Chapter 4
Modeling of Vehicle-Cargo Interaction Under Different Environments

Frank Otremba and José A. Romero

Abstract The safety of any transport system depends on a multitude of conditions, parameters and circumstances. In this regard, the interaction of the carried cargo with the carrying vehicle represents a factor influencing the overall safety of any transport. The effects of cargo on the vehicle have to do with the vibration or shifting of the cargo, affecting the lateral stability of the vehicles and the braking performance. Such interaction has been associated to road crashes and maritime vehicles capsizing. Simulation of cargo-vehicle interaction thus represents an interesting topic when a reduction in transport accidents is pursued. In this paper, the fundamentals principles for simulating the interaction of the liquid cargo and the carrying vehicle, is presented. In the case of a road transportation, the proposed simplified simulation methodologies, show good agreement with a full-scale test.

Keywords Braking performance · Experimental approach · Newton approach
Ship stability · Sloshing · Transition matrix approach

4.1 Introduction

The level of safety of a transport depends in great extent, of factors associated to the dynamic forces that are developed due to the motion of the cargo on the vehicle. The mobility of the cargo within the vehicle is exhibited when the cargo is liquid or is hanging from the vehicle chassis. However, the most common situation of cargo vibration on the vehicle, occurs in the case of liquid cargo. Liquid cargo can include a variety of products, of different densities and levels of danger. Physical properties

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affecting the vehicle dynamics, however, include the density and viscosity of the carried cargo.

The density of the cargo influences the inertia of the liquid, while its viscosity affects its damping characteristics. The density plays a crucial role in the context of the regulations involving trucks' weight and dimensions, because in order to observe those regulations, the vehicles have to travel partially filled.

Partially filled tankers pose particular stability risk to the transport, regardless of the transportation mode. The motion of the liquid cargo in the context of transportation, is called sloshing.

Sloshing of the cargo implies at least three negative effects on the vehicle dynamics: (i) lateral cargo shifting that affects the longitudinal and/or lateral position of the vehicle's center of gravity; (ii) a vertical shifting of the center of gravity of the vehicle, further affecting the longitudinal/lateral stability of the cargo; and (iii) the potential dynamic coupling of the liquid and vehicle vibration.

Figure 4.1 illustrates cargo shifting situation, in case of a cylindrical road tanker, travelling at several fill levels while negotiating a turn.

Figure 4.2 illustrates the calculation of the roll moments for a sloshing and non-sloshing cargoes. It is assumed in this figure, that the first mode of sloshing vibration is occurring, which is acceptably realistic. However, the lateral acceleration, defining the lateral slope of the fluid's free surface, is exaggerated, to better visualize the geometric relationships so created.

From the isosceles triangle in Fig. 4.2, the following expression for *a* can be deduced:

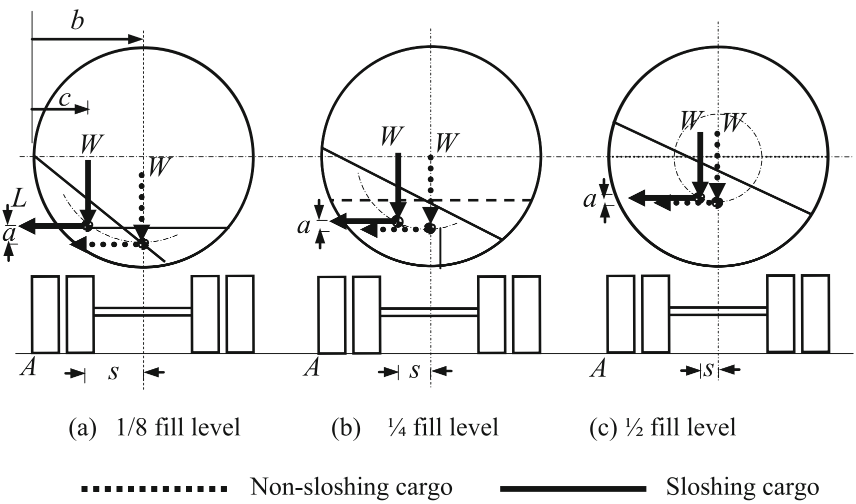


Fig. 4.1 Vertical and lateral shifting of the cargo, when a partially loaded road tanker is subjected to lateral accelerations

