PORT SAID ENGINEERING RESEARCH JOURNAL
Faculty of Engineering - Port Said University
Volume 17 No. 1 pp: 23:31

Vibration and Modal Analysis of Liquefied Natural Gas Tanks

Lotfie Abdel-Latif, Anwar Kandil**,Ebtisam Abdel-Gwad***, and Ayman Asaad*****

** Em. Prof, Mechanical Design Dept., Faculty of Engineering, Matareia, Helwan University.*
*** Em. Prof, Production Eng. and Mech. Design Dept., Faculty of Engineering, Port Said University.*
**** Assoc. Prof, Production Eng. and Mech. Design Dept., Faculty of Engineering, Port Said University.*
***** Section Head of Canal CNG Stations, NGV Company (Car Gas), Egyptian Petroleum Ministry.*

ABSTRACT

Liquefied natural gas (LNG) tanks are considered essential structures. Storage tanks in particular, are important to the continued operation of natural gas distribution systems in the event of earthquakes. The Finite Element (FE) method is utilized to model the tank, as well as the contained fluid. ANSYS 12, a finite element code that combines structural and fluid simulation capabilities, has been used to model the inner steel tank, LNG fluid, and outer concrete tank in the three-dimensional space and perform modal and nonlinear seismic analysis. The tank wall is modelled by shell elements. The LNG has been represented as contained fluid elements. In this paper, the analysis results for mode shapes and natural frequencies obtained by ANSYS 12 are compared with those calculated by theoretical calculations using the guidelines for seismic design of liquid storage tanks presented by Indian Institute of Technology -2007. The results obtained for the fundamental frequency and mode shapes gave basic knowledge and better understanding of LNG tanks in dynamic analysis.

Key words: LNG tanks, Modal Analysis, Finite Element Method, Mode Shapes, and Natural Frequency.

1. Introduction

LNG storage tanks are lifeline structures and strategically very important, since they have vital use in industries and nuclear power plants [1]. Past earthquakes have demonstrated the seismic vulnerability and damage of tanks occurred in the form of buckling of tank wall due to excessive development of compressive stresses, failure of piping systems and uplift of anchorage system [2]. The seismic behavior of LNG storage tanks is highly complex due to fluid–structure interaction leading to a tedious design procedure from earthquake-resistant design point of view [5]. Housner [7] developed a lumped mass model of rigid liquid storage tanks and investigated its seismic response. These models were modified by Haroun [3], which takes into account the flexibility of the tank wall in the seismic analysis.

The conventional technique to safeguard the tanks against vibration damages has obtained by component strengthening, in which the size of different members is increased to resist more random vibration forces.

The alternative technique is the tank base isolation, by introducing special isolation system between the base and foundation of the tank. One of the goals of base isolation is to shift the fundamental frequency of a structure away from the dominant frequencies of random vibration ground motion and fundamental frequency of the fixed base structure.

2. Construction of LNG Tank

The construction of an LNG tank is complex and special types of materials have to be used [3]. Modern LNG tanks are generally double walled, so that proper insulation between the walls can isolate thermal effects to the inner tank only. LNG is stored in a temperature of (-168°C) under very small pressure about 0.03kPa [3]. Common practice favors constructing the inner tank of nickel steel (9% Ni). The outer tank is constructed of either post-tensioned reinforced concrete or carbon steel. The tank usually rests on a concrete base slab or a reinforced concrete ring beam. Piled foundations are also common in cases of poor soil conditions. In this study a model of LNG cylindrical steel tank has been used with an inside diameter of 74 m, height of 37.4 m. Roof of the tank consists of stiffened steel plates supported on roof truss. Tank is filled with LNG liquid of specific gravity (relative density) 0.471.Tank has a base plate of 5 mm thickness

Corresponding author: E-mail address: lotlatif2014@gmail.com

supported on hard soil. Specific weight of steel plates is 78 kN/m^3.

LNG tank construction and material details are shown in Fig.1 along with the generic dimensions for the 150,000m^3 capacity anchored LNG tank that could be constructed in a region of moderate to high seismicity has been applied.

The inner tank is roofless and height to radius ratio (H/R) is close to unity. The shell wall has a thickness of 10 mm at the top which gradually increases to 30 mm at the base. The bottom plate is (5 mm) thickness but near the connection with a thicker wall of (25 mm) annular steel plate is provided all around the circumference. The outer tank is made of reinforced concrete. A base mat of 1500 mm is provided beneath the whole structure. Post tensioned concrete walls are used with a base thickness of 1200 mm. The thickness is gradually reduced to 600 mm at height of 10 m and then is kept constant along the remaining height. When a storage tank is fully filled with LNG liquid, the behaviors of structure are affected by the inner filled liquid. This phenomenon is so-called fluid-structure interaction.

