A Study on Effect of Fluid on the Modal Characteristics of Ground Supported Water Tanks

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Abstract. Liquid storage tanks are one of the essential lifeline structures which should function even after natural disasters. Water tanks in particular are essential for proper supply of water in the affected areas and for fire-fighting purposes. Sloshing is an important phenomenon occurring in partially filled tank with free surface. It can cause violent liquid motions that can cause instability in carrier-vessel and structural damage in the tank walls. To maintain the structural integrity of the carrier vessels, modal characteristics should be known as the impact of sloshing will increase when the excitation frequency matches with the natural frequency of container and result in resonant condition. This study investigates the modal characteristics such as natural frequency, mode shapes and participation factors should be investigated.

1. Introduction

Liquid sloshing is a major phenomenon occurring in stationary or moving containers that cause greater concern in various fields like civil, aerospace, nuclear engineering, design of ship and road tankers. In fluid dynamics, sloshing can be defined as the movement of two or more non-miscible fluids (liquids and gases) inside another object which is undergoing motion. Liquid storage tanks are considered as important lifeline structures. They should remain functional after natural disaster like earthquake. Seismic excitations are formed during earthquakes that cause severe damage to the tanks which in turn results in serious injury to life and loss of property. The walls of tanks are subjected to hydrodynamic pressure due to heavy sloshing during earthquake in the case of ground supported tanks. Therefore to understand the response to dynamic loads, the modal characteristics like natural frequency, mode shapes and participation factors should be investigated. This paper mainly focuses on the modal characteristics of steel square tanks. Bayraktar [1] investigated the dynamic characteristics of cylindrical steel tank filled with oil. The 3-D dynamic characteristics of partially filled elastic, rectangular tanks were investigated by Zhou and Liu [2]. An analytical method was proposed by Hashemi [6] to determine the dynamic behaviour of flexible rectangular fluid containers. Rayleigh-Ritz method is used to develop simplified solutions. But the resulting frequencies from these methods may underestimate or overestimate the exact solution due to inappropriate assumptions. Thus in order to overcome these drawbacks, finite element analysis can be effectively used. The modal characteristics can be investigated
using the FEM models. 3D mode shapes can be visualised easily which are difficult to obtain via theoretical approach.

In this paper, a square tank with different fill levels are considered to investigate the modal characteristics using the finite element method. ANSYS software is used to develop finite element models. The convective and impulsive frequencies and corresponding mode shapes with various boundary condition and fill levels are determined. Three boundary conditions are used: base fixed and free at top, clamped-clamped and clamped-free ends at the bottom and top of the tank, respectively. All the translations and rotations are restricted at the base of the tank for the fixed condition whereas, the edge of the base is restricted similarly for the clamped conditions. The fixed base is given by assigning full fixity to the whole base slab, while in the clamped condition; only the edges of base slabs are clamped. The fill levels considered are empty, 25%, 50%, 75% and full tank condition. The effect of fluid level and boundary condition on modal characteristics is evaluated by carrying out modal analysis.

2. Geometric configuration
A scaled down model of square tank with height 300 mm, width 500 mm, and thickness 3 mm is selected for modal analysis. The material of tank is considered as steel. The material properties, Young’s modulus of elasticity and Poisson’s ratio are given as 210 GPa and 0.3 respectively. The mass density of the tank material is 7850 kg/m$^3$. The tank is filled with fluid to four different heights from the tank base. Water, having a mass density of 1000 kg/m$^3$ and a bulk modulus of elasticity of 2.2 GPa is used as the fluid. The speed of sound in water is 1483 m/sec. The tank was first analysed for empty condition and then the analysis was done for different fill condition.

3. Finite element analysis
Finite element analysis of water tanks are done using ANSYS Workbench 2019 R1. Geometric modelling of water tank is done using Design Modular (DM). Modal is used for empty tank condition and Modal Acoustics is used for all other fill levels to determine frequency and mode shapes. The Navier-Stokes equation, continuity equation and conservation of momentum equation govern the fluid motion in a tank.

- **Navier-Stokes equation:**

$$\frac{\partial (\rho u)}{\partial t} + \rho \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) = \rho x - \frac{\partial p}{\partial x} + \frac{1}{3} \mu \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) + \mu \nabla^2 u$$

where $\rho$ is the density, $t$ is time, $p$ is pressure, $\mu$ is dynamic viscosity, and $u$, $v$, $w$ are velocity components in $x$, $y$, $z$ direction.

**Continuity equation:**

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0$$

- **Conservation of momentum:**

$$\frac{\partial}{\partial t} (\rho \vec{V}) + \nabla \cdot (\rho \vec{V} \vec{V}) = -\nabla p + \nabla (\sigma) + \rho g + \vec{F}$$

$\sigma$ is the stress tensor, $\rho g$ and $\vec{F}$ are the gravitational body force and external body force respectively.

