Active Vibration Control Analysis of Storage Tank by Using Smart Material

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Abstract

Storage tank is the most important equipment in oil industries. The main parts of floating storage tank are shell plate, bottom plate and floating roof plate. Storage tank especially with floating roof affected by undesired vibrations which generated by wind force and earthquakes force. The shell of tank exposed to these vibrations despite of there is wind girder and as a result simple slant or buckling occurs on the shell over time. This simple slant or buckling on the shell of tank prevented the floating roof from moving up and down and then storage tank will become out of order unless will do reconstruction for it with extremely high cost. This problem is the topic of this research and happened at many projects in south of Iraq. Smart storage tank is the solution to this problem. Active vibration control (AVC) cancelled all vibrations which caused instability to the storage tank. Storage tank embeds by Piezoelectric (smart material) to make AVC for it that contained of sensor and actuator. Smart material gives extremely big force in short time and hence quick response rate. Output feedback control is one of the methods for AVC that used in this research. ANSYS parametric design language (APDL) employ to obtain numerically modelled for storage tank due to complex structure and require to get couple filed analyses (displacement for tank and voltage for Piezoelectric). Output feedback control has been represented by finite element method. The load of wind or earthquakes forces applied to tank by sin wave (harmonic excitation) piezoelectric shaker. AVC achieved by selected the best of actuation voltages and the best of control gains and as the result the amplitude of displacement without control is ± 0.015m and with control is ± 0.0006m.

Keywords: Smart material, Storage Tank, Active vibration control.

Introduction

Storage tank used to store oil products in depots and refineries in very large quantities. It consists of shell plate, bottom plate and roof plate that supported by wind girder and guide well for floating roof to enable it to resist bending, compressive and torsional loads. In spite of this strong structure, the undesired vibration is generated because of wind force and earthquakes force. AVC works by sensing signal from sensor and then take this signal to calculate the require actuator reflected force to original force that caused undesired with same amplitude. This process take about 0.001 second (time step) to work therefore the stability of storage tank get with very short time automatically. There are many application of AVC nowadays such as bridges, trusses, buildings, mechanical systems and automobiles.

1. Storage Tank Structure

The design of floating storage tank has been according to API 650 STD. by using APDL ANSYS. The capacity model that used for this research is 5000 m3 storage tank with 23 m diameter and 12 m high. The shell for this tank divided to six courses according to design and hydro test liquid level. Each course has 2m high. The first course has thickness 8mm, the second course has thickness 7mm and from third course to sixth course has thickness 6 mm. The annular and bottom plate has thickness 9mm and the roof plate has thickness 7mm. [1], the type of material which used for plates is ASTM A 283 Gr.C and its mechanical properties are shown in table1. The storage tank structure is shown in the Figure 1.

3. Finite Element Method

Finite element modeling for smart storage tank is presented to evaluate the mathematical model which contained of mass, stiffness, and damping matrix of the tank. After obtain mathematical model for force vibration (Equations of Motion) and apply boundary conditions the solution obtain numerically by using the Mechanical APDL (ANSYS) program to evaluate the natural frequency, mode shape, and force vibration response with or without control.

3.1 Stiffness Matrix [k]e for Shell Element

The stiffness matrix could be obtained from calculating the strain energy U. Applying the principle of variation approach [2], the strain energy for the element may be written as:

$$U = \frac{1}{2}\iiint_V \left(\bar{\varepsilon}_e^T \bar{\sigma}_e\right) dV \tag{1}$$

Where:

$$\bar{\varepsilon} = [B]\bar{\delta} \tag{2}$$

$$\bar{\sigma}' = [D']\bar{\varepsilon}' \tag{3}$$

Substitute equations (2) and (3) in equation (1) get,

$$U = \frac{1}{2}\bar{\delta}_e^T \left[\iiint_V [B]^T [D][B] dV\right]\bar{\delta}_e \tag{4}$$

Or

$$U = \frac{1}{2}\bar{\delta}_e^T [K]_e \bar{\delta}_e \tag{5}$$

Where, $[K]_e$ is the element of stiffness matrix and as below

$$[K]_e = \iiint_V [B]^T [D][B] dV \tag{6}$$

3.2 Mass Matrix [M]e for Shell Element

The matrix of mass $[M]_e$ might be obtained by calculation the kinetic energy KE [2], and can be written as:

$$KE = \frac{1}{2}\dot{\bar{\delta}}_e^T \left[\rho \iiint_V [N]^T [N] dV\right]\dot{\bar{\delta}}_e \tag{7}$$

Or,

$$KE = \frac{1}{2}\dot{\bar{\delta}}_e^T [M]_e \dot{\bar{\delta}}_e \tag{8}$$

Where, $[M]_e$ is the mass matrix and is defined as:

$$[M]_e = \rho \iiint_V [N]^T [N] dV \tag{9}$$

Where, $[N]$ is the shape function matrix.

3.3 Equation of Motion for Finite Element

The equation of motion (or dynamic equation) can be derived, using the energy balance principle which involves that "the summation of the structure energies is stationary", i.e., the summation of kinetic energy, dissipation energy, strain energy and potential energy is stationary, or

$$KE + DE + U + PE = Stationary \tag{10}$$

If these energies are defined in terms of a nodal displacement vector $\bar{\delta}$, then,

$$\frac{\partial}{\partial \bar{\delta}}\left(KE + DE + U + PE\right) = 0 \tag{11}$$

The potential energy PE (with the absence of body forces) can be written as:

$$PE = -W = -\bar{\delta}_e^T \bar{F}_e(t) \tag{12}$$

Where, $\bar{F}_e(t)$ is the nodal forces vector.

Substitute equations (5), (8), and (12) in equation (11) gives,

$$\frac{\partial}{\bar{\delta}_e}\left(\frac{1}{2}\dot{\bar{\delta}}_e^T [M]_e \dot{\bar{\delta}}_e + \frac{1}{2}\dot{\bar{\delta}}_e^T [C]_e \dot{\bar{\delta}}_e + \frac{1}{2}\bar{\delta}_e^T [K]_e \bar{\delta}_e^T - \frac{1}{2}\bar{\delta}_e^T \bar{F}_e(t)\right) = 0 \tag{13}$$

The derivation of first term of upper equation is obtained as below:

$$\frac{\partial}{\partial \bar{\delta}_e}\left(\frac{1}{2}\dot{\bar{\delta}}_e^T [M]_e \dot{\bar{\delta}}_e\right) = \frac{d}{dt}\frac{\partial \dot{\bar{\delta}}_e}{\partial \bar{\delta}_e}\frac{\partial}{\partial \dot{\bar{\delta}}_e}\left(\frac{1}{2}\dot{\bar{\delta}}_e^T [M]_e \dot{\bar{\delta}}_e\right) = \frac{d}{dt}\left([M]_e \dot{\bar{\delta}}_e\right) = [M]_e \ddot{\bar{\delta}}_e$$

