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Research Paper

Analysis of Smart Structures with Different Shapes of Piezoelectric Actuator

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ABSTRACT

In this work, a finite element (FE) model of piezoelectric smart structures has formulated in ANSYS. The modal analysis of cantilever beam structure is carried out by using the Block Lanczos solver. The piezoelectric patches are located at the region of maximum strain for better control effect. The active vibration concept is demonstrated through simulation study in ANSYS for different shapes of actuators like rectangular, triangular s & rhombus. Closed loop simulation has also been done using strain feedback and displacement feedback. The tip displacements with and without the controller have been obtained and the performance of the proposed smart system is being evaluated for vibration control. From the responses of the each model with different shape of actuator patch, it has been observed that the control effect is better with rhombus patch.
Keywords: piezoelectric smart structures, active vibration control, different shape's actuator

1. Introduction

The area of active vibration control is becoming more significant in the field of engineering application because of the involvement of highly vibrating machines, fluctuating loads, complexity of design and engineered materials. Experimental work in this field is evolving very fastly due to the availability of digital instrumentation, smart sensors and actuators, signal processing and control modules. So this area has become truly interdisciplinary because it includes elements of control engineering and structural dynamics. Hence the need of less vibrating, quieter and damped machines, tools and equipments is well recognized. The piezoelectric materials are of great significance as they can be used as both sensors as well as actuators because they can sense the ambient vibrations and can convert it into an electric voltage which is proportional to the magnitude of vibration. Due to the direct piezoelectric effect sensor produces the charge which is then supplied to the controller. According to suitable control law controller lines the charge and supply it to the actuator. The piezoelectric actuator as a patch is adhered on the host. Actuator produces pinching effect due to the input lined charge on the surface of the host which damps the attenuating vibrations of the beam. Here converse piezoelectric effect is used. Young-Hun analyze the response of an active damping structure for steady state inputs for three dimensional finite element model patched with piezoelectric sensors and actuators[1]. The stiffening effects of a smart piezolaminnated composite beam consisting piezoceramic patches adhered on its surface were analyzed by Haim Waisman , Haim Abramovich (2002) by considering first-order shear deformation theory and linear piezoelectric constitutive relations[2]. S.Narayanan, V. Balamurugan (2003) used pin force model for analyzing influence of actuators by placing them on the proper size and on proper position and considering mass, stiffness and electromechanical coupling effects of the piezoelectric laminates[3]. Using the finite element code a design method was developed for smart structures by S.X. Xu, T.S. Koko (2004) and used finite element model analysis for control design[4]. Karagulle et al. (2004) used APDL (ANSYS Parametric Design language) in ANSYS for analyzing active vibration control of two-degrees of freedom system in conjunction with Laplace transform method[5]. A general analysis and design scheme of piezoelectric smart structures using ANSYS and observer filter identification approach was proposed by Xing-Jian Dong et al., (2006) and analyze the efficiency of OKID approach in vibration control of piezoelectric smart structures[6]. The effectiveness of linear quadratic regulator (LQR), linear quadratic Gaussian (LQG) and optimal control strategies in diminishing the vibrations of smart beams was studied by C.M.A. Vasques, J. Dias Rodrigues (2006) [7]. For the optimal placement of collected pairs of piezoelectric actuator-sensor on a thin plate

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Kumar, K.R. and S. Narayanan, (2008) used a model-based linear quadratic regulator (LQR) controller and developed multi-input-multi-output model using finite element method[8]. Integration of control methods into finite element solutions (ICFES) with ANSYS done by Levent Malgaca(2010) and used ICFES simulation for analyzing active control of free and forced vibrations for a smart laminated composite structure (SLCS) and compared it with experimental results[9]. For active control of vibrations Ismail Kucuk et al. (2011) studied a specific structure which was in the form of Euler-Bernoulli beam with piezoelectric actuators adhered on top and bottom surfaces of the beam. These finite size piezo patches provide the control force to damp vibrations. The equation of motion includes Heaviside functions and their derivatives. To minimize the dynamic response of the beam at a specified terminal time an optimal control theory is formulated [10].
In the recent past, Rectangular shape piezoelectric materials sensors/actuators have been commonly used for active vibration control. Due to high actuation voltage of rectangular shape piezoelectric materials, piezoelectric materials having low actuation voltage can be developed for the active vibration control which will further depends on the shape of piezoelectric materials. However, other shapes like triangular, rhombus have not been investigated for better control. This works considers the different shapes of piezoelectric material for vibration attenuation and compare the responses for better control effect.