3. Finite Element Modeling

The Finite Element (FE) method is utilized to model the inner and outer tank, as well as the contained liquid. ANSYS12, a finite element code that combines structural and fluid simulation capabilities, is used to model the tank structure in the three dimensional space and perform modal and nonlinear seismic analysis. Taking advantage of the cylindrical tank symmetry, one can model only half of the structure [6]. Fig. 2 represents the meshing of the outer concrete tank while the figure 3-a shows the meshing of the inner steel tank.

The total number of nodes is 139, 63, and 2792 for present outer shell, inner shell and inner fluid elements respectively. The total numbers of elements used for modeling are 135, 62, and 13840 for outer shell, inner shell and inner fluid respectively.

LNG tank has been modeled using the three categories shown in the table 1. The geometric configuration of the vibrating tank can be completely determined by a set of independent coordinates. This number of independent coordinates, for most systems, is termed the number of degrees of freedom (DOF) of the system.

Table 1: Modeling Method of LNG Tank with ANSYS

Category	3 Dimension Model
LNG Liquid	FLUID
Inner Tank	3D SHELL
Outer Tank	3D SOLID / 3D SHELL

The details of categories of modeling are listed as following:-

3.1. LNG Liquid

The fluid (LNG) domain is modeled with three dimensional, eight-noded, 24 DOF fluid elements. These elements have 3 DOF at each node (displacement in three directions) and are used to model contained fluids that have no net flow rate and do not exhibit very large nodal displacements [4]. Fig.3-c shows the finite element meshing of the LNG fluid.

3.2. Fluid-Structure Interaction

The interaction between the tank and the fluid is accounted by properly coupling the nodes that lie in the common faces of these two domains. This means that proper meshing of each domain must ensure that the external nodes of the fluid elements will exist in the same geometrical points with the nodes of the shell elements. Fig.3-b shows part of section showing internal elements used for the finite element meshing of the LNG fluid as well as of inner tank.

3.3. Outer Tank

The outer concrete tank is modeled with eight-noded, 24 DOF solid elements (SOLID45). These elements have three translational DOF in each node.

4. Sloshing and Natural Frequency

The $\boldsymbol{n^{th}}$ natural sloshing frequency, $\boldsymbol{f_n^c}$ may be conveniently expressed by [9]

$$\boldsymbol{f_n^c = \frac{c_n^c}{2\pi}\sqrt{\frac{g}{R}}}$$

The values of coefficient $\boldsymbol{c_n^c}$ for n = 1 can be obtained for the range of $0.3 \leqslant H/\boldsymbol{R} \leqslant 3$ and $\boldsymbol{g}$ is gravity acceleration = $9.81 m/s^2$ and $\boldsymbol{c_n^c}$ value equals 1.2 for H/R = 1.1[9]. The fundamental basis for the Veletsos–Yang procedure is the assumption that the whole structure mass vibrates in the first mode of vibration [5]. Usually, the first mode of vibration is the dominant mode of the response.

The Veletsos–Yang procedure requires knowledge of the fundamental natural frequency of the tank-liquid system.

The fundamental frequency estimated was found to be in good accuracy for tanks with $\mathbf{H}/\boldsymbol{R}$ = 0.3–1.2 [8]. The fundamental natural frequency of the tank-fluid system is shown to be conveniently expressed in the form of [5]:

$$\boldsymbol{f} = \frac{\mathbf{1}}{\mathbf{2}\boldsymbol{\pi}}\frac{\boldsymbol{c_l}}{\boldsymbol{H}}\sqrt{\frac{\boldsymbol{E}}{\boldsymbol{\rho}}}$$

$\boldsymbol{f}$ is in Hertz (Hz, cycles per second),
$\boldsymbol{c_l}$ = nondimensional coefficient depends on the tank properties. Values of the coefficient $\boldsymbol{c_l}$ have been presented by Haroun and Housner [7] and summarized in table 2.
$\boldsymbol{E}$ and $\boldsymbol{\rho}$ are the modulus of elasticity and the mass density of the steel tank wall, respectively.

Table 2: Values of the Coefficient c_l

H/R	c_l
0.39	**0.0898**
0.63	**0.0911**
0.97	**0.0756**
1.07	**0.081**
1.08	**0.0732**

5. Modal Analysis

Figure 4 shows the fundamental modes of outer Pre Stressed Concrete (PSC) tank. The first fundamental frequency of outer tank only indicated 1.56 Hz approximately and the second mode shape indicated 1.9 Hz approximately. The first and second modes are beam deformation shape while the third mode is wall deformation mode. The "Block Lanczos Method" (default) [10] is selected to solve the eigenvalue problem. This method is recommended when the model consists of shell elements.