The other terms can be easily derived to get the final form of the dynamic equation of finite element.

$$[M]_e \ddot{\bar{\delta}}_e + [C]_e \dot{\bar{\delta}}_e + [K]_e \bar{\delta}_e = \bar{F}_e(t) \tag{14}$$

$$[C] = \alpha * [M] + \beta * [K] \tag{15}$$

Where α and β are structural damping constant

4. Piezoelectric (PZT) Equations

The displacement of electric D (charge per unit area C/m2) is related to the field of electric E (V/m) in unstressed of one dimensional dielectric medium by

$$D = e\,E \tag{16}$$

Where:
e = the Piezoelectric dielectric constant
As well as in elastic body one dimensional set in zero field of electric, therefore the stress T (N/m2) and the strain S are related by

$$S = s\,T \tag{17}$$

Where:
s = inverse of the Young modulus (the Piezoelectric compliance).
For PZT material, the electrical constitutive and mechanical equations coupled as following.

$$S = s^E T + d\,E \tag{18}$$

$$D = d\,T + \varepsilon^T E \tag{19}$$

Where in Equation (18):
d = PZT constant for the strain to the field of electric E in the absence of mechanical stresses.
sE = the compliance for the electric field E is constant.
Where in Equation (19):
d for the displacement of electric D to the stress under zero electric field E (m/V or Coulomb/Newton).
εT = constant of dielectric under constant stress.
If the orientation of the polarization synchronizes with direction 3 then constituent equation for the sensing and actuation mechanisms can be rewritten in matrix form [3]:
Actuation:

$$\begin{Bmatrix} S_{11} \\ S_{22} \\ S_{33} \\ 2S_{23} \\ 2S_{13} \\ 2S_{12} \end{Bmatrix} = \underbrace{\begin{bmatrix} s_{11} & s_{12} & s_{13} & 0 & 0 & 0 \\ s_{12} & s_{22} & s_{23} & 0 & 0 & 0 \\ s_{13} & s_{23} & s_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & s_{66} \end{bmatrix}}_{\text{Compliance}} \begin{Bmatrix} T_{11} \\ T_{22} \\ T_{33} \\ T_{23} \\ T_{13} \\ T_{12} \end{Bmatrix} + \underbrace{\begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \\ 0 & d_{24} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}}_{\text{Coupling}} \begin{Bmatrix} E_1 \\ E_2 \\ E_3 \end{Bmatrix} \tag{20}$$

Sensing:

$$\begin{Bmatrix} D_1 \\ D_2 \\ D_3 \end{Bmatrix} = \underbrace{\begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{bmatrix}}_{\text{Coupling}} \begin{Bmatrix} T_{11} \\ T_{22} \\ T_{33} \\ T_{23} \\ T_{13} \\ T_{12} \end{Bmatrix} + \underbrace{\begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix}}_{\text{permittivity}} \begin{Bmatrix} E_1 \\ E_2 \\ E_3 \end{Bmatrix} \tag{21}$$

Examining actuator equation (20), when field of electric E3 distributed parallel to the polarization direction, the extension noticed along same direction (polarization direction) and its amplitude controlled by the coefficient of piezoelectric constant d33 then Shrinkage obtained along orientation one (1) and two (2) orthogonal to the field of electric which command by d31 and d32 respectively. As well as PZT has isotropic behaviour (d31 = d32) in the plane.

5. Finite Element Method for piezoelectric

Mechanical APDL (ANSYS) program offers coupled field elements with three dimensional piezoelectric for modelling smart storage tank. Modal, static, transient analysis and full harmonic solved with finite element program. They have the capability of modelling piezoelectric. Piezoelectric elements have four degree of freedom (DOF) with every node has ux, uy, uz and volt. In this study of vibration reduction, should use 'coupled-field analysis' in order to couple the interaction between field of electric and applied forces to make finite element of smart structure. The coupled field element shall be containing all necessary nodal DOF.

Piezoelectricity treated as linear theory which the piezoelectric, elastic, and dielectric coefficients considered constants. Constituent equations which Mechanical APDL (ANSYS) use to represent the model of piezoelectric material rearranged in matrix form as below [4].

$$\begin{Bmatrix} \{T\} \\ \{D\} \end{Bmatrix} = \begin{bmatrix} [c] & [e] \\ [e]^T & [-\varepsilon] \end{bmatrix} \begin{Bmatrix} \{S\} \\ \{-E\} \end{Bmatrix} \quad (22)$$

For finite element of piezoelectric, by use nodal solution variables and shape functions can obtain displacements and electrical potentials as following:

{uc} = [Nu]T {u} (23)

Vc = [NV]T {V} (24)

Where

{uc} = displacements for element in x, y, z orientations

Vc = potential of electrical for element

[Nu] = shape functions matrix of displacement

[NV] = shape function of electrical potential

{u} = vector of nodal displacements

{V} = vector of nodal electrical potential

Thus vector of the strain {S} and vector of electric field {E} related to the displacements and potentials respectively as below,

$\{S\}= [B_u] \{u\}$ (25)

$\{E\}= - [B_V] \{V\}$ (26)

Where:

$$[B_u]=\begin{bmatrix} \partial/\partial x & 0 & 0 \\ 0 & \partial/\partial y & 0 \\ 0 & 0 & \partial/\partial z \\ \partial/\partial y & \partial/\partial x & 0 \\ 0 & \partial/\partial z & \partial/\partial y \\ \partial/\partial z & 0 & \partial/\partial x \end{bmatrix} \quad (27)$$

$$[B_V]=\begin{Bmatrix} \partial/\partial x \\ \partial/\partial y \\ \partial/\partial z \end{Bmatrix} \{N^V\}^T \quad (28)$$

PZT elements mechanical response expressed by the equation of motion [5]:

{div[T]} + {f} = ρ{ü} (29)

Where T, f, ρ and ü are stress, body force in unit volume, density and acceleration, respectively.

PZT elements Electrical response described by Maxwell’s equation:

{∂D/∂x} = 0 (30)

With the application of variational principles on the mechanical equilibrium equation, Equation (29) and the electrical flux conversation equation, Equation (30), in conjunction with the approximate field of equation (23, 24, 25, 26) and the Constituent properties in Equation (22), the finite element formulation of piezoelectric can be derived with nodal quantities:

$$\begin{bmatrix} [\mathbf{M}] & [\mathbf{0}] \\ [\mathbf{0}] & [\mathbf{0}] \end{bmatrix} \begin{Bmatrix} \{\mathbf{u}^{\cdot\cdot}\} \\ \{\mathbf{v}^{\cdot\cdot}\} \end{Bmatrix} + \begin{bmatrix} [\mathbf{C}] & [\mathbf{0}] \\ [\mathbf{0}] & [\mathbf{0}] \end{bmatrix} \begin{Bmatrix} \{\mathbf{u}^{\cdot}\} \\ \{\mathbf{v}^{\cdot}\} \end{Bmatrix} + \begin{bmatrix} [\mathbf{K}] & [\mathbf{K}^{\mathbf{Z}}] \\ [\mathbf{K}^{\mathbf{Z}}]^{\mathbf{T}} & [\mathbf{K}^{\mathbf{d}}] \end{bmatrix} \begin{Bmatrix} \{\mathbf{u}\} \\ \{\mathbf{V}\} \end{Bmatrix} = \begin{Bmatrix} \{\mathbf{F}\} \\ \{\mathbf{L}\} \end{Bmatrix} \quad (31)$$

Where:

[M] = mass matrix from volume and density.

