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# A coupled multimodal and boundary-element method for analysis of anti-slosh effectiveness of partial baffles in a partly-filled container

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ABSTRACT

The liquid slosh within a partially-filled moving horizontal cylindrical container with different designs of longitudinal baffles is analyzed for predicting transient lateral slosh force and overturning moment, assuming inviscid, incompressible and irrotational flows. A boundary element method is initially formulated to solve the spectral problem of free liquid slosh using the zoning method involving the velocity potentials alone of the half free-surface length, which significantly increases the computational efficiency. The resulting natural slosh frequencies and modes are subsequently implemented in a linear multimodal method to obtain generalized coordinates of the free-surface under a lateral acceleration excitation. Damping due to baffles, estimated from the energy dissipated per cycle, is also implemented into the multimodal equation. The validity of the model is illustrated through comparisons with available analytical solutions. The results are presented for the tank with bottom-mounted, top-mounted and center-mounted partial baffles of different lengths. The effects of baffle design and length on the natural slosh frequencies/modes, damping ratios and hydrodynamic coefficients are further investigated. The lateral force and overturning moment due to liquid motion within the container are derived in terms of generalized coordinates and the natural slosh modes. It is shown that the multimodal method yields computationally efficient solutions of liquid slosh within moving baffled containers. The results suggest that top-mounted baffles are most effective in suppressing the fluid slosh force under more likely fill height conditions in road tankers (well above 50% of diameter), when the baffle is partly submerged in the liquid domain. The center-mounted baffle was effective under intermediate fill levels in the vicinity of 50%, while the bottom mounted baffle was effective only under very low fill heights.



## 1. Introduction

It is known that liquid oscillations in partially filled tank vehicles subject to excitations during braking and/or steering cause undesirable hydrodynamic forces and moments of significant magnitude. Such forces and moments adversely affect the direction dynamics and stability of the partly-filled vehicle and may impose higher stresses on the container structure. Anti-slosh devices such as transverse baffles are widely used in order to limit the adverse liquid slosh effect on directional performance and stability of the tank vehicles. While the effects of ring and radial baffles on liquid slosh suppression in missiles and storage tanks has been extensively studied (e.g., [1,2]), the role of baffles in limiting fluid slosh in tank trucks has been addressed in relatively fewer studies. Furthermore, the regulations governing design of tanks recommend the use of baffles only for circumferential reinforcement of the tank shell with little or no consideration of fluid slosh effects on lateral or roll stability limits of tank vehicles [3,4]. Capital cost reductions and difficulty associated with cleaning of the tank in a general-purpose road tanker fleet are the main reasons that prohibit the use of baffles.

The effects of fluid movement within the tank on directional performance and roll stability of partly-filled tank trucks and tractor-tank-trailer combinations have been investigated using widely different methods. The vast majority of these have provided vehicle steering and braking responses considering steady-state fluid slosh (e.g., [5,6]). This approach, however, cannot provide the transient slosh forces and moments, whose magnitudes are known to be substantially greater than the corresponding steady state values. Analogous mechanical-equivalent and pendulum models have also been proposed to study the transient fluid slosh effects on vehicle responses (e.g., [7,8]). Both the steady-state and mechanical analogous models cannot be applied to analyses of

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fluid slosh within tanks with baffles, which are known to provide substantial slosh damping.

A few studies have employed linear slosh theory for analysis of anti-slosh effects of baffles. Goudarzi and Sabbagh-Yazdi [9] developed an analytical model based on potential flow and linear slosh to evaluate damping effects of horizontal and vertical baffles in rectangular tanks. Faltinsen et al. [10] and Faltinsen and Timokha [11] presented analytical solutions for free liquid slosh in rectangular tanks with a slat screen mounted vertically in middle of the tank. The effect of solidity ratio of the baffle on lateral sloshing was also investigated using a multimodal approach. Hasheminejad and Mohammadi [12] obtained natural slosh frequencies and pressure modes of free liquid sloshing in a circular tank with surface-touching horizontal baffles, bottom-mounted and surface-piercing vertical baffles using successive conformal transformations of the fluid domain. A similar method has also been used to obtain slosh force and overturning moment in half-filled elliptical containers equipped with vertical or horizontal side baffles under a lateral acceleration excitation [13,14]. The damping effect of the baffles was neglected, while the method involved elaborate successive transformations of the fluid domain using special functions.

Apart from the analytical models, computational fluid dynamics (CFD) techniques have been widely applied for simulation of liquid slosh in baffled tanks. Modaressi-Tehrani et al. [15] developed a three-dimensional model of a partly-filled cylindrical tank with three conventional baffles with a centrally-located single-orifice to obtain transient slosh forces and moments under longitudinal and combined lateral/longitudinal accelerations idealizing braking and turning excitations. Yan et al. [16,17] simulated three-dimensional liquid slosh in a 'Reuleaux triangle' cross-section tank with different transverse baffles designs under similar lateral and/or longitudinal acceleration excitations. The results showed that conventional transverse baffles offer significant suppression of longitudinal slosh force and pitch moment, but offer only little resistance to fluid slosh under lateral excitations arising from the steering maneuvers.