Figure 5 shows the fundamental modes of inner liquid sloshing. The first periodic time mentioned earlier is about 8.33 seconds i.e., 1/ 0.12 Hz. and well identical to the theoretical value from the guidelines for seismic design of liquid storage tanks presented by Indian Institute of Technology [5]. The comparison of sloshing frequencies is presented in Table 3. The radial variations of first three sloshing modes, normalized such that the maximum absolute value of the ordinate of each mode is unity, are shown in Fig.5. The curves in Fig.5 indicate that the first mode shape is almost a horizontal line. At the LNG free surface a sloshing of fluid is appeared in the second and third modes. Therefore, when checking the freeboard, one must check the available height between fluid surface and tank surface.

Figure 6 shows the first three interaction modes of fluid-structure system. The fundamental mode of fluid-structure interaction system (coupled system) is different from that of the sole structure system without fluid. The first fundamental frequency of inner steel tank (including LNG fluid) is 10.52 Hz. It could be conceived that interaction between the fluid and tank walls has rather clear effects in mode shapes and have been noticed as high values of frequencies. In ANSYS 12, the interaction between the tank and the fluid is accounted by properly coupling the nodes that lie in the common faces of these two domains [3]. This means that proper meshing of each domain must ensure that the external nodes of the fluid elements will exist in the same geometrical points with the nodes of the shell elements. It can be recognized that the inner liquid modeling used in present study is capable of performing dynamic analysis of LNG tank properly considering the fluid-structure interaction effects.

Table 3: Comparison of Sloshing Frequencies Results

Mode No.	Theoretical	ANSYS 12
1	**0.12 Hz**	**0.12 Hz**
2	**0.18 Hz**	**0.19 Hz**
3	**0.23 Hz**	**0.25 Hz**
4	**0.24 Hz**	**0.27 Hz**
5	**0.31 Hz**	**0.33 Hz**

6. Conclusion

The following conclusions are drawn from the trends of the results of the present study:

1. The FE method had been used to model the LNG tank, as well as the contained fluid. ANSYS 12 was utilized to perform the modal and nonlinear analysis in the three-dimensional space.
2. The fundamental frequency of the LNG tank changes due to the effects of inner LNG fluid.
3. For outer structure tank, the stiffness or mass contribution of inner tank affecting the outer tank is very negligible.
4. Results of the modal analysis predicted by theoretical guidelines of Indian Institute of Technology -2007 matches the corresponding values obtained using ANSYS 12 with acceptable marginal errors.
5. The fluid-solid interaction methodology used in this study proved appropriate and acceptable results.

References

[1] D. Moss, “Pressure vessel design manual,” Gulf Professional Publishing is an imprint of EIsevier 200 Wheeler Road, Burlington, 2004, USA.

[2] B. Geyer and J.Wisuri , “Handbook of storage tank systems,” Marcel DekkerPublishing Inc., New York Publishing, 2000, USA.

[3] P. Christovasilis, “Seismic analysis of liquefied natural gas tanks,” Msc. Thesis, department of civil, structural and environmental engineering, state university at buffalo, 2006, USA.

[4] A. Elhosiny, M. Zidan, and H. Orfy, “Seismic response of liquid storage tanks resting on the ground,” 11th ICSGE, Ain Shams University, 2005, EGYPT.

[5] S. Jain, and O. Jaiswal, “Guidelines for seismic design of liquid storage tanks,” Indian Institute of Technology Kanpur, 2007, India.

[6] M. Jin., J. Jeon, and W. Kim, “Earthquake response analysis of LNG storage tank by axisymmetric finite element model,” 13th World Conference on Earthquake Engineering, Aug. 2004,Vancouver, Canada.

[7] W. Housner, and A. Haroun, “Dynamic analysis of liquid storage tanks,” California Institute of Technology, Pasadena,1981, USA.

[8] P. Asfura., N. Sumodobila, and R. Beigi, “Dynamic analysis of large steel tanks,” 17th International Conference on Structural Mechanics in Reactor Technology, Aug. 2003, Prague, Czech Republic.

[9] Z. Ozdemira, M. Souli, and M. Fahjan, “Application of nonlinear fluid-structure interaction methods to seismic analysis of anchored and unanchored tanks,” Journal of Engineering Structures, vol. 32: Elsevier Science Ltd., 2010, pp. 409–423.