[K] = mechanical stiffness matrix from elastic matrix.

[Kz] = stiffness matrix of piezoelectric from piezoelectric matrix.

[Kd] = dielectric stiffness matrix from dielectric matrix.

{F} = vector of mechanical force.

{L} = charge vector.

[M], [K], [Kz] and [Kd] matrices represented as below:

Structural mass matrix: [M] = v∫ ρ [Nu][Nu]T dv. (32)

Structural stiffness matrix: [K] = v∫ [Bu]T c [Bu] dv. (33)

Piezoelectric coupling matrix: [kz] = v∫ [Bu]T e [BV] dv. (34)

Dielectric conductivity matrix: [Kd] = v∫ [BV]T ε [BV] dv. (35)

The calculated of energy coefficients for each piezoelectric element as follows:

Elastic energy: UE = 1/2 {S}T [c] {S}. (36)

Dielectric energy: UD = 1/2 {E}T [ε] {E}. (37)

Electromechanical coupling energy: UM = - 1/2 {S}T [e] {E}. (38)

Potential energy: Ep = UE + UD. (39)

6. Element Type of Smart storage tank in Mechanical APDL (ANSYS)

The smart storage tank consists of shell, bottom, annular, roof and piezoelectric therefore the tank will be divided into elements for the isotropic without orthotropic and coupled field to obtain the finite element analysis for smart storage tank. The number of mesh which used for smart storage tank is 4500 elements.

6.1 SHELL181 Element Description:

SHELL181 is appropriate to analyzing thick to thin shell structure. It has translations (displacement) in the x, y and z orientations and rotations about the x, y, and z orientations therefor at every node has six degrees of freedom and it is four node elements. Change in shell thicknesses are accounted for analyses such as the shell has six different thicknesses. Element formulation according to logarithmic true strain and measures stress. [6]

6.2 SOLID5 Element Description:

SOLID5 is 3-D magnetic, piezoelectric, electric, thermal and structural field with able to coupling between these fields. This element consist of 8 nodes. Each node has ux, uy and uz displacements. With up to 6 DOF at each node. SOLID5 dives large deflection and stress stiffening when used for piezoelectric and structural analyses. Prism shaped element is formed by defining duplicate node numbers. For tank element of prism shaped used for modeling system which has geometric curvature (i.e. cylinder). When chosen this type of piezoelectric, Mechanical APDL ANSYS depend on behaviors of SOLID5 in ux, uy, uz and volt. ux, uy and uz indicates displacements in x, y and z orientations and volt indicates the difference in potential energy for the electrical particles between two sites. [6] The element type and boundary condition is shown in the figure 2.

7. Output Feedback Control (AVC)

Output feedback is a theory for closed-loop system for smart storage tank with controlled by position and or velocity feedback. The system has the form as the following [7]

$$M\ddot{q}(t) + C\,\dot{q}(t) + K\,q(t) = f_f + f(t). \qquad (40)$$

Where, $f(t)$ is external disturbance forces (such as wind force or earthquakes force) and f_f is control force stem from the action of r force actuators and defined as the following

$$f_f = B_f\,U. \qquad (41)$$

Here, the r ×1 vector u represents the r input, one for every control device (actuator). The matrix B_f represents the locations on the tank of any actuators or devices that used to apply the forces u. such as, piezoelectric actuator or electromechanical attached to the tank. The feedback of the velocity and position, let y denoted s×1 vector of sensor outputs as the following

$$y\,(t) = C_p q(t) + C_v \dot{q}(t). \qquad (42)$$

C_p and C_v are s × n matrices of displacement and velocity influence coefficients, with structure got by the sensor locations and the electronic gains by the transducers used to measure the various state variables and the s denotes the sensors number. Equation (42) represents those coordinates that measured as part of the AVC. In this paper taken the matrix C_v zero due to don't use velocity feedback. The special form of the input u is chosen as following

$$U(t) = -G_f\,y(t) = -\,G_f C_p q(t) - G_f C_v \dot{q}(t) \qquad (43)$$

the r × s matrix G_f represented feedback constant gains. The control law form (equation 43) is output feedback, due to the input proportional to the measured output for the response y. If Equation (41) substitute to Equation (40) gives the closed-loop system as the following [8]:

$$M\ddot{q}(t) + C\,\dot{q}(t) + K\,q(t) = B_f\,U(t) + f(t) \qquad (44)$$

In this study, function of the response coordinates of interest is the control vector u, denoted by the vector y, i.e. $U(t) = -G_f\,y$. Equations (42), (43) and (44) can be representation in the block diagram of Figure (3).

8. Active Vibration Control Simulation in Smart Storage tank

AVC analyses achieved with using mechanical APDL (ANSYS).Control action inserted into the finite element model which has multi DOF vibration process. Controls accomplishment got in finite element environment by described the outputs and inputs of the block diagram step by step. Input reference value taken zero in feedback (closed loop) vibration control system to reflect the signal of sensor for each time step to produce reverse force to the original force (vibration). The voltage (VS) (strain rate) instantaneous value of for the sensor location during time step subtracted from zero to estimate the signal value error. The amplifier gain (KV) and control gain (KC) multiplied by error value to estimate the voltage value (VA) which used this voltage as the input to the actuator node for each time step. The control gain (KC) value taken differently for obtain the optimal vibration control. The processes continuous for selected time until the response reached steady state. The optimal location for piezoelectric as sensor and actuator is near from fixed point due to in this location maximum strain and stress is produced.

8.1 Force Vibration due to PZT Shaker (Harmonic Excitation)

Vibration considered for First mode in the feedback control analysis. The closed feedback block diagram given in Figure 4. Force vibration is obtained from PZT shaker this shaker is programing to provide the smart structure harmonic excitation (Sine Wave) which represents wind and earthquake forces and then control this excitation by AVC. Control action is achieved with the program code after the finite element of the smart storage tank with PZT shaker is constructed. Sin wave created in the finite element model before beginning of feedback. The first time step solved by apply the excitation voltage (harmonic wave) to the PZT shaker and then the nodal solutions of the finite element model known for the next time step. The excitations are applied again in the first step of the feedback. The voltage known from the first step that obtain from PZT sensor. Error signal got after calculated the voltage value. At the end of closed loop the error signal multiplying with gain KC & KV to produced actuation voltage (VA) and hence produce the reflected force to original force. This process continues until control the vibration and the response reduced.

