Study of Liquid Sloshing using a Multibody Approach

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The objective of this investigation is to develop a total Lagrangian liquid sloshing solution procedure based on finite element floating frame reference (FFR) formulation and absolutely nodal coordinate formulation (ANCF). The proposed liquid sloshing modeling approach can be used to avoid the difficulties of integrating most of fluid dynamics formulations, which are based on the Eulerian approach, with multibody system dynamics formulations. The use of this approach allows for developing an inertia-variant fluid model that accounts for the dynamic coupling between different modes of the fluid displacements. The FFR model is integrated with a MBS railroad vehicle model in which the rail/wheel interaction is formulated using a three-dimensional elastic contact formulation that allows for the wheel/rail separation. Several simulation scenarios are used to examine the effect of the distributed liquid inertia on the motion of the railroad vehicle. The results, obtained using the sloshing model, are compared with the results obtained using a rigid body vehicle model. The comparative numerical study presented in this investigation shows that the effect of the sloshing tends to increase the possibility of wheel/rail separation as the forward velocity increases, thereby increasing the possibility of derailments at these relatively high speeds. Several ANCF examples are also presented in this investigation in order to shed light on the potential of using the ANCF liquid sloshing formulation used in the railroad field.

Numerical Results

Sloshing effect on the motion of railroad vehicle. In order to examine the sloshing effect on the motion of the vehicle, another equivalent rigid-body model was used for the purpose of comparison. This rigid body model is obtained by assuming the fluid body to be rigid while keeping all other model parameters the same. Both tangent and curved track are used in this investigation to examine the sloshing effects.

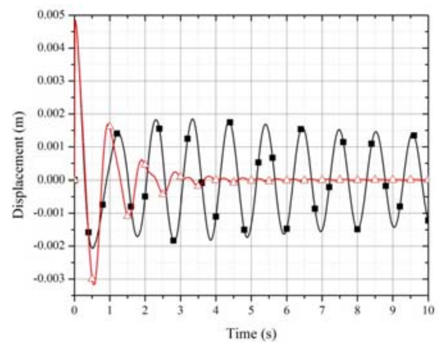

Fig. 1 Lateral displacement of the rear wheelset with forward velocity of 25m/s (56mph) (—■—Rigid body , —△— Flexible body)

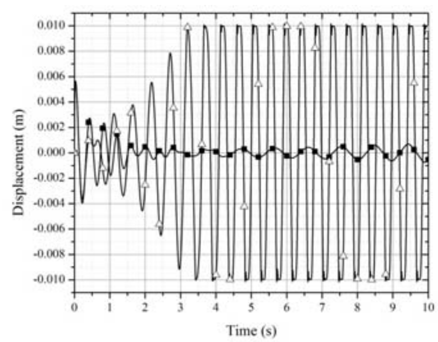

Fig. 2 Lateral displacement of the rear wheelset with forward velocity of 60m/s (134mph) (—■—Rigid body , —△— Flexible body)

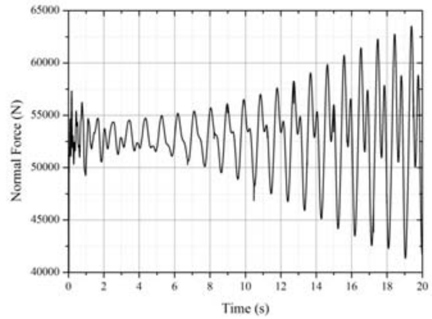

Fig. 3 Normal contact force on the right wheel of the rear wheelset of the rear bogie in the rigid body model with forward velocity of 60 m/s (134mph)

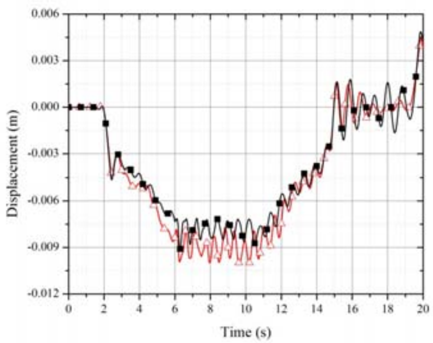

Fig. 4 Lateral displacement of the rear wheelset with respect to the track (—■—Rigid body, —△— Fluid body)

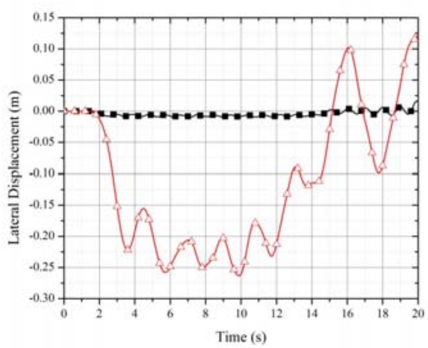

Fig. 5 Change of the center of mass with respect to the track (—■—Rigid body , —△— Fluid body)

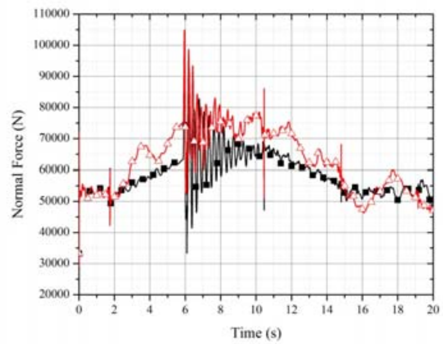

Fig. 6 Normal contact force of the right wheel of the rear wheelset of the rear bogie (—■—Rigid body , —△— Fluid body)