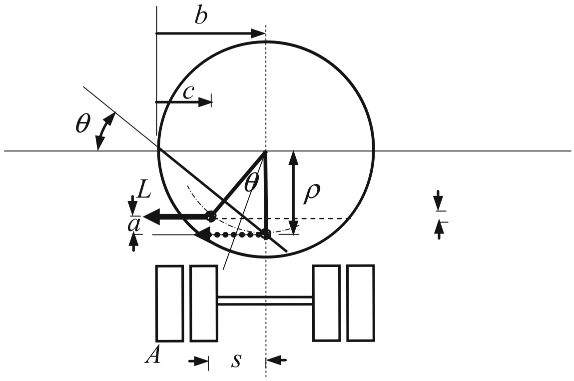


Fig. 4.2 Representation of the vertical and lateral shifting of the center of gravity of the cargo (one-quarter fill level, maximum lateral acceleration)

$$a = \rho\ \sin(\theta/2)(2)\,(\sin(\theta/2) \quad (4.1)$$

When negotiating a turn, there are two moments acting on the vehicle: one to destabilize it, and the other to stabilize it. The destabilizing moment is represented by the inertia force derived from the turning maneuver, while the stabilizing moment derives from the vertical acceleration (gravity). When the cargo shifts both vertically and laterally, the stabilizing moment is affected. Figure 4.3 illustrates the effect of lateral acceleration and fill level, on the resulting overall moment (stabilizing minus destabilizing moments). According to these results the lateral acceleration influences in a significant way the increase of the moments to destabilize the vehicle. For the lateral acceleration considered (0.068 g), the increase of roll moment varies from 5 to 20%, as a function of the fill level. However, it should be noted that in the case of the minimum fill level considered, the inertia associated to this volume of cargo, would represent a very small amount with respect to the total inertia of the vehicle (chassis and body). Consequently, while the increase of the roll moment is the greater for this low fill level, the consequences on the lateral stability of the vehicle, would be minimal.

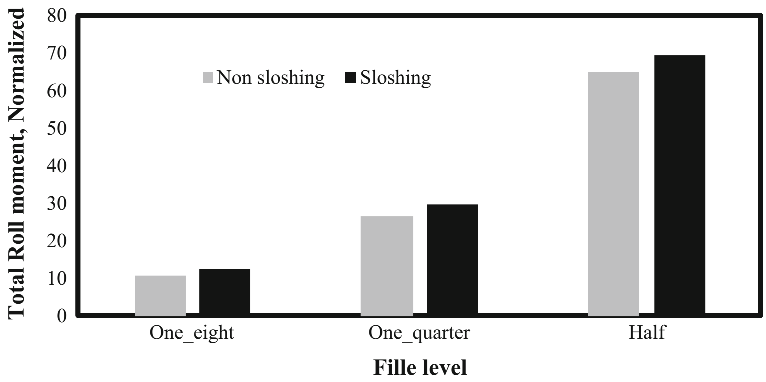
On the other hand, the longitudinal dynamics of the sloshing cargo keeps a close relationship with the lateral effect described above. Figure 4.4 describes this longitudinal acceleration situation, where the resulting pressure on any point on the front head or surface of the tank, is the result of a vertical pressure p_v, plus a longitudinal pressure p_L. Both of these pressures depend on the longitudinal acceleration, as such acceleration defines the angle of the liquid's free surface, as follows:

$$p_v = \rho\, g y = \gamma\, y \quad (4.2)$$

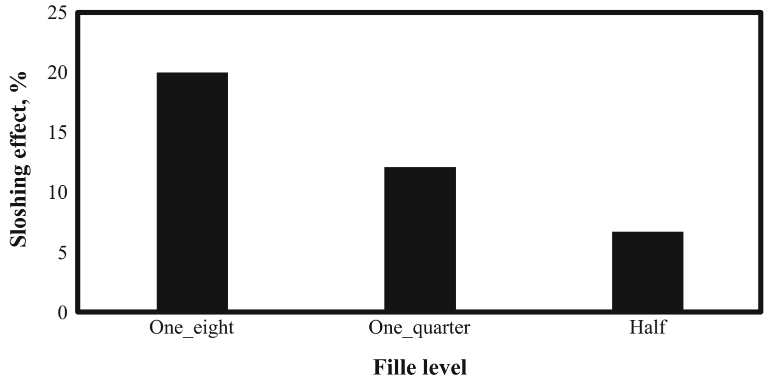
$$p_L = \rho\, a_L\, L \quad (4.3)$$

where ρ_L is the mass density of the liquid (kg/m^3); a_L is the longitudinal acceleration of the vehicle; and g is the acceleration due to gravity.

This paper is based upon a WCECS 2017 Conference paper [1].



(a) Effect of the cargo shifting on the level of roll moment.



(b) Cargo shifting effect on the increase of the roll moment.

Fig. 4.3 Cargo shifting effect on the roll moments (lateral acceleration of 0.667 m/s^2)

4.2 Modelling Principles

While the representations described above correspond a steady state condition, for both the lateral and the longitudinal behavior of the liquid in the tank, there is the need to model the oscillation characteristics of the fluid within the tank. For that, a simplified model has been proposed and used in a multitude of cases to simulate such dynamics. Until recently, however, the dynamic properties of the pendulum representing the sloshing cargo, has been based upon experimental data [2]. Such pendulum property is its length. The basis for such approach derives from the free vibration of a liquid in a rectangular tank, called "gravity waves", according to the following equation [3]:

$$c = \lambda f = \sqrt{\left(\frac{g}{\kappa} \tanh \kappa h\right)} \tag{4.4}$$

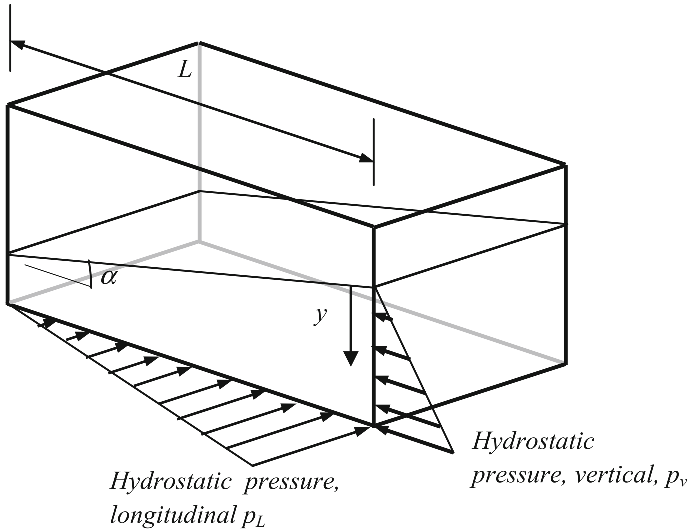


Fig. 4.4 Superposition of hydrostatic pressures (vertical and longitudinal)

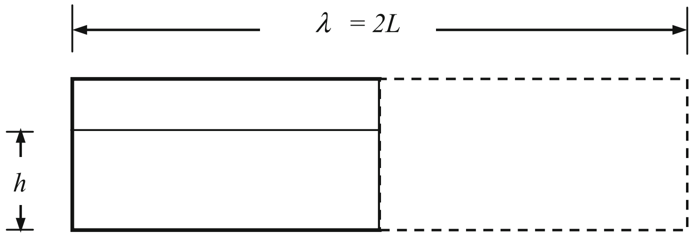


Fig. 4.5 Natural free sloshing frequency in a rectangular container

where κ is the wave number, equal to $2\pi/\lambda$. This is illustrated in Fig. 4.5.

Consequently, the pendulum representing the sloshing cargo, has a length as a function of the following equation:

$$f = \frac{1}{2\pi}\sqrt{\frac{g}{l_p}} \tag{4.5}$$

According to this approach, it if feasible to simulate the transient and steady state of the sloshing of the cargo within the tankers.