9. Result and Discussions for Smart storage tank

The results of force vibration and active control vibration are investigated for smart storage tank. Mode shapes and natural frequencies found with and without piezoelectric patch. Active control vibration is applied for force vibration by used output feedback control to remove the undesired vibration.

9.1 Natural Frequency & Mode Shape

Natural frequencies and Mode shapes of six natural frequencies for the tank without and with PZT patch are shown in table 2 and figure 5 to 6. Observe that the natural frequencies with or without PZT are fixed at each mode that indicated add piezoelectric as sensor and actuator to the tank didn't affect the stiffness of tank (natural frequency changes directly with stiffness and indirectly with mass) due to smart materials are light metals when compare it with tank and hence storage tank as a passive control didn't need any change with physical parameters (mass [M] and stiffness [K]) or redesign when add PZT to it. Notice that from the figure of mode shape how the floating roof moving up and down as well as left to right.

9.2 Force Vibration due to PZT Shaker (Harmonic Excitation)

Harmonic excitation is obtain by piezoelectric shaker and it is produced about ± 0.015m amplitude at the shell of tank in the form of (X=X0 sin wt) and this amplitude is depend on the voltage which applied to piezoelectric shaker. Force vibration response of smart storage tank is simulated for different control gain and different actuation voltage. The shell displacement response is shown in Figures 7 to 16 for storage tank with and without active vibration control. Note that from the results the best control gain is 28 and maximum actuation voltage is 610 due to the amplitude of displacement for the shell of storage tank when control OFF is about ± 0.015m and amplitude when control ON for gain 28 is ± 0.0006m that mean all undesired vibration are removed and storage tank become safe from unwanted vibration which cause prevented the floating roof from moving, crack, fatigue, buckling …etc. Table 3 shows the amplitude of shell displacement with different controller gain and actuation voltage.

10. Conclusions

The main conclusions which noticed from the present study listed below:
1. The optimal location of piezoelectric is near from fixed point due to maximum strain and stress produced over there.
2. The optimal control gain is 28 after this gain such as 30 the system will become unstable.
3. The simulations for the active vibration control of the storage tank for force vibration (Harmonic wave) show that the amplitude for the vibration reduced effectively and vibration suppression is obtained for various gains, the maximum reduced amplitude was from ± 0.015 m to ± 0.0006 m.
4. Output feedback control (AVC) is very effected for vibration reduction when compare it with another type of control such as passive control.
5. The control law can insert directly into the finite element programs by programing all control equations inside script code APDL ANSYS.

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Table1. Mechanical Properties

Item & Material	Mechanical Properties	
Plates ASTM A 283 Gr.C	Density [kg/m^3]	7800
	Elasticity Modulus E [Pa]	27E+6
	Poisson ratio υ	0.29

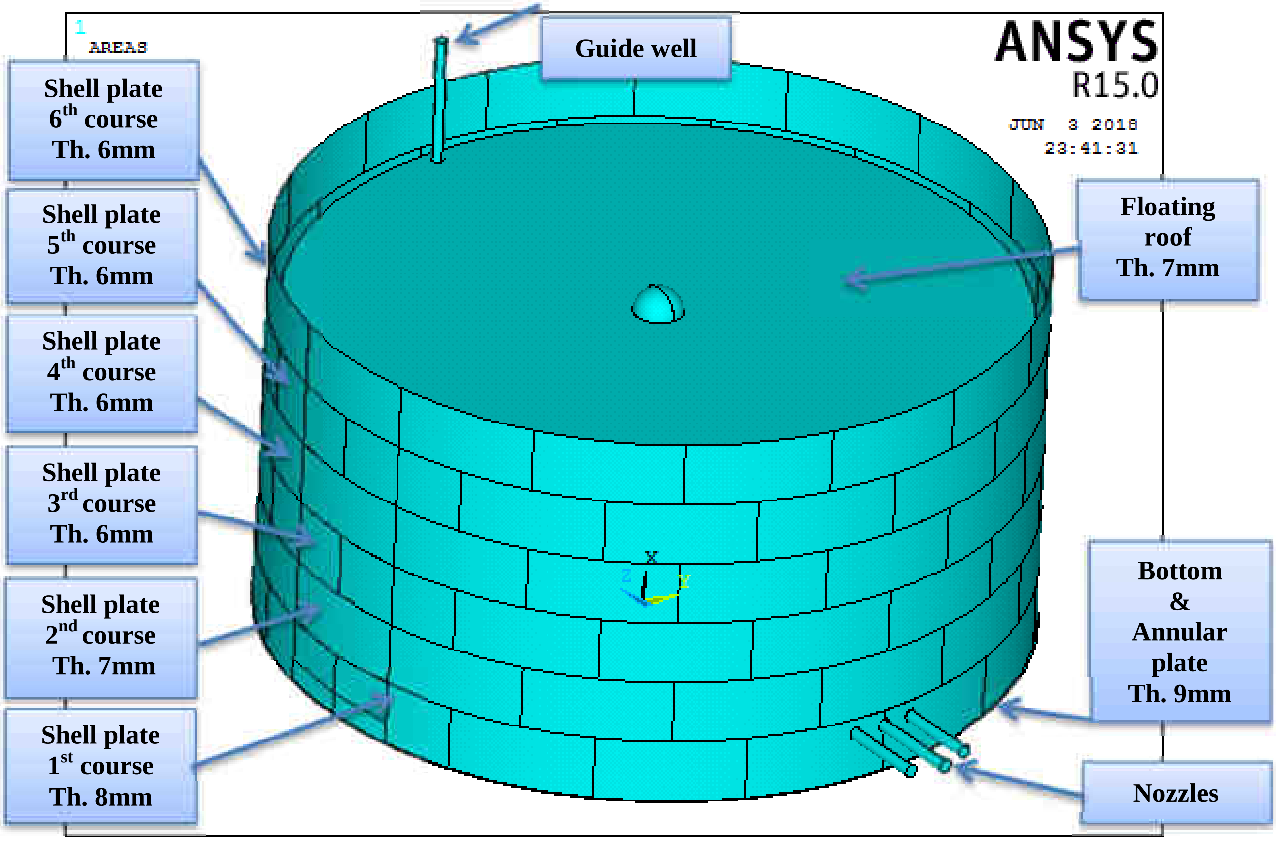

Figure1. Storage tank structure (Size 5000 m3)