[10] ANSYS, Inc., Training Manual for ANSYS and ANSYS Workbench Release 12.0, Canonsburg, 2009, USA.

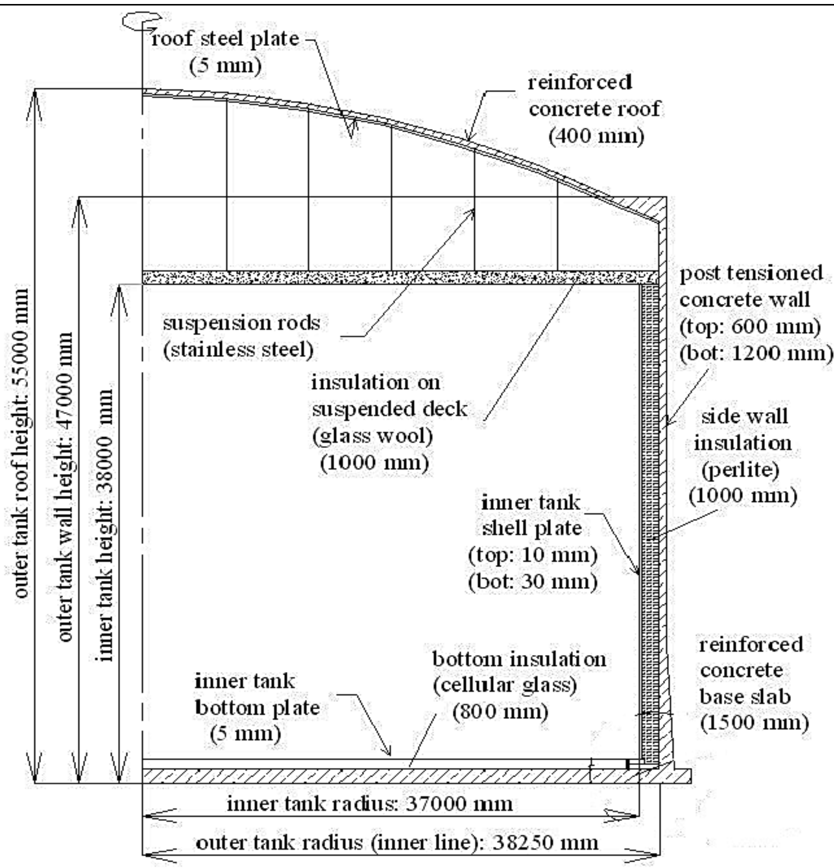


Fig. 1: Construction of the LNG Tank [3]