2. Finite Element (FE) Formulation of Cantilever Beam

A cantilever beam with piezoelectric actuator is considered. Cantilever boundary conditions are applied to the FE model. The dimension of the cantilever beam is taken as 450 × 20 × 1.5 mm. The dimension of the actuator is 25×20×1 mm. The actuator is located at 10 mm from the fixed end. The FE model is created using SOLID45 and SOLID5 elements for the aluminum beam and the piezoelectric patch after material properties are defined. The nodes of the beam and piezoelectric material are coincided by taking equal element size. The degrees of freedom, volts, are coupled between nodes of actuator and beam. The FE model of the smart beam is shown in Fig. 1. Cantilever boundary conditions are defined for the nodes at x = 0. Natural frequencies are calculated with modal analysis by using the Block Lanczos solver. Mode shapes of the smart beam corresponding to the first three natural frequencies. The first mode is considered to calculate the time step.

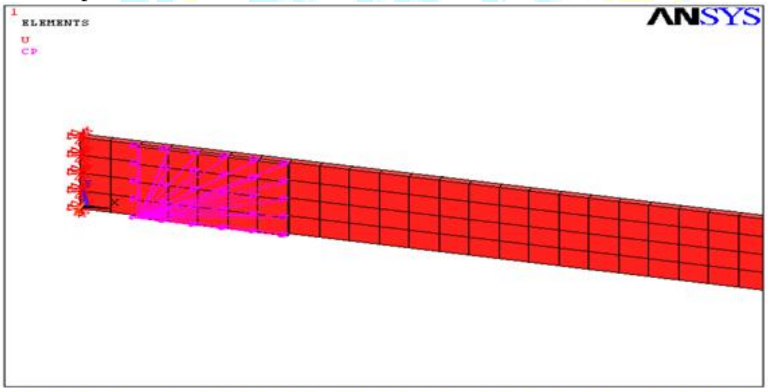

Figure 1: Finite Element Model of Smart Beam with Rectangular Patch

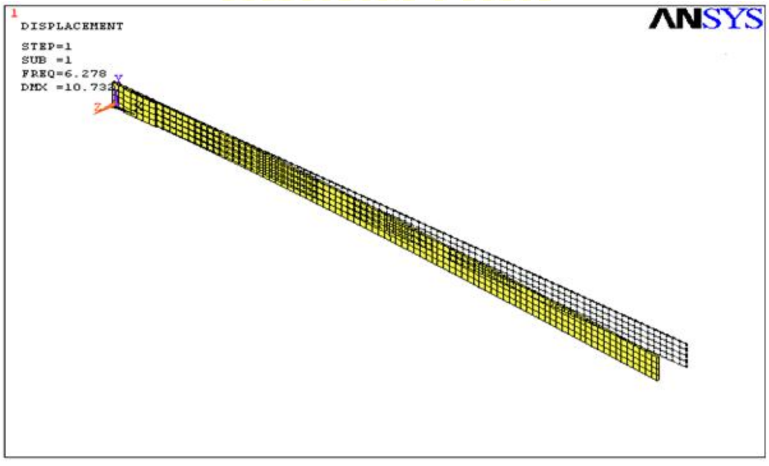

Figure 2: Natural Frequency, Mode1