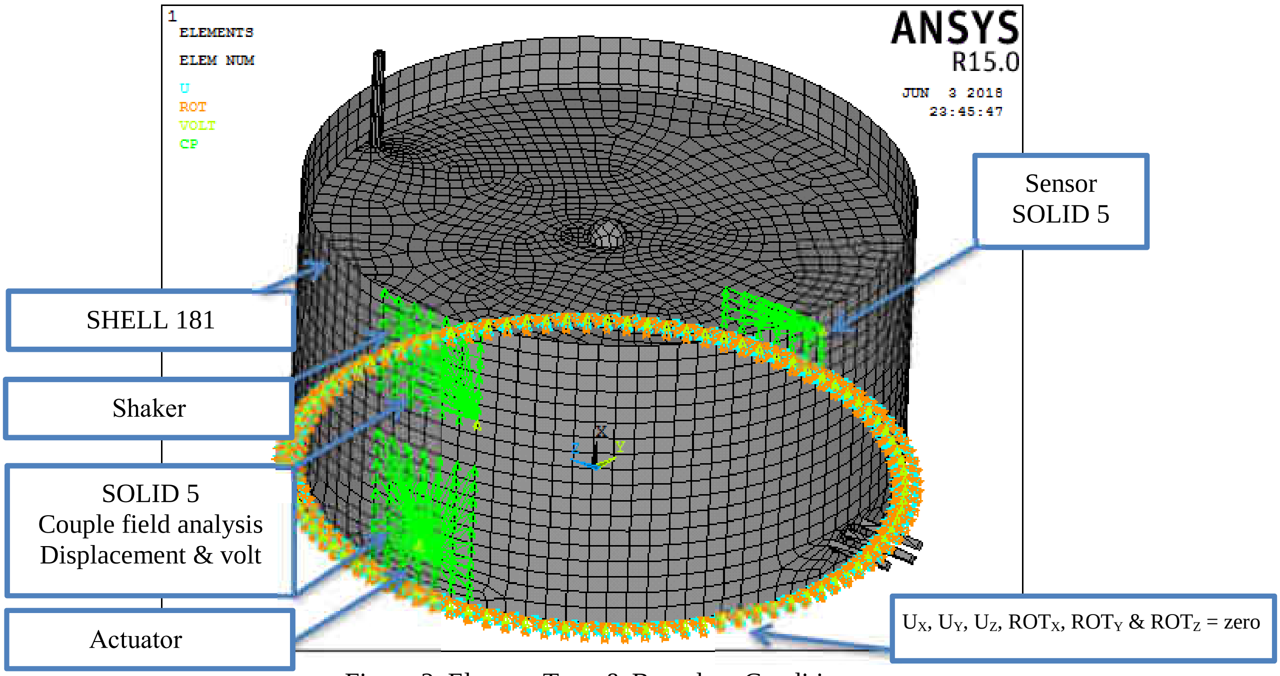

Figure 2. Element Type & Boundary Condition

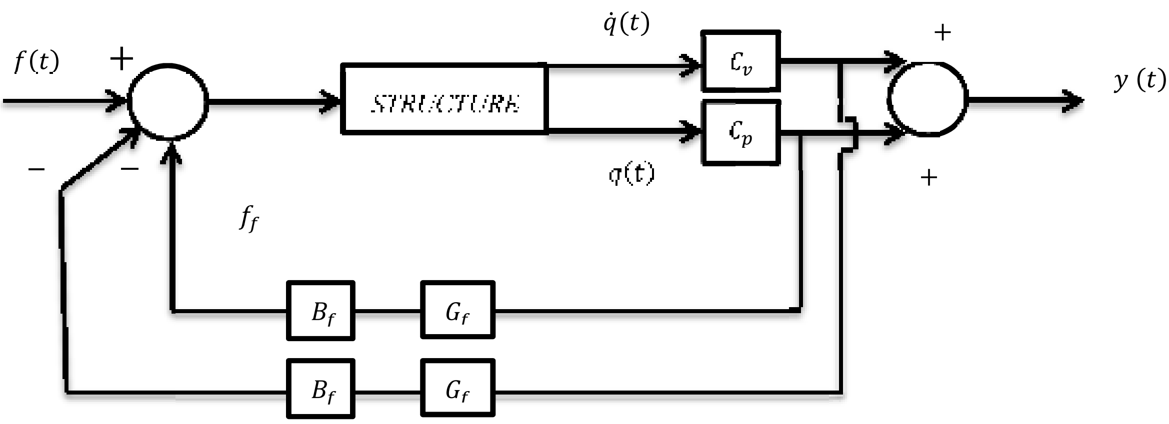

Figure 3. Block Diagram of Output Feedback System

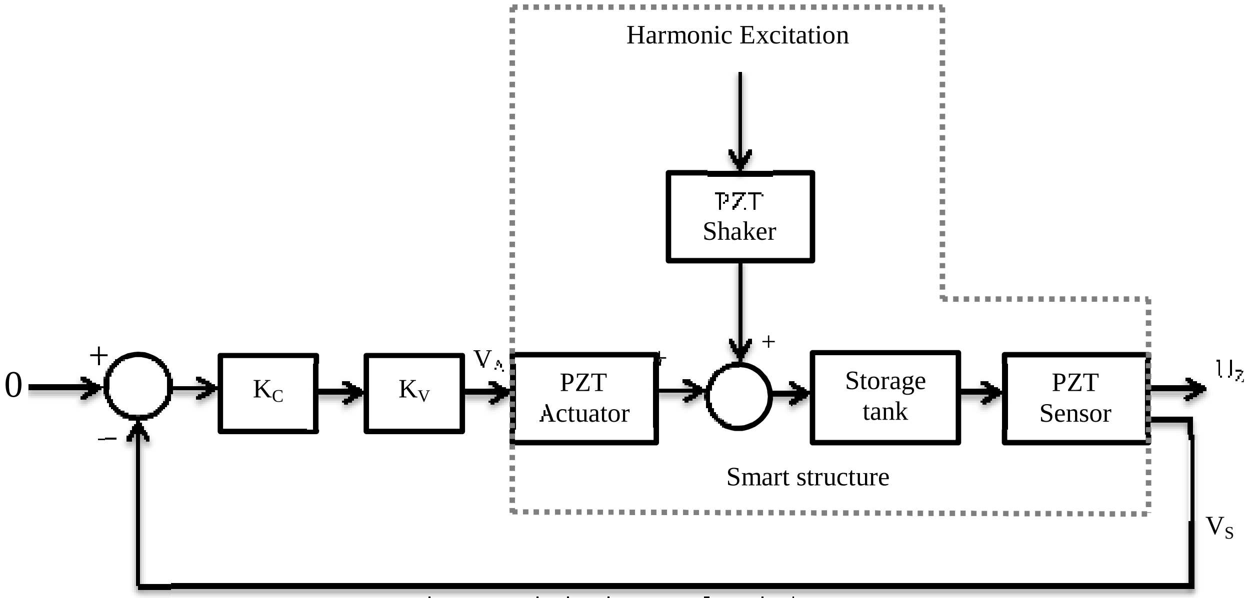

Figure 4. Block Diagram of Analysis

Table2. Frequency of storage tank

Frequency HZ	N.F without PZT	N.F with PZT
f_1	0.919E-04	0.919E-04
f_2	0.195E-03	0.195E-03
f_3	0.290E-03	0.290E-03
f_4	0.406E-03	0.406E-03
f_5	0.653E-03	0.653E-03
f_6	0.001039	0.001039

