The dynamic behavior of moving rectangular liquid filling

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Abstract: - This paper is revolved around analyzing the dynamic behavior of the liquid filling in the various moving rectangular reservoirs. For sake of clarity, when the contained liquid vibrates, the liquid exerts the hydrodynamic pressure on the reservoir. Then, the theoretical background of the total and hydrodynamic pressure on the rectangular reservoir is described. Thereafter, our interest is to perform to the experimental and numerical analysis associated with the behavior of moving rectangular liquid filling.

Key-Words: - liquid, rectangular tank, moving, pressure, frequency, experiment

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1 Introduction

The dynamic behavior of the liquid filling in the different kind of moving reservoirs is the interesting subject for investigation [1]. The liquid sloshing in of moving liquid-containing or liquid-transporting structures is conjugated with the various technical problems and the understanding of the sloshing mechanism is very important [2,3]. The sloshing is the oscillation of the liquid mass in moving engineering storage structures, and it is characteristically by the wave motion from one side to other side within the container [4-6]. When the frequency of the container motion is close to the natural frequency of the liquid filling, then the sloshing answer is the extreme and the extreme liquid movement can cause the high local impact loads on the storage structures [7-12].

The liquid is characterized by the different types of motion [13]: simple planar, non-planar, rotational, irregular beating, symmetric, asymmetric, quasi-periodic, chaotic. The types of the motion are depending on the shape of the storage structure and the type of the excitation [14-18]. The amplitude of the slosh depends on the liquid-fill dimensions, the properties of liquid, the geometry of storage structure, the excitation frequency, and the excitation amplitude [19].

The liquid splashing plays important role for the reliability and safety design of the storage structures, because the eventual damages of storage structures used for storage of hazardous liquids (petroleum, liquefied natural gas, different kind of chemical and radioactive waste) are catastrophic [20]. Potential damage of storage structures and possible leakage of the liquids have far-reaching consequences [21]. They are not only financially but especially environmental degradation [22-25]. The knowledge of the phenomenon of the contained liquid sloshing, the knowledge of dynamic interaction between the contained liquid and the storage structure, the knowledge hydrodynamic effect on solid domain of storage structures, as well as the frequency properties of the liquid and the liquid-structure system plays a decisive basis in designing the storage structure resistant to earthquakes [26].

The behavior of liquid filling in a storage structures has investigated by many researchers and engineers [27]. In 1933, Westergaard had determined the hydrodynamic pressures acting on rectangular dam subjected to horizontal acceleration [28]. The simplified analysis of the hydrodynamic pressure on the tank walls and tank bottom subjected to a horizontal acceleration had investigated by Housner [29], he had established the impulsive and convective components of the hydrodynamic pressure in a rigid
tank wall by introducing a simplified method of the hydrodynamic analysis in the system tank-liquid and adopting the concept of two dynamic components - dynamic impulsive and convective masses. Velestos [28] had also discussed the hydrodynamic pressure on rigid and flexible wall. Haround, Velestos and Malhotra had introduced the mechanical model for the flexible storage structure [28].

2 Effect of moved liquid-filling due to horizontal acceleration

In the section, the liquid is considered incompressible, inviscid, by neglecting the gravity force, the liquid motion is described by the Euler equations that are expressed as

$$\frac{∂u}{∂t} + u \frac{∂u}{∂x} + v \frac{∂u}{∂y} + w \frac{∂u}{∂z} = - \frac{1}{ρ} \frac{∂p}{∂x},$$  

(1)

$$\frac{∂v}{∂t} + u \frac{∂v}{∂x} + v \frac{∂v}{∂y} + w \frac{∂v}{∂z} = - \frac{1}{ρ} \frac{∂p}{∂y},$$  

(2)

$$\frac{∂w}{∂t} + u \frac{∂w}{∂x} + v \frac{∂w}{∂y} + w \frac{∂w}{∂z} = - \frac{1}{ρ} \frac{∂p}{∂z},$$  

(3)

where $u$, $v$, and $w$ are the velocity components in the $x$, $y$, and $z$ directions respectively, $ρ$ is total pressure, $ρ$ is the density, and $t$ is time [30,31].

When the contained liquid is subjected to horizontal motion, the liquid domain exerts the hydrodynamic pressure together with hydrostatic pressure on tank structure (domain walls and bottom) of ground-supported liquid-containing or liquid-transporting structures [32].

