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Research Paper

DESIGN AND ANALYSIS OF FLEXIBLE STRUCTURES WITH PARAMETRIC UNCERTAINTIES FOR ACTIVE VIBRATION CONTROL USING 'ANSYS'

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ABSTRACT

The flexible beams are the common structural elements of many engineering applications which are subjected to vibrations. These vibrations can severely affect the fatigue life of the structures and any parametric uncertainty can even worsen the situation. These parametric uncertainties are caused by factors such as joint clearances, friction, material non-uniformities and manufacturing and assembly errors. This work deals with the study of uncontrolled and controlled dynamic responses of a cantilever beam like structures with parametric uncertainties subjected to an impulse load at the tip of the beam. An integrated analysis procedure has been developed for the control of structures. ANSYS parametric design language (APDL) was used to incorporate the closed loop control laws into the finite element (FE) models. Simulations were performed by varying the height and width of a beam. Simulation results shows that active vibration suppression is achieved even in the presence of uncertainties

Keywords: *parametric uncertainty, FEM, PID, flexible structures*

1. Introduction

Vibration is an important aspect of many engineering systems, from machine tools to structure-borne noise in aircraft. In most cases, such vibration is undesirable and requires attenuation or vibration control.

The flexible beams are the common structural elements of many engineering applications which are subjected to vibrations. These vibrations can severely affect the fatigue life of the structures and any parametric uncertainty can even worsen the situation. These parametric uncertainties are caused by factors such as joint clearances, friction, material non-uniformities and manufacturing and assembly errors during the applications. Active vibration controls can be used to eliminate undesired vibrations in engineering structures with parametric uncertainties.

This work deals with the active vibration control of beam like structures with parametric uncertainties. A finite element model based on Euler-Bernoulli beam theory is utilized to study the dynamic characteristics of structures with uncertainties.

Flexible structures are generally characterized by the undamped natural frequencies and damping ratios of their flexible modes. These parameters are subject to errors when they are estimated. Such uncertainties are important and should be taken into account in a controller design. The proper capture of modal parameter uncertainties in dynamic models of flexible structures for control has been the subject of ongoing efforts.

In this study, the closed loop control laws are incorporated into the finite element (FE) models by using ANSYS parametric design language (APDL).. First, the procedure is tested on the active vibration control problem with three degree of freedom system to validate the method. The analytical results obtained by the Laplace transform method and by ANSYS are compared. It is observed that the analytical results were well matched with the results obtained through ANSYS. The convergence study for finalizing the mesh size is performed and modal analysis of beam structure is carried to find out the mode shapes and natural frequencies of the beam. Then the harmonic and transient analysis of a cantilever beam is done with the variation in the parameters like height and width to account for the uncertainty in the structures and finally the active vibration control is applied to suppress the vibrations using ANSYS.The active vibration concept is demonstrated through simulation study in ANSYS for proportional integral derivative (PID) controller

Karagulle et al. (2004) introduced the active vibration control using APDL (ANSYS Parametric Design language) in ANSYS. They analyzed the results obtained from the APDL for the two-degrees of freedom system and found superiority with the Laplace transform method. Samuel da Silva and V. Lopes Júnior studied Robust control to Parametric Uncertainties in Smart Structures Using Linear Matrix Inequalities. Shu-Xin Wang *, Yan-Hui Wang, Bai-Yan He Dynamic modeling of flexible multibody systems with parameter uncertainty. Nabil Aouf and Benoit Boulet discussed Uncertainty Models and Robust Complex-Rational Controller Design for Flexible Structures.Radek Matušů, Roman Prokop, and Libor Pekař studied Parametric and unstructured approach to uncertainty modelling and robust stability analysis. The main motivation of this work is to develop general design and analysis scheme by incorporating the control law directly into the FE programs. The closed loop control law is incorporated into the FE models by using APDL. The FE analysis with closed loop control actions are carried out by ANSYS. Closed loop-FE simulations of flexible structures like cantilever beam with parametric uncertainties are performed. The control gains are determined by the simulations.

2. Three-degrees of freedom spring mass system

In this, first the results are obtained for the active vibration control of a three degree of freedom system analytically & then results are compared with ANSYS modeling & simulation. It was observed that the ANSYS results were in close proximity with the analytical results.