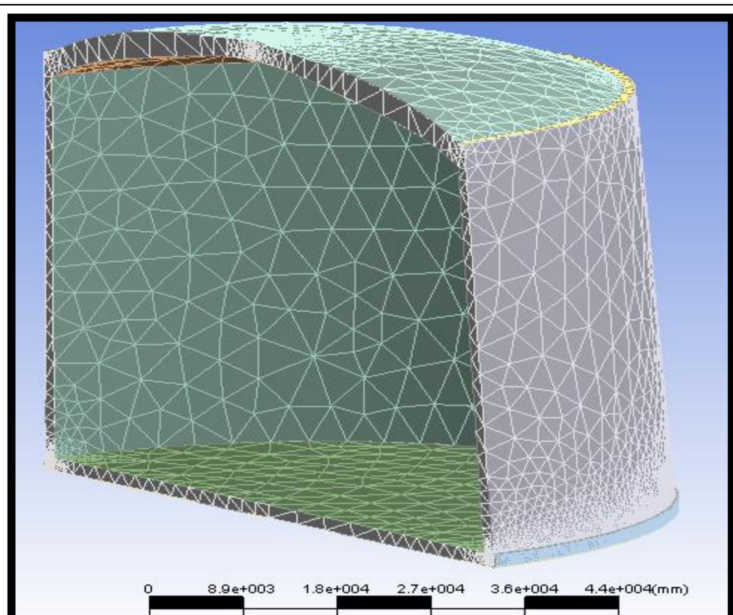
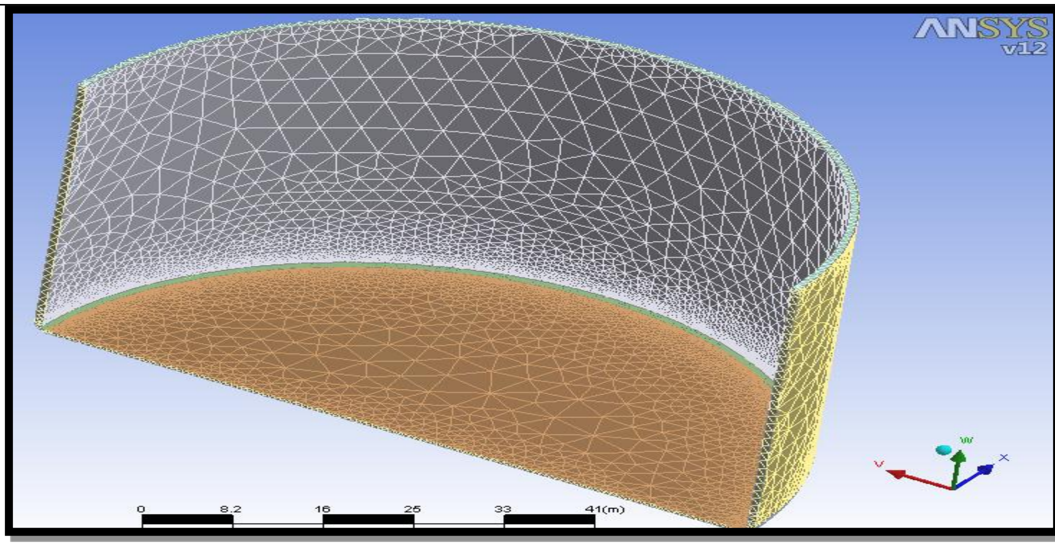
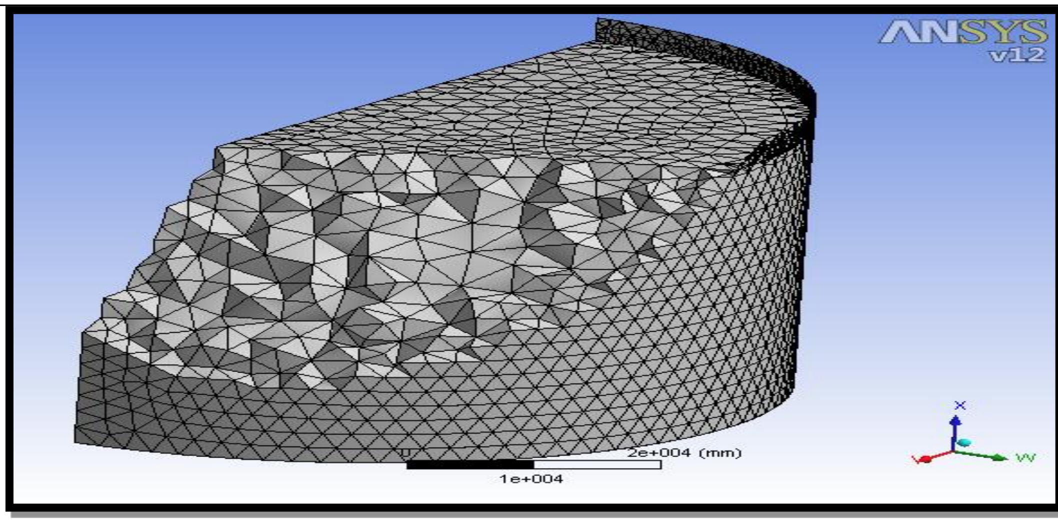


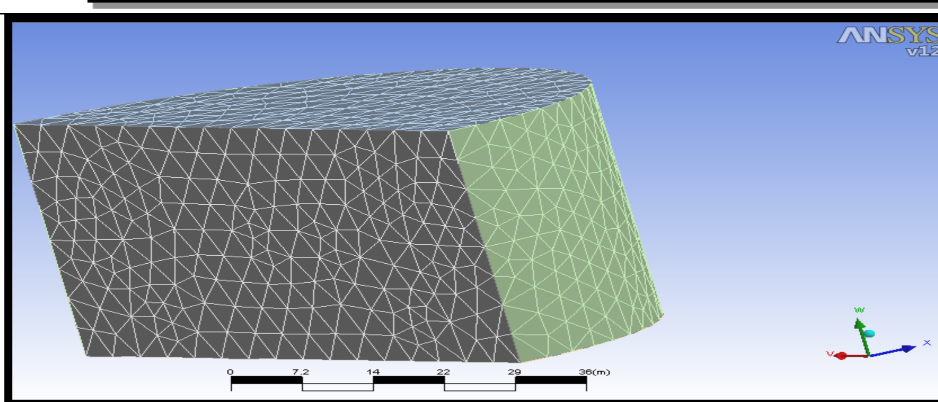
Fig. 2: Finite Element Meshing of the Outer Concrete Tank



a)



-b)