The total pressure of liquid domain is given by the absolute summation rule of the hydrostatic and hydrodynamic pressure

$$p(t) = p_{HS}(t) + p_{HD}(t).$$  

(4)

The total hydrodynamic pressure is obtained by the absolute summation rule of the impulsive and the convective pressure

$$p_{HD}(t) = p_i(t) + \sum_{n=1}^{∞} p_{cn}(t).$$  

(5)

2.1 The hydrodynamic impulsive pressure

The hydrodynamic impulsive pressure of the contained liquid domain is given on the side vertical wall of the rectangular tank solid domain by

$$p_{iw}(ξ, t) = C_{iw}(ξ) ρ H A_g(t),$$  

(6)

$$C_{iw}(ξ) = \frac{\sqrt{3}}{2} (1 - ξ^2) \tanh \frac{\sqrt{3} L}{H}.$$  

(7)

Fig. 2: The function $C_{iw}(ξ)$ of the impulsive wall pressures distribution of liquid for various reservoir slenderness parameter $γ$ of liquid filling

Fig. 3: The function $C_{ib}(ξ)$ of the impulsive bottom pressures distribution of liquid for various reservoir slenderness parameter $γ$ of liquid filling
The distribution of the hydrodynamic impulsive pressure of the contained liquid domain is given on the bottom of the rectangular tank solid domain by

\[ p_{ib}(\xi, t) = C_{ib}(\xi) \rho H A_g(t), \quad (8) \]

\[ C_{ib}(\xi) = \frac{\sqrt{3}}{2} \left( \sinh \frac{\sqrt{3}}{2} \frac{\sqrt{3} \xi}{H} / \cosh \frac{\sqrt{3} H}{2L} \right). \quad (9) \]

### 2.2 The hydrodynamic convective pressure

The hydrodynamic convective pressure of the contained liquid domain is given on the side vertical wall of the rectangular tank solid domain by

\[ p_{cnw}(\xi, t) = \sum_{n=1}^{\infty} Q_{cnw}(\xi) \rho L A_c(t), \quad (10) \]

\[ Q_{cnw}(\xi) = 0.833 \cosh \left( \frac{3\xi}{2L} \right) \cosh \left( \frac{3\xi}{2L} \right) \quad (11) \]

The distribution of the hydrodynamic convective pressure of the contained liquid domain is given on the bottom of the rectangular tank solid domain by

\[ p_{cnb}(\xi, t) = \sum_{n=1}^{\infty} Q_{cnb}(\xi) \rho L A_c(t), \quad (12) \]

\[ Q_{cnb}(\xi) = 2.5 \left( \frac{\xi}{2L} \right)^{-4} \left( \frac{\xi}{2L} \right)^{-3} \tanh \left( \frac{H}{2L} \cdot \sqrt{\frac{3}{2}} \right) \quad (13) \]

In Eqs. 3-11 gills following

\( H, L \) are inner dimensions of liquid filling, Fig. 1,
\( \gamma = H / L \) is the liquid slender parameter [-],
\( \xi = z / H \) is the vertical dimension [-],
\( \zeta = x / L \) is the horizontal dimension on bottom [-],
where \( x \in (-L; L) \),
\( C_{nm}(\zeta) \) is the hydrodynamic impulsive pressure distribution on the side vertical wall of the rectangular tank solid domain [-],
\( C_{ib}(\xi) \) is the hydrodynamic impulsive pressure distribution on the bottom of the rectangular tank solid domain [-],

\( Q_{cnw}(\xi) \) is the of the hydrodynamic convective pressure distribution on the side vertical wall of the rectangular tank solid domain for \( n \) mode [-],
\( Q_{cnb}(\xi) \) is the of the hydrodynamic convective pressure distribution on the side vertical wall of the rectangular tank solid domain for first mode [-],
\( Q_{cnb}(\zeta) \) is the of the hydrodynamic convective pressure distribution on the bottom of the rectangular tank solid domain for \( n \) mode [-],
\( Q_{c1n}(\xi) \) is the of the hydrodynamic convective pressure distribution on the bottom of the rectangular tank solid domain for first mode [-],
\( A(t) \) is time-history ground acceleration [m/s²],
\( \omega_n \) is frequency of the single degree of freedom oscillator [m/s²] that has the circular frequency
\( n \) is mode of liquid oscillation,
\( \rho \) is the density of liquid [kg/m³],
\( g \) is gravitational acceleration [m/s²],
\( t \) is time [s].
distribution, \( Q_{c1w}(\zeta) \) is the convective vertical wall pressures distribution, \( Q_{c1b}(\zeta) \) is the convective bottom pressures distribution.