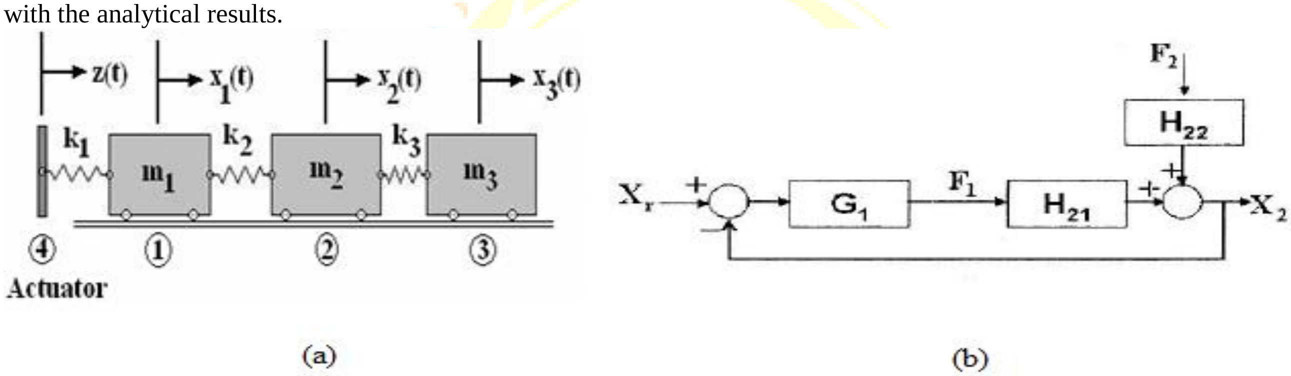

Figure 1. (a) The three-degrees of freedom system((m1=m2=m3=5 kg, k1=k2=k3=500 N/m) and (b) block diagram of the closed loop control system

2.1 Analytical Solution

The system considered and a block digram of the closed loop control system are shown in figure 1. f_2 is the vibration generating force, and f_1 is the controlling force. X_r, X_2, F_1 and F_2 are the Laplace transforms of the reference input (x_r), output displacement (x_2), the forces f_1 and f_2, respectively. G_1 is the transfer function of the control action, and is taken as

$$G_1(s) = k_p + \frac{k_i}{s} + k_D(s) \tag{1}$$

for the PID (proportional-integral-derivative)control . Kp, K_i, K_D are the proportional, integral, derivative constants, respectively. H_{21} is the transfer function from F_1 to X_2, and H_{22} is the transfer function from F_2 to X_2. The reference input, X_r, is taken as zero for the vibration control. $X_e(t)$ is defined as the error signal, where $X_e(t) = X_r(t) - X_2(t)$. The vibration generating force is taken as a unit impulse in the study, and thus F2(s) =1

The equation of motion for undamped multi-degrees of freedom vibrating system is given as

$$[M]\{\ddot{x}\} + [k]\{x\} = \{f\} \tag{2}$$

where M, K and f are the mass, stiffness and force matrices, respectively. Applying Lagrange equation, the mathematical model of the system in figure 1(a) can be found as

$$\begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix} \begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \\ \ddot{x}_3 \end{Bmatrix} + \begin{bmatrix} k_1+k_2 & -k_2 & 0 \\ -k_2 & k_2+k_3 & -k_3 \\ 0 & -k_3 & k_3 \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \\ x_3 \end{Bmatrix} = \begin{Bmatrix} k_1 \\ 0 \\ 0 \end{Bmatrix} z(t) \tag{3}$$

Then the transfer functions can be written as the following, after substituting the values of the masses and stiffness:

$$H_{11}(s) = \frac{s^4 + 900s^2 + 9000}{D(s)} \tag{4}$$

$$H_{12}(s) = \frac{300s^2 + 9000}{D(s)} \tag{5}$$

$$H_{12}(s) = \frac{9000}{D(s)} \tag{6}$$

Where

$$D(s) = s^6 + 1500s^4 + 540000s^2 + 27000000 \tag{7}$$

Substituting $X_r(s)=1$ and $F_{2(s)}=1$, the transfer function of the closed loop system in figure 1(b) is found to be

$$X_2(s) = \frac{27\text{x}10^6(K_d s^2 + K_p s + K_i)}{s^7 + 100K_d s^6 + (1500+100K_p)s^5 + (12\text{x}10^4 K_d + 100K_i)s^4}$$

$$+ (540\text{x}10^3 + 12\text{x}10^4 K_p)s^3 + (12\text{x}10^4 K_i + 27\text{x}10^6)s^2$$
$$+ (12\text{x}106K_p + 27\text{x}10^6)s \ + 27\text{x}10^6 K_i \tag{8}$$

$x_2(t)$ can be found by taking the inverse Laplace transform of $X_2(s)$. The time histories of $x_2(t)$ are given in figure 2 for the uncontrolled and controlled cases.

