

Baffle Design Analysis for a Road Tanker: Transient Fluid Slosh Approach

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ABSTRACT

Baffles are known to help reduce the amplitude of fluid slosh in partly filled tanks, particularly during braking and acceleration. The transient fluid slosh approach is proposed to evaluate the effectiveness of baffle designs. A computational fluid dynamic (CFD) fluid slosh model is developed using the VOF (volume of fluid) technique coupled with a Navier-Stokes solver. The validity of the model is demonstrated using the experimental data acquired with a scale model tank. The validated CFD model is subsequently formulated for a full scale tank and simulations are performed under excitations idealizing the straight-line braking maneuvers to investigate the anti-slosh role of four different transverse baffles concepts. The fluid slosh responses are analyzed in terms of the fundamental slosh frequency, and the resulting forces and moments under different fill volumes of liquid cargos of constant load. The simulation results show that the natural frequency and peak magnitudes of slosh forces and moments strongly depend on the baffle design and the fill volume. The transverse baffles yield significantly higher longitudinal mode slosh frequency, and lower longitudinal force and pitch moment. The shape and locations of baffles orifices play significant role in suppressing the transient fluid slosh. Highly effective anti-slosh effect is also observed for the partial baffle designs under higher fill levels.

INTRODUCTION

The liquid cargo contained in a partly filled road tank vehicle is prone to dynamic slosh motion when the vehicle is subject to external maneuver- or road-induced excitations. A number of studies have shown that dynamic load shifts caused by steady-state fluid slosh, affect the braking and directional properties of vehicles in a highly adverse manner [1-3]. 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 [4,5]. Considering that the free surface oscillations during transient fluid slosh persist over long durations, the resulting dynamic load shifts and forces attributed can lead to significantly lower roll stability limits [4] and braking performance [6]. Baffles are

commonly used as effective means of suppressing the magnitudes of fluid slosh, apart from enhancing the integrity of the tank structure. Although a few studies have shown that the anti-slosh effectiveness of the baffles depend upon baffle design and their arrangement [1,7-9], only limited efforts have been made to assess the roles of baffle design factors in view of the braking performance. The baffle geometry and spacing, together with the orifice size and location with respect to the liquid free surface could be the primary control variables for suppressing the fluid slosh.

The slosh motion of the liquid free surface has been extensively studied since early 1960's, and various approaches have been attempted for the slosh analysis. 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 [1,10-12]. Wang et al. [1] used the quasi-static approach (QS) 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. The study concluded that equally spaced compartments yield minimum longitudinal load shift under straight-line braking maneuvers, 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 the 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 [5]. 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. The design of tanks and baffles thus necessitates considerations of the transient fluid slosh behaviour, particularly for vehicles carrying partial loads, such as those employed in general purpose transportation of bulk liquid products.

Mechanical analogy [13-16] and analytical methods [17-19] have been employed to analyze the dynamic fluid slosh responses. These methods, however, pose considerable difficulties in parameter identification and are generally limited to low amplitude oscillations for the baffled tanks. Alternatively, the anti-slosh

properties of baffles designs have been investigated through laboratory experiments employing small size tanks of different geometry [4,7-9,20]. 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 the braking inputs. Strandberg [7] investigated the roll stability of an elliptic scaled model tank equipped with longitudinal solid compartment walls and concluded that addition of three longitudinal separating walls could yield significant increase in the overturning limit (from 2.4 to 6.3 m/s²). Such walls, however, would add excessive weight and hinder the cleaning task. Lloyd et al. [8] studied the slosh damping effects of different rigid baffles designs for a circular tank, including solid dished, oblique, spiral, round, and perforated designs. The study concluded that the lightweight perforated baffle yield greater damping effect. Younes et al. [9] evaluated the effects of dimension, shape, numbers and arrangement of baffles in a rectangular tank and reported that the size and location of the vertical baffles may significantly influence the hydrodynamic damping. Yan et al. [4] measured the slosh forces and moments characteristics in a scaled model 'Reuleaux triangle' cross-section tank with either single- or multiple-orifice baffles under different longitudinal and lateral acceleration excitations. The measured data revealed that the transverse baffles yield significantly higher longitudinal slosh frequency, and lower longitudinal force and pitch moment, irrespective of the fill volume.