Table3. Amplitude of Shell Displacement of Storage Tank

Control Gain (K)	Max. Actuation Voltage	Amplitude (M)
0	0	± 0.015
10	200	± 0.01
10	400	± 0.008
25	400	± 0.004
25	500	± 0.0025
27	550	± 0.0015
28	610	± 0.0006

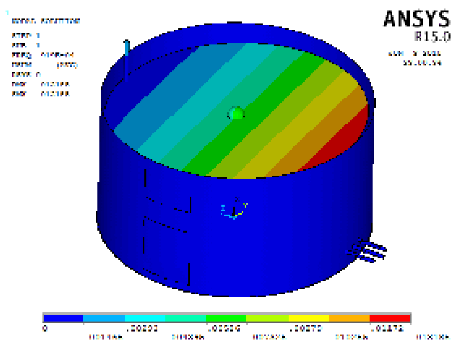

Figure5. (a) 1st N.F & mode shape with PZT

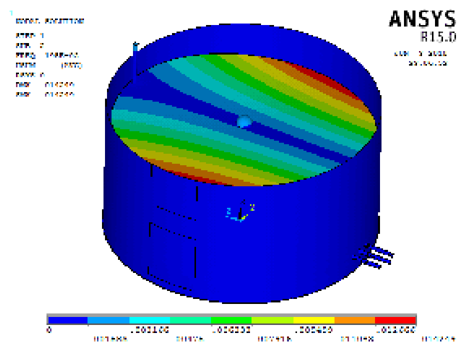

Figure5. (b) 2nd N.F & mode shape with PZT

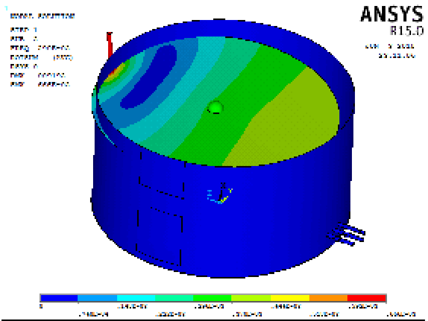

Figure5. (c) 3rd N.F & mode shape with PZT

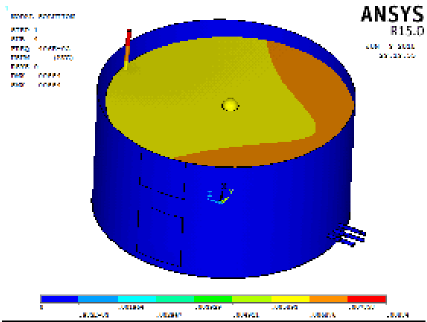

Figure5. (d) 4th N.F & mode shape with PZT

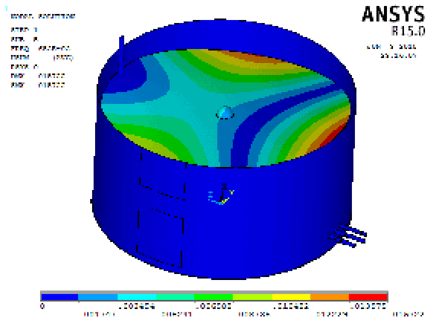

Figure5. (e) 5th N.F & mode shape with PZT

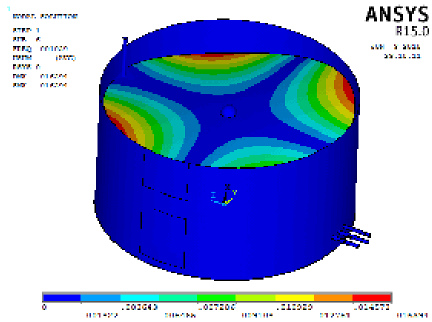

Figure5. (f) 6th N.F & mode shape with PZT

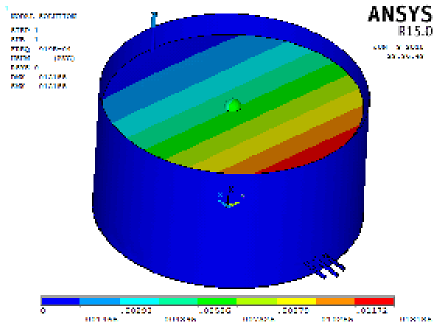

Figure6. (a) 1st N.F & mode shape without PZT

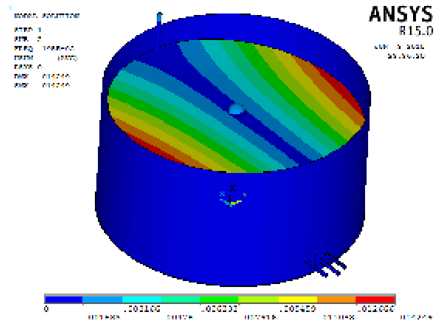

Figure6. (b) 2nd N.F & mode shape without PZT

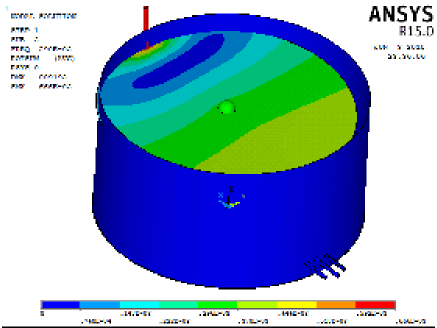

Figure6. (c) 3rd N.F & mode shape without PZT

