



Range of applicability of the linear fluid slosh theory for predicting transient lateral slosh and roll stability of tank vehicles



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ABSTRACT

An analytical model is developed to study the transient lateral sloshing in horizontal cylindrical containers assuming inviscid, incompressible and irrotational flows. The model is derived by implementing the linearized free-surface boundary condition and bipolar coordinate transformation, resulting in a truncated system of linear ordinary differential equations, which is numerically solved to determine the fluid velocity potentials followed by the hydrodynamic forces and moment. The model results are compared with those obtained from the multimodal solution. The free-surface elevation and hydrodynamic coefficients are also compared with the reported experimental and analytical data as well as numerical simulations to establish validity of the model. The capability of the model for predicting non-resonant slosh is also evaluated using the critical free-surface amplitude. The model validity is further illustrated by comparing the transient liquid slosh responses of a partially filled tank subject to steady lateral acceleration characterizing a vehicle turning maneuver with those obtained from fully nonlinear CFD simulations and pendulum models. It is shown that the linear slosh model yields more accurate prediction of dynamic slosh than the pendulum models and it is significantly more computationally efficient than the nonlinear CFD model. The slosh model is subsequently applied to roll plane model of a suspended tank vehicle to study the effect of dynamic liquid slosh on steady-turning roll stability limit of the vehicle under constant and variable axle load conditions. The results suggest that the roll moment arising from the dynamic fluid slosh yields considerably lower roll stability limit of the partly-filled tank vehicle compared to that predicted from the widely reported quasi-static fluid slosh model.

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1. Introduction

Liquid-transporting vehicles are known to constitute higher safety risks due to their low stability characteristics, primarily attributed to high center of mass and interactions of the sloshing cargo with the vehicle. Fluid sloshing in partially filled tanks has been associated with a large number of tank truck accidents, which pose unreasonable risks to the road safety, particularly when hazardous products (hazmat) are involved. Hazmat release occurred in 86 percent of the rollover accidents involving tank trucks, and 50 percent of such accidents resulted in fires and explosions [1,2]. Based on a U.S.

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Department of Transportation report [3], 31 percent of the fatalities associated with rollovers of commercial truck vehicles occurred with tank trucks. Although the number of rollovers account for less than 1 percent of the total tank trucks fleet in the US [1], the associated fatalities and economic losses are considered to be most unreasonable. The destabilizing effects of liquid sloshing also influence the dynamic performance of railway tank cars, ship tankers and aerospace vehicles in a highly adverse manner [4,5]. Safety and structural performance of ground and elevated storage tanks under seismic excitations are also significantly affected by the liquid sloshing [6]. These suggest that dynamic liquid sloshing must be considered and accurately modeled in applications involving free-surface flows.

The basic problem of liquid sloshing involves evaluations of sloshing forces and moments as well as natural frequencies of the free liquid surface, which are known to affect the dynamics of the vehicle system. Fundamentally, these depend on a number of design and operating parameters such as liquid-fill depth, liquid properties, tank geometry, nature of excitation and anti-sloshing devices, if present. Fluid slosh in moving containers has been widely investigated using different methods. The study of interactions between the sloshing liquid and the vehicle system, however, has been mostly limited to the steady-state and mechanical analogy models of the liquid cargo. Quasi-static fluid slosh models have been widely used to predict steady-state position of the liquid free-surface, and the effects on roll stability and directional response characteristics of the vehicles (e.g. [7,8]). These have suggested lower rollover threshold accelerations of partially filled tank vehicles compared to the equivalent rigid cargo vehicles.

Alternatively, the liquid slosh in moving containers has been analyzed using mechanical analogous models of the sloshing cargo. The applications of such models, however, necessitate prior estimations of the model parameters, which have been evaluated analytically [9], and through CFD simulations [10] and experimentation [11]. The applications of such models in analyses of coupled liquid cargo-vehicle system have been limited due to complexities associated with identification of model parameters.

Although the quasi-static method permits efficient analyses of steady-state load shift and directional responses of the tank trucks, the effect of transient liquid slosh is entirely neglected. A number of studies have investigated dynamic fluid slosh in partly-filled tanks subject to longitudinal and/or lateral accelerations using CFD methods (e.g. [12,13]). These have invariably shown significant transient slosh under applied acceleration inputs, and that peak slosh forces and moments are substantially greater than those predicted from a quasi-static model, suggesting only limited validity of the quasi-static method under transient maneuvers or high amplitude excitations. The implementations of CFD fluid slosh models in vehicle dynamics simulations have also been limited due to excessive computational demands. Yan and Rakheja [14], Biglarbegian and Zu [15] and Thomassy et al. [16] have investigated braking and steering responses of partly filled tank trucks by integrating the CFD fluid slosh model to the vehicle dynamic model. These involved highly inefficient and elaborate data transfers between the vehicle and the fluid slosh models.

Alternatively, linear liquid slosh models offer promising potential for efficient analyses of coupled liquid cargo-vehicle system dynamics. The general equations of motion of the fluid within a rigid container can be simplified assuming an ideal liquid with negligible viscosity effect, and incompressible and irrotational flows. Modaressi-Tehrani [13] has shown negligible viscosity effects on transient slosh forces and moments for a range of liquid cargo products. Under these conditions, the Navier–Stokes equations can be reduced to potential flow equations. Ibrahim [17] suggested that exact solutions of potential flow equations are limited to linear liquid sloshing within regular tank geometries with straight walls such as rectangular and upright-cylindrical containers. Conformal mapping technique has been employed for analysis of the linear slosh in other tank geometries, where the original tank geometry is transformed into a regular geometry in which the Laplace equation together with the wall and free surface boundary conditions are solved explicitly. Budiansky [18] and McIver [19] used this method to solve the potential flow equation for free liquid sloshing in two-dimensional cylindrical and spherical containers and reported the natural slosh frequencies in terms of the liquid fill level. Hasheminejad and Mohammadi [20] employed the conformal mapping technique to study the effect of anti-sloshing devices on the two-dimensional free liquid oscillations in horizontal cylindrical containers. The study suggested that a long pair of surface-touching horizontal side baffles have considerable effect on natural slosh frequencies, while the bottom mounted vertical baffles were not effective in limiting the slosh. Similar findings were also reported in [21,22] for half-full elliptical tanks with same baffle configurations. Two-dimensional liquid slosh in half-full horizontal cylindrical vessels subjected to transverse excitations was also investigated by Papaspyrou et al. [23] using an analytical approach.

Among all the methods employed for simulation of fluid slosh, analytical models seem to be attractive due to the simplicity associated with their integration to the multibody vehicle dynamic models. Only a few studies, however, have reported analytical solutions for transient liquid sloshing in tanks with curved walls, which have been mostly limited to half-filled tanks [21–24]. Problem of transient lateral sloshing in horizontal cylindrical containers with arbitrary fill ratios is only addressed using the variational method. Faltinsen and Timokha [25] suggested a multimodal model for analysis of transient lateral slosh based on a modified Trefftz variational method considering a special set of harmonic functions. Patkas and Karamanos [26] solved the flow field equations using the variational method based on the Galerkin discretization of the potential function. The applicability of the analytical fluid slosh models in directional analysis of partly filled tank-trucks with varying fill height and curved cross-sections have thus met limited success.

In the present study, the transient liquid slosh in horizontal cylindrical containers subjected to a lateral acceleration excitation is studied using an efficient analytical model based on the linear slosh theory. The validity of the developed model is examined using the available measured data and the results obtained from the analytical and numerical simulations. The range of validity of the linear slosh theory is also investigated considering high amplitude liquid slosh under excitations in the vicinity of the

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