Dynamics of Lateral Liquid Sloshing in Flat Cylinder Tanks

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Abstract: As a complicated fluid-solid coupling multi-body system, the modelling of tankers are quite difficult. Many efforts had been made to establish equivalent mechanical model to describe liquid sloshing in tanker to simplify the modelling of tankers. The investigation on dynamics of liquid sloshing in tanks will be of great significance and a necessary support. FLUENT software was used to simulate liquid sloshing in flat cylinder tank under the situation of different lateral acceleration and liquid fill level, the center of mass (CM) of liquid bulk was utilized to analyze the dynamics of liquid sloshing. It turned out that the trajectory of liquid bulk's CM could be described by a curve, not the whole liquid bulk participates in sloshing, and there is a strong nonlinear characteristics in sloshing damping.

1 INTRODUCTION

Road tank vehicles are commonly used in carrying a wide range of liquid cargoes, mainly of a dangerous nature. At the same time, tankers also create severe traffic safety problems, which would result in huge people injury and property damage. Therefore, great attention must be paid to tanker driving safety.

It was universally accepted that liquid sloshing in partially-filled tanks is the most important factor result in tanker traffic accidents (Hasheminejad *et al*, 2009). As a complicated fluid-solid coupling multi-body system, it is quite hard to model tank vehicles, not even to investigate tankers' dynamic characteristics (Rumold, 2001). On the assumption of an equivalent mechanical model was established to describe liquid sloshing in tanks, the modelling of tanker and its dynamic analysis will be an easy work (Salem, 2000; Zheng *et al*, 2012; Qing *et al*, 2011; Utsumi, 2004). Hence, the purpose of this paper is to investigate dynamics of liquid sloshing in flat cylinder tank which are widely used in tankers. The research result will be a support for the establishment of equivalent mechanical model.

2 FLUENT SIMULATION FOR LATERAL LIQUID SLOSHING IN FLAT CYLINDER TANKS

The software of FLUENT was used to simulate lateral liquid sloshing in flat cylinder tanks. By FLUENT simulation, lateral sloshing force acting on tank walls, liquid bulk's transient CM, and sloshing moment on specific point were recorded. Also, sloshing animation was generated to judge subjectively whether software simulation could reproduce lateral liquid sloshing correctly or not.

2.1 Tank model

A flat cylinder tank model with a length of 1 m and a radius of 0.86 m was used in this study. The radius of this tank model was decided according to market survey on cross-sectional area of tanks on tank vehicles. It was showed that the value was about 2.5 m^2. The length of this tank model was set given the consideration of calculation simplicity of the mass of liquid bulk.

Only lateral liquid sloshing was taken into account in the flat cylinder tank, and liquid sloshing in different cross sections were supposed to be the same. Therefore, the three dimensional liquid sloshing in cylinder tank could be substituted for two dimensional sloshing in tank cross sections.

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A pressure inlet was set on the top of tank cross section. The circular cross section model was meshed with elements of quadrangle, and pave was selected as the meshing type.

2.2 Sloshing condition

Liquid fill percentage was used to describe the volume or the mass of liquid bulk in the tank. It was defined as the ratio of the height of liquid free surface to the diameter of the tank. Lateral liquid sloshing under the condition of different liquid fill levels was considered, and the liquid fill level was set to be 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, respectively.

In practical situation, lateral acceleration of tank vehicles is hardly to exceed 1.0 g. therefore, lateral acceleration acts on tank was set to be 0.1 g, 0.2 g, 0.3 g, 0.4 g, 0.5 g, 0.6 g, 0.7 g, 0.8 g, 0.9 g and 1.0 g, respectively.

The purpose of this study was to investigate inherent dynamics of liquid sloshing and to establish equivalent mechanical model. There hence, free oscillation of liquid bulk should be simulated to acquire sloshing parameters. To simulate free oscillation of liquid bulk, liquid bulk's CM should be away from equilibrium position. Two different methods to obtain the initial condition of free oscillation were proposed. For the first one, forced oscillation under the action of lateral acceleration was carried out first. While the center of mass of liquid bulk arrives at the highest point, the simulation of forced oscillation was stopped. Then, the ended moment in this forced oscillation case was taken as the initial condition of free liquid sloshing. For the second one, liquid free surface was set to be tilted at the very beginning of free oscillation simulation. Gradient of tilted liquid free surface was obtained by

$$\theta_0 = \text{atan}\left(a_y / g\right) \quad (1)$$

where a_y is lateral acceleration acting on tanks.