The natural frequency for the \( n \)th mode is given by

\[
\omega_n^2 = \frac{n^2 g}{2L} \tanh\left(\frac{nnH}{2L}\right).
\]

3 Experimental Analysis

The rectangular tank in the shape of the glass hollow block was used to carry out the experiment. The inside dimensions of the tank were: the length \( L \) 39.2 cm, the height \( H_{\text{wall}} \) 19.2 cm and the width \( B \) 24.2 cm. The height \( H \) represents the maximum dimension of possible full filling with liquid. The vertical wall thickness of the tank was 3.8 mm and the thickness of the tank bottom was 5 mm. The transparent square grid with the raster size 1 cm was mounted on the tank front side, the largest side, for the possibility of better video documentation of the liquid movement, see Fig. 6.

The liquid filling was water - H\( _2 \)O by using the minimum amount of potassium permanganate, chemically 2KMnO\( _4 \). The water was acquired the light purple colour for better possibilities of the recording the shape of the liquid. The liquid filling with the filling of height \( H = 15 \) cm was considered for the analysis of this paper. The filling of the rectangular tank with the water was excited by horizontal harmonic motions

\[
x_j = A \cdot \sin(2 \pi f t)
\]

where \( f \) is the excitation frequency [Hz], and \( A \) is the excitation amplitude [m] that has the value 0.5 cm or 1 cm, respectively.

![View of the experiment workplace and test equipment](image)

![View of the PC control screen](image)
Table 1: The frequencies of liquid filling

| number | Frequency $f$ |
|--------|--------------|
| 1.     | 1.30 Hz      |
| 2.     | 1.99 Hz      |
| 3.     | 2.45 Hz      |
| 4.     | 2.83 Hz      |
| 5.     | 3.17 Hz      |

| number | Frequency $f$ |
|--------|--------------|
| 6.     | 3.47 Hz      |
| 7.     | 3.75 Hz      |
| 8.     | 4.00 Hz      |
| 9.     | 4.25 Hz      |
| 10.    | 4.48 Hz      |

Fig. 8 documents the phenomena of sloshing for various excited amplitudes and frequencies. The monitored wave heights were different, they were depended mainly on the excited frequency, and on the amplitude also. If the liquid filling was excited by the frequency close to the natural frequency, then large waves were formed until the liquid flushed out. Fig. 8a), Fig. 8b), and Fig.8c) show the relatively calm free surface of the liquid with the small waves. Fig. 8d), Fig. 8e), and Fig.8f) present the large wave of the liquid free surface. These waves could be measured and recorded. The maximum measurement height of the liquid wave was 15 cm in this experiment. Fig. 8g), Fig. 8h), and Fig.8i) document
the markedly splashing state of the liquid. The fluid flushes out from the tank, the fluid was spilled out of the tank. Thus, the measurement of the wave heights was not possible, and this condition is documented with the wave height 16 cm from the original surface in Fig. 9. Only frequencies up to the value of the first natural frequency were tested in this experiment. The peak waves of liquid for 15 cm water filling were presented in Fig. 9 in depending on frequency, see Fig. 9a, and in depending on acceleration, see Fig. 9b. The peak waves of liquid excited with amplitude 0.5 cm is documented with red triangle, and with amplitude 1.0 cm with black circle. The first frequency of the 15 cm height rectangular tank liquid filling is \( f_1 = 1.30 \) Hz, see Table 1, and the first frequency is also shown by vertical dash light blue line in Fig. 9a. The culmination of the waves close to the first frequency is evident. The next second and higher modes (shapes) were not monitored.

4 Numerical Analysis

The numerical analysis was simulated for rectangular liquid filling (H₂O) with horizontal dimension 192 mm x 392 mm and height 150 mm contained in rectangular glass container. The liquid filling contained in glass tank was excited by the horizontal harmonious motion with amplitude 5 mm and frequency \( f = 1 \) Hz. The Finite Element Method (FEM) was used to the impeccable rigid container (vertical walls and bottom) in numerical simulation. For that, we consider the 2D numerical model of the dimension 392 mm x 150 mm, see Fig. 1, and the liquid boundary conditions of the liquid domain that are outlined as:
- the free surface – upper border,
- "BOUNDARY-CONDITION WALL", it is the fictitious rigid wall with the possibility of rigid solids movement - side vertical and bottom borders [34].

The frequency of the simulated horizontal harmonious excitation was \( f = 1 \) Hz and the excite amplitude was 5 mm. The record of the input excited horizontal displacement was shown for numerical simulation of the problem in Fig. 10.

5 Results and conclusion

The results of numerical simulation were obtained for first four seconds of movement. The peak value of the hydrostatic and total pressure arises in the bottom of the liquid domain. The value of the hydrostatic pressure is given by known analytical solution: \( \rho g H = 1000 \cdot 9.81 \cdot 0.15 \) and the peak value of the hydrostatic pressure is also 1 471.5 Pa.