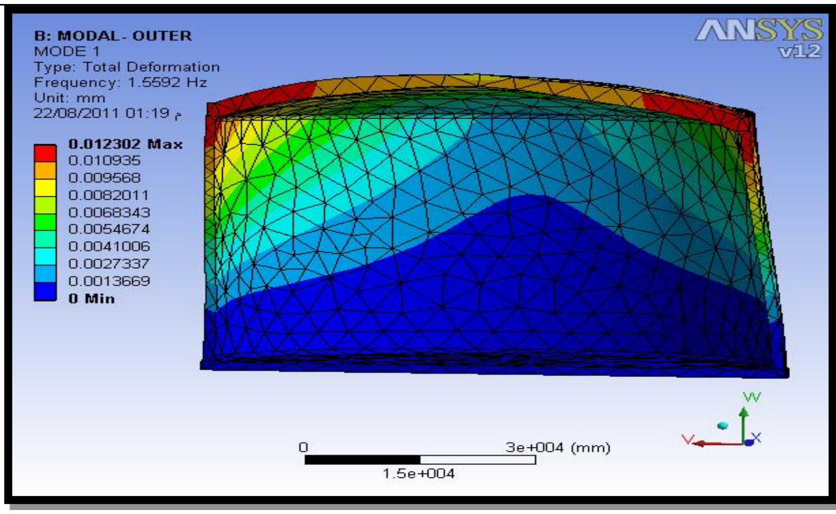


Information

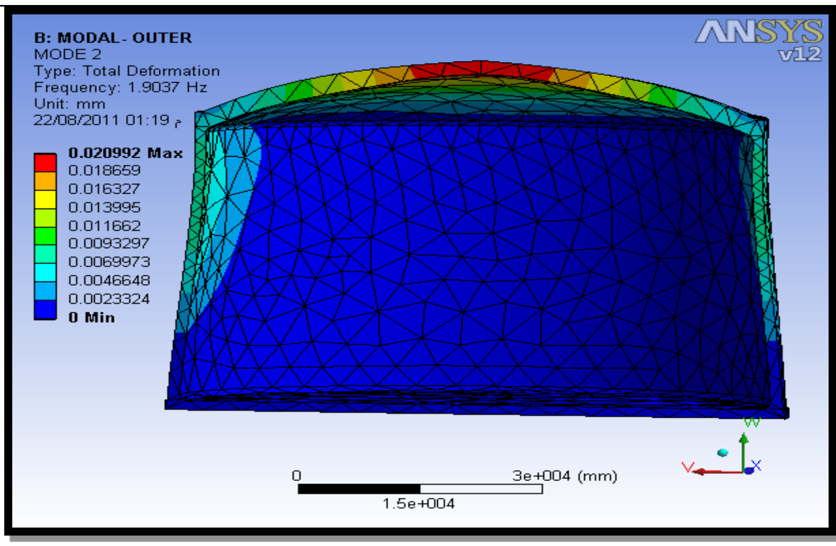
Mesh statistics	
Total number of nodes	2792
Total number of tetrahedra	13840
Total number of pyramids	0
Total number of prisms	0
Total number of elements	13840

-c)

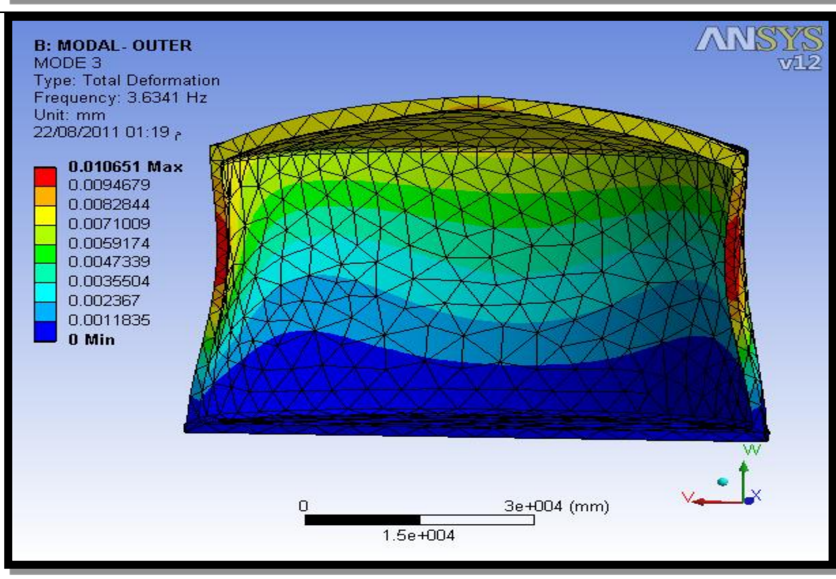
Fig. 3: Finite Element Meshing of LNG Tank Components using ANSYS 12
a) Inner Steel Tank
b) Part of Section Showing Internal Elements
c) LNG Fluid