The mechanical analogy of the sloshing cargo with the pendulum, involves a mechanical system that is able to vibrate, and that is supported by the chassis of the vehicle. That part of the vehicle, further represents a mechanical spring-mass-damper system. Figure 4.6 illustrates the resultant model, in which the simple pendulum rests on an equivalent mechanical system representing the sprung mass of the vehicle.

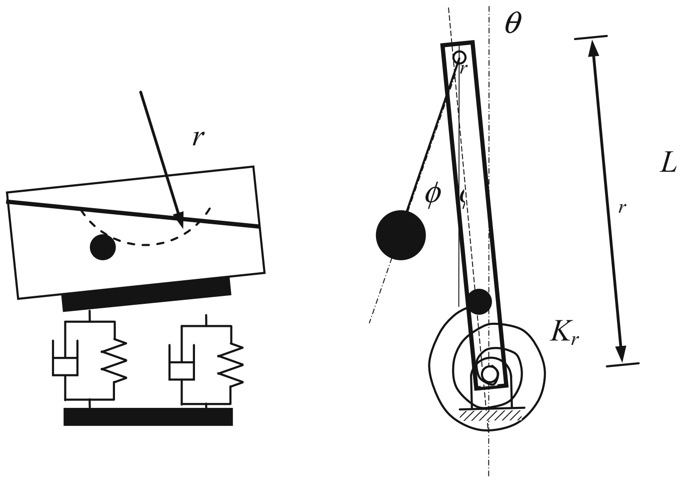


Fig. 4.6 Model of sloshing cargo, supported on the sprung mass of the vehicle

The resulting mechanical system representing the sloshing cargo and the sprung mass of the vehicle, consists of a two degree-of-freedom system, namely, the sloshing angle of the first mode of vibration of the fluid, and the pitch or roll motion of the sprung mass of the vehicle. Derivation of the equations of motion can be done through the use of Newton's Second Law.

On the other hand, the linear mathematical model resulting from the combination of the different mathematical approaches just described, are solved on the basis of the solution of a first order system. For this, the second-order equations are expressed as vector state variables, as follow [4]:

$$\{\dot{y}(t)\} = [A]\{y(t)\} + [B]\{Y(t)\} \tag{4.6}$$

where the matrices $[A]$ and $[B]$ are coefficient matrices, expressed in terms of the mechanical properties of the system (stiffness, damping, inertial and dimensional characteristics). The time-discrete exact solution of this system of equations, results as follows [4]:

$$\{y(t + \Delta t)\} = [\Phi]\{y(t)\} + [\Gamma]\{Y(t)\} \tag{4.7}$$

where $[\Phi]$ is the transition matrix; $[\Gamma]$ is the particular response matrix; and $\{Y(t)\}$ is the perturbation vector. The size of the different vectors and matrices of this method, thus depends on the number of degrees of freedom of the resulting system. The state vector for a two-degree-of-freedom system, is four, as it involves the state variable and its derivative. On the other hand, a number of particular response matrix $[\Gamma]$ can be generated, as a function of the number of perturbations, $\{Y(t)\}$.

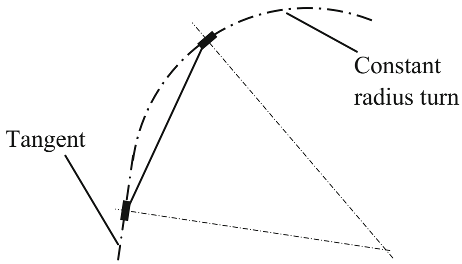


Fig. 4.7 Methodology two calculate the instantaneous lateral acceleration of a vehicle while incorporating into a curved infrastructure

To simulate the circulation of the vehicles along the infrastructure, there is still another modelling principle that must be considered for the simulation of the tanker vehicles dynamic response to the geometrical characteristics of the infrastructure. This principle considers the instantaneous lateral acceleration on the vehicle when it incorporates to the curved part of the infrastructure, as a function of the geometrical characteristics of the road, rail or maritime infrastructure. Figure 4.7 describes the situation of the vehicle when entering a curve portion of the infrastructure. The respective formulation is described in [5], to calculate the instantaneous radius of curvature when the vehicle passes from a tangent to a constant radius turn.