While the second method to simulate liquid free oscillation was much easier than the first one, it was used to simulate liquid sloshing in this study.

2.3 Simulation settings

A 2D planer, transient simulation was used to simulate liquid sloshing in flat cylinder tank. Pressure-based was selected as the solver. Air and water were multiphase flows in tank model, and air was set to be the primary phase. The volume of water, and intersection line between air and water were defined by user defined function. Laminar was used as the viscous model. Pressure inlet was set on the top of circular cross section, and the pressure inlet was also set to be reference pressure location. Gravity was acted on the liquid bulk, who directs to the negative y-axis. The scheme of PISO was used as pressure-velocity coupling method. For other parameters, they were accepted as software default setting.

Sloshing force and moment were monitored during simulation. Liquid bulk's CM was calculated and recorded by user defined function.

3 DATA FILTERING BY WAVELET

Liquid bulk's CM was used to investigate sloshing dynamics in this study. Before dynamic analysis, data filtering was carried out. Many filtering methods were tried, it turned out that wavelet filtering has the best performance. Therefore, liquid bulk's CM, including x-coordinate and y-coordinate, was filtered by wavelet. Sym8 was chosen as the wavelet function, and 8 layer decomposition was done. Comparison of liquid bulk's CM before and after wavelet filtering was presented in Figure 1. Also, oscillation angle of liquid bulk's CM, which was a function of *x*-coordinate and *y*-coordinate, was also presented to illustrate data filtering result.

In Figure 1, oscillation angle was obtained by

$$\theta = \text{atan}\left(-x / y\right) \quad (2)$$

where x is the x-coordinate of liquid bulk's CM, y is the y-coordinate of liquid bulk's CM.

Noise in raw data was with small amplitude and did have regular frequencies. Reason that bring irregular noise should be calculation accuracy error. For this situation, wavelet filtering was a pleasure select.

Compared with *x*-coordinate, *y*-coordinate has noise with rather large amplitude. That is to say that *y*-coordinate of liquid bulk's CM has much violent changes in sloshing, and the change trend along *y*-axis has much lower possibility than that along *x*-axis.

Oscillation angle obtained by filtered liquid bulk's CM is much smoother that that obtained by raw data, which reveals the correctness of data filtering.

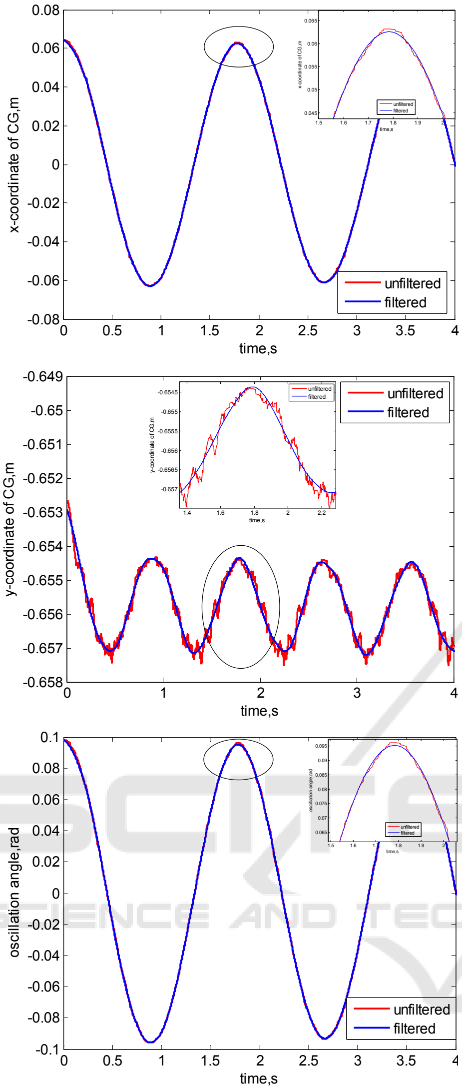


Figure 1: Comparison of liquid bulk's CM before and after wavelet filtering.