The transient fluid slosh analysis has 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 [5,21-25], under time-varying maneuvers-induced accelerations [5,21]. Only limited applications of the CFD methods, however, could be found for three-dimensional slosh analyses of baffled highway tanks [5,21]. Popov et al. [21] studied the effect of size and location of the orifice on a longitudinal baffle on the slosh control using a 2-D 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. An increase in the orifice opening, up to 20% of the area, showed negligible influence on the peak moment. Modaressi et al. [5] studied the forces due to transient 3-D fluid slosh in a full size cylindrical baffled tank using the CFD code, the model validity was not addressed.

In the present paper, a dynamic CFD slosh model of a 'Reuleaux triangle' cross-section tank (proposed Kang et al. [26]) is formulated and its validity is evaluated using the laboratory-measured data. Subsequently, the fluid slosh model is formulated for a full size tank with different baffles designs. The slosh frequency and transient slosh forces and moments are evaluated under

different fill volumes and longitudinal acceleration excitations to assess the effectiveness of selected baffle designs.

FLUID SLOSH MODELING AND VALIDATION

SLOSH MODELING

The fluids contained in a partially-filled tank, can be regarded as a two-phase (gas-liquid) flow with identical or different species. The weight densities of the two fluids, however, are largely different. In such flows, the inertial forces are dominant relative to the viscous force and the viscous effect could be negligibly small [27]. A laminar flow is assumed since the fluid slosh under typical directional maneuvers occurs at low velocities. In the model, air is regarded as the primary phase and liquid as the secondary phase. The liquid flow is described by the unsteady incompressible continuity and Navier-Stokes (N.S.) momentum equations:

$$\nabla \cdot \vec{u} = 0 \quad (1)$$

$$\rho \left(\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla) \vec{u} \right) = -\nabla p + \mu \nabla^2 \vec{u} + \vec{f} \quad (2)$$

where " ∇ " is the gradient operator; " $\nabla \cdot$ " is the divergence operator; " ∇^2 " is the Laplace operator; p is the pressure; ρ is fluid density; μ is fluid viscosity; $\vec{u}$ is the velocity vector and $\vec{f}$ is the body force vector representing the forces arising from accelerations due to gravity and external disturbances, such as maneuver-induced time-varying accelerations. The above modeling was realized using the FLUENT 6.2.16 software [28], which uses the finite volume method to discretize the integral form of the governing equations. The governing equations are solved sequentially using the segregated solver with no-slip boundary condition and static state initial condition.

While the solutions yield the flow velocities, the gas-liquid interface is tracked by solving the volume fraction equation [22]:

$$\frac{\partial \lambda}{\partial t} + \nabla \cdot (\vec{u} \lambda) = 0 \quad (3)$$

where λ is the volume fraction function, where a unity value indicates that the cell is completely occupied by the liquid, a zero value refers to the cell completely occupied by the gas. A grid cell, partially occupied by the liquid, assumes a value between 0 and 1, depending on the fraction of both fluids. The gas-liquid interface is thus determined by the cells with λ values lying between 0 and 1.

The resulting slosh force components along the lateral, (F_y), longitudinal (F_x) and vertical (F_z) axes are computed from the integration of the pressure over the liquid wetted tank and baffle boundaries. The resulting moments about the roll (M_x), pitch (M_y) and yaw (M_z) axes are subsequently derived from integration of the force and position vectors of individual cells with respect to a chosen reference origin (see Fig. 1).

MODEL VALIDATION

The validity of the fluid slosh model of the tank with and without baffles was examined using the measured data acquired on a scaled model tank. The numerical model was formulated using the scale model tank geometry (Fig. 1). Considering the model applicability on the full scale tank, the model tank for the purpose of validation was made in a relatively large dimension, while the cross-section geometry maintained similar. The total length and cross-section area of the test tank were 1.85 m and 0.426 m², respectively, with total volume capacity of 788 ℓ. The test tank and the model employed two different designs of flat transverse baffles: (i) a single-orifice baffle (245.5 mm orifice diameter); and (ii) a multiple-orifice baffle comprising 34 small orifices (38.1 mm diameter) and a large 101.6 mm diameter orifice at the geometric center. The porosity of the two baffles was approximately 11% of the cross-section area.