4.3 Examples

The models described in the previous section, as well as the equation solving methodology, are used to simulate two common situations in liquid cargo transportation. On the one hand, an emergency braking maneuver is simulated, of a trailer tanker combination. For that, the model consists of a longitudinal pendulum, and the vehicle is equipped with Antilock Brake System. Figure 4.8 schematically illustrates the trailer tanker [1]. Two of the seven load compartments, were instrumented to sense the hydrostatic pressure on the compartment's wall.

The braking algorithm consisted of a bang-bang control, set to an optimal wheel slip of 0.2, leading to a maximum braking coefficient of 0.7. The role of sloshing on the braking efficiency of the vehicle, is defined on the basis of the stopping distance. Figure 4.9 illustrates the measured braking acceleration, with maximum decelerations on the order of 0.65 g [6].

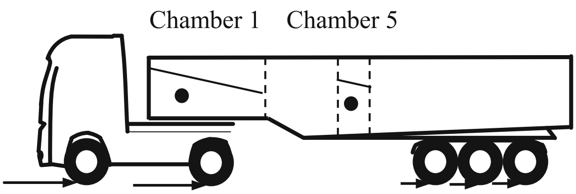


Fig. 4.8 Schematic representation of a tractor-trailer combination for carrying liquid cargo

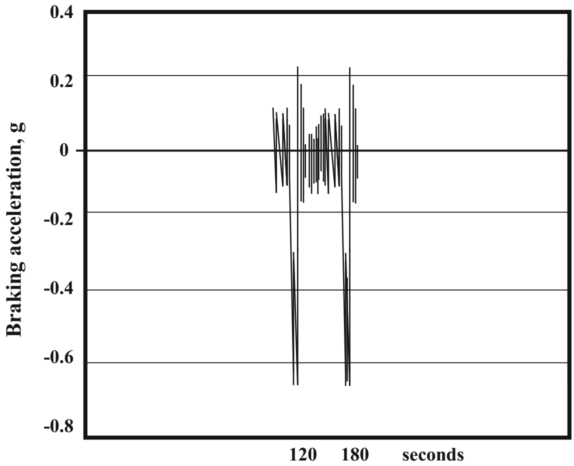


Fig. 4.9 Experimental data of the braking acceleration [1]

Figure 4.10 illustrates the measured and simulation data, of the hydrostatic pressure on the pressure sensors of the two instrumented chambers. According to these data, there is a close correlation between both data. Furthermore, Fig. 4.11 illustrates a detailed view of the hydrostatic pressure once the vehicle was in rest, where the natural frequency of the sloshing was appropriately reproduced through the simulation.

According to these results, the longitudinal dynamics of the sloshing cargo—vehicle system, can be closely reproduced through the use of simplified models, for both, the vehicle and the sloshing cargo.

The simulation methodologies described above are now used to simulate the roll behavior of a ship when travelling along a river infrastructure.

Figure 4.12 describes the roll plane of a ship when subjected to a lateral acceleration. As it was described in the previous section, the sloshing cargo is simulated through a simple pendulum, whose characteristics are defined on the basis of a validated methodology to calculate the natural sloshing frequency of the fluid within the vessel.

A series of simplifications are assumed for this model, including the bottom of the river tanker, which is semicircular instead of flat [7].

Figure 4.13 illustrates the simulation results from this model. It should be noted that the non-sloshing condition was obtained by artificially increasing the damping of the sloshing cargo within the tanker. According to these results, the sloshing cargo represents a dangerous situation, as the maximum roll angle increases in a certain percentage.