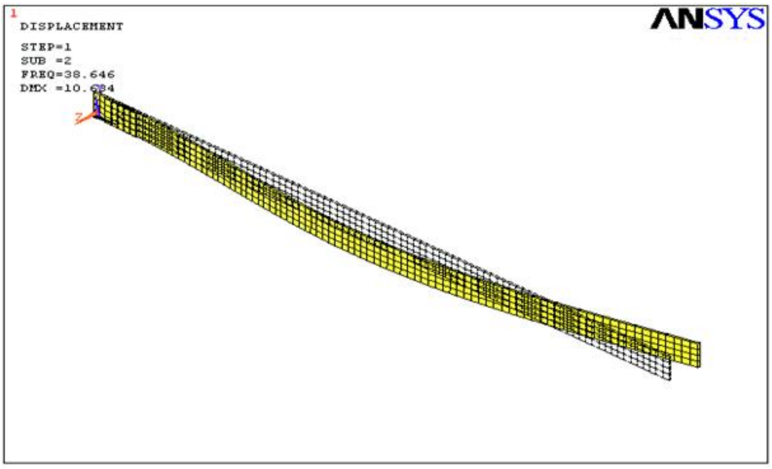

Figure 3: Natural Frequency, Mode2

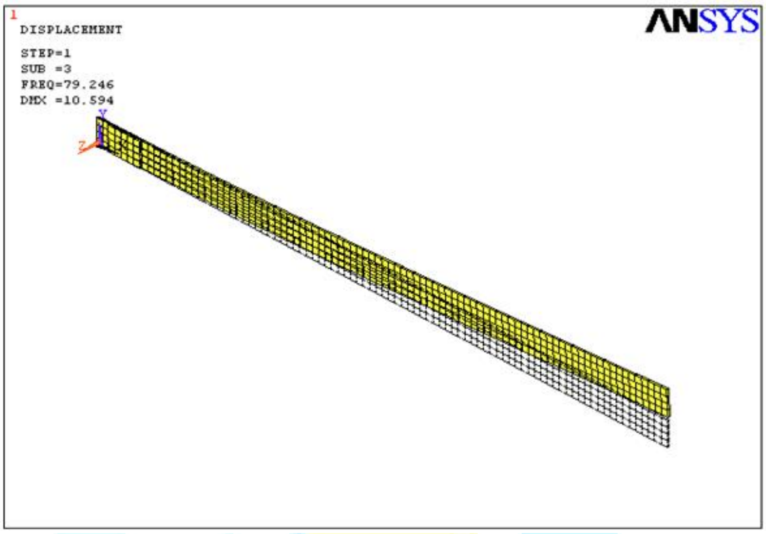

Figure 4: Natural Frequency, Mode3

Table 1: Dimensions and material properties of beam with piezo patch

Material	Length (mm)	Width (mm)	Thickness (mm)	Density (kg/m^3)	Young's modulus (N/m^2)
Aluminum	450	20	1.5	2700	70e9
PZT Actuator/Sensor	25	20	1	7500	50e9

3. Open Loop System with Rectangular patch under transient loading

The first mode is considered to calculate the time step and Δt is 0.007974 . The coefficients of Rayleigh damping are interrelated by 0.66α = β in transient analysis. $V_a = 0$ at t = Δt. For t = Δt and Fe=0 at subsequent time steps the impulsive forces are given as Fe=Fo. Open loop result will obtain with following macro.

```
alpha=4e-4 ! Rayleigh damping coefficients
Beta=2*alpha/3
/SOL
ANTYPE, 4
TRNOPT, FULL
LUMPM,0
FLST,2,1,1,ORDE,1
FITEM,2,453
/GO
F,P51X, FZ,1
ddele,nv,volt
DELTIM,0.0079743417579595892257073639856398, 0, 0
OUTRES,ERASE
OUTRES, ALL, ALL
ALPHAD, alpha
BETAD, beta
LNSRCH, 1
PRED,ON,,ON
TIME,0.0079743417579595892257073639856398
timint,on,ALL
KBC,0
tintp,,0.25,0.5,0.5
LSWRITE,1,
FLST,2,1,1,ORDE,1
FITEM,2,453
FDELE,P51X,FZ
TIME,10
LSWRITE,2,
LSSOLVE,1,2,1,
```