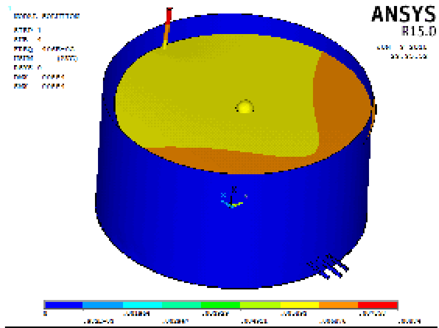

Figure6. (d) 4th N.F & mode shape without PZT

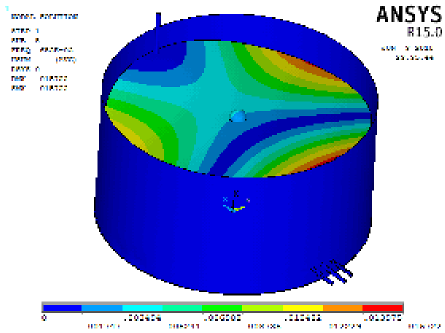

Figure6. (e) 5th N.F & mode shape without PZT

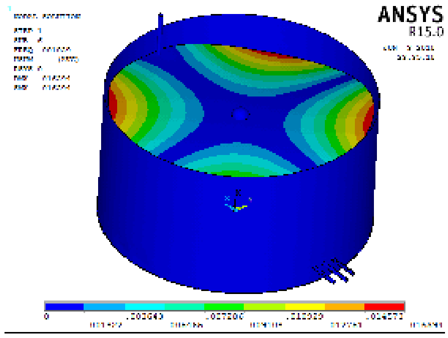

Figure6. (f) 6th N.F & mode shape without PZT

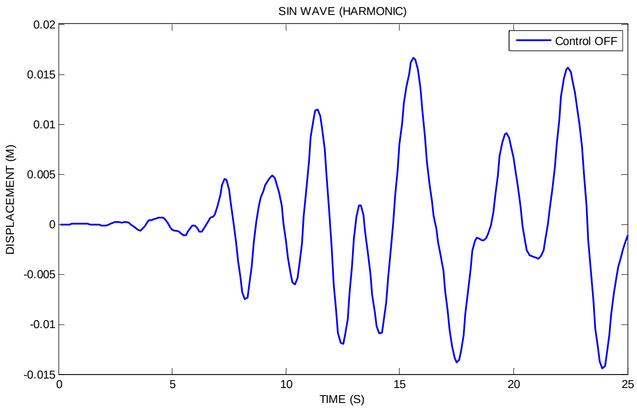

Figure7. Shell displacement Response (K=0)

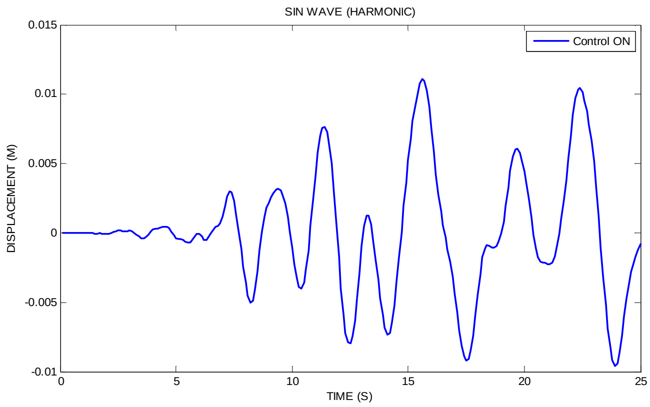

Figure8. Shell displacement Response (K=10, V max. =200)

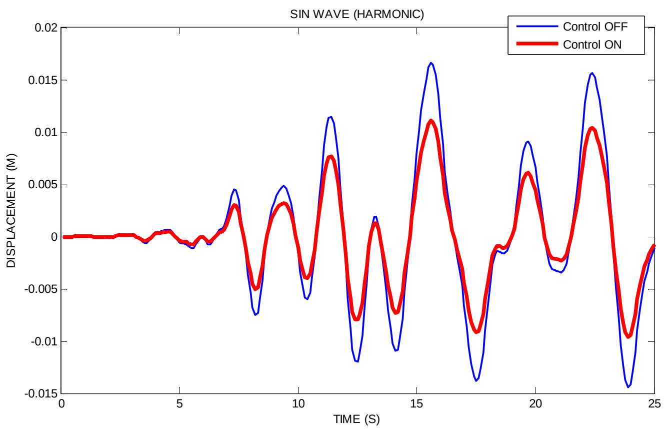

Figure9. Different between responses for K=0 and K=10 (V Max. =200)

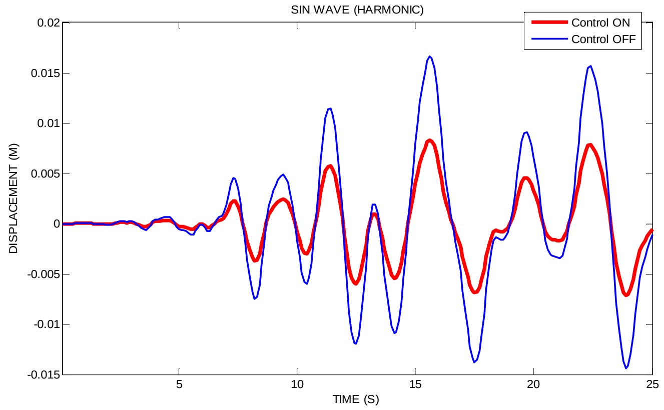

Figure10. Different between responses for K=0 and K=10 (V Max. =400)

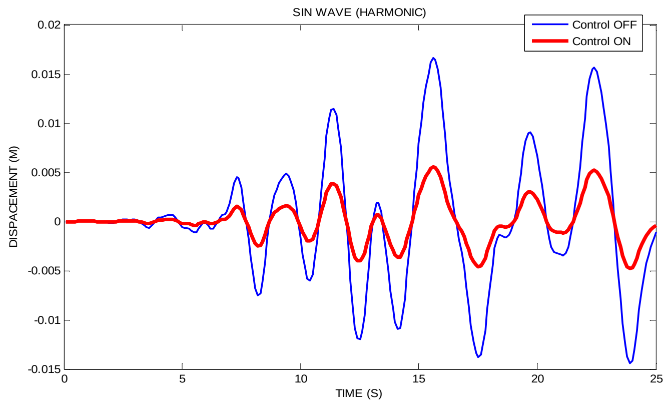

Figure11. Different between responses for K=0 and K=25 (V Max. =400)

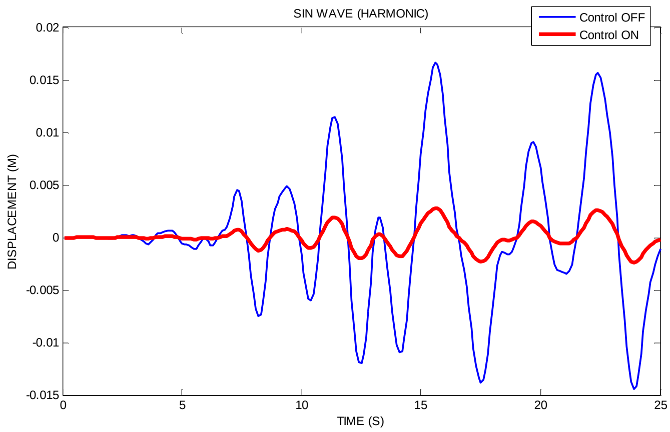

Figure12. (A) Different between responses for K=0 and K=25 (V Max. =500

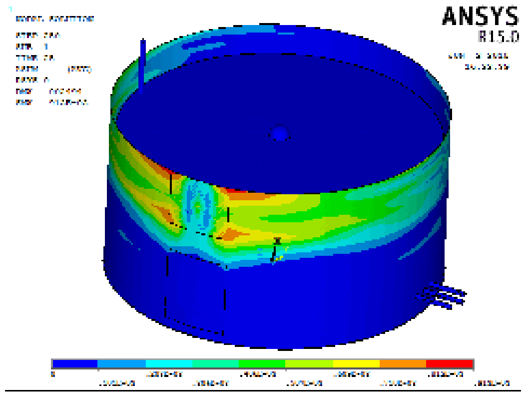

Figure12. (B) Displacement & Acceleration (K=25, V max. =500)