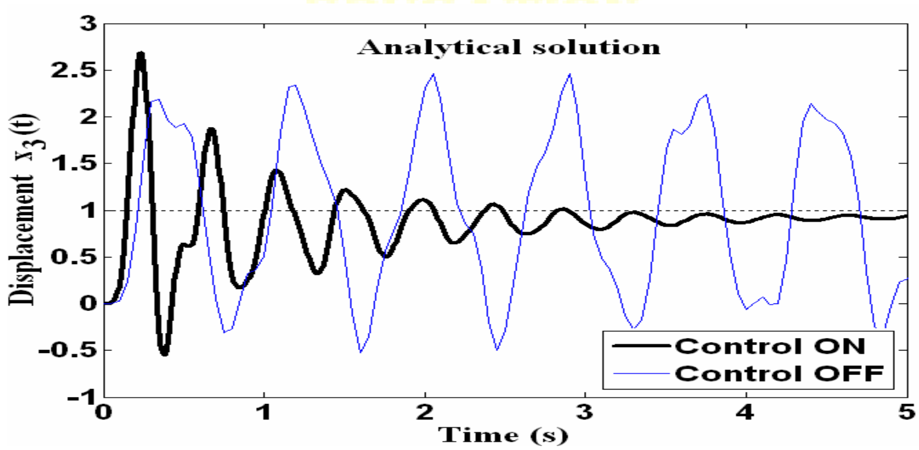

Fig 2 Analytical Solution for controlled & uncontrolled case

2.2 Solution by ANSYS

Closed loop simulation is performed by utilizing computer-aided engineering program ANSYS. Control actions are incorporated into the FE model of multi-degrees of freedom vibratory system using APDL. The elements MASS21 and COMBIN14 are used in order to construct the FE model of 3-DOF system. MASS21 is the lumped mass while COMBIN14 is the spring-damper. The value of damper is taken zero since damping is ignored. Modal analysis is performed to find the undamped natural frequencies of the system. The closed loop control is realized with the following macro :

```
sum=0
errp=0

*do,t,2*dt,ts,dt
*get,x1,node,1,u,x
*get,x2,node,2,u,x
*get,x3,node,3,u,x
err=1-(x1+x2+x3)/3
sum=sum+err*dt
diff=(err-errp)/dt
ucon=kp*err+ki*sum+kd*diff
d,4,ux,ucon
errp=err
time,t
solve
*enddo
```

The variables dt, ts and err are the time step, the time at steady state and the error signal, respectively. The reference value is taken as 1 to calculate the error signal. The time step is taken as dt=1/60f3, where f3 is the highest undamped natural frequency since the differential control requires smaller time steps for higher accuracy. So, dt= 0.00335 s. The uncontrolled and controlled responses obtained by closed loop simulation are shown in figure 3. It is observed that the analytical and ANSYS solutions are in agreement. This agreement of the two methods validates the method adopted in the research.

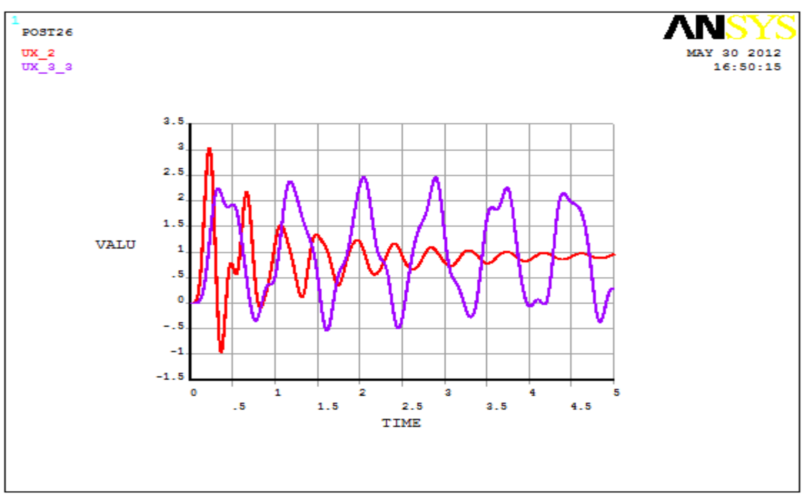

Fig 3 ANSYS Solution for controlled and uncontrolled case

Effect of uncertainty in stiffness

To introduce uncertainty in the 3-DOF system, 10 percent variation in the stiffness of the springs is done and the response is observed using ANSYS. It was observed that although there is not much variation in the amplitude of the vibration but the system vibrates in a different phase as shown in figure 4. So, there is a requirement of vibration control since any uncertainty in the system can severely affect the vibration pattern of the system which can lead to failure of the system.

