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An Analysis of Baffles Designs for Limiting Fluid Slosh in Partly Filled Tank Trucks

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Abstract: This study presents an analysis of effectiveness of different designs of baffles, including the conventional, partial and oblique, in limiting the manoeuvre-induced transient as well as steady-state fluid slosh forces and moments in a partly-filled tank truck. The effect of an alternating arrangement of partial baffles is also explored. A three-dimensional computational fluid dynamics model of a partly-filled tank is developed to study the relative anti-slosh properties of different baffles designs and layouts under combined idealized longitudinal and lateral acceleration fields and different cargo loads. The analyses are also performed for a cleanbore tank, which is validated using the widely-used quasi-static slosh model. The results suggest that the conventional transverse baffles offer important resistance to fluid slosh under braking manoeuvres, while the obliquely placed baffles could help limit the longitudinal as well as lateral fluid slosh under combined lateral and longitudinal acceleration excitations.

Keywords: Tank trucks, lateral and longitudinal dynamic fluid slosh, antislosh, baffles, oblique baffles.

1. INTRODUCTION

In road tankers, the free surface of liquid cargo may experience large excursions for even very small motions of the container. The resulting dynamic load shifts in the roll and pitch planes could influence the roll and pitch moments, and mass moments of inertia of the fluid cargo, and may contribute to degradation of the handling and directional stability limits. This problem is common in fuel tanks of automobiles, aircrafts and large ships and tankers. Reported studies on dynamics of partly filled tank vehicle combinations have invariably shown that the roll dynamics and braking properties of such vehicles are strongly influenced by fluid slosh in an adverse manner [e.g., 1-3]. It has been shown that the free surface oscillations of low viscosity fluids in partly-filled tank trucks persist over long durations, and can lead to significantly lower roll stability limits and braking performance [4-6]. The magnitudes of dynamic load shift, slosh forces and moments are strongly dependent upon the fill volume and the tank geometry. Baffles are commonly used as effective means of suppressing the magnitudes of fluid slosh, apart from enhancing the integrity of the tank structure, although only a few studies have assessed roles of baffles design factors in view of the braking and roll dynamics performance.

The slosh motion of the liquid free surface has been extensively studied since early 1960's using various approaches. The quasi-static hydrodynamic modeling is a simple and convenient method for deriving the steady-state liquid surface position, which has been mostly used for the directional stability analysis of tank trucks. The steady-state roll stability limits of various tank truck combinations have been investigated using the quasi-static liquid load shift in the roll plane [3,7]. Wang *et al*. [1] used the quasi-static approach to analyze the influence of number and size of compartments on the longitudinal load transfer and straight-line braking performance of a partially filled tank truck, and concluded that equally spaced compartments yield minimum longitudinal load shift under straight-line braking manoeuvres, irrespective of the fill level. A quasi-static slosh model, however, is limited to fluid slosh in the steady state, and cannot be applied to study effects of baffles, particularly the forces and moments arising from the transient slosh. Moreover, the fundamental slosh frequencies in a full size cleanbore tank occur in the 0.16-0.26 Hz range in the longitudinal mode, and in 0.56-0.74 Hz in the lateral mode, depending upon the fill volume and tank size [6,8-10]. These frequencies may lie in the vicinity of the steering frequency and the rotational modes of the sprung mass, and could lead to resonant oscillations. It has been further shown that the magnitudes of destabilizing forces and moments during the transient slosh are significantly higher than those attributed to steady-state or quasi-static slosh [4,6,11].

Alternatively, mechanical analogous of fluid slosh and analytical methods have been employed to analyze the transient as well as steady-state dynamic fluid slosh responses [5,12-15]. The mechanical-equivalent models, however, may pose considerable challenges in parameter identification and are generally limited to low amplitude slosh. Furthermore, such models have been limited to cleanbore tanks only. The transient fluid slosh analyses have been increasingly conducted using the computational fluid dynamics (CFD) methods based on the Navier-Stokes solvers coupled with the Volume-of-Fluid (VOF) technique. These numerical approaches are known to be effective for simulating large-amplitude fluid slosh, under time-varying manoeuvre-induced accelerations [5,11,16,17]. Only limited applications of the CFD methods, however, could be found for three-dimensional slosh analyses of baffled highway

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tanks. Modaressi-Tehrani *et al*. [6] and Yan *et al*. [4] studied the forces due to transient 3-D fluid slosh in a full size cylindrical and an optimal baffled tank, proposed in [3], using the CFD methods, and showed that the peak longitudinal slosh force is strongly dependent upon the baffle design.

The longitudinal and lateral load transfer caused by fluid slosh in a partly-filled tank can be substantially limited by anti-slosh or slosh damping devices. The tank trucks generally employ transverse baffles with a large central orifice and a nearly semi-circular equalizer opening at the bottom. The effects of such baffles on the longitudinal and lateral fluid slosh have been investigated in only a few experimental and analytical studies [4,6,18-21]. These have shown that presence of transverse baffles could limit slosh only in the longitudinal direction. The longitudinal baffles, on the other hand, could substantially limit the lateral load transfer, but are considered impractical due to additional excessive weight and interfere with the cleaning tasks.

The effect of size and location of baffle orifice on the slosh has been reported in only two studies involving rectangular [11] and a generic [4] cross-section tank. Popov *et al*. [11] studied the effect of size and location of the orifice of a transverse baffle using a 2-dimensional scaled rectangular tank model, and concluded that an orifice opening equal to 5% of the baffle area would yield a 29% increase in the peak overturning moment for a fill depth ratio of 70%, when compared to that caused by tank with a separating wall. Comparable magnitudes of slosh forces and moments, however, have been reported for orifice opening ranging from 8 to 20% of the cross-section area [4]. The study also investigated the effects of an equalizer and alternate baffle designs on the magnitude of transient slosh force and moments, and concluded that an equalizer has negligible effect on liquid slosh, while a multi orifice baffle behaves similar to a conventional single orifice baffle.

Alternatively, anti-slosh properties of baffles designs have been investigated through laboratory experiments employing small size tanks of different geometry [18,20-22]. These have generally studied damping properties from free oscillations or slosh under harmonic or single-cycle sinusoidal inputs. Such excitations do not provide sufficient data relevant to the effectiveness of baffles under a braking input. In a recent study, Yan *et al.* [20] conducted experiments using scaled baffled and unbaffled tanks of cross-section, similar to the optimal tank geometry proposed in [3] to identify slosh frequencies, and resultant forces and moments. The experimental results showed that addition of transverse baffles caused a significant increase in longitudinal mode natural frequency, while the lateral mode frequency was not affected. The peak magnitudes of longitudinal slosh force and pitch moment also decreased significantly in the presence of transverse baffles. Lloyd *et al.* [18] experimentally investigated various baffles, including solid dished, oblique, spiral, round, and perforated designs, and concluded that the lightweight perforated baffle could serve as the best anti slosh device. The effectiveness of baffles in suppressing fluid slosh, however, is dependent upon its geometry and layout. Furthermore, the slosh control analyses of baffles designs necessitate considerations of the transient fluid slosh behaviour.