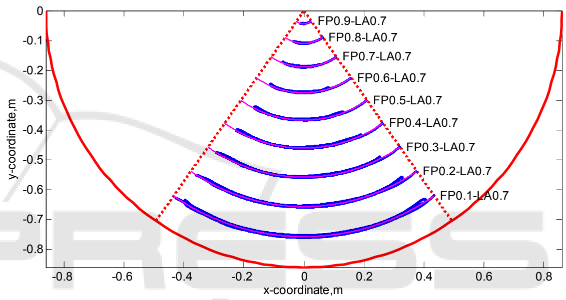
4 DYNAMICS OF LATERAL LIQUID SLOSHING

Dynamics of lateral liquid sloshing was investigated by filtered liquid bulk's CM. Its moving trajectory, oscillation frequency and damping were researched in this study.

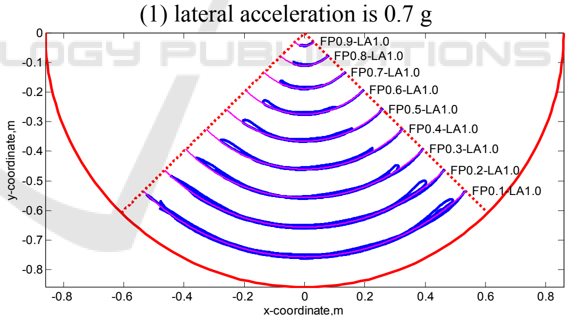
4.1 Trajectory of the center of mass of liquid bulk

Trajectory of the center of mass of liquid bulk under different lateral accelerations, i.e. different tilted liquid free surface, were presented in Figure 2 as blue lines. Also, circle which has the radius that is equal to the mean value of distances from liquid bulk's transient CM to the center of tank cross section was also presented as pink line. The tank was expressed by red line. The maximum oscillation angle of liquid bulk's CM, which was defined by the tilt angle of liquid free surface at the very beginning, was expressed by dotted red line.

For each tilted liquid free surface, liquid fill percentage changes from 0.1 to 0.9. FP is short for liquid fill percentage, and LA is short for lateral acceleration in Figure 2.



(1) lateral acceleration is 0.7 g



(2) lateral acceleration is 1.0 g

Figure 2: Trajectory of liuqid bulk's CM under different lateral acceleration and fill percentage

It was quite clear that the trajectory of liquid bulk's CM coincides well with the specific circle. A much more detailed investigation showed that R-square between the two lines is 1.00 for most cases, only case of FP=0.1, LA=1.0 g and FP=0.2, LA=1.0 g is 0.99. This result revealed that the trajectory of liquid bulk's CM could be described by a circle, and radius of this circle is the mean value of distances from liquid bulk's transient CM to the center of tank cross section.

4.2 The part of liquid bulk participates in sloshing

An interesting phenomenon was discovered from curves of oscillation angle of liquid bulk's CM which can be obtained by equation (2), as shown in Figure 3. It was quite clear that liquid sloshing is a damped oscillation, whose amplitude decreases as time goes on. Differences in amplitude between peaks were smooth and small, however, the difference between original oscillation angle and amplitude of the first peak are quite large, and the difference does not keep constant under different simulation conditions. It seems like that after liquid bulk sloshes under the action of gravity, its CM drops greatly and it could not arrive at its original position.

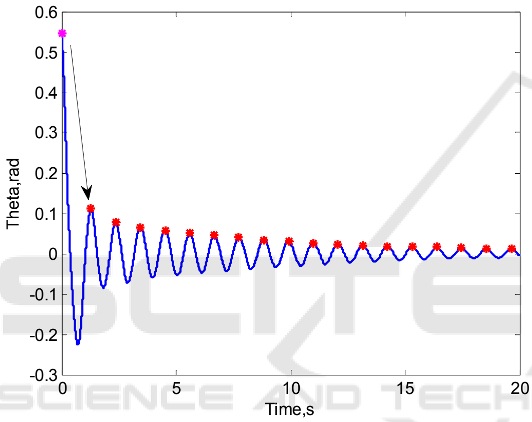


Figure 3: Curves for oscillation angle of liquid bulk's CM when LA=0.6,FP=0.9

A ratio was defined to describe the difference between the original oscillation angle of liquid bulk's CM and amplitude of the first peak, which is expressed by

$$ra = \theta_{P1} / \theta_0 \qquad (3)$$

where θ_{P1} is amplitude of the first peak.