The applications of CFD methods for assessing the fluid slosh effects on braking and steering dynamics of partly-filled tank trucks, however, have been limited to a very few studies. This is likely due to extreme computational demands, and complexities involving elaborate data transfers and coordinate transformations between the vehicle and the dynamic fluid slosh models [18–20]. In an attempt to develop computationally efficient coupled vehicle-fluid slosh dynamic models, a few studies have characterized the dynamic fluid slosh in moving containers under lateral and longitudinal accelerations through mechanical analogous models. While the simplicity of the mechanical equivalent models could permit real-time simulations of directional responses of a partly-filled tank vehicle, the identification of equivalent mechanical model parameters poses certain complexities. The model parameters are generally estimated from experimental data [21] or slosh responses obtained through CFD simulations [22]. Such models, however, have been mostly limited to clean-bore tanks with only one exception [21].

Among the different methods employed for simulation of dynamic fluid slosh, the methods based on linear slosh theory could yield reasonably accurate predictions of slosh forces and moments over the ranges of typical vehicle maneuvers in a highly efficient manner [23]. The multimodal models integrating linear slosh theory seem to be beneficial and practical due to the simplicity associated with their integration to the vehicle dynamic models. The multimodal studies of liquid slosh in tanks used in liquid transporting vehicles, however, have been mostly limited to the clean-bore tanks (e.g., [24]). Multimodal models, in general, require estimation of natural slosh frequencies and modes, which can be obtained using numerical techniques. For baffled tanks, the natural slosh modes may be obtained efficiently using the boundary element method (BEM). In the BEM, the fluid flow in a baffled container is evaluated considering the distribution of singularities along the surfaces enclosing the liquid domain. The resulting boundary integral equations are then solved by discretizing the fluid boundaries, which is far more efficient than the finite element method (FEM), where the entire fluid domain has to be discretized [25].

Although BEM has been used in many studies, the applications of the method for modal analysis of liquid slosh in baffled tanks have been limited to only a few, particularly for the horizontal baffled tanks used in transportation of liquid products. Firouz-Abadi et al. [26] employed BEM together with a zoning method to enhance the computational efficiency to study the effects of baffles on natural frequencies of slosh in rectangular and spherical tanks. Natural frequencies of liquid oscillations in a rectangular tank with a vertical baffle and upright cylindrical tank with a ring baffle were obtained by Sygulski [27] using the BEM considering baffles as double layers immersed in the liquid. The effect of ring baffles on the natural sloshing frequencies were also investigated by Gedikli and Erguven [28] using a variational BEM. Gedikli and Erguven [29] also reported responses of an upright cylindrical tank with a ring baffle subject to a seismic excitation using the BEM and superposition of modes.

The primary motivation of this study arises from the desire for developing an efficient tool for real-time simulations of fluid slosh in baffled tanks and its effect on directional performance of partly-filled tank vehicles. In the present study, a multimodal model, based on the linear slosh theory, is presented to characterize dynamic fluid slosh in a partially filled circular tank with three different longitudinal baffles: bottom-mounted; top-mounted and center-mounted. Eigenvalues and eigenvectors of free liquid slosh are initially obtained using BEM. For this purpose, the fluid boundaries are discretized using linear elements. The general eigenvalue problem is then reduced by considering only the elements on the half-length of the free-surface, which significantly reduces the computational time. The resulting eigenvalues and eigenvectors are subsequently incorporated into a multimodal representation of lateral liquid slosh to compute the velocity potential followed by the hydrodynamic pressure, slosh force and roll moment. Furthermore, the slosh damping due to baffles is estimated from the mean energy dissipation rate, and implemented into the multimodal analysis. The validity of the model is illustrated using the available analytical benchmarks. The effects of different baffle designs/lengths on the slosh frequencies, modes, hydrodynamic coefficients and damping ratio are further illustrated together with those on the slosh force and overturning moment imposed on the tank structure. It should be noted that apart from the slosh force and moment, many vehicle design factors including the inertia, dimensions, suspension, tires and steering system affect the directional stability of the partly-filled tank vehicle, which are not attempted in this study.

## 2. Formulations

### 2.1. Natural sloshing modes and frequencies

Consider a horizontal cylindrical container of radius $R$ with a typical baffle in the mid-longitudinal plane, as shown in Fig. 1a. The Cartesian coordinate system $Oyz$, located at the center of the tank, is used with the $z$-axis directed upward, and the liquid fill-level $h$ is measured with respect to the tank bottom "$B$", while the $z_0$ and $y_0$ denote the coordinates of the free-surface at the intersection of the tank wall. The free surface slosh modes for the baffled tank can be obtained using the boundary element