3.1 Finite element models
The square tank is generated using 3-D finite elements as shown in figure 1. SOLID187 element is used to model the square tank which is a higher order 3-D tetrahedral element, with one extra node at the middle of each side of the element. These are defined by ten nodes. Each node has three degrees of freedom, with translations in the nodal $x$, $y$ and $z$ directions. FLUID220 is a twenty nodded acoustic element which is used to divide the fluid region into identical 3-D elements. The element node has four degrees of freedom at each node, with translations in the nodal $x$, $y$ and $z$ directions and pressure. The fluid element is coupled with the tank surface by adding FSI flag at the interface, which will couple the pressure degrees of freedom of the nodes. The governing equations of acoustics, namely 3-D wave equation have been discretised taking into account the coupling of structural motions and acoustic
pressure at the interface. Contact and sliding between 3-D target surface and a deformable surface is defined by the element CONTA174. The target surface is defined by 3-D TARGE170 which is used only for rigid bodies. The model consists of 15754 nodes and 6195 elements as shown in figure 2.

![Figure 1. Square tank with 50% fill level and its finite element model.](image1)

3.2. Modal analysis
Mode-frequency (modal) analysis is done to determine natural frequencies and mode-shapes of the square tank. There are two distinct components for frequency of liquid in moving rigid containers-impulsive and convective. These two components have a direct effect on the performance and dynamic stability of moving containers. The fluid filled tank was analysed for convective and impulsive frequencies using Modal Acoustics. The frequency corresponding to the upper part of the fluid in the tank near the free surface, which vibrates in low frequencies and independent of the tank walls, is the convective frequency. The frequency of the remaining fluid, i.e., the part that moves with the tank walls, and that vibrates in higher frequencies, is the impulsive frequency.

3.2.1. Modal Acoustics. Modal Acoustics analysis usually involves modelling the fluid medium as well as the surrounding structure in order to determine frequencies and standing wave patterns within a structure. The physical region and acoustic region is assigned to the tank. For getting convective frequencies free surface boundary condition is also assigned. This boundary condition enables to specify a plane as a free surface in order to consider sloshing effects on model. Gravitational acceleration values need to be defined before assigning free surface to properly define the sloshing problem. Similarly for getting impulsive frequencies the top surface of liquid is assigned a pressure of 0 Pa. The set up for impulsive and convective frequencies are shown in figures 2 (a) and (b) respectively. In both cases fluid solid interface is assigned to the necessary contact regions.

![Figure 2. Modal Acoustics setup. (a) Impulsive and (b) Convective frequencies.](image2)

4. Results and discussions
The first three mode shapes of half-filled tank and empty tank with clamped-free boundary condition are shown in figures 3 and figure 4, respectively. The comparison of impulsive frequencies for different boundary conditions is shown in figure 5. As the depth of fluid increases, the frequency of tank decreases for all the three boundary conditions. The fluid effect is similar for clamped-free and fixed base condition.
The frequencies of clamped-clamped condition show drastic decrease in frequencies up to 50% of fluid level which shows that fluid effect is more significant in this range of fluid level for clamped-clamped case. Above 50% fluid level, there is not much difference in frequencies for clamped-clamped case, but for clamped-free and fixed base case, there is slight variation in frequency above 50%. The fluid has more prominent effect on frequency in clamped-clamped condition as compared to other two conditions. Thus the frequency of tank depends on both fluid depth and boundary conditions.
The convective frequencies for various fill conditions are shown in figure 6. The convective frequency increases with increase in the fluid depth, due to decrease in convective mass of fluid. Depending on the confinement provided by the tank, the mass of impulsive and convective fluid varies. Thus greater the confinement greater is the impulsive liquid and smaller the convective liquid. Due to this reason, the tank with lower fluid level has higher impulsive frequency and lower convective frequency.

The normalised frequency of first mode of tanks for different boundary conditions and fluid depth are depicted in figure 7. The normalised frequency can be defined as the ratio of frequency in loaded condition and that of empty condition which is expressed in percentage. The fluid inside the tank will decrease the frequency in impulsive mode and effect of fluid is significant for fluid level below 50%. The normalised frequency for full tank condition is 56% for clamped-free and fixed base conditions whereas for clamped-clamped condition the normalised frequency is 36% which is lower than that of other two boundary conditions. This confirms the fact that the effect of fluid is more prominent in the clamped-clamped condition.
5. Conclusions
Finite element analysis of several models with different boundary conditions and fluid levels were carried out to find the impulsive and convective frequencies and corresponding mode shapes of square tank. From the study conducted, the following conclusions can be drawn:

- The frequency of tank will decrease with inclusion of fluid inside the tank. The impulsive frequencies are more at lower fluid level which goes on decreasing with increasing the fluid level.
- The convective frequency of the tank will increase with increase in the fluid depth in the tank due to decrease in the mass of convective fluid.
- The fluid has more impact on clamped-clamped condition than clamp-free and fixed base condition for fluid depth below 50%.
- The maximum rate of decrease in frequency was in clamped-clamped condition i.e. 36% compared to 56% in clamp-free and fixed base conditions.

6. References
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