In the present paper, concepts in different designs of lateral baffles are proposed and a dynamic CFD slosh model of a circular cross-section tank with different baffle designs is formulated. The model validity is evaluated using the results attained from a quasi-static model. The relative antislosh effectiveness of the baffles is evaluated in terms of transient slosh forces and moments, and fundamental slosh frequencies for different cargo loads under manoeuvre-induced lateral and longitudinal acceleration fields.

2. FLUID SLOSH MODELING

The fluid flow within a partly-filled tank subject to lateral and/or longitudinal acceleration field can be considered as a two-phase flow comprising the gas and liquid phases. The motion of the incompressible liquid can be represented by the momentum and mass conservation equations. Assuming that the fluid slosh under typical directional manoeuvres occurs at relatively low velocities, the three-dimensional flow is considered to be laminar [23]. For the constant viscosity liquid flow, the governing equations of fluid flow with respect to an inertial Cartesian coordinate system can be expressed as [4]:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-g_x-\frac{1}{\rho}\frac{\partial P}{\partial x}+\upsilon(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2})$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-g_y-\frac{1}{\rho}\frac{\partial P}{\partial y}+\upsilon(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2})$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-g_z-\frac{1}{\rho}\frac{\partial P}{\partial z}+\upsilon(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}) \quad (1)$$

and

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (2)$$

where u, v and w are the liquid velocity components along x, y and z directions, respectively, P is fluid pressure, υ is the kinematic viscosity of the fluid, and g_x, g_y and g_z are the unit body forces acting along the x, y and z directions, respectively, representing longitudinal and lateral acceleration excitations, and the fluid mass. A homogeneous field of body force has been assumed in the formulations of momentum and mass conservation equations, which are solved in conjunction with appropriate boundary conditions to compute the velocity components and pressure distribution in the flow domain as a function of time and space. It would be reasonable to assume that the tank is bounded by a rigid wall, which yields that the velocity component normal to the wall is zero at the boundary, implying no-slip boundary condition.

The deformation of the free surface at each instant of time could be derived assuming irrotational flow with no horizontal displacement of particles at the free surface, which leads to a kinematic restriction in the following form:

$$v=\left(\frac{\partial}{\partial t}+u\frac{\partial}{\partial x}\right)\eta\,; \quad (3)$$

where η is the displacement of the free surface from its mean position.

The above equation exhibits limitations in analyses, when a folded free surface occurs. The concept of tracking the volume of liquid instead of free surface has thus been widely used. The methodology known as VOF (Volume of Fluid) permits the analysis of deformation of free surface flow through numerical solution techniques [16, 24]. The VOF model is a surface-tracking technique applied to a fixed mesh. It is designed for two or more immiscible fluids where position of the interface between the fluids such as the gas and liquid, in the case of a partly filled tank, is of interest. In the VOF model, a single set of momentum equations is shared by the fluids, and the volume fraction of each of the fluids in each computational cell is tracked throughout the domain.

2.1. Method of Solution

The equations of three dimensional fluid flows, satisfying the boundary conditions are solved using the FLUENT software [25]. The VOF method, available within the FLUENT environment, is applied to solve for transient flows involving free surface separation and air within the non filled cross section of the tank. The momentum and mass conservation equations are discretized using finite volume technique considering each cell as a control volume. For the transient analyses, the governing equations must be discretized in both space and time. The spatial discretization for the time dependent equations is identical to the steady state case, while the temporal discretizations involve integration over a time step. The FLUENT software applies segregated solver to obtain sequential solutions of the governing equations using the PISO (Pressure-Implicit with Splitting of Operators) pressure correction and pressure-velocity coupling technique [26]. The tracking of volume of fluid (VOF) method is used to locate the interface between the two fluid phases: liquid and air.

The dynamic load shift due to sloshing cargo is generally expressed by variations in the instantaneous cg coordinates with respect to the static cg coordinates. The instantaneous coordinates of center of gravity of the liquid (cg) can be obtained from the volume integrals over the liquid phase of the domain. Alternatively, for the discrete mesh, the coordinates are evaluated from:

$$Y_{cg} = \frac{\sum_{c}^{liquid} y_c A_c}{\sum_{c}^{liquid} A_c}\ ;\ Z_{cg} = \frac{\sum_{c}^{liquid} z_c A_c}{\sum_{c}^{liquid} A_c} \text{ and } X_{cg} = \frac{\sum_{c}^{liquid} x_c A_c}{\sum_{c}^{liquid} A_c} \tag{4}$$

where x_c, y_c and z_c are instantaneous coordinates of a cell 'c' with respect to mid-point of the tank, 'M', as shown in Fig. (**1**). In the above equations, the limit '*liquid*' defines the domain of integration, and A_c is the cell area in the concerned plane.

The resultant forces acting on the container structure are computed from the distributed pressure acting on the wall. The integration over the wetted area of the wall cells yields:

$$F_x = \sum_{c}^{wetted\,area} \left(P_c \vec{A}_{cx}\right);\ F_y = \sum_{c}^{wetted\,area} \left(P_c \vec{A}_{cy}\right) \text{ and } F_z = \sum_{c}^{wetted\,area} \left(P_c \vec{A}_{cz}\right) \tag{5}$$

where F_x, F_y and F_z are the resultant forces acting on the tank wall, P_c is fluid pressure at the centroid of the cell '*c*' in the wall zone, '*wetted area*' defines the wetted area of the wall, and $\vec{A}_{cx}, \vec{A}_{cy}$ and $\vec{A}_{cz}$ are the effective areas of the boundary cell c along *x*, *y* and *z* directions, respectively.

