EFFECT OF FLUID PHYSICAL PROPERTIES ON ROLLOVER STABILITY IN TERMS OF DAMPING OF DYNAMIC FORCES & MOMENTS IN FLUID SLOSHING

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ABSTRACT

Fluid sloshing inside a moving container is often responsible for rollover accidents. In a partially filled container, the liquid moves from side to side resulting in the sloshing phenomena. This can cause the rollover of the container because the sloshing amplifies the forces exerted by the inside fluid on the walls of container. Container's shape, size and fluid properties such as viscosity, density and surface tensions are of paramount importance regarding fluid sloshing. The effect of kinematic viscosity on the damping of dynamic forces and moments, generated as result of fluid sloshing in a moving fuel container, is analyzed in this study. Computational fluid dynamic (CFD) models for different shapes (circular & elliptical) and size of container were developed in CFD GEOM. Different fluid properties were applied and simulations were run in CFD ACE. The increase of kinematic viscosity of the fluid was found to have no effect on peak dynamic forces and moments for each fill level. On the other hand with the increase of density of the fluid the peak dynamic forces and moments increased. Damping factors were calculated for dynamic forces and moments for each fill level and different kinematic viscosities and densities of the fluids. An increasing trend was found in the damping factor for each fill level with the increase of kinematic viscosity and densities of the fluid, but this increase of damping was of insignificant magnitude. It was also found on the basis of peak forces and peak moments generated for the same fill levels that the elliptical containers are suitable for the shipment of fluid material.

Index Terms: Fluid Sloshing, Kinematic Viscosity, Damping Factor, Partially filled tankers
INTRODUCTION

Phenomenon of fluid sloshing is found to have very critical impact on the safety of humans & environment. Sloshing happens in the gas tank of automobiles, in the wing of an aircraft where the fuel is stored and in water tower during an earthquake. The transport of hazardous goods constitutes approximately 10% of the road transport [1]. Fluid sloshing is one of the main reasons behind the rollover accidents of heavy commercial vehicles, because these vehicles have very low rollover stability as compared to light vehicles. Terrifying incidents in the past, such as San Carlos, Spain [2], or Herborn, Germany [3] clearly illustrate the scale of damage that could be involved. Rollover stability of heavy duty vehicles attracts many researchers. Rollover threshold are expressed in gravitational units (g). Rollover threshold for heavy duty vehicles such as tankers truck are well below 0.5 g [4]. At lower rollover threshold fluid sloshing can contribute in greater amount to the instability of heavy duty vehicle. Viscous damping is the inherent property for all most all kinds of fluids. Damping is the outcome of the loss of energy. The amount of this energy loss depends upon the type of applied force, viscosity of the fluid and, shape and size of the container. The fact that this viscous damping can be very useful in overcoming the rollover as a result of fluid sloshing attracts many researchers. In studies [5] and [6] magnitude and frequency of sloshing have been studied using trammel pendulums. In study [7] the fundamental frequency for 50% filled horizontal cylindrical tank was analytically obtained. But the pendulum models used in studies [5] & [6] were unable to simulate the viscous damping. Fluid movement in a moving container such as heavy duty tankers having lower threshold, can be quite complex to analyze. Also experimental investigations were found to have major drawbacks, such as; high cost excessive noise in measuring instruments, lack of repeatability of test results. The main objective of the study was to find out the effect of different fluid properties on the dynamic forces and moments induced in partially filled road containers as a result of fluid sloshing during constant radius maneuver, and to find a general expression for viscous damping in term of tank geometry, fill level, kinematic viscosity of the fluid and the type of maneuver. Therefore a computational fluid dynamics (CFD) model was developed in current research to study the effect of fluid properties (mainly kinematic viscosity), container shape and fill levels on the damping of fluid sloshing. Circular and elliptical shapes were selected for the analysis purpose at four different fill levels. Both kinematic viscosity and density was found to have a slight effect on the damping factor of the fluid sloshing inside a tank but only density of the fluid effect the peak dynamic forces and moments during sloshing inside a fuel tankers. On the basis of these dynamic forces and moments it was found that elliptical shape is the suitable for the transportation of liquid cargoes.

MODEL DEVELOPMENT AND VALIDATION

For selection of Geometry the studies of Sanker [8] was considered. An elliptical tank with the major radius (a) of 1.38395 and a minor radius (b) of 0.691975, and circular tank of radius 1.38395 were modeled in CFD GEOM. Four different fill levels (30%, 50%, 70% & 90%) were considered to validate the model, shown in Fig. 1 & 2.