-a) Mode 1 , f = 1.56 Hz

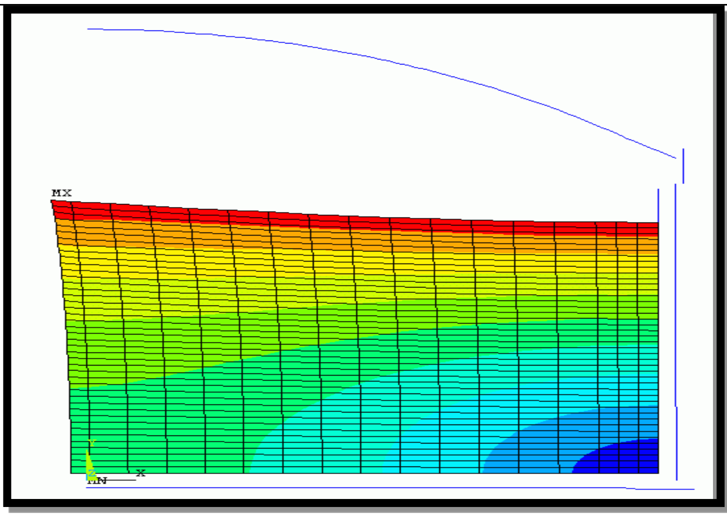


-b) Mode 2, f = 1.90 Hz

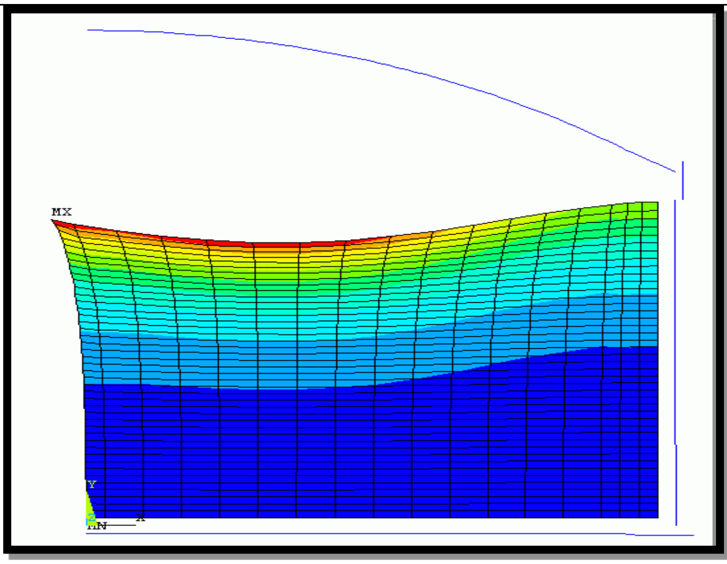


-c) Mode 3, f = 3.63 Hz

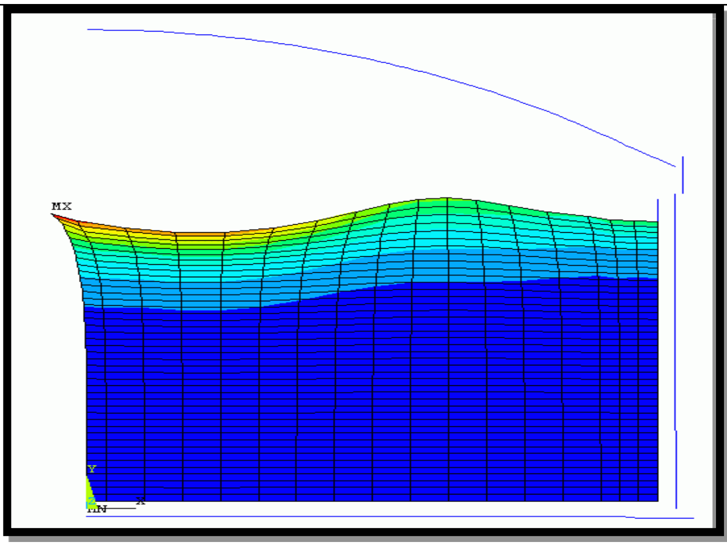
Fig. 4: Outer Tank Deformation Mode Shapes for LNG Tank