The pitch, roll and yaw moments due to liquid slosh are computed about the tank base 'O' from the distributed pressure or force acting on the wetted structure boundary and position vector of the individual cells, as shown in the roll plane in Fig. (**2**), such that:

$$\vec{M} = \sum_{c}^{A_w} \vec{r}_c \times \left(P_c \vec{A}_c\right) \tag{6}$$

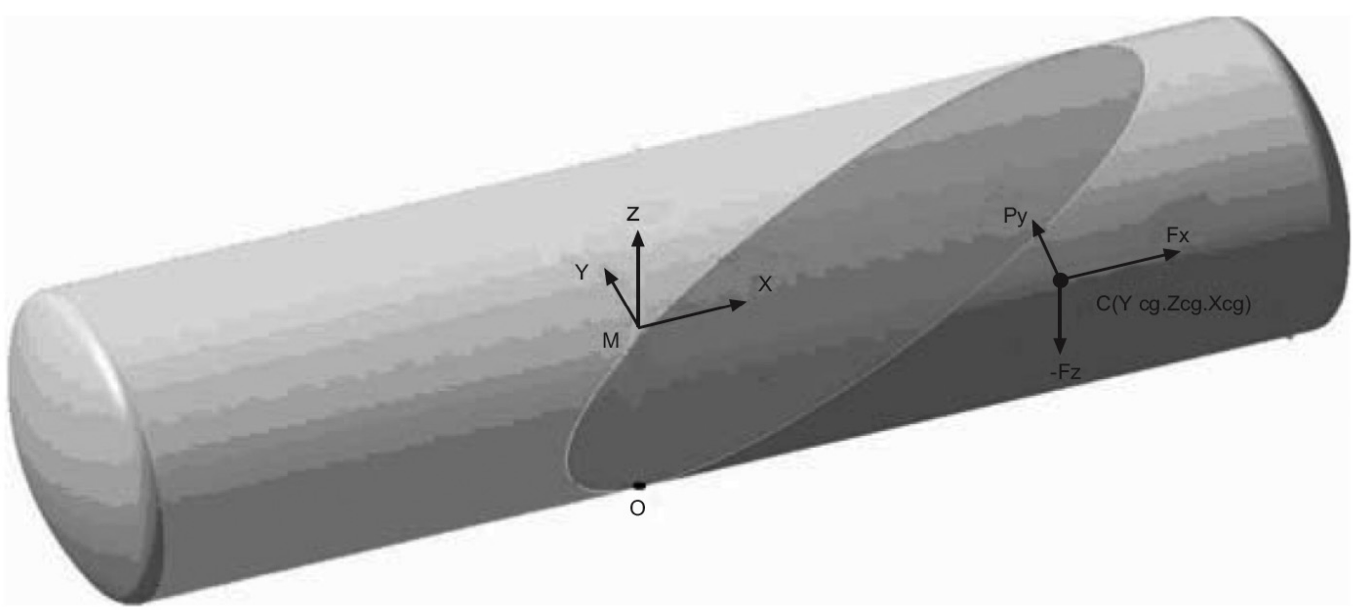

Fig. (1). Steady-state free surface of liquid in a partly-filled clean bore tank subject to longitudinal and lateral acceleration.

where $\vec{M}$ is moment vector and r_c is position vector of cell '*c*' with respect to the tank base 'O'.

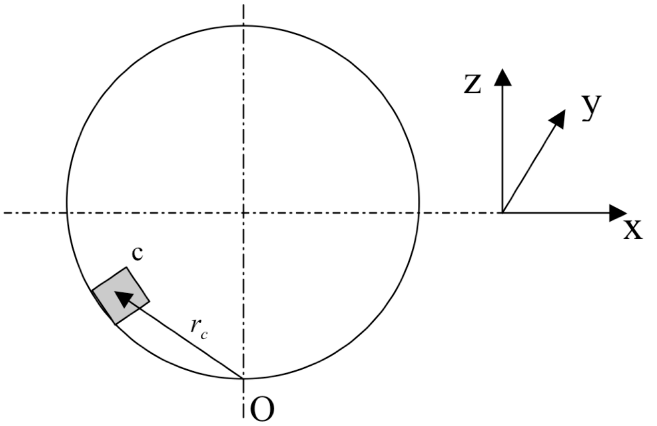

Fig. (2). Computation of moments due to transient slosh forces from the distributed pressure on the wetted boundary.

2.2. Analysis of Baffle Designs

A 7.55 *m* long circular cross-section tank of 1.015m radius and 25.525 m^3 volume is considered for the analyses of fluid slosh and baffles designs. The full load capacity of the tank is approximately 22,000 kg, assuming a full load of gasoline ($\rho = 850 kg/m^3$, $\nu = 0.0687 kg/ms$). The geometry is considered adequate for a three or four-axle straight tank in accordance with the current weights and dimensional regulations. The origin of the coordinate system used is located at the geometric centre of the tank. The moments due to fluid slosh, however, are calculated with respect to projection of the geometric centre at the bottom of the tank, point 'O', as shown in Fig. (**3**). The geometry of the baffles bulkheads is chosen in accordance with DOT CFR code [27] and ASME boiler and pressure vessel code [28]. Three nearly equally-spaced baffles are considered, and each baffle is provided with an equalizer at the bottom with total opening area being 1% of the tank cross section area, as shown in Fig. (**3**).

The tank models were developed using four different baffles designs and layouts, as shown in Fig. (**4**). These included the tank models employing:

1. conventional baffles with a large central orifice of opening area of 12% of the total tank cross-section area, denoted as configuration 'B1' and shown in Fig. (**4b**);
2. obliquely placed conventional baffles, shown in Fig. (**4c**) and denoted as 'B2';
3. partial baffles arranged in an alternating pattern without an equalizer, as shown in Fig. (**4d**), denoted as 'B3'; and
4. semi-circular orifice baffles of identical opening area, as shown in Fig. (**4e**), denoted as configuration 'B4'.

The analyses are also performed for a clean-bore tank, which is denoted as configuration 'B0' and shown in Fig. (**4a**). The baffles employed in configuration 'B3' would help reduce the tank weight, while those in 'B2' would yield larger tank weight. The curvature of baffles used in configurations 'B3' and 'B4' is identical to that of the conventional baffles for tank configuration 'B1' and the tank heads. The longitudinal spacing between the baffles is in the order of 1.72 m, which is less than the maximum baffle spacing specified in the CFR code [27].

The simulations were performed to investigate the effect of different baffle configurations, fill volume, and magnitude and direction of acceleration excitations on the magnitudes of slosh forces and moments. The dynamic fluid slosh analyses were performed for three different fill levels to explore the effectiveness of baffles. These included the low (40%), intermediate (60%) and high (80%) fill levels, where the percent fill level is defined as the ratio of fill height from the bottom of the tank to the tank diameter. The three fill levels correspond to fluid volumes of 10.21, 15.31 and 20.42 m^3, respectively, and cargo loads of 8678.5, 13017.7 and 17357 *kg* ($\rho = 850 kg/m^3$, $\nu = 0.0687 kg/ms$).