![Fig. 1. 50% Fill Level (Elliptical Tank)](image-url)
Analysis for both tank shapes was then done in CFD ACE. Volume of Fluid (VOF) module was used. Surface reconstruction method was set to second order PLIC for accurate VOF behavior predictions and faster convergence. Gauss Theorem was used to predict gradient of VOF. Explicit time integration scheme was used because of its greater stability and better convergence. To simulate the constant radius turn maneuver, lateral acceleration of 0.3g was applied. Simulation was run for 8 seconds with auto time step for better convergence. Horizontal Force acting on the tank wall & moment at the bottom of the tank was then calculated from the output file generated by CFD ACE.

To validate the model, simulation results were then compared with the published results [8] for same tank configuration (geometry & fill levels). The developed model was verified by comparing the CF (Coefficient of Force) & CM (Coefficient of Moment) with those presented in [8], Table. I and Fig. 3 & 4.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>30%</td>
<td>1.53/ 1.61/ 1.45</td>
<td>1.47/ 1.57/ 1.41</td>
</tr>
<tr>
<td>50%</td>
<td>1.47/ 1.52/ 1.32</td>
<td>1.44/ 1.53/ 1.29</td>
</tr>
<tr>
<td>70%</td>
<td>1.29/ 1.41/ 1.19</td>
<td>1.31/ 1.41/ 1.19</td>
</tr>
<tr>
<td>90%</td>
<td>1.17/ 1.20/ 1.13</td>
<td>1.15/ 1.20/ 1.12</td>
</tr>
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</table>
As it is evident from the above graphs and tabulated values of CF and CM the analysis results were within the accepted deviation range of 9%.

RESULTS AND DISCUSSION

In the first step, water’s density was chosen as the analysis pivot point while analysis was carried out using the kinematic viscosities of the fluids shown in Table II. In the second step, different fluids with different physical properties were used for analysis.

**TABLE II: FLUIDS USED IN THE ANALYSIS**

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Kinematic Viscosity (M²/S)</th>
<th>Density (Kg/M³)</th>
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<tbody>
<tr>
<td>SAE 30 (Transmission Oil)</td>
<td>4.24E⁻⁴</td>
<td>912</td>
</tr>
<tr>
<td>KAROSIN</td>
<td>2.71E⁻⁶</td>
<td>820</td>
</tr>
<tr>
<td>GASOLINE</td>
<td>4.6E⁻⁶</td>
<td>680</td>
</tr>
<tr>
<td>JP8 (Jet Petroleum)</td>
<td>1.3E⁻⁶</td>
<td>778</td>
</tr>
<tr>
<td>Fuel Oil 6 (Engine Oil)</td>
<td>0.006</td>
<td>890</td>
</tr>
<tr>
<td>WATER</td>
<td>1.6E⁻⁶</td>
<td>997</td>
</tr>
</tbody>
</table>

KINEMATIC VISCOSITY VS DYNAMIC FORCES & MOMENTS

The effect of change in kinematic viscosity of same fluid (water) on horizontal forces, pressure moments and viscous moments generated due to fluid slosh are depicted in Fig. 5-7.
The minimum peaks of 8950 Nm and 6730 N were observed for the kinematic viscosity of Fuel Oil 6. Considering the massive difference in the kinematic viscosities of water and fuel oil 6, but
the difference in peaks for both moment and forces is negligible. It is apparent from Fig. 7 the peak viscous moment generated by Fuel Oil 6 is about 138 Nm. This value is insignificant as compared to the peak pressure moment generated for Fuel Oil 6. Therefore it could be ratiocinated that change in kinematic viscosity has no effect on dynamic forces and moments generated due to fluid sloshing. These forces and moments are mainly responsible for diminishing the roll over stability in tanker trucks.

B. DIFFERNT FLUIDS VS DYNAMIC FORCES & MOMENTS

The effect of changing the fluid properties (including kinematic viscosity and density both) on horizontal forces, pressure moments and viscous moments generated due to fluid slosh are depicted in Fig. 8-10.