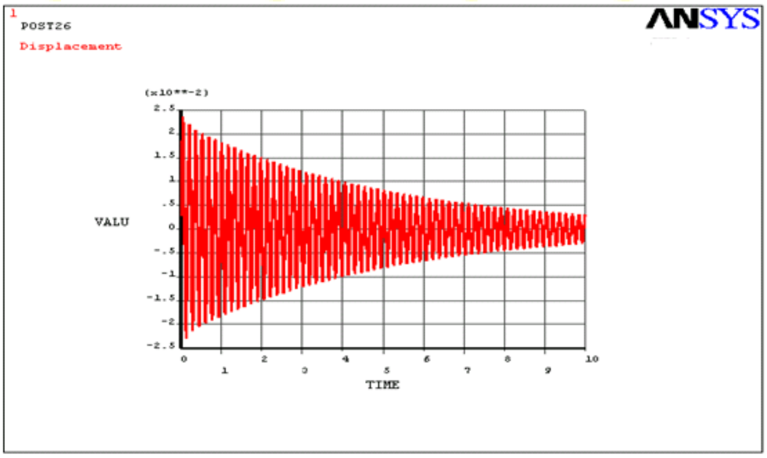

Figure 5: Tip Displacement of smart beam under transient loading

3. Closed Loop Simulation

3.1 Closed Loop Simulation using Strain Feedback

The sensor is located between the two nodes for strain feedback. At selected sensor location strain is calculated and multiplied by K_s then it is subtracted from zero. To control the vibration, zero value is the reference input value. Error signal is the difference between the sensor signal and the input reference. At a time step V_a is determined by multiplying the error value by K_c and $K_{v..}$ Strain is used as feedback for closed loop control system.

```
/solu
*set,dt, 0.007974
*set,ts,10
*set,nv,911
*set,nr1,28
*set,nr2,33
*set,dx,0.005
*set,ks,10000
*set,kv,30
*set,kc,5
*set,va,0
*do,t,2*dt,ts,dt
*get,u1,node,nr1,u,x
*get,u2,node,nr2,u,x
err=0-ks*(u2-u1)/dx
va=kc*kv*err
d,nv,volt,va
time,t
solve
*enddo
```

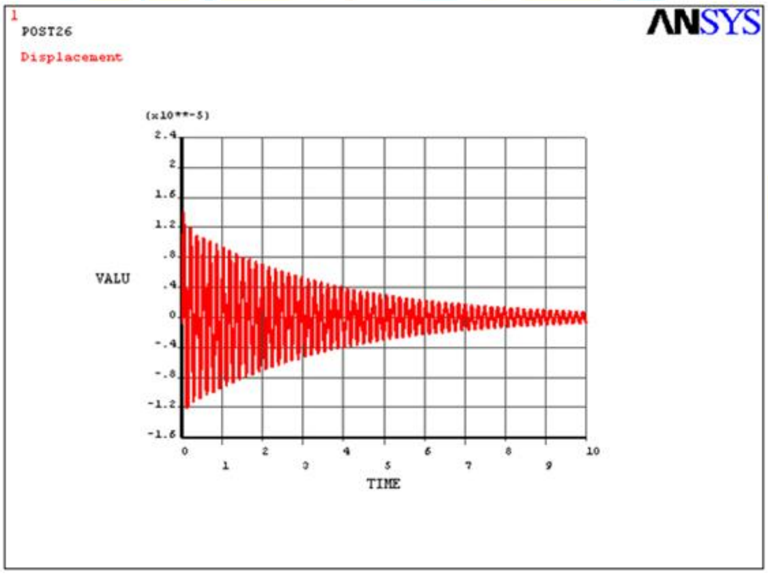

Figure 6: Tip Displacement of smart beam under Closed Loop Simulation (Strain Feedback)