The peak value of the total pressure arises in the left or the right bottom edge of the liquid domain. The total pressure of the liquid filling given by the numerical simulation using FEM is 1 554 Pa. Fig. 11 documents of the pressure distribution and the shape of liquid domain in time 2.775 s, it is the time when the peak value of liquid pressure arises. The peak value of liquid pressure arises in bottom edge nodes, in the left bottom edge node - it is 75 (named LBE), and in right bottom edge node - it is 51 (named RBE). The node 75 (LBE) is documented by small triangle in Fig. 11.
Fig. 1: The pressure distribution and the shape of the liquid domain in time 2.775 s.

Fig. 12 is shown the shapes and the pressure distributions of the liquid domain a) in time 1.300 s and b) 2.775 s, respectively. The liquid filling during the horizontal movement of the tank is alternately loaded once on one side and then on the other side: right side Fig. 12a), and left side Fig. 12b). Related to this, the changes of the pressure in the liquid domain, and the movement of the originally calm liquid filling level (origin of waves).

Fig. 12: The pressure distribution of moving liquid domain in time 1.300 s and b) in time 2.775 s of the liquid domain.

The next Fig. 13a-c show the time-dependent response of the liquid domain - the total liquid pressure:

a) in the LBE node of the liquid domain,

b) in the RBE node of the liquid domain,

and c) in the MB node, the middle bottom node of the liquid domain.

The comparison of the time-dependent response - the total pressure of the liquid domain in nodes LBE and RBE is presented in Fig. 14. Obviously, the time-dependent responses of liquid domain - the pressures are completely asymmetric in LBE and RBE nodes.

Fig. 13: The time-dependent response of the liquid pressure in node a) LBE, in node b) RBE, in node c) MB.

Fig. 14: Comparison of the time-dependent response of the total liquid pressure in LBE and RBE.

Fig. 15: Comparison of the pressures distribution (hydrostatic pressure and peak total pressure) on vertical side of liquid domain.
Fig. 15 documented the comparison of the pressure distribution on the vertical side of the liquid domain, i.e. the total pressure which act on the vertical wall of the tank. The dashed black line represents the hydrostatic pressure, and the red line represents the peak value of the total moved liquid domain pressure. The total pressure was obtained by FEM. The level “0” means bottom of the liquid domain on vertical side and “1” means free surface level of the liquid domain on vertical side.

![Image](image1)

Fig. 16: The shape of liquid domain and the vertical displacement a) in time 1.325 s and b) in time 1.80 s

![Image](image2)

Fig. 17: The liquid vertical displacement of liquid domain a) for RTE and LTE nodes in time 1.325 s and b) for MT node in time 1.80 s

Fig. 16 shows the shape and the vertical displacement of liquid domain. Fig. 16a) documents the peak vertical displacement response of the liquid domain on right side, it is in time 1.325 s and Fig. 16b) shows the peak vertical displacement on left side, it is in time 1.80 s.

Fig. 17a) shows the comparison of the time-depended response - the vertical displacement of the liquid domain in the nodes: LTE (left top edge) of the free surface and in RTE (right top edge) of the free surface, respectively. It is seen that the time-depended responses of the liquid domain - the vertical displacements are completely asymmetric. The time-depended response of the liquid domain (the vertical displacement) in the nodes LTE and RTE correlates about the zero value, the zero value is the original free surface of the liquid domain in time of the quit situation.

Fig. 17b) documents the time-depended response of the liquid domain - the vertical displacement in the node MT (middle top) of the free surface.

6 Conclusion

The dynamic behaviour of the liquid filling in the moved rectangular reservoir due to the horizontal harmonic motion was analysed in this paper. The rectangular liquid filling (water) with the height of filling 15 cm was considered and it was excited by the horizontal harmonious motions with amplitude 5 mm and frequency \( f = 1 \) Hz.

The experimental results confirmed the analytical calculated value of the first frequency. The experimental results confirmed that the liquid filling was excited at the frequency close to the natural frequency, then the large waves were formed until the liquid flushed out.

The numerical solution documents the numerical simulation possibility of quitter state of the moved liquid domain by using FEM. The peak values of the total liquid pressure given by the numerical simulation document the increase of the pressure in case of moving of the liquid filling. The pressure highest values occur at the bottom of liquid domain. The numeric analysis documents that the original free surface does not remain calm. Due to the horizontal exciting starts the swaying of the free surface to the large waves until the liquid flushed out, it is depended on the shape of the liquid domain and the excited frequencies of the liquid filling.

This study is one of the contributions to the analysis of the interaction between the tank and the liquid. The knowledge of the liquid effect during the liquid storage tank movements, as well as the frequency properties of the tank-liquid systems are the basis for good analysis and design of structures / devices resistant to the hydrodynamic action of the liquid charge.
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