) $[45/-45]_s$

Figures 11 and 12 show uncontrolled and controlled time responses of forced vibration. It is observed from results that as the control gain increases the tip deflection decreases and the time taken to reach steady state is less in DVF control than DF control.

IV. SUMMARY

Piezoelectric materials have major role in active vibration control. Piezoelectric materials are preferred for active vibration control because of their coupling nature. These materials are inexpensive, lightweight and easily bonded on to the surface and embedded into the structures. ANSYS software provides a mean for FE modelling of smart structures, coupled field analysis and closed loop control actions can be simulated by integrating control laws into the ANSYS.

In this study, Active vibration controls of composite structures with piezoelectric material under free and forced vibrations are studied. The responses of structure using different control laws have been demonstrated. It is observed that the time taken to reach steady state using DVF control is relatively smaller than that of DF control.

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