-a) Mode 1 , f = 0.12 Hz

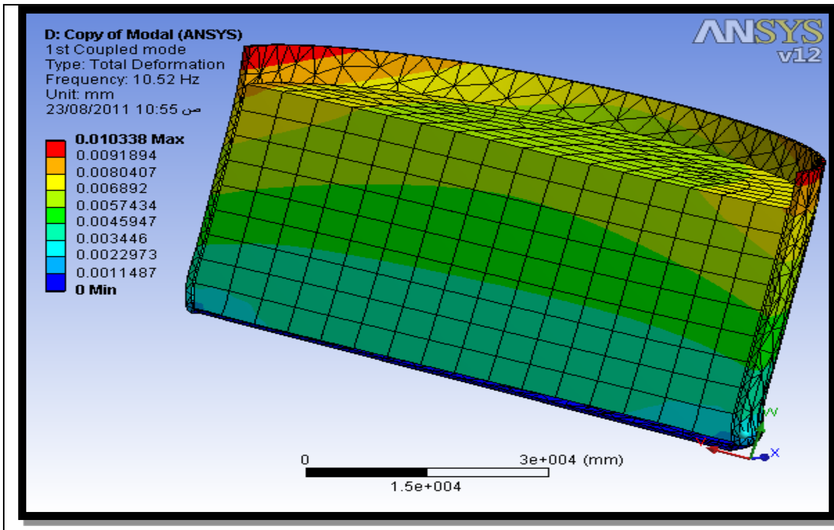


-b) Mode 2, f = 0.19 Hz

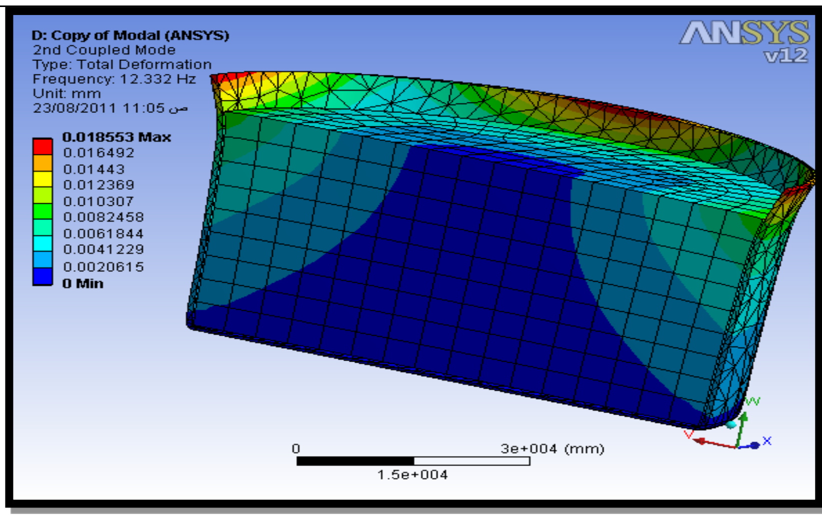


-c) Mode 3, f = 0.25 Hz

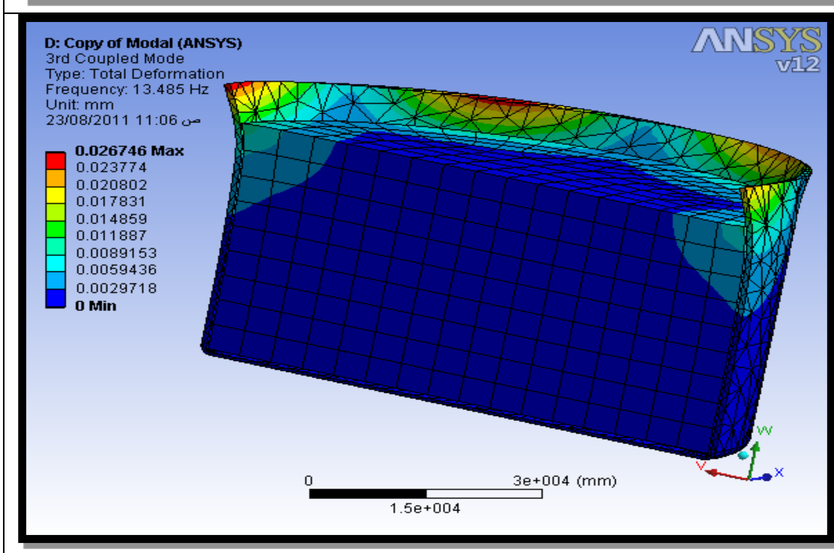
Fig. 5: Liquid Sloshing Mode Shapes For LNG Tank



-a) Mode 1 , f = 10.52 Hz



0b) Mode 2, f = 12.33 Hz



-c) Mode 3, f = 13.48 Hz

Fig. 6: Coupled (Fluid-Structure Interaction) Deformation Mode Shapes For LNG Tank