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ANCF analysis of the crude oil sloshing in railroad vehicle systems

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ABSTRACT

With the increase in *crude oil* rail transportation, accurate modelling of non-Newtonian crude oil rheological properties and the corresponding nonlinear sloshing effects becomes necessary in order to establish safety and operation guidelines. In this investigation, nonlinear continuum-based crude oil constitutive models are used in a total Lagrangian formulation to study the effect of the sloshing on railroad vehicle dynamics and stability. In particular, the Oldroyd constitutive model is employed to capture the non-Newtonian characteristics of three different crude oil types; classified as *light*, *medium*, and *heavy*. The crude oil complex deformation shapes are captured using the finite element (FE) absolute nodal coordinate formulation (ANCF). The FE continuum-based liquid sloshing formulation is systematically integrated with a fully nonlinear multibody system (MBS) railroad vehicle algorithm that allows for wheel/rail separation. A general penalty contact approach is developed to allow for studying the effect of sloshing suppression devices such as bulkheads. Different braking scenarios, including electronically controlled pneumatic (ECP) braking are considered to study the effect of crude oil sloshing on the train longitudinal stability. The ECP braking computer simulations show that increasing the crude oil viscosity can lead to approximately 30% reduction in the maximum coupler force compared to the light oil case. It is observed that the coupler force response to the sloshing excitations as the result of ECP braking reaches steady state faster as the viscosity increases. Furthermore, installing the bulkheads in tank cars can lead to a 70% reduction in the maximum coupler force and more uniform distribution of the normal contact forces to the front and rear wheels. The effect of crude oil rheological properties on the centrifugal forces during curve negotiation is also evaluated. The curve negotiation results show that the increase in crude oil density is responsible for exacerbating train lateral instability effects, thus the risk of vehicle roll over, especially when the train travels at a speed higher than the balance speed.

1. Introduction

While the derailments of trains transporting hazardous materials (HAZMAT) have been reduced in the past few years, the economic and environmental damage resulting from the HAZMAT rail transportation remains a serious daily threat, particularly with the increasing demand for crude oil transportation. In order to reduce such a damage, more credible safety

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and operation guidelines as well as design standards must be developed based on accurate and scientifically convincing physics-based modeling techniques. Minimizing HAZMAT-transportation accidents can be achieved by developing computer simulation approaches that accurately account for the continuum-based crude oil rheological material properties, allow optimizing the tank car designs, test rail equipment durability, and examine new braking system concepts. The Federal Railroad Administration (FRA) reported that the safety of HAZMAT rail transportation in the United States has significantly improved over the past fifty years [1]. However, the increasing demand of crude oil and other HAZMAT transportation has resulted in several deadly and environmentally damaging rail accidents. Several derailment accidents during the past two decades involved the release of hazardous materials; examples of which are the train derailments in North Dakota [2] and Ontario [3], and the train collisions in Texas [4] and South Carolina [5]. Among the most recent accidents, a train carrying crude oil derailed in the Chicago area with an estimated leak of 45,000 gallons in the summer of 2017 [6]. In order to avoid accidents involving HAZMAT transportation, the railroad industry is actively conducting multiple research projects to improve railroad vehicle designs. The Volpe National Transportation System Center is performing studies on the structural integrity of railroad tank cars transporting hazardous materials [7]. A new project called the Next Generation Rail Tank Car (NGRTC) is a collaborative research and development effort sponsored by multiple companies with the aim of improving tank car design [8]. Nonetheless, understanding the liquid sloshing phenomenon is necessary in order to better identify the cause of and potentially prevent future HAZMAT transportation derailments.

2. Background and scope of the investigation

This investigation is focused on integrating continuum-based crude oil rheological constitutive laws, such as the *Oldroyd constitutive model*, with computational MBS algorithms for the study of the sloshing effect on railroad vehicle dynamics. Using the physics-based modeling approach developed in this study, one can distinguish between different crude oil viscosity properties and their effect on the rail vehicle motion and stability. The development of such continuum-based sloshing models is necessary in order to have alternatives for the simplified non-physics-based discrete mass-spring system models often used in the analysis of liquid sloshing, as will be discussed in this section. This section also provides background materials that explain the motivation for this study and defines the scope and specific contributions of this investigation.

2.1. Liquid sloshing and classical vibration problems

Sloshing is not a typical mechanical vibration problem because the motion of fluids is not influenced by the restoring forces that produce and sustain solid oscillations. A typical vibration problem requires the existence of two basic elements; *inertia* and *restoring force elements*. While damping can significantly influence mechanical vibrations, damping is not a necessary element for discrete-mass vibrations to exist. The restoring elastic force element does not enter into the definition of the liquid sloshing phenomenon or its mathematical description. Fluids do not have restoring forces; the fluid motion is mainly influenced by the viscous forces often defined using the Navier-Stokes equations. Because stiffness coefficients cannot be determined from viscosity coefficients using any parameter identification method, discrete mass-spring system sloshing models are not physics-based. A fluid can flow out of a container or a tank car, as in the case with deadly, costly, and environmentally damaging accidents, because of the lack of restoring forces that can be mathematically defined using a strain energy function.

The fluid/container interaction is often modeled using a penalty force approach to enforce *unilateral constraints*. Such unilateral constraint forces cannot be derived from a fluid strain-energy function, which cannot be justified using physics principles. Because fluid forces are viscous forces defined using dissipation functions and not strain energy functions, the use of costly experiments to validate non-physics-based discrete mass-spring sloshing models needs to be justified. For this reason, the focus of this paper will be on the development of new continuum- and physics-based crude oil sloshing models that allow for using appropriate and realistic viscosity coefficients to study the effect of the oil motion on the rail vehicle dynamics and stability.

2.2. Experimental testing and simulation models

To better understand the dynamic loads applied to railroad tank cars, wheels, and couplers; it is important to develop liquid sloshing formulations, which account for the nonlinear fluid/structure interaction effects, which occur during the complex railroad operating conditions. The liquid oscillations resulting from the interaction with the tank walls result in uneven loading even in normal service conditions and represent a potential source of instability, derailment, and structural failure. In order to reduce the severe sloshing oscillations of viscous fluids, tank cars can be fully loaded. This solution, however, may lead to a significant increase of the axle load and normal wheel/rail contact forces, especially when high-density fluids like crude oils are transported. Many railroad accident investigations are mainly focused on fatigue analysis, collision dynamics, and structural response. In order to conduct these investigations successfully and produce reliable results, an accurate load spectrum must be defined. The load spectrum can be produced experimentally by means of advanced microprocessors and sensors mounted on the rail car equipment. Nonetheless, experimental testing is extremely expensive, prone to human error, highly sensitive to weather conditions, and often show large data variations within the same set of measurements. Reliance on experimental data can be reduced only if complex high-fidelity MBS railroad vehicle models with