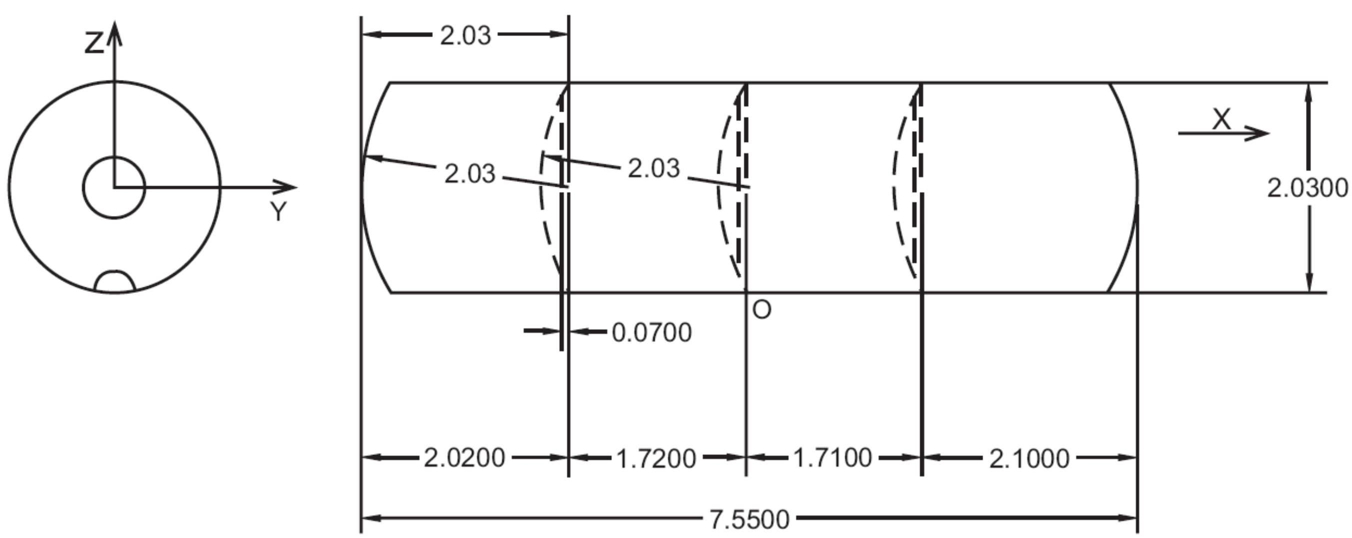

Fig. (3). The geometry of the tank equipped with three conventional lateral baffles.

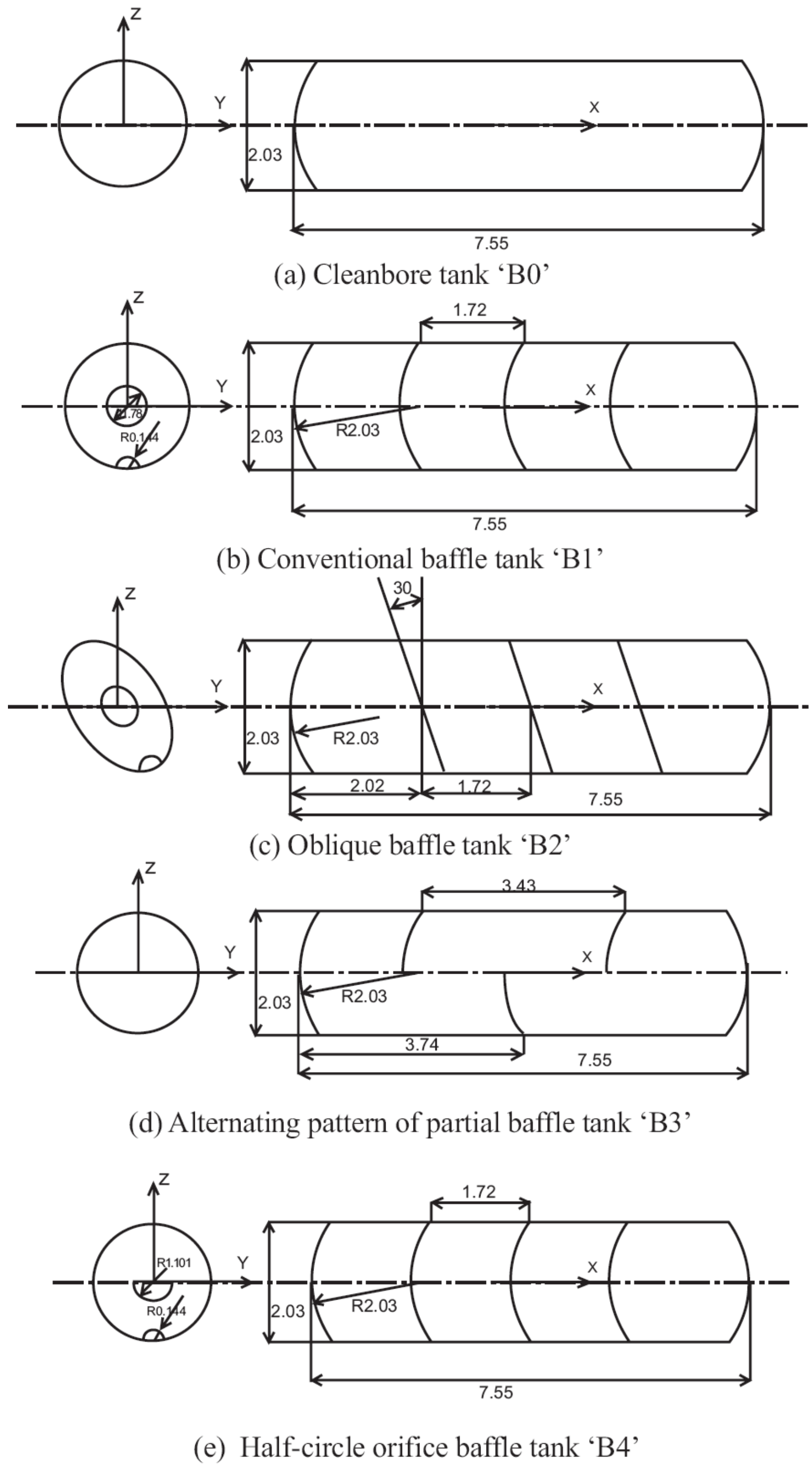

Fig. (4). Schematics of the tank and baffle configurations considered for the analyses.