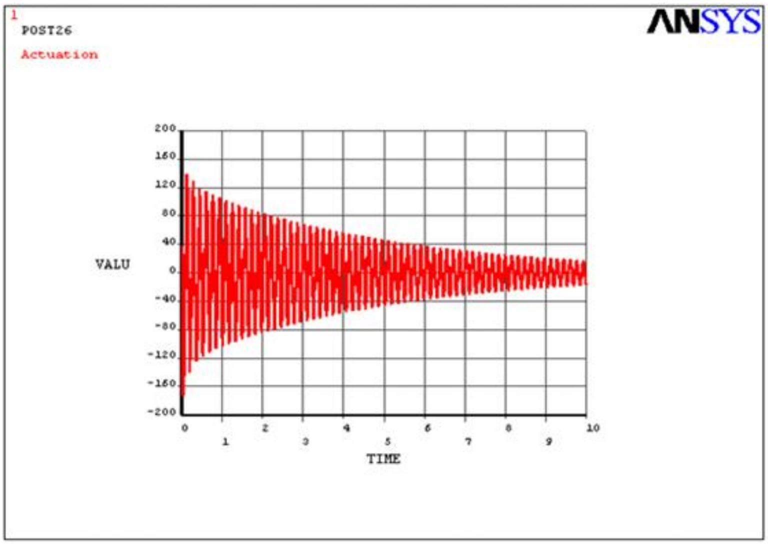

Figure 7: Actuation Voltage

3.2 Closed Loop Simulation using Displacement Feedback

At selected location the tip displacement is calculated and multiplied with K_s and then subtracted from zero. To control the vibration the zero value is the reference input value. Error signal is the difference between the sensor signal and the input reference. At a time step V_a is determined by multiplying the error value with K_c and K_v. Displacement is used as feedback for closed loop control system.

```
/solu
dt=0.00797
ts=2
kv=30 ! Amplifier gain
ks2=250
kp2=3
vmax=270
ref=0
*do,t,2*dt,ts,dt
*get,uztip,node,903,u,z
err=ref-ks2*uztip
va=kp2*kv*err
d,nv,volt,va
time,t
solve
*enddo
finish

/solu
dt=0.00797
ts=10
dxp=0.005
kv=30
ks2=250
kp2=1
vmax=270
ref=0
*do,t,2*dt,ts,dt
*get,uztip,node,903,u,z
err=ref-ks2*uztip
va=kp2*kv*err
*if,va,ge,vmax,then
va=vmax
*endif
```

```
*if,va,le,-vmax,then
va=-vmax
*endif
d,nv,volt,va
time,t
solve
*enddo
finish
```

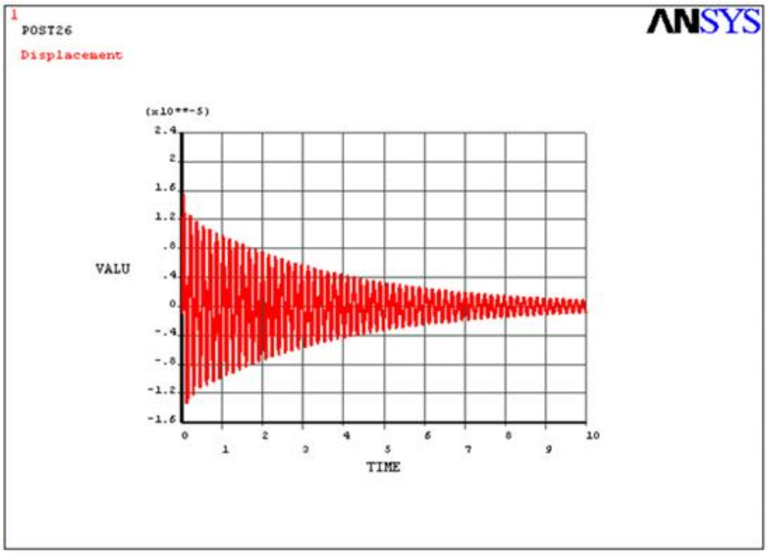

Figure 8: Tip Displacement of smart beam under Closed Loop Simulation (Displacement Feedback) K_p=3

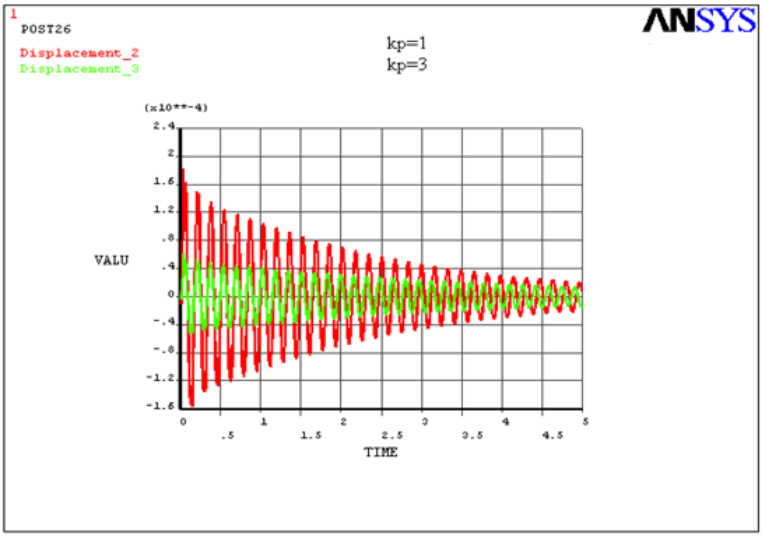

Figure 9: Comparison of responses at different gains of Proportional controllers (K_p=1, K_p=3)