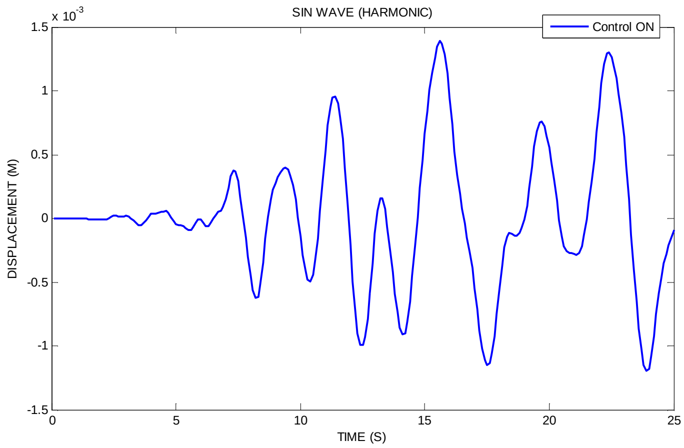

Figure13. (A) Shell displacement Response (K=27, V max. =550)

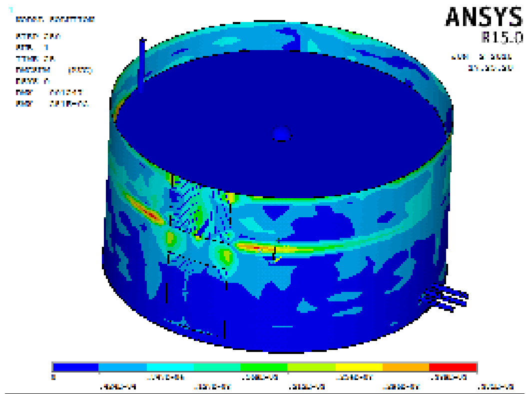

Figure13. (B) Displacement & Rotation Acceleration (K=27, V max. =550)

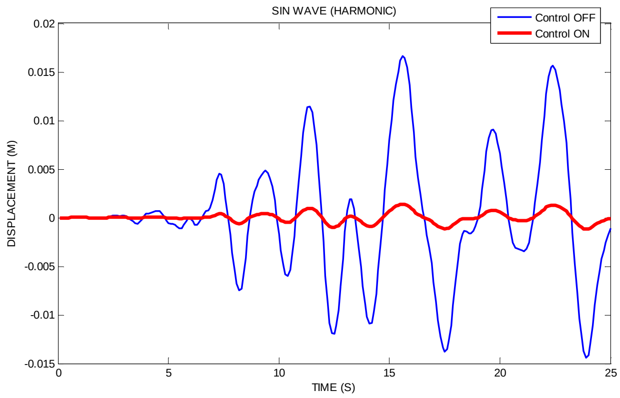

Figure14. Different between responses for K=0 and K=27 (V Max. =550)

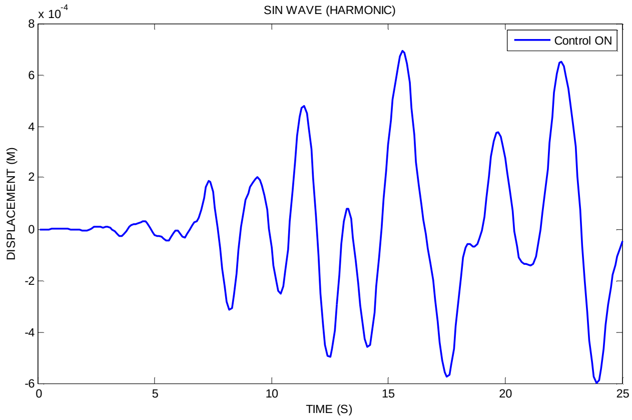

Figure15. (A) Shell displacement Response (K=28, V max. =610)

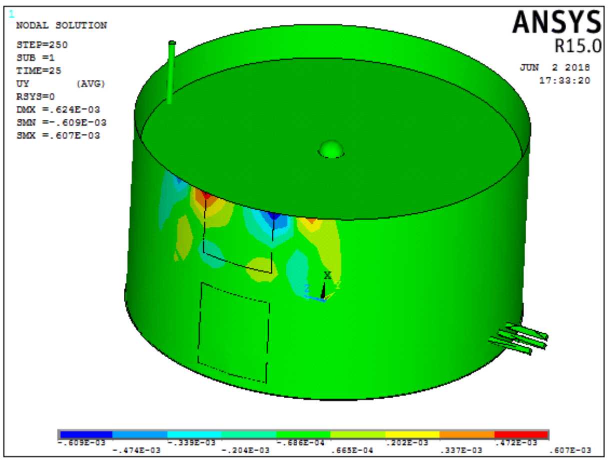

Figure15. (B) Shell displacement (K=28, V max. =610)

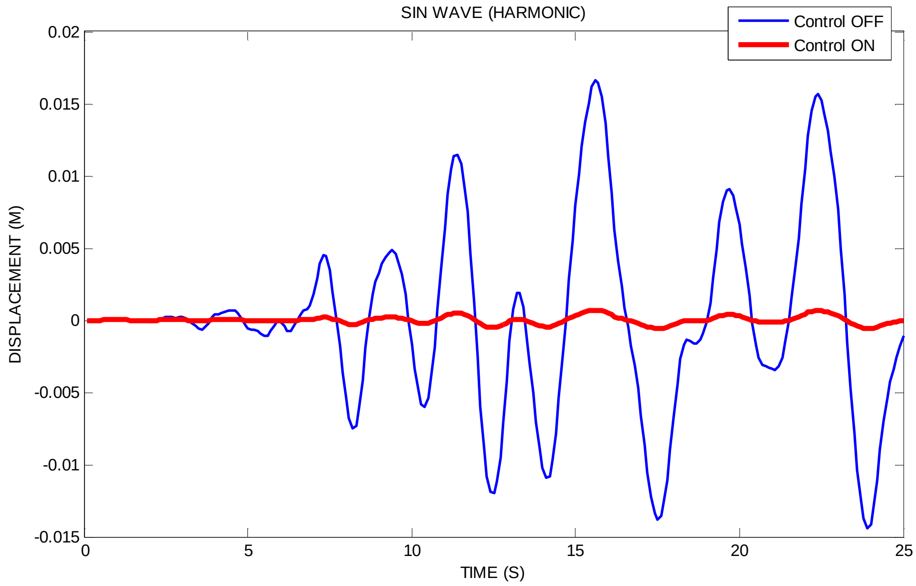

Figure16. Different between responses for K=0 and K=28 (V Max. =610)