Fig. 8. Comparison of Horizontal Forces

Fig. 9. Comparison of Pressure Moments
Considering the results obtained in step 2, as depicted in Fig. 8 & 9, it shows that the maximum peak in pressure moments and forces was observed for water (9220 Nm and 7012 N). The minimum peak values were found for Gasoline (6112 Nm and 4560 N). Moreover, water has maximum density while gasoline has minimum density among all the fluids considered. This underscores that the denser fluid enhances the chances of tanker rollover. The viscous moments, as shown in Fig. 10, were again found to be least effecting the roll over stability.

**C. DAMPING FACTOR FOR SAME VS DIFFERENT FLUID**

Figure. 11 & 12 describe the effect of kinematic viscosity on damping factor for same fluid and different fluids respectively. A comparison of damping factors for both set of analysis has been done in Fig. 13.
Damping factor is usually considered for numerically scrutinizing the extent of system stability and sloshing behaviour. Logarithmic decrement ($\delta$) accounts for the rate of decrease of liquid sloshing. Damping factor ($\zeta$) is given as:

$$\delta = \frac{1}{n} \ln \left( \frac{x_0}{x_n} \right)$$

$$\zeta = \frac{\delta}{2\pi}$$

(1)  
(2)

Where ‘n’ corresponds to the number of peaks, ‘$x_0$’ represents the magnitude of first peak and ‘$x_n$’ represents the magnitude of last peak. The damping factor ($\zeta$) were then calculated using the above equation for each fluid and fill level, and then plotted against the kinematic viscosities of the fluids (Fig. 11 & 12). The damping factor ($\zeta$) was plotted on the y-axis and ln(kinematic viscosity) on x-axis. Considering Fig. 11 and 12 it is is reflected that with the increase of kinematic viscosity damping factor increases a little but is insufficient to damp out the fluid slosh. Maximum damping factor of 0.0072 is obtained for Fuel Oil 6 which is very less than damping factor required and system is still
under-damped. A steady increase in the damping factor was observed (Fig. 11) for the same liquid when only the kinematic viscosities were changed unlike the second case (Fig. 12) with totally different fluids. This difference in behaviour of damping factor for both cases may be attributed to other properties of the fluids such as, density and molecular weight.

A trend of higher increase in damping factor was observed in higher density fluids as evident in Fig. 13. However, the damping factor were very low in both cases. It may be concluded that the effect of viscous damping is negligible for the set of kinematic viscosities and maneuvers (constant radius turn) that have been considered in this study.

D. **SHAPES OF THE CONTAINER**

Finally the effect of container shape on dynamic forces and moments was analyzed (Fig. 14 & 15).

![Fig. 14. Comparison of Peak Horizontal Forces](image)

![Fig. 15. Comparison of Peak Pressure Moments](image)

The peak values for dynamic forces and pressure moments were found to be lowered in elliptical tank as compared to the circular tank. So it can be concluded that circular tank have a greater tendency to rollover due to fluid excursion effects.

**CONCLUSION**
For all the applied conditions, the result of analysis showed that values of viscous moments on the wall of container were almost negligible as compared to the pressure moments. It was found that with the change of kinematic viscosity only there is almost negligible change in horizontal forces (on the wall of container) and pressure moments (at the bottom of container). But it was observed that by changing the entire fluid (kinematic viscosity & density), horizontal forces and pressure moments vary for every fluid. The maximum peak in pressure moments and forces was observed for water and the minimum peak values were found for Gasoline. The analysis also showed that denser fluid enhances the chances of tanker rollover. On the basis of dynamic forces and moments, it was concluded that circular tank, as compared to elliptical, have a greater tendency to rollover due to fluid excursion effects. The increase of kinematic viscosity has negligible effect in damping out the fluid slosh. Although higher damping factor was obtained with denser fluids but it was also insufficient to damp out the fluid slosh. So it can be concluded that the effect of viscous damping is negligible for the set of kinematic viscosities and maneuvers (constant radius turn). Hence, there is no need to find a relationship for viscous damping in terms of tank geometry, fill level, kinematic viscosity and type of maneuver being performed by the partially filled container.

FUTURE RECOMMENDATIONS
This study was mainly focused on studying the damping effect of kinematic viscosity of the fluids inside the tankers using CFD analysis. However trammel pendulum model can also be used to study and simulate the damping effects in partially filled tankers. A two-dimensional analysis was performed in this study; however a three-dimensional analysis can give more realistic result if the experimental values of the input acceleration experienced by the container during various road maneuvers are available. Baffles also play a vital part in damping out the fluid slosh. Effect of various baffle configurations on fluid sloshing could also be studied.

REFERENCES