In the first simulation scenario considered, two constant forward velocities of 25 m/s (56 mph) and 60 m/s (134 mph) along the tangent track are considered. All wheelsets are assumed to have 0.5 m/s initial lateral velocity. Figure 1 shows that, at the low speed when hunting is not significant, the fluid body introduces damping that tends to reduce the amplitude of the hunting oscillations, making the system more stable as compared to the rigid body model. However, if the forward velocity is increased to 60 m/s (134 mph), the fluid body model becomes more unstable as compared to the rigid body model, as demonstrated by the results of Fig. 2. Figures 3 shows the normal force for the rigid and fluid body models, respectively. The results presented in these two figures show that the liquid sloshing can cause impulsive forces between the wheel and rail, leading to spikes in the contact force. More importantly, the liquid sloshing can lead to wheel/rail separations which can increase the possibility of rollover and derailment.

In the second simulation scenario, the results obtained using the rigid and fluid body models are compared when the vehicle negotiates a curved track at 35 m/s speed with no initial lateral velocity. Figure 4, which depicts the lateral displacement of the wheelset with respect to the track, shows that the fluid body model has larger lateral displacement due to the sloshing effect. Figure 5 shows the change in the location of the center of gravity of the fluid body in the lateral Y direction. The results of this figure show that the change in the position of the center of mass is more significant when the vehicle negotiates a curved track. The results of Figs. 6 shows that changing the location of the fluid body center of mass leads to a different distribution of the normal contact forces on the wheels. That is, the wheels which carry the highest loads in the fluid body and the rigid body models can be different.

ANCF fluid element capability. The dimensions of the element are $a = b = c = 1\text{m}$, while the mass density $\rho = 1.0\times10^3\ \text{kg/m}^3$, the gravity force $\mathbf{F}_g = [0 \quad 0 \quad -9.8]^{\text{T}}\ \text{m/s}^2$, the penalty coefficient $k_{IC} = 1.0\times10^6\ \text{N/m}$, and the shear viscosity $\mu = 0.00093\,\text{Pa}\cdot\text{s}$. The simulation time is assumed to be 1s. In this simulation scenario, the fluid element bottom surface is assumed to be in contact with the ground. The fluid is assumed to move freely under the effect of gravity. The results obtained also demonstrated that the fluid maintained constant volume. This simulation scenario also shows that the proposed ANCF fluid elements can capture large displacements using a total Lagrangian approach, as shown in Fig. 7.

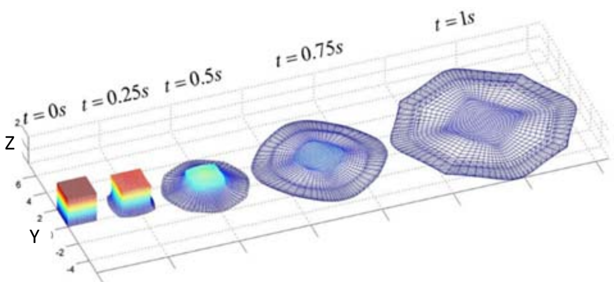

Fig. 7 Eight-element fluid/ground surface interaction

In other example, the one-element model previously considered in this section is used to fill a container subjected to a prescribed harmonic motion with different frequencies in the *y* direction. As shown in Fig. 8, when the container movement is $0.1\sin(3t)$, the fluid experiences sloshing and the height reaches 1.16 m. The height reaches 1.35m for the $0.1\sin(8t)$ movement and 2.23m for the $0.3\sin(8t)$ movement. By investigating these three results, one could see that if the harmonic motions have the same amplitude, increasing the frequency would lead to the more sever fluid sloshing while in the other case, if the harmonic motions have the same frequency, increasing the amplitude would also lead to more sever fluid sloshing which are consistent with common sense. More details on FFR and ANCF modeling of the rail car liquid sloshing may be found in the investigations [1, 2].

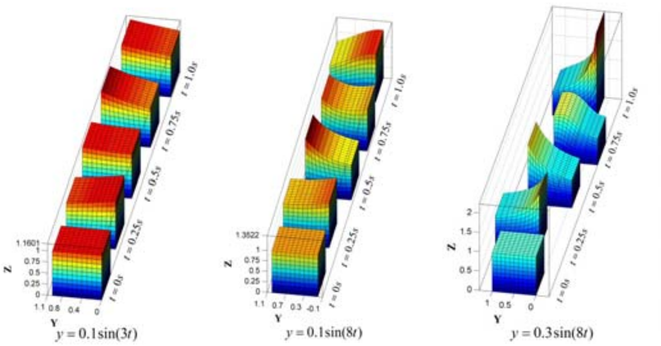

Fig. 8 Sloshing problems solution using one finite element

References

1. Wang, L., Octavio, J.R.J., Wei, C., and Shabana, A.A., 2014, "Low Order Continuum-based Liquid Sloshing Formulation for Vehicle System Dynamics", ASME Journal of *Computational and Nonlinear Dynamics*. Vol. 10(2), Article ID 021022.
2. Wei, C., Wang, L., and Shabana, A.A., 2014, "A Total Lagrangian ANCF Liquid Sloshing Approach for Multibody System Applications", ASME Journal of *Computational and Nonlinear Dynamics* (in press).

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