In the laboratory experiments, three 3-axes dynamometers were used to measure the resulting slosh forces and moments. A long-stroke (40 cm) servo hydraulic actuator was used to generate different excitations of varying amplitudes along the lateral (continuous and single-cycle sinusoidal) and longitudinal harmonic and ramp-step) axes, in an independent manner. The experiments were performed with tank filled with 30, 50 and 70% volume of water.

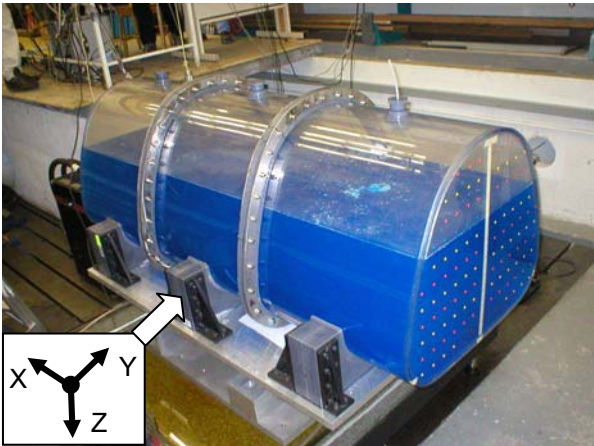


Fig. 1: A pictorial view of the experimental setup designed for the validation of fluid slosh model.

The validity of the models of the tank with and without baffles was evaluated in terms of the slosh natural frequency, and transient slosh forces and moments. As an example, Table 1 compares the fundamental natural

frequencies attained for the baffled tank with single-orifice baffles through the frequency spectra of slosh forces under frequency sweep excitations. It should be noted that the experiments could not be performed with the 30%-filled single-orifice baffled tank due to excessive amount of trapped fluid between the consecutive baffles. The comparisons show good agreements between the simulation results and the experimental data for different fill volumes.

Table 1: Comparisons of lateral and longitudinal mode fundamental slosh frequencies derived from simulation and experiment results.

Fill	Baffle	Lateral		Longitudinal	
		Model	Measured	Model	Measured
50%	Single orifice	0.95	1.00	1.04	1.08
70%		1.04	1.13	1.10	1.14
30%	None	0.81	0.78	0.34	0.36
50%		1.00	0.96	0.45	0.45
70%		1.13	1.08	0.53	0.52

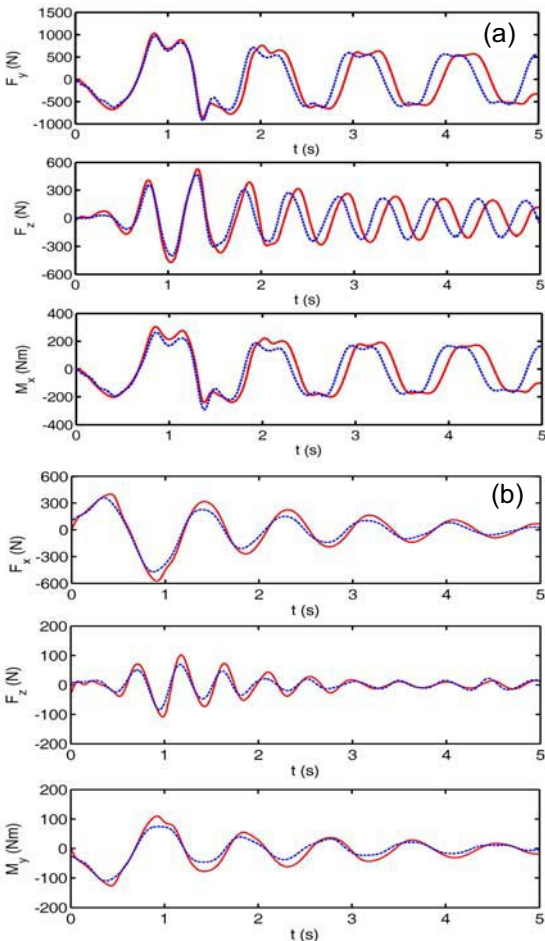


Fig. 2: Comparisons of slosh forces and moments derived from the model with the measured data for the 50%-volume filled tank with single-orifice baffles under: (a) lateral single-cycle input of 1.93 m/s² magnitude at 1 Hz; and (b) longitudinal idealized ramp-step input of 0.89 m/s². —, simulation; - - -, experiment.

Good agreements were also observed between the measured and computed transient slosh forces and