The simulations were performed under simultaneous lateral and longitudinal acceleration idealizing a braking-in-a-turn maneuver. Rounded ramp-step variations in acceleration excitations were considered along the longitudinal and lateral axes. The excitation was synthesized to realize linearly varying acceleration for t<0.5 s and a constant magnitude at t≥0.5 s, as shown in Fig. (**5**). The discontinuity associated with the ramp-step function was eliminated by introducing an arc function around t=0.5 s, tangent to both the linear and constant acceleration segments. The constant *G* in Fig. (**5**) refers to the constant acceleration magnitude, and T_a denotes the upper limit of linearly increasing segment with slope *a*.

3. RESULTS AND DISCUSSIONS

3.1. Model Validation

The dynamic fluid slosh model for each tank configuration was analyzed using the selected mesh size and step size, and the steady-state slosh force and moment responses were computed from the pressure distributions using Eqs. (6) and (7). The responses were evaluated under rounded ramp-step acceleration excitations applied along the longitudinal ($g_x = 0.30g$) and lateral ($g_y = 0.25g$) axis. The model validity was examined by comparing the slosh forces and moments responses with those derived from the quasi-static formulations [3]. Since the quasi-static formulations are valid only for clean-bore tanks, the three-dimensional quasi-static and dynamic slosh models of the partly-filled clean-bore tank (configuration B0) were initially solved under ramp-step longitudinal (g_x =0.3) and lateral (g_y =0.25) acceleration excitations for three fill conditions (40, 60 and 80%). The simulations were performed over an extended period of 20 *s* so as to achieve steady-state values, which were found to be identical to those derived from the quasi-static (QS) model, reported in [3]. The steady-state values were also identical to the mean values of the transient responses.

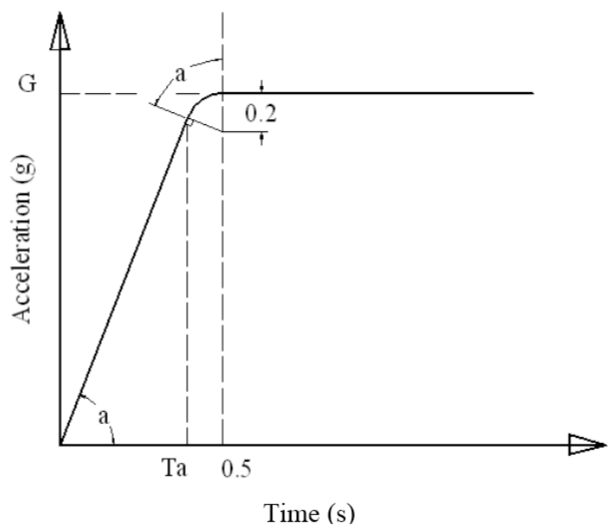

Fig. (5). Rounded ramp-step acceleration excitation.

Fig. (**6**) illustrates comparisons of the steady-state longitudinal (F_x) and lateral (F_y) slosh force responses under selected manoeuvres with those derived from the QS analysis, while the corresponding roll and pitch moment responses are compared in Fig. (**7**) for the three fill volumes considered. The comparisons suggest reasonably good agreements between the steady-state or mean dynamic and the quasi-static responses for all the fill levels considered. Some deviations between the two, however, are also observed, particularly, under intermediate and higher fill levels. The steady-state responses tend to be slightly higher than the corresponding QS responses, while the peak difference was found to be below 4%. This deviation is attributed to slightly different fluid volume and fluid mass estimated from the mesh defined in the Fluent software. The results suggest that a higher fill volume yields higher steady-state and QS forces due to higher inertia.

The model validity was also examined by comparing the fundamental slosh frequencies of the clean-bore tank with those reported in the published studies. For this purpose, the transient lateral and longitudinal force responses of the partly-filled tanks obtained over the 20 s period were re-sampled at a rate of 40 Hz. The dominant frequencies of slosh forces were subsequently identified through Fast Fourier Transform (FFT) of the time-histories of the force responses with frequency resolution of 0.05 Hz. The analyses revealed fundamental slosh frequencies in the pitch plane of 0.15, 0.20 and 0.26 Hz under fill conditions of 40, 60 and 80%, respectively. These frequencies compare very well with those reported by Abramson [8] for a cylindrical tank with flat end caps (0.16, 0.21 and 0.26 Hz). The fundamental slosh frequencies in the roll plane were obtained as 0.56, 0.61 and 0.74 Hz for the 40, 60 and 80% fill levels, respectively, which were also quite comparable with those reported in [8,10].

3.2. Influences of Baffles Design and Layout

The transient fluid slosh responses of the selected baffles configurations (B1, B2, B3 and B4) were evaluated under

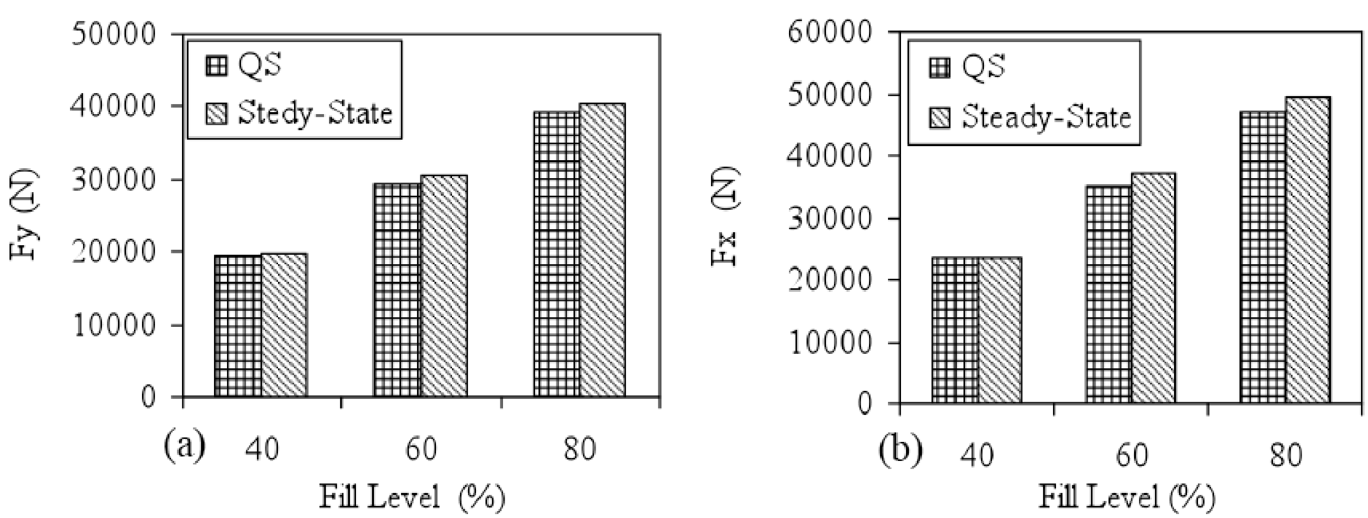

Fig. (6). Comparisons of steady-state lateral and longitudinal force responses of the dynamic fluid slosh and quasi-static (QS) models of the partly-filled clean-bore tank under g_x =0.3g and g_y =0.25g: (**a**) lateral force (F_y); and (**b**) longitudinal Force (F_x).