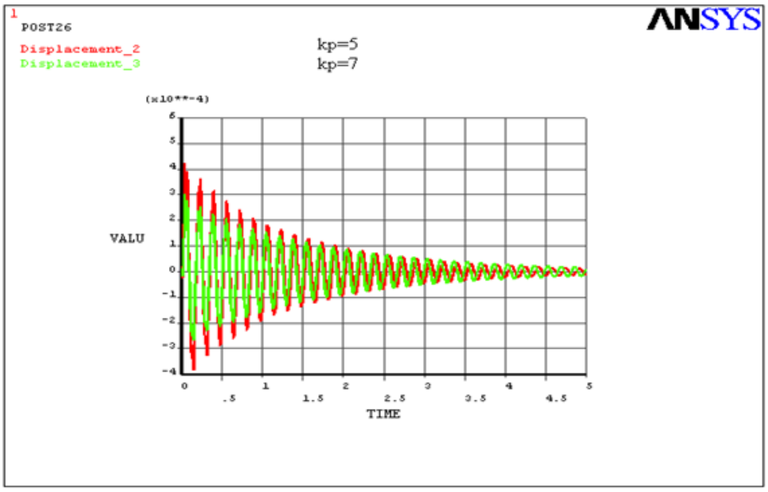

Figure 10: Comparison of responses at different gains of Proportional controllers
As the value of gain of proportional control increases, the amplitude of control loop response decreases.

4. Cantilever Beam with Triangular Patch

The FE model of cantilever beam with triangular piezoelectric patch is prepared. The closed loop responses are obtained at values 1, 2 and 3 of proportional controller gain with displacement feedback as shown in Fig. 12 & 13.

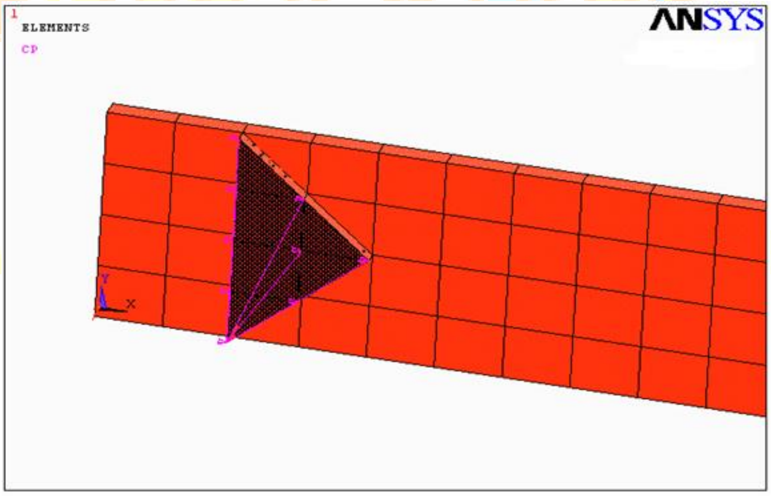

Figure 11: Cantilever Beam using Triangular Patch

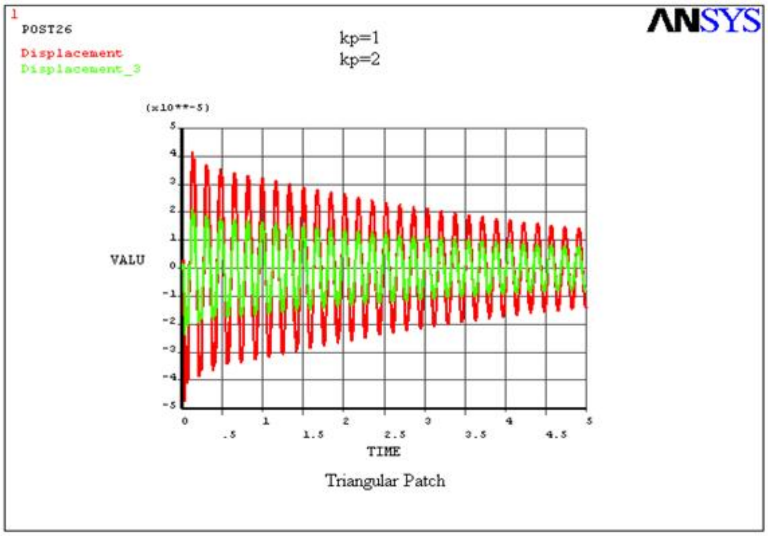

Figure 12: Comparison of responses at different gains of Proportional controllers