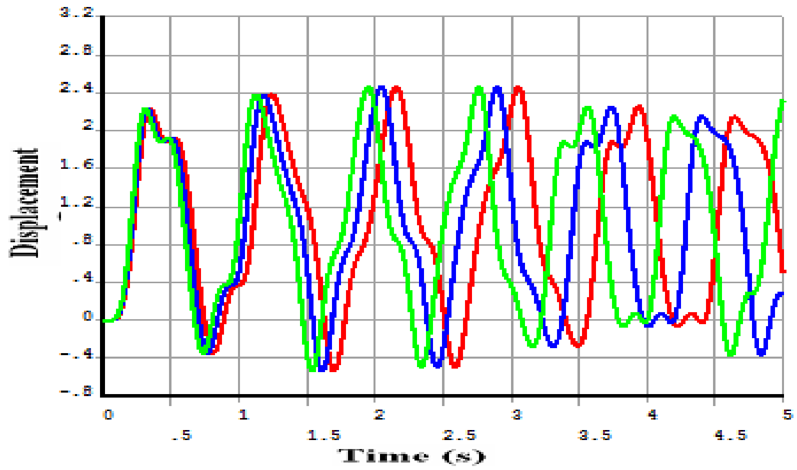

Fig. 4 Effect of uncertainty in stiffness

It concludes that there is a need to apply control on the vibrations to prevent the damage to the system. Again the active control is carried out with "*do-*enddo" loop and the results of the control action are compared with the uncontrolled cases with varying stiffness.

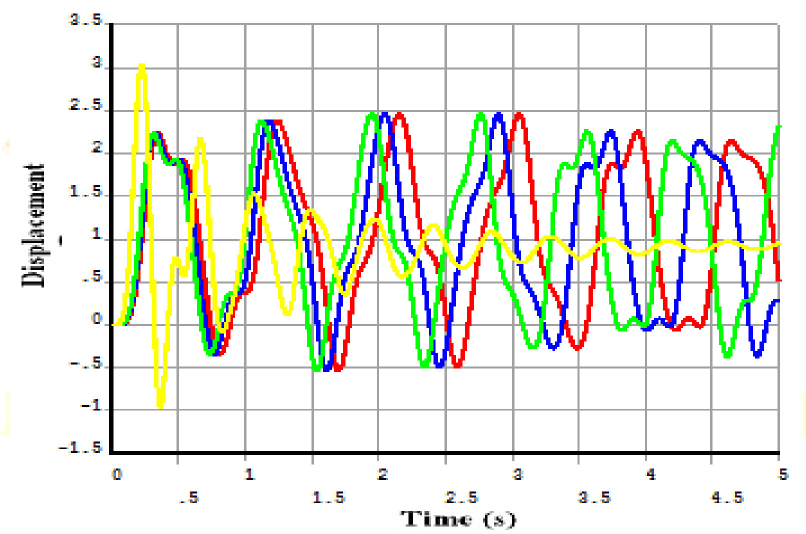

Fig. 5 ANSYS Solution for Controlled Case

It is clear from the Fig. 5 that same controller $(k_p = 4, k_i = 1, K_d = 0.1)$ is suitable for controlling the vibration for all the three cases. As it is clear from the figure that the settling time as well as magnitude of the vibration is reduced remarkably by using the active control method so, it proves to be an effective tool in controlling vibration. Thus if we can apply this method of control to the flexible structures which are used more often than not in the mechanical equipments then the damage to the equipments which is caused by the vibrations can be reduced to a good extent.

Flexible structures

In this section, figure 6 shows cantilever beam which is fixed at one end and free at the other.