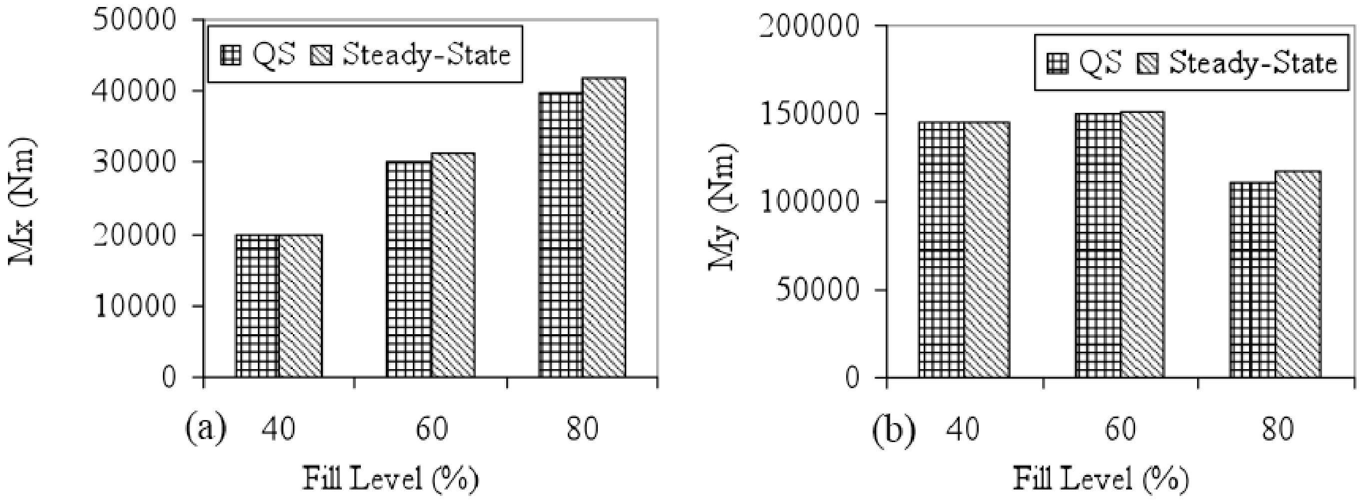

Fig. (7). Comparisons of steady-state roll and pitch moment responses of the dynamic fluid slosh and quasi-static (QS) models of the partly-filled clean-bore tank under g_x =0.3g and g_y =0.25g: (**a**) roll moment (M_x); and (**b**) pitch moment (M_y).

rounded ramp-step acceleration excitations applied along the longitudinal ($g_x = 0.30g$) and lateral ($g_y = 0.25g$) axis to study the effects of baffles. Figs. (**8**, **9**) illustrate the time histories of longitudinal and lateral slosh force responses, respectively, attained for the 40 and 60% filled tanks. The figures also show the responses of the clean-bore tank for both fill levels. The results clearly show the significant benefits of transverse baffles in limiting the fluid slosh in the longitudinal direction. For the lower fill, the peak lateral and longitudinal force responses of a partly-filled tank with conventional baffles (B1) are only slightly higher than those of an oblique or partial baffle tanks (B2 and B3). The oscillations in the lateral force response of the oblique baffled tank (B2) tend to diminish rapidly compared to those of the other baffled tank configurations with lower fill. The lateral force responses of B1, B3 and B4 configurations exhibit continued oscillations of considerable magnitudes. It has been generally suggested that transverse baffles do not offer resistance to fluid slosh in the roll plane [6, 21].

The results in Fig. (**9**) suggest that presence of baffles could help reduce the peak magnitude of lateral slosh force developed under applications of simultaneous lateral and longitudinal acceleration excitations, and that an oblique placement of transverse baffles would yield greater reduction in the peak lateral force. This is attributed to the oblique baffles providing considerable resistance to slosh in both roll and pitch planes. The flow visualization further illustrated delayed accumulation of liquid at the front end of the oblique baffled tank, which caused the oscillations in longitudinal force to diminish that are observed for the lateral baffled tanks. The lateral force caused by slosh in the cleanbore tank under lower fill tends to diminish rapidly, which is attributable to flow separation. The results also show that the fluid motion in the B4 tank yields lower magnitudes of steady-state lateral and longitudinal slosh forces, particularly under the higher fill level. This suggests ineffectiveness of the transverse baffles in suppressing the lateral force, which is attributed to the dominant load shift occurring in the roll plane, where transverse baffles provide negligible resistance, while oblique baffles provide relatively greater resistance.

Figs. (**10**, **11**) illustrate the time histories of roll and pitch moment responses, respectively, attained for the 40% and 60% filled selected tank configuration subject to $g_x = 0.30g$ and $g_y = 0.25g$. The results suggest that the roll moment oscillations for the clean-bore tank (B0) and oblique baffled tank(B2) tend to diminish rapidly, while the transverse baffled tanks (B1, B3 and B4) responses exhibit continued oscillations of considerable magnitudes, as observed for the lateral slosh force in Fig. (**9**). While the peak roll moment response of the oblique baffled tank is only slightly higher than that of other baffled tank. Continuous oscillations are mostly attributed to the constraints imposed by the transverse baffle walls on the fluid motion. The absence of this constraint, as in the case of the clean-bore tank tends to suppress oscillations in the slosh moment. The lower magnitudes of oscillations of the roll moment due to oblique baffles is also attributable to relatively lower degree of constraint caused by these baffles. The semi-circular orifice and conventional baffles yield comparable magnitudes of roll and pitch moment for the low fill level (40%). The semi-circular orifice baffle (B4), however, yields lower magnitudes of roll moment compared to the conventional B1 baffles under the intermediate (60%) fill level, as observed for the lateral force response in Fig. (**9**). This is attributed to relatively lower load shift in the longitudinal direction through the semi-circular orifice baffles. The lower roll moment response would help achieve enhanced roll stability of a partially-filled tank truck. The peak roll moment response of the alternating arrangement of partial baffles (B3) is comparable to that of the conventional baffles under lower fill but higher under the higher fill volume.

