Study of the effect of baffles on longitudinal stability of partly filled fuel tanker semi-trailer using CFD

Hong Duc Thong¹,², Tran Minh Tai¹,³, Huynh Phuoc Thien³,*

ABSTRACT
Sloshing of liquid in partially filled fuel tanker vehicles has a strong effect on the directional stability and safety performance. Under the maneuver of the vehicle, such as steering, braking, or accelerating, the liquid fuel in the tanker tends to oscillate. As a result, hydrodynamic forces and moments raise. It leads to reduce the stability limit and the controllability of the vehicle. To minimize the effect of sloshing, the baffles are usually added to the tanker. This paper presents the study of the effect of baffles on the longitudinal stability of the fuel tanker semi-trailer using the computational fluid dynamics (CFD) approach. A three-dimensional fluid dynamic model of a typical tanker with different baffle configurations is developed. The User Defined Function (UDF) is used to control the acceleration of the tanker according to the simulation scheme. Transient simulations are performed for the cases of constant acceleration longitudinal maneuvers with different levels of fuel in the tanker. The volume of fluid (VOF) and air obtained from the simulation is used to indirectly calculate the center of gravity of the tanker. The post-processing results show that the baffles could provide resistance to the fluid sloshing, resulting in an improvement of the longitudinal stability of the tanker semi-trailer. The results also prove that the benefit of the baffle to the fuel tanker vehicle’s stability depends on the size of the baffle, as well as the number of baffles. The 40% height three baffles model is the proper baffle model to resist the longitudinal sloshing in the partially filled tanker of the studied trailer. By adding baffles, shifting of load on the kingpin and the rear axis are less than 5% and 2% as the tanker is filled with 50% and 70% fluid level respectively.

Key words: Baffle, longitudinal dynamic fluid slosh, sloshing simulation, tanker semi-trailer

INTRODUCTION
As a tanker semi-trailer with a partially filled liquid tanker is in acceleration or deceleration, the carrying fluid tends to oscillate. This phenomenon is preferred as sloshing, a form of fluid-structure interaction. One of the major effects of sloshing is to cause the change of the center of gravity of the fluid when the tanker semi-trailer doing the braking or turning maneuver. As a result, the dynamic load shift in the roll and pitch planes could affect the roll and pitch moments, and the mass moments of inertia of the fluid cargo and may lead to a reduction in the directional stability limits and the controllability of the vehicle.

To prevent large scale sloshing, baffles are usually added to the tanker structure. Studies on the effect of baffle configuration on sloshing phenomenon using both theoretical and experimental approach have been carried out for the past several decades. However, only a few theoretical studies deal with the complicated case of sloshing such as tanker semi-trailer in braking or turning maneuver. The experimental approach could give a visual view of sloshing. But, it requires well preparation of equipment such as excitation system, acceleration acquisition system and wave-height measurement system¹. In addition, it is difficult to carry out the experiment on large testing objects².

In recent years, the numerical approach using Computational Fluid Dynamics (CFD) analysis plays an important role in predicting the behavior of fluid-structure interaction in the sloshing. Time and cost-saving can be achieved by using the CFD as a tool to find out the proper model in a group of potential models. Besides that, CFD can deal with the flow limitation and the complicated boundary condition. Several techniques have been used to numerical simulate of liquid sloshing, consisting of boundary element integral methods, finite element methods for potential flow, finite difference/volume methods solving the Navier–Stokes equations, and the smoothed particle hydrodynamics method². Among these numerical approaches, the method based on Navier – Stokes solver coupled with the Volume-of-Fluid (VOF) technique is proper to simulate large-amplitude fluid slosh under time-varying excitation acceleration, as well as to track the liquid free surface³.

In this paper, the study of the effect of baffles configuration on the longitudinal stability of an ellipse cross-
section tanker semi-trailer is discussed. The Ansys Fluent software is used to solve the Navier–Stoke equation. The Volume of Fluid model is chosen to formulate the interaction of multiphase of fluid in the tanker\(^4\). The User-Defined-Function (UDF) is used to vary the acceleration of the tanker according to the simulation scheme.

**METHODOLOGY**

**Physical Model and Static Stability Analysis**

The study is carried out on the tanker semi trailer’s Physical Model and Static Stability Analysis. The tanker model of KCT G43-BX40-02 made by Tan Thanh Trading Mechanic Corp, Viet Nam\(^5\). The main components of the trailer are shown in Figure 1. Detail of load distribution on the kingpin and the rear axles is illustrated in Table 1.

**Simulation Modelling**

**Numerical Model**

The numerical simulation is done on the fuel tanker semi-trailer G43-BX40-02. To simplify, the tanker is considered to have ellipse cross-section with the dimension of 2.5 m in height 1.96 m in wide. The total length of the tanker is 10.5 m. The fore and aft bulkheads of the tanker are assumed to be flat, and the baffles are also flat. The origin of the coordinate system used is located at the geometric center of the tanker, the x-axis is along the longitudinal axis of the tanker, the z-axis is in the vertical direction. The baffles are installed in the lateral plane with equal distance along the x-axis, and symmetry about the OXY plane axis is in the vertical direction. Figure 2 depicts the overall dimension of the tanker.

There baffle configurations that have quantity of baffle of 3, 4, and 5 are considered. On each configuration, the baffles’ height is set to 30%, 40%, and 50% of the tanker’s height. In general, baffles are flat, the overall shape of baffle is similar to the tanker cross-section. The baffle is symmetric about the longitudinal and lateral axes. The baffles that have a height of 40% and 50% of the tanker’s height are shown in Figure 3.

The simulations were performed under time-varying acceleration along the longitudinal axis as shown in Figure 4. In the first 0.1 seconds of the simulation, the acceleration is set to zero. The fuel tanker vehicle is then accelerated at a constant acceleration of 0.7 m/s\(^2\) in 7.9 seconds. As the vehicle reaches the velocity of 20 km/h, its acceleration is then set to 0 and remain at that value for the rest of simulation. For all of the simulation, the translation acceleration is set to 9.81 m/s\(^2\) in the direction of –Z-axis\(^6\).

**Simulation method**

The simulation of sloshing of fluid in the fuel tanker under the time-varying acceleration excitation is done using the commercial Computation Fluid Dynamics software, namely Ansys Fluent version 18.2. The process of simulation and post-processing of the results is illustrated in the flowchart in Figure 5. The Fluid Flow (Fluent) module of Ansys Workbench is used to create the geometry of the tanker and baffles. The unstructured mesh is used to smooth the transition at the tanker wall and the baffles. The mesh quality is controlled to be fined during the automatic mesh generation. The wireframe view of the mesh is shown in Figure 6, while the detail of the mesh is listed in Table 2.

In order to track the center of gravity of the fluid sloshing, the Volume of Fluid (VOF) multiphase model is activated in the solving model of Ansys Fluent. Two phases of air and gasoline are used to represent the gasoline and air in the partially filled tanker. The VOF model was designed to capture the position of the interface between two immiscible fluids. The volume fraction of each phase in every cell is tracked throughout the domain by a set of momentum equation between phases. The VOF model relies on the hypothesis that the fluids are not interpenetrating. In each computational cell, the total volume fraction of all phases equal to 1\(^4\). The detail of the solver and the fluid properties are illustrated in Table 3.

In order to model the time-varying acceleration motion of the tanker, the User-Defined-Function (UDF file) is used. This file describes the motion of the tankers’ geometry according to the model of the tanker’s acceleration. By running the Ansys Fluent on the Visual Studio Developer Command Prompt, the UDF file can be built, loaded into a library in Fluent. The functions defined by the UDF file will control the motion of the mesh via the setting in the dynamic mesh task page of Fluent\(^7\).

**Post processing of simulation results**

The exported data is set to contain the information of the volume of each computational cell of the mesh \(V_c\), and the volume fraction of liquid in each cell, \(vof(c)_{gas}\). As a result, the mass of liquid in each cell can be calculated by the formula:

\[
M_c = \rho_{gas} V_c \cdot vof(c)_{gas}
\]

Three cases are existing for the value of \(vof(c)_{gas}\):
- \(vof(c)_{gas} = 1\): the cell full of gasoline
- \(vof(c)_{gas} = 0\): the cell full of air (empty of gasoline)
Table 1: Load distribution on the kingpin and rear axles

| No. | Quantity                        | Value (kg) | Load on kingpin (kg) | Load on rear axles (kg) |
|-----|---------------------------------|------------|----------------------|-------------------------|
| 1   | Plate to install kingpin        | 115        | 115                  | 0                       |
| 2   | Landing leg                     | 150        | 105                  | 45                      |
| 3   | Side shield                     | 80         | 40                   | 40                      |
| 4   | Main beam & accessory           | 3870       | 0                    | 3870                    |
| 5   | Rear shield & light sys.        | 150        | -45                  | 195                     |
| 6   | Tanker                          | 5050       | 1960                 | 3090                    |
| 7   | Full gas. load (40 cubic meters)| 29600      | 12840                | 16760                   |
| 8   | Net weight at zero load         | 9415       | 2175                 | 7240                    |
| 9   | Gross weight at full load       | 39015      | 15015                | 24000                   |

*Figure 1: Forces acting on the trailer*

*Figure 2: The tanker’s geometry equipped with three lateral baffles*
Figure 3: The shape of the baffle that have a height of 40% (a) and 50% (b)

Figure 4: The acceleration excitation along the longitudinal axis.

Table 2: Detail of mesh quality for the case of 3 baffles

| Quantity         | 30% height | 40% height | 50% height |
|------------------|------------|------------|------------|
| Sizing function  | Uniform    | Uniform    | Uniform    |
| Relevance center | Fine       | Fine       | Fine       |
| Max face size    | 0.16m      | 0.16m      | 0.16m      |
| Defeature size   | 8e-04      | 8e-04      | 8e-04      |
| Smoothing        | Medium     | Medium     | Medium     |
| Node             | 10980      | 11499      | 14311      |
| Element          | 5089       | 56025      | 55383      |
- 0 < \text{vof(c)_{gas}} < 1$: the cell is partially filled with gasoline (in the free surface between gasoline and air).

By assuming that the center of gravity of fluid in the free surface cell is at the centroid of the cell, the instantaneous center of gravity of the liquid in the tanker can be obtained from the volume integrals over the computational domain. Alternatively, for the discrete mesh, the estimation of the center of gravity is done by:

\[
X_{cg} = \frac{\sum c M_c x_c}{\sum c M_c}, \quad Y_{cg} = \frac{\sum c M_c y_c}{\sum c M_c}, \quad Z_{cg} = \frac{\sum c M_c z_c}{\sum c M_c}
\]

In which, \(x_c, y_c, z_c\) are the coordinate of the centroid of the cell \(c\) with respect to the original coordinate of the tanker.

**RESULTS AND DISCUSSIONS**

**Static Stability**

The static stability of the trailer can be obtained by taking into account the load of gasoline to the change of the static center of gravity. As changing the liquid level, the load of fluid will be changed, while the weight of other components is remaining. Resulting
Figure 6: The wireframe mesh of tanker with 3 baffles, baffle height = 50%

Table 3: Detail of model and parameter setting of the solver

| Model and parameter       | Setting                                    |
|---------------------------|--------------------------------------------|
| Solving type              | Pressure based, time transient             |
| Multiple phase model      | Volume of Fluid                            |
| Number of Eulerian phases | 2                                          |
| Volume fraction parameter | Explicit                                   |
| Volume fraction cutoff    | $1 \times 10^{-6}$                          |
| Courant number            | 0.25                                       |
| Viscous model             | Reliable k – epsilon                       |
| Near wall treatment       | Scalable wall function                     |
| Pressure velocity coupling| SIMPLE                                     |
| Gradient model            | Least squares cell based                   |
| Pressure model            | PRESTO                                     |
| Momentum model            | Second order upwind                       |
| Tracking surface method   | Geo – Reconstruct                          |
| Transient Formulation     | First order implicit                      |
| Primary phase             | Air                                        |
| Secondary phase           | Gasoline liquid                            |
| Air density (kg/m$^3$)    | 1.225                                      |
| Air viscosity (kg/m-s)    | $1.7894 \times 10^{-5}$                   |
| Gasoline density (kg/m$^3$) - $\rho_{gas}$ | 830                                       |
| Gasoline viscosity (kg/m-s) | 0.00332                                  |

in the shifting of the center of gravity, and the redistribution of load on the kingpin and the rear axles. The redistribution load on the kingpin and the rear axles at different mode of liquid fluid level are shown in Table 4.

The distance from the center of gravity of the liquid fluid in the tanker to the kingpin can be calculated using the formulate: $L_1 = L_0 G_2 / G_1 = 4.490m$. In which, $L_0 = 7.930$ m is the wheelbase of the trailer.

**Dynamic Stability**

The dynamic stability of the trailer is evaluated by calculating the shifting of load due to the sloshing of fluid under a time-varying acceleration excitation. At a certain level of fluid in the tanker, the free surface of the liquid will be changed as the sloshing is occurred. As a result, the location of the center of gravity of fluid is varied, leading to a redistribution of load on the kingpin and the rear axles.

The calculation of load on the kingpin during sloshing is done by: $G_{1t} = G_1 (L_1 + \Delta x_{cg \_tanker}) / L_0$. In which, $\Delta x_{cg \_tanker}$ is the shifting of the center of gravity of the liquid fluid obtained from the post processing of simulation results. Therefore, the shifting of load on the kingpin due to sloshing can be obtained by: load shifting on the kingpin = $G_{1t} - G_{1t}$. Similarly, the load and the shifting of load on the rear axles can be obtained by applied the following formulate: $G_{2t} = G_2 - G_{2t}$, and load shifting on the kingpin = $G_{2t} - G_2$.

**Effect of the Number of the Baffle on the Load Distribution**

To study the effect of the quantity of baffle to the dynamic stability of the semi-trailer, the lateral baffles are inserted to the tanker. The baffle’s height equals 40% the height of the tanker, while the baffle quantity
Table 4: Load on the kingpin and the rear axles at different load mode of the tanker

| Load mode | $G_r$: Gross weight (kg) | $G_{11}$: Load on kingpin (kg) | $G_{22}$: Load on rear axles (kg) |
|-----------|-------------------------|--------------------------------|---------------------------------|
| 100%      | 29600                   | 12840                          | 16760                           |
| 90%       | 26640                   | 11556                          | 15084                           |
| 70%       | 20720                   | 8988                           | 11732                           |
| 50%       | 14800                   | 6420                           | 8380                            |

As set to be three, four, or five baffles. In these simulation cases, the gasoline is set up at 70% of the tanker volume. The simulation result in term of volume fraction of gasoline is depicted in Figure 7.

As seen in Figure 7a, b, c, the liquid fluid is moving toward the rear of the tanker at the time of observation. Therefore, it can be predicted that dynamic load will increase in the rear of the tanker, and decrease in the front of the tanker. Detail of the redistribution of load on the kingpin and the rear axles is shown in Table 5, the static gross weight of the trailer is 20720 kg.

Figures 8 and 9 illustrate the amount of changing in the load distribution on the kingpin and the rear axles at different baffle configuration.

As seen in Figure 8 and Figure 9, the baffles help to slow down the redistribution of load on the kingpin and the rear axles. The three and five baffle models give good results in preventing the shifting of the center of gravity of the trailer in comparison with the model of four baffles. At the time of observation, it can be recognized in all cases of the simulation that load is reduced on the kingpin and increase on the...
rear axles. In comparison to the three baffles model, the model with five baffles provides better resistance against the sloshing. The reduction of load on the kingpin of five baffles model (0.76%) is lightly smaller than in the three baffles model (1.64%). The increase of load on the rear axles of the five baffles model (0.59%) is a little bit smaller as compared with the case of the three baffles model (1.26%).

However, as evaluating the term of cost and simplicity, the three baffles model has more advantages than the five baffles model. Therefore, the tanker with three lateral baffles will be used for further study on the effect of baffle height on the longitudinal stability of the trailer.

Three baffle height of 30%, 40%, and 50% are used to find out which model will give better results in reducing of shifting of the center of gravity of the trailer as under sloshing. The simulation results in terms of volume fraction of fluid for the liquid level of 50% are depicted in Figure 10a, b, c.

The simulation result of the 70% liquid level is similar to the case of the fluid level of 50%. The 40% baffles’ height model gives the best result in preventing the load shifting, while the largest load shifting occurs in the 30% baffles’ height model. The volume fraction of gasoline for three models of baffle height is illustrated in Figure 11.

The result of load shifting for the case of 90% liquid level is shown in Table 8. The volume of fluid on the computational domain is depicted in Figure 12. It can be seen that the fluid does not have much space for sloshing. With the baffle height of 30% and 40% the baffles nearly submerge in the liquid fluid and have less effect in reducing the fluid oscillation. Baffle height of 50% provides a better reduction of sloshing.
Table 6: Effect of baffle’s height on the load redistribution – fluid level of 50%

| Baffle height (%) | Static load (kg) | Dynamic load (kg) | Shifting of load (%) |
|------------------|-----------------|------------------|---------------------|
|                  | King-pin        | Rear axles       | King-pin            | Rear axles          |
| 30               | 6420            | 8380             | 4326                | 10474              | -32.61             | 24.99  |
| 40               | 6420            | 8380             | 6206                | 8594               | -3.33              | 2.55   |
| 50               | 6420            | 8380             | 5853                | 8947               | -8.83              | 6.76   |

Table 7: Effect of baffle’s height on the load redistribution – fluid level of 70%

| Baffle height (%) | Static load (kg) | Dynamic load (kg) | Shifting of load (%) |
|------------------|-----------------|------------------|---------------------|
|                  | King-pin        | Rear axles       | King-pin            | Rear axles