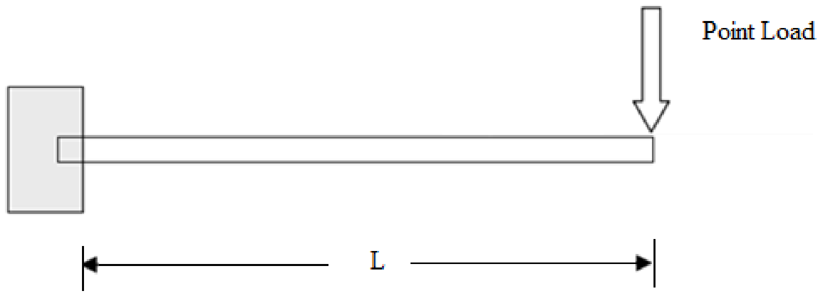

Fig. 6 Configuration of beam type structure

Numerical Example and Discussion

As an illustrative example, consider a cantilever beam having the following characteristics:
L= Length of the beam = 2 m, b= width of the beam = 0.3 m, h = thickness of the beam = .0925 m, E = Young's Modulus of the beam 20.5e10 Pa and ρ = density = 7830 Kg/m^3.

Transient analysis

(a) Uncontrolled Vibration (Open Loop System)

The first mode is considered to calculate the time step and Δt is 0.000833.In the transient analysis, the coefficients of Rayleigh damping (α and β) are defined. 0.66α=β is taken in this study. Fe=F_0 (impulsive force) for t=Δt and Fe=0 at the subsequent time steps. Open loop result is shown in fig 7.

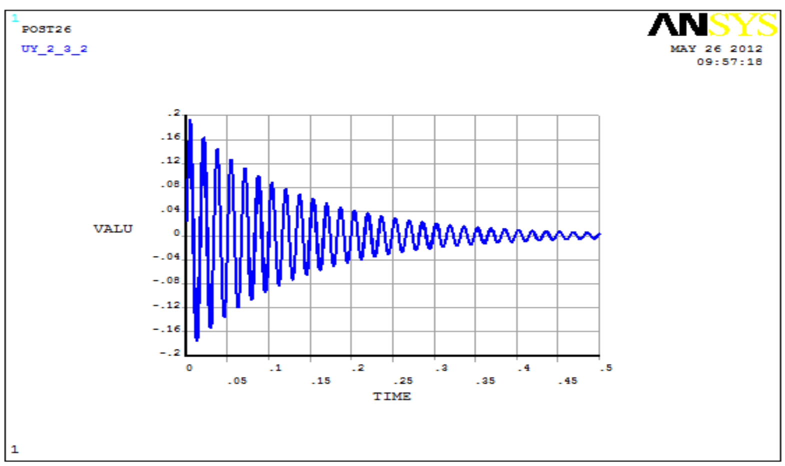

Fig.7 Tip Displacement of cantilever beam under transient loading

Effect of Uncertainty on transient response

Fig. 8 shows the effect of change in the width on the pattern of vibration. It is clear from the figure that as the width is increased the amplitude of vibration decreases and on decreasing the width amplitude increases.

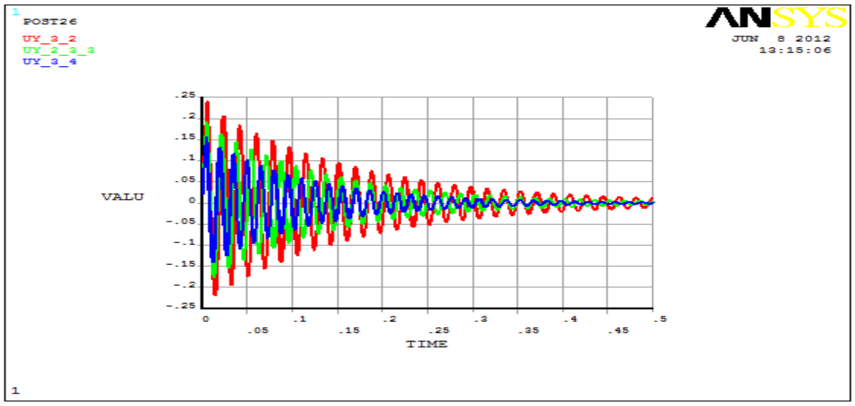

Fig.8 Effect on vibration due to change in width

Thus with change in the dimensions of a structure its natural frequency changes and hence there is a change in the response of a structure to the impulse loads.

(b) Controlled Vibration (Closed Loop simulation)

The control loop simulation is obtained by displacement feedback control.

