Journal of Sound and Vibration 405 (2017) 208–233

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Nonlinear finite element analysis of liquid sloshing in complex vehicle motion scenarios

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ARTICLE INFO

Article history:
Received 17 November 2016
Received in revised form
11 May 2017
Accepted 11 May 2017
Handling Editor: W. Lacarbonara

Keywords:
Liquid sloshing
Centrifugal forces
Absolute nodal coordinate formulation
Tanker truck

ABSTRACT

The objective of this investigation is to develop a new total Lagrangian continuum-based liquid sloshing model that can be systematically integrated with multibody system (MBS) algorithms in order to allow for studying complex motion scenarios. The new approach allows for accurately capturing the effect of the sloshing forces during curve negotiation, rapid lane change, and accelerating and braking scenarios. In these motion scenarios, the liquid experiences large displacements and significant changes in shape that can be captured effectively using the finite element (FE) absolute nodal coordinate formulation (ANCF). ANCF elements are used in this investigation to describe complex mesh geometries, to capture the change in inertia due to the change in the fluid shape, and to accurately calculate the centrifugal forces, which for flexible bodies do not take the simple form used in rigid body dynamics. A penalty formulation is used to define the contact between the rigid tank walls and the fluid. A fully nonlinear MBS truck model that includes a suspension system and Pacejka's brush tire model is developed. Specified motion trajectories are used to examine the vehicle dynamics in three different scenarios – deceleration during straight-line motion, rapid lane change, and curve negotiation. It is demonstrated that the liquid sloshing changes the contact forces between the tires and the ground – increasing the forces on certain wheels and decreasing the forces on other wheels. In cases of extreme sloshing, this dynamic behavior can negatively impact the vehicle stability by increasing the possibility of wheel lift and vehicle rollover.

1. Introduction

The field of fluid dynamics has been extensively studied for decades using, for the most part, Eulerian approaches. Another area of application that has recently seen significant advances is vehicle dynamics, which is often examined using MBS algorithms based on a total Lagrangian approach. Nonetheless, fluid-vehicle interaction impacts many areas of science and technology including rail, highway, aerospace, and marine transportation. Although materials, including crude oil and other hazardous materials (HAZMAT), are transported using a variety of methods, including rail, shipping vessels, and pipelines, transportation by highway vehicle dominates the industry, generating more revenue and creating more jobs than the other modes of transportation combined, as shown by the data presented in Table 1. Due to the extent of public roads in the US and the sheer volume of freight vehicles, the tonnage of materials transported using highway vehicles far outweighs all other methods. This is true for both non-hazardous and hazardous materials, as shown in Table 2 [1].

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http://dx.doi.org/10.1016/j.jsv.2017.05.021

Table 1
Economic characteristics of the transportation Industry in 2007 [1].

Mode	Establishments	Revenue (millions)	Paid employees
Highway	**120,390**	**217,833**	**1,507,923**
Railway[a]	563	49,400	169,891
Waterway	1721	34,447	75,997
Pipeline	2529	25,718	36,964

[a] Data for railway are for 2009.

Table 2
Freight tonnage in 2007 [1].

Mode	Hazardous materials		Non-hazardous materials		Total tons (Thousands)
	Tons (Thousands)	*Percentage of Mode*	*Tons (Thousands)*	*Percentage of Mode*	
Highway	**1,202,825**	**14**	**7,575,888**	**86**	**8,778,713**
Railway	129,743	7	1,731,564	93	1,861,307
Waterway	149,794	37	253,845	63	403,639
Pipeline	628,905	97	21,954	3	650,859
Air	362	10	3256	90	3618

Rollovers are more common in tanker trucks than passenger vehicles because trucks have a higher center of gravity. Rollovers can occur due to a variety of reasons, including vehicle and road conditions, load size, and the most common, driver error, which accounts for up to 78% of tanker truck rollovers [2]. Hazardous materials are regularly transported by tanker trucks, and accidents in which the tank is compromised and the contents are released can lead to damage to the environment and the surrounding infrastructure, fires and explosions, and civilian injuries and casualties [3,4]. In the last decade alone, highway transportation accidents comprised the majority of all HAZMAT incidents, with 144,296 out of a total of 166,494 incidents; other incidents include air, railway, and water transportation accidents. Highway accidents have also proven to be the most deadly and costly, accounting for 100 out of 105 documented fatalities and 1520 out of 2129 injuries, at a cost of $6.1 billion out of $8.2 billion in damages [5]. Therefore, thorough testing and virtual prototyping are necessary to ensure better vehicle design and stability. However, because physical prototyping is expensive, inefficient, and time-consuming, it is necessary to develop accurate predictive models to investigate the effect of liquid sloshing on the dynamics of highway vehicles subject to different loading conditions and motion scenarios.

Although recent advances allow for modeling more accurate fluid behavior, most commonly used models are insufficient in adequately capturing the dynamics of the fluid in complex motion scenarios, particularly in the cases of three-dimensional finite rigid body rotations. Early sloshing models represented the fluid as a series of planar pendulums or mass-spring systems [6–9]; spherical and compound pendulums were later used to capture nonlinearities in the motion and damping was added to include the effect of energy dissipation [10]. Discrete inertia models have been used extensively in studying sloshing dynamics in the aerospace industry since 1960s [8,11,12]. However, while these discrete inertia models have been improved over time, such models cannot be used to accurately capture the change in inertia due to a change in fluid shape and the complex dynamics that results from the vehicle motion [13]. Furthermore, the discrete rigid body models do not allow for modeling the continuous free surface of the fluid, and it has been found that such models significantly under-predict the maximum amplitude of oscillation and the sloshing frequency [14]. Nonetheless, discrete pendulum models are still being used to study the effect of fluid sloshing on vehicle dynamics and stability because of the difficulties encountered in integrating computational fluid dynamics (CFD) and vehicle modeling algorithms [15]. This is attributed to the fact that CFD investigations are mostly focused on the use of the Eulerian approach and do not consider the effect of three-dimensional rotations, which cannot be accurately captured using existing incremental FE formulations. Consequently, most FE fluid models are simplistic due to the inherent difficulties in accurately capturing the fluid behavior, particularly in applications related to vehicle dynamics. For example, a sloshing fluid will experience large deformation and finite rotation, and many commercial FE formulations are not capable of handling such behaviors accurately or efficiently. Furthermore, because of the interaction between fluid and the tank walls, liquid sloshing results in variety of dynamic behaviors, including symmetric and asymmetric motion, planar and non-planar motion, and rotational and irrotational motion [16–18]. Furthermore, in flexible body dynamics, the centrifugal forces which result from curve negotiation are not simply measured by the rigid body dynamics equation mV_s^2/r, where m is the mass of the body, V_s is the forward velocity, and r is the radius of curvature of the curve [19]. In flexible body dynamics the centrifugal forces take a more complex form that depends on the body deformation. Additional difficulties arise when more accurate or complex fluid models are integrated into full vehicle models. Many FE and CFD formulations, for example, do not easily lend themselves to integration with MBS algorithms as discussed in the literature [18].