The pitch moment caused by fluid slosh is most significantly influenced by the baffles design, as seen in Fig. (**11**). Considering that the dynamic load transfer and thus the braking performance of a vehicle is directly influenced by

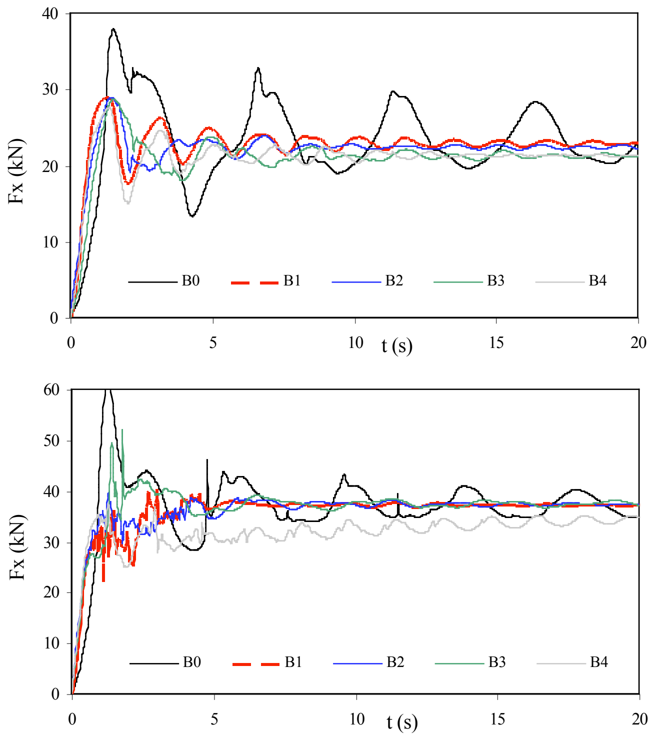

Fig. (8). Time-histories of longitudinal slosh force responses of selected baffled tanks subject to $g_y = 0.25g$ and $g_x = 0.30g$: (**a**) 40% fill level; and (**b**) 60% fill level

the pitch moment caused by the sprung mass, the pitch moment response of the partly-filled tank truck could be directly related to its braking performance [1,3]. The results show most significant variations in the magnitude of the pitch moment response of the clean-bore tank (B0), irrespective of the fill level considered.

The presence of baffles not only diminishes the peak pitch moment but also yields lower steady values due to portions of fluid being trapped in lower section of the tank between two consecutive baffles or between the baffle and the end cap. The conventional baffle tank exhibits this behaviour under lower fill level, while the steady-state moment magnitude is larger under the intermediate fill compared to the other baffles, as seen in Fig. (**11b**). The steady state pitch moment response of the oblique baffled configuration (B2) is comparable to that of the 'B1' configuration under lower fill but significantly lower under the 60% fill level. This may be attributed to relatively greater amount of fluid trapped between the oblique baffles under a higher fill level. The alternating arrangement of partial baffles also yields lower steady-state pitch moment under the higher fill compared to the conventional baffles. This suggests that partial baffles could provide slosh control comparable to the conventional baffles, while the structure weight could be reduced. The semi-circular orifice baffles ('B4') attain significantly lower peak as well as steady-state pitch moment compared to all other configurations for the 60% fill level, while the responses are either comparable or lower under the lower fill level. This is attributed to relatively lower load shift in the longitudinal direction through the semi-circular orifices, particularly under the higher fill level. The steady-state pitch moment response of configuration B4 is nearly 40% of the corresponding magnitude of the conventional baffled 'B1' tank under the 60% fill level.

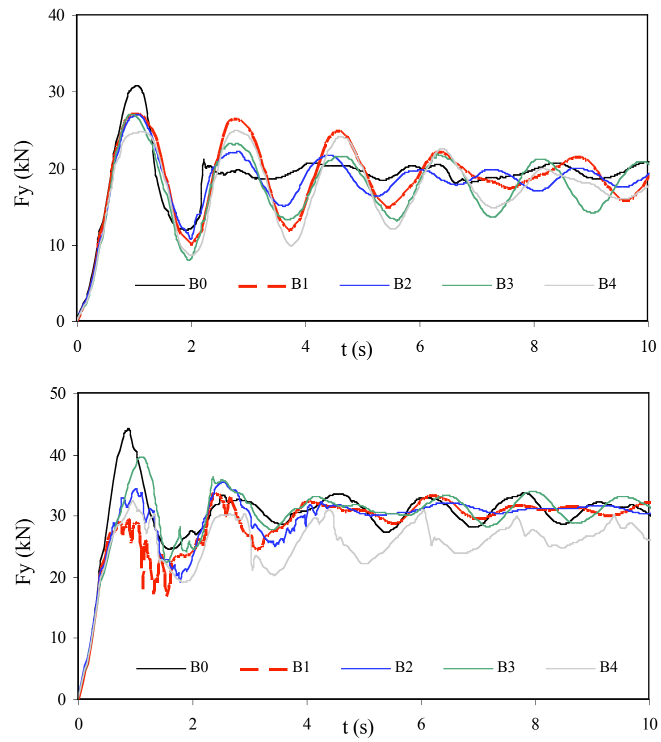

Fig. (9). Time-histories of lateral slosh force responses of selected baffled tanks subject to $g_y = 0.25g$ and $g_x = 0.30g$: (**a**) 40% fill level; and (**b**) 60% fill level.

The liquid load transfer in the longitudinal plane of different partly-filled tank configurations were also examined through flow visualization. As an example, Fig. (**12**) compares the nearly steady-state (t = 20 *s*) load transfers and the fluid free surface in the configurations with conventional (B1) and semi-circular orifice (B4) baffles with 60% fill level. It can be seen that the liquid tends to accumulate towards the front end of the tank while the accumulation is significantly more in B2 tank than B4, while the free surface gradient is uniform in all the baffled segments. The flow pattern in B4 tank shows more uniform load distribution compared to the B2 tank, particularly in the three leading segments, which contributes to lower pitch as well as roll moment in the steady-state, as seen in Figs. (**10**, **11**), respectively. The results suggest that proposed semi-circular orifice baffles provide better slosh control in the longitudinal plane, which is attributable to the geometry which serves as a solid compartment for the fluid within in the upper-half of the tank. Considering that the tanks would generally transport loads with fill greater than 50%, the baffles with semi-circular orifice in the lower-half section could provide more effective control of load shift and thus improved braking performance.