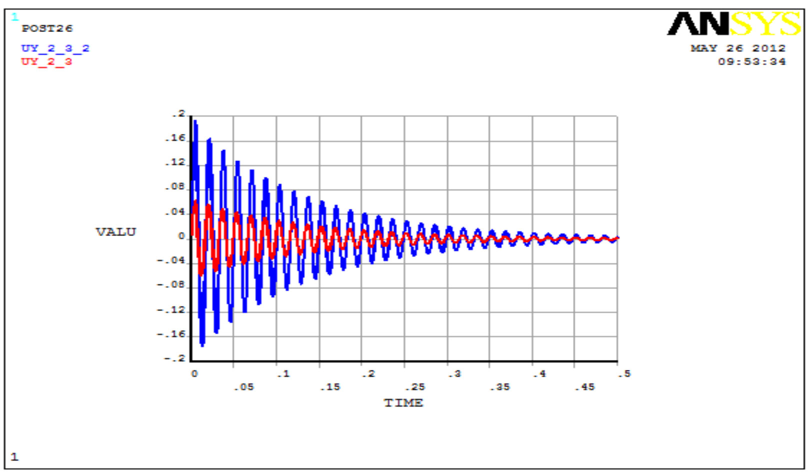

Fig.9 Control and uncontrolled simulation of cantilever beam using ANSYS

The figure 9 shows the comparison between the closed loop and open loop simulation. It is clear from the figure that on the application of the control procedure the amplitude of vibration reduces.

Active vibration control in presence of uncertainty

For controlling the vibration when uncertainty is involved in the system a robust PID controller is designed having the gain values as K_p=4, K_i=1, K_d = 20.As depicted from the figure 13 the amplitude of the vibration of the beam is reduced significantly on the application of a PID controller.

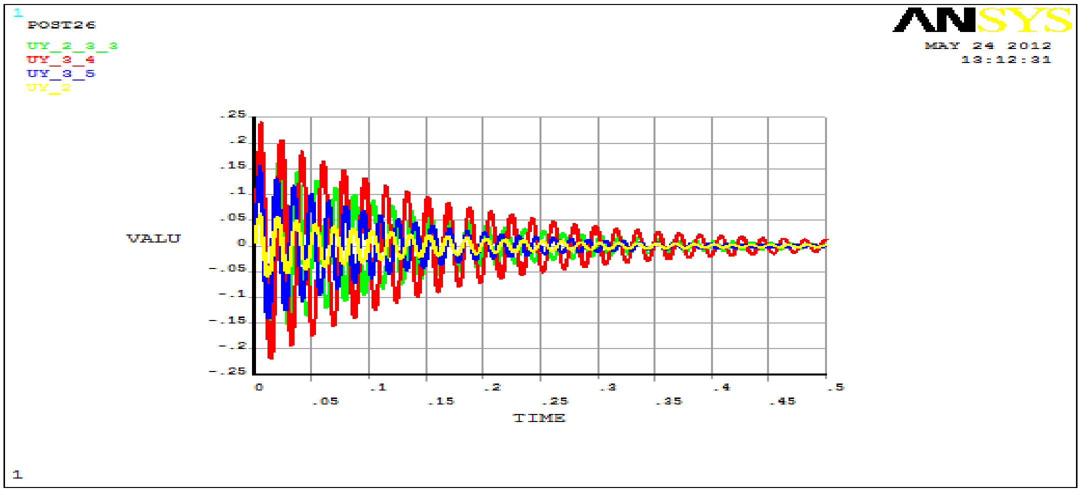

Fig.10 Closed and Open loop Simulation by ANSYS

Result & Conclusion

The active control of flexible beams under free vibration is simulated and experimentally studied. By incorporating the control law directly into the FE programs, the closed loop control problems of flexible structures in presence of uncertainties can be analyzed more easily. Modeling of flexible structures, determining the feedback gain and evaluating the performance of the design are the main steps in the active vibration control. This can be achieved by the procedure developed in this work. The results show that the energy of the controlled responses is smaller than that of uncontrolled response for higher gains. Better vibration suppressions are achieved for Kp = 60 in displacement feedback. It is observed that experimental results performed by other scientists and simulation results are in good agreement. User friendly FE programs such as ANSYS, ABAQUS, MSC/NASTRAN and control programs such as MATLAB are currently available. It is necessary to develop macros to integrate control actions to the FE programs as proposed in this thesis. Graphical user interface (GUI) procedures can be produced in the FE programs, so the users can simulate control problems without developing macros.

The following issues may be investigated in the future:

- Active control of structures having complicated geometries can be analyzed with the procedure proposed.
- Optimal control laws can be incorporated into the FE models of structures using the proposed technique.
- The control of structures having different types of actuators such as fluid power and servo motor can be simulated by the proposed techniques
- The FE matrices can be exported to other computer programs such as MATLAB to perform closed loop vibration control analyses

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