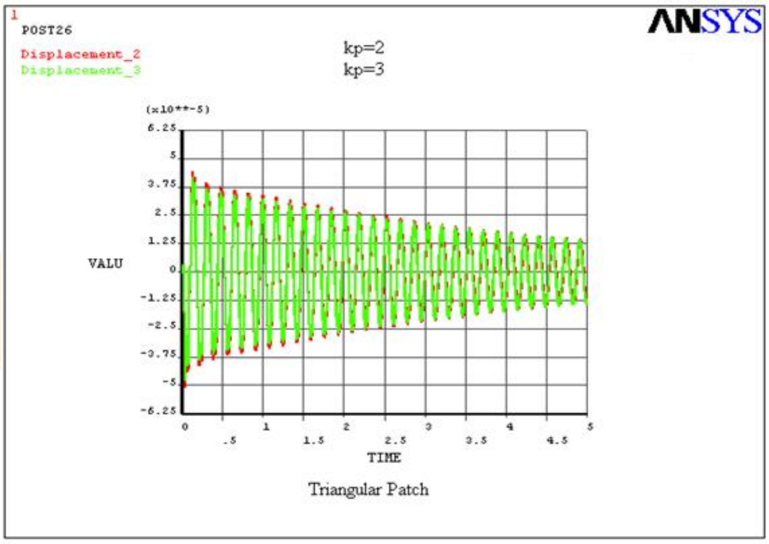

Figure 13: Comparison of responses at different gains of Proportional controllers

5. Cantilever Beam with Rhombus Patch

The FE model of cantilever beam with rhombus piezoelectric patch is prepared. The patch is placed on the beam such that the diagonal of the rhombus coincide the mid-plane of the beam as shown in Fig. 14. The closed loop responses are obtained at values 1, 2, 3 and 4 of proportional controller gain as shown in Fig. 15 & 16.

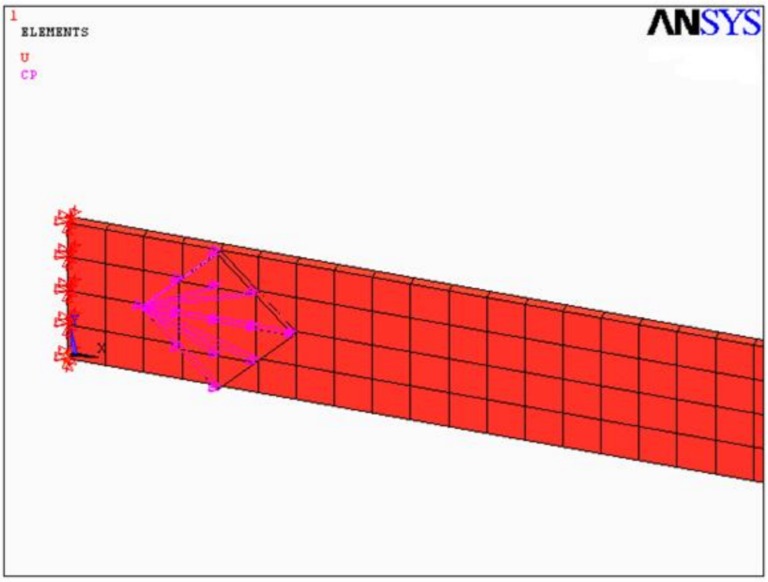

Figure 14: Cantilever Beam using Rhombus Patch

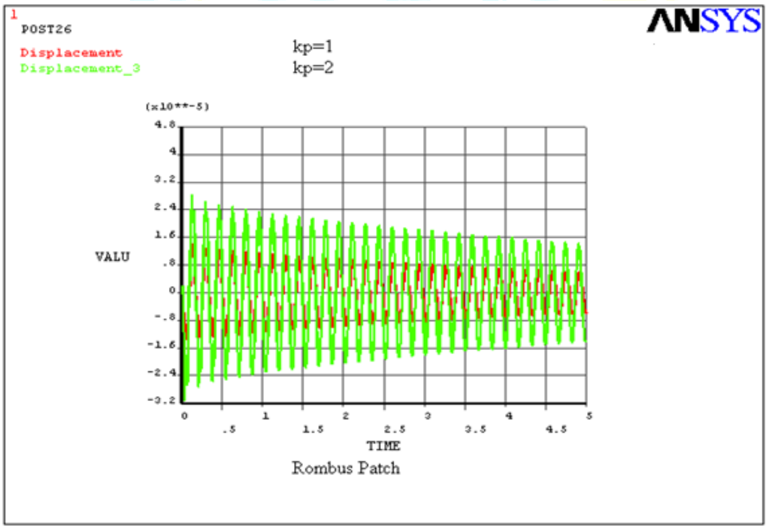

Figure 15: Comparison of responses at different gains of Proportional controllers