4. CONCLUSIONS

The effectiveness of different baffles designs in controlling the magnitudes of fluid slosh and thus load

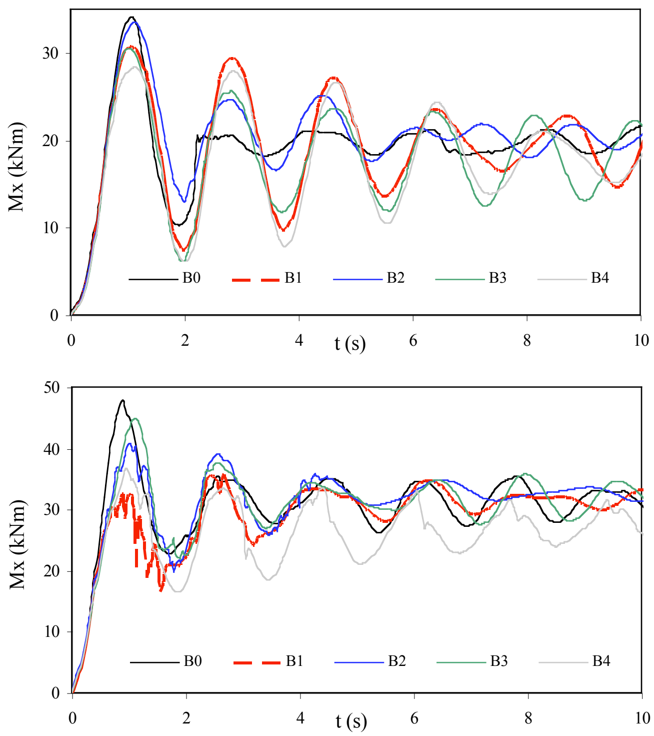

Fig. (10). Time-histories of roll moment responses of selected baffled tanks subject to $g_y = 0.25g$ and $g_x = 0.30g$: (**a**) 40% fill level; and (**b**) 60% fill level.

transfers in the roll as well as pitch planes of a partly-filled circular cross-section tank is investigated. The transient as well steady-state forces and moments caused by fluid slosh under simultaneously applied longitudinal and lateral accelerations were evaluated through development and solutions of a CFD model of the partly-filled tank. The steady-state magnitudes of forces and moment responses of the cleanbore tank agreed very well with those evaluated from the widely used quasi-static fluid slosh model. The validity of the model is further demonstrated through good agreements of the fundamental slosh frequencies with those reported in a few published studies. The slosh forces and moments responses of the partly-filled tank clearly show most significant effects of baffles on the longitudinal load transfers, while the effects on the lateral load transfer is very small. The pitch plane load transfer, however, is strongly dependent on the baffle design. The conventional baffles provide effective control of fluid slosh in the longitudinal direction but offer negligible resistance in the roll plane. An oblique arrangement of baffles offers considerable resistance to lateral fluid slosh in the roll plane as well as longitudinal fluid slosh in the pitch plane. The partial baffles are generally ineffective in the roll plane but anti-slosh performance in the longitudinal direction is comparable to the conventional baffle. Considering that the partial baffles yield lower structure weight and thus the cost, these may be considered meritorious over the conventional baffles. The semi-circular orifice baffles offer most significant reductions in the longitudinal load transfer, and the peak and steady-state magnitudes of the pitch moment, particularly when the static free surface occurs above the baffles opening. Such baffles could thus yield improved braking performance and yaw stability limits of partly-filled tank trucks. The semi-circular orifice baffles also yield lower magnitude of steady-state roll moment under the intermediate fill level considered in this study, which is attributable to greater containment of fluid between the successive baffle or between the baffles and tank heads.

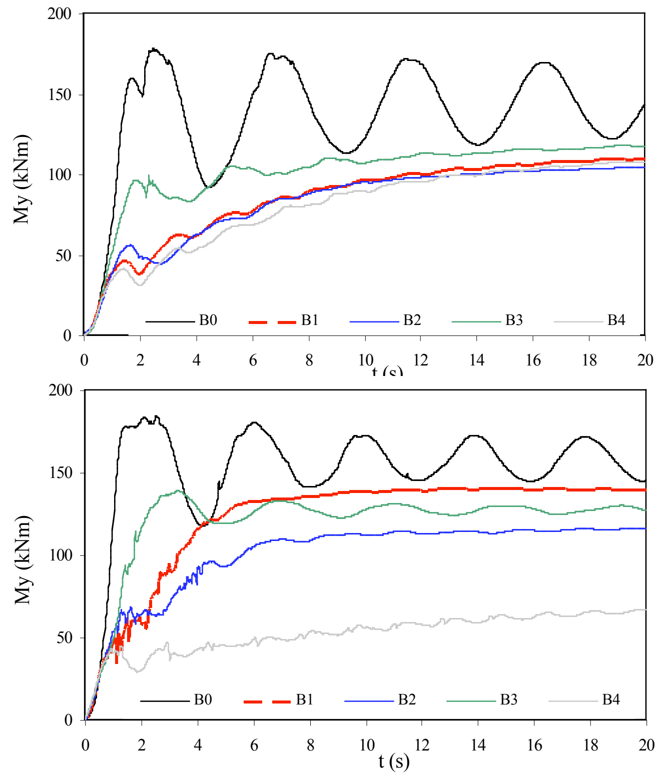

Fig. (11). Time-histories of pitch moment responses of selected baffled tanks subject to $g_y = 0.25g$ and $g_x = 0.30g$: (**a**) 40% fill level; and (**b**) 60% fill level

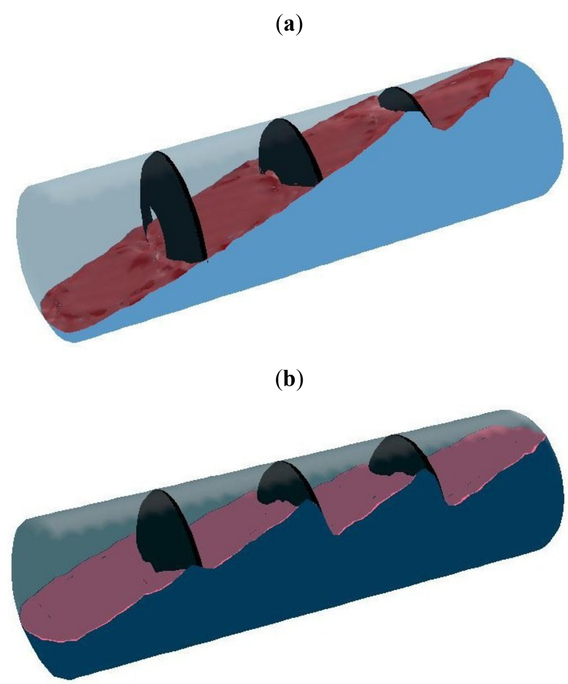

Fig. (12). Comparison of free surface position of liquid cargo in tanks with 0.25 g and 0.3g excitation at 20 sec: (**a**) 60% fill level for 'B1'; (**b**) 60% fill level for 'B4'

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