For all simulation conditions, *ra* was calculated and presented in Figure 4. While lateral acceleration keeps constant, *ra* decreases with the increasement of liquid fill level. Besides, while liquid fill percentage keeps constant, *ra* decreases with the increasement of lateral acceleration. The ratio changes from 0.98-0.17.

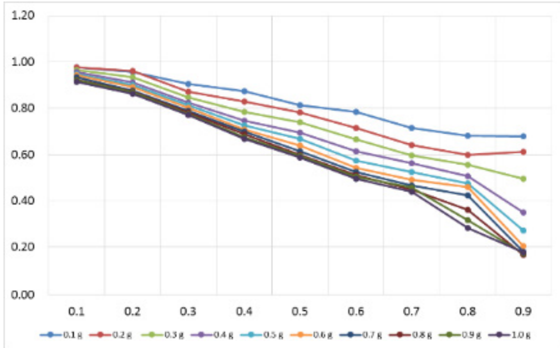


Figure 4: ra in different simulation conditions

The great drop from original oscillation angle was supposed not be caused by damping, due to the fact that damping coefficient obtained by the ratio is too large. A possibility reason lead to this phenomenon is the fact that not the whole liquid bulk participates in sloshing. For simulation initial condition, liquid bulk's CM was set to away from equilibrium position. Its coordinate was determined by gradient of liquid free surface, tank shape, and liquid fill level. As the simulation starts, liquid bulk's CM moves towards the equilibrium position, and it will arrives at a highest position under the action of inertial force. However, due to the fact that not the whole liquid bulk participates in sloshing, liquid bulk's CM cannot arrives at its original position, or even arrives at a position that is close to its original position. After the first peak, liquid bulk oscillates under the action of inertial force, and its amplitude decreases gradually because of damping.

It was also drawn from Figure 4 that the part of liquid that participates in sloshing decreases with the increasement of lateral acceleration and liquid fill level.

4.3 Liquid sloshing frequency and damping

Sloshing frequency and damping were studied according to curves of oscillation angle. As shown in Figure 5 and Figure 6. Peaks and valleys of oscillation angle were picked out, and oscillation period can be obtained by time interval between adjacent peaks or valleys. Periods obtained by peaks and those obtained by valleys have little difference, their mean values are almost the same.

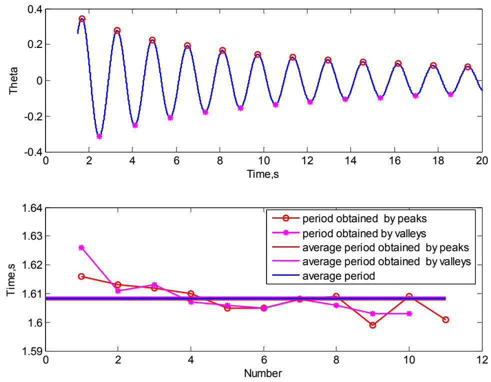


Figure 5: Sloshing frequency when FP=0.5, LA=0.6 g

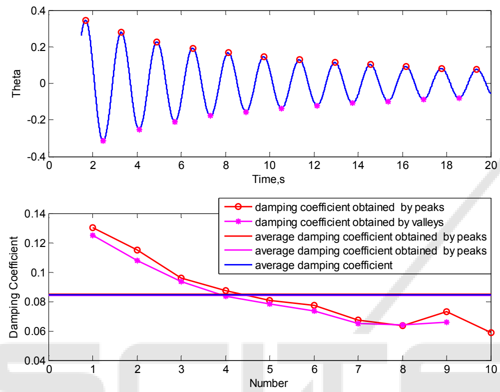


Figure 6: Sloshing damping when FP=0.5, LA=0.6 g

Besides, there is not an apparent changing trend in period with time grows. Therefore, the mean value of periods obtained by peaks and those obtained by valleys is supposed to be sloshing period. Based on that, sloshing frequency in different simulation conditions were acquired, which were listed in Table 1.