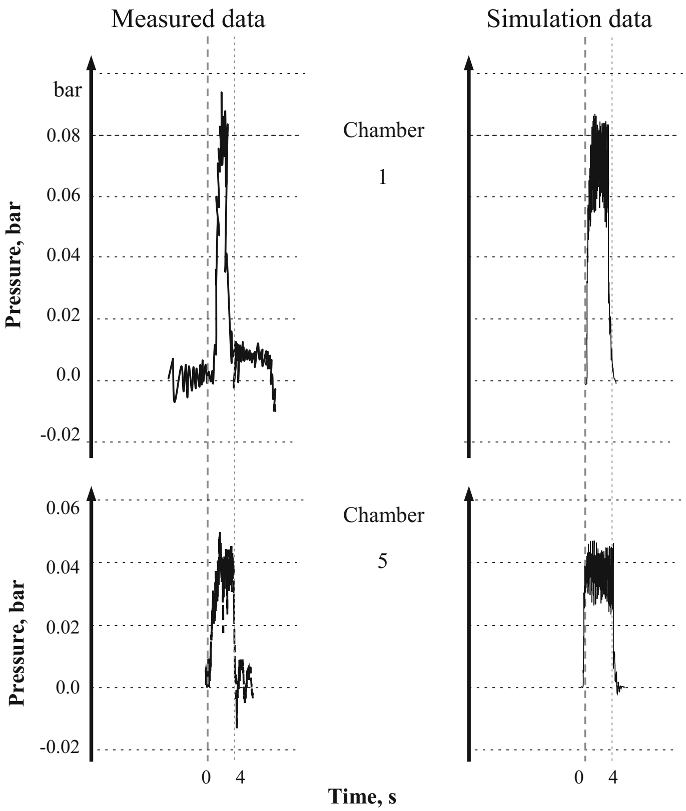
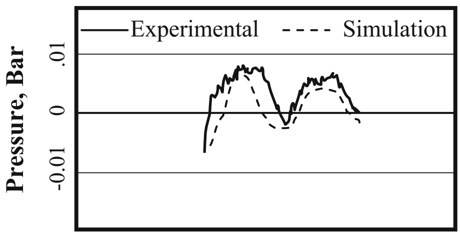


Fig. 4.10 Simulation and measure data for the pressure on the vehicle's chambers

Fig. 4.11 Simulation and experimental data of the residual vibration of the sloshing cargo



4.4 Conclusions

A simplified physical modelling and an equation-solving algorithm, have been presented to simulate the behavior of a vehicle (tanker) under road and maritime infrastructure conditions. For the road infrastructure, the emergency braking of a semi-trailer tanker, was presented, and for the maritime environment, the travelling of a river ship was modelled. In the case of the braking maneuver, experimental results

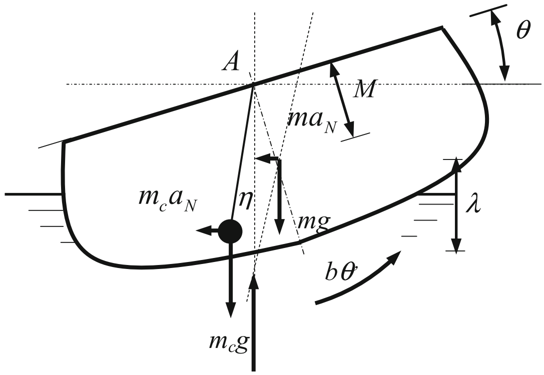


Fig. 4.12 Roll model for a ship when subjected to lateral accelerations due to infrastructure's geometric design

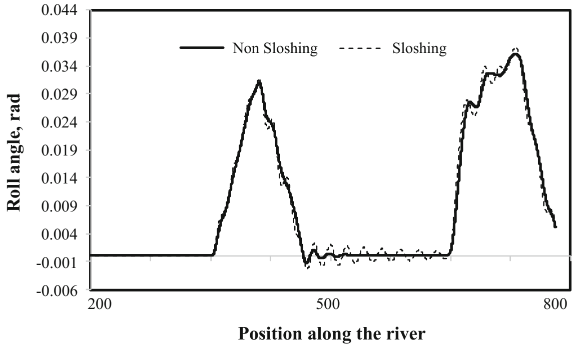


Fig. 4.13 Time response history of the roll angle for a sloshing and non-sloshing cargo when the ship travels along a winding river

are compared with theoretical results, finding a good agreement between both series of data. The simulation of a ship along a river infrastructure containing several turns, reveals that the roll stability of the ship can be affected by the sloshing cargo. The simulation principles can be considered for other environments and conditions. For example, the performance of a braking maneuver under the conditions of changing, simultaneously, the speed of the vehicle, and the direction of the vehicle.

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