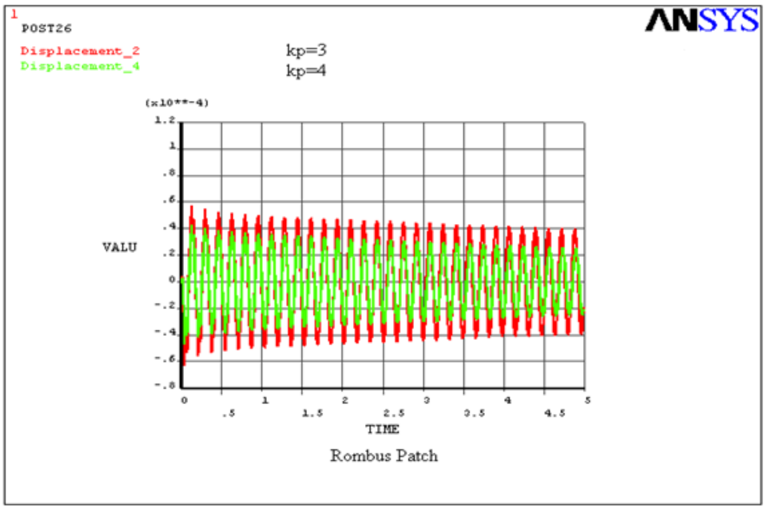

Figure 16: Comparison of responses at different gains of Proportional controllers

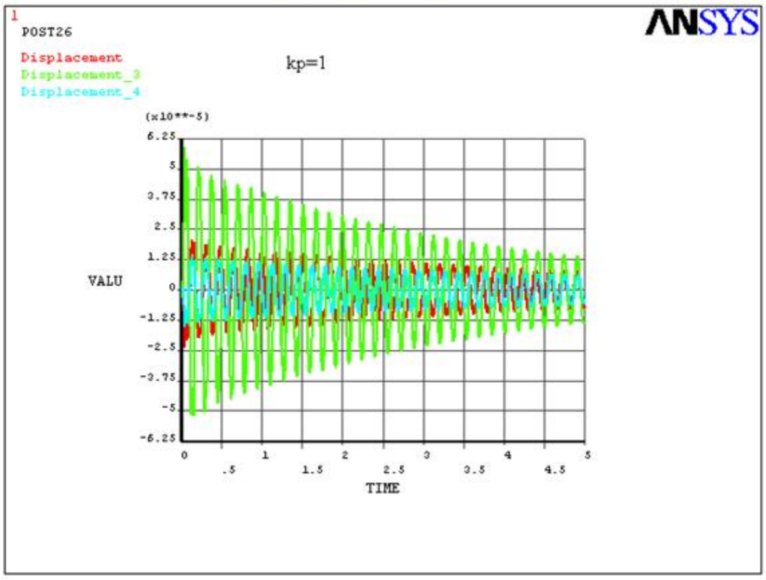

Figure 17: Comparison of responses at same gain (K_p=1) for Rectangular Patch, Triangular Patch & Rhombus Patch

6. Conclusion

The FE models of cantilever beam with different shapes of actuator patch like rectangular, triangular and rhombus have been successfully designed with ADPL (ANSYS parametric design language). The responses of different model are obtained. It can be inferred from the response characteristics that transient response is predominant without control and sufficient vibrations attenuation can be achieved with controller gain. It has also been observed from the simulation results that the modeling smart structure with different shapes of actuator establish a considerable change in system's structural vibration characteristics. From the responses of the each model with different shape of actuator patch, it is observed that the control effect (i.e. peak response and settling time) is better with rhombus patch. However, in terms of contact area, the triangular patch is having lesser area than other with better control effect which can be revealed from Table 1.

Table 2: Comparison of shapes of piezoelectric actuators

S.No	Shape of Piezoelectric Patch	Contact Area Sq.mm	Settling Time without control	Settling Time with control
1	Rectangular	500	8.4 sec	6.5 sec
2	Triangular	100	7.2 sec	6 sec
3	Rhombus	200	6.6 sec	5.5 sec

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