Damping coefficient can also be obtained by adjacent peaks or valleys, which is expressed by

$$\beta = \frac{1}{nT} \ln \frac{\theta_{pi}}{\theta_{p(i+n)}} \tag{4}$$

where T is oscillation period, θ_{pi} is amplitude of the *i*th peak or valley, $\theta_{p(i+n)}$ is amplitude of the *(i+n)*th peak or valley. Damping coefficients obtained by peaks or valleys have quite little difference. However, damping coefficient drops with time flies, which means that damping characteristics of lateral liquid sloshing is nonlinear. Furthermore, the changing trend of damping coefficient is quite apparent, which cannot be ignored.

The mean value of damping coefficients obtained by peaks and valleys were also calculated, which were listed in Table 2.

5 CONCLUSIONS

Lateral liquid sloshing in flat cylinder tanks under the situation of different lateral acceleration and cargo fill percentage were simulated by FLUENT. The center of mass of liquid bulk were used to investigate dynamics of lateral liquid sloshing, it was discovered that:

(1) The trajectory of liquid bulk's CM could be described by a curve.

(2) Not the whole liquid bulk participates in sloshing.

(3) Sloshing frequency almost keeps constant, but its damping coefficient drops gradually with time goes on.

Based on the dynamics of liquid sloshing, equivalent mechanical model can be established. This will be the future work. Furthermore, dynamics of lateral sloshing for other kinds of liquid should be investigated to get much more universe conclusions.

Table 1: Frequency of lateral liquid sloshing

FP \ LA	0.1g	0.2g	0.3g	0.4g	0.5g	0.6g	0.7g	0.8g	0.9g	1.0 g
0.1	1.8232	1.8247	1.8292	1.8341	1.8397	1.8459	1.8522	1.8581	1.8646	1.8685
0.2	1.7777	1.7825	1.7853	1.7885	1.7918	1.7962	1.8013	1.8087	1.8141	1.8192
0.3	1.7274	1.7322	1.7335	1.7364	1.7391	1.7418	1.7444	1.7471	1.7503	1.7530
0.4	1.6702	1.6725	1.6747	1.6758	1.6774	1.6789	1.6808	1.6823	1.6838	1.6856
0.5	1.5999	1.6038	1.6052	1.6051	1.6095	1.6083	1.6089	1.6095	1.6100	1.6114
0.6	1.5193	1.5200	1.5208	1.5223	1.5234	1.5256	1.5259	1.5255	1.5264	1.5270
0.7	1.4174	1.4190	1.4200	1.4238	1.4207	1.4212	1.4221	1.4227	1.4224	1.4205
0.8	1.2800	1.2823	1.2840	1.2824	1.2831	1.2840	1.2833	1.2836	1.2850	1.2836
0.9	1.0730	1.0768	1.0750	1.0781	1.0783	1.0802	1.0825	1.0821	1.0826	1.0830

Table 2: Damping of lateral liquid sloshing (10^{-2})

LA / FP	0.1g	0.2g	0.3g	0.4g	0.5g	0.6g	0.7g	0.8g	0.9g	1.0 g
0.1	0.69	0.80	0.95	1.14	1.35	1.54	1.71	1.85	1.99	2.10
0.2	0.56	1.62	2.03	2.34	2.83	3.06	3.33	3.43	3.55	3.65
0.3	1.79	3.51	3.65	4.55	5.01	5.31	5.54	5.80	6.21	5.98
0.4	2.25	4.30	5.63	6.01	6.79	7.02	7.47	7.52	7.94	8.29
0.5	2.73	5.26	7.12	7.17	9.53	8.45	8.82	8.98	8.63	9.05
0.6	4.28	8.02	9.35	10.70	11.31	11.57	11.82	11.30	11.24	11.34
0.7	5.39	9.81	11.43	12.10	11.95	11.93	12.69	13.24	13.05	12.47
0.8	5.74	10.26	11.70	11.92	11.79	13.01	12.81	13.11	13.58	12.75
0.9	4.81	9.73	10.69	11.32	12.16	12.04	12.46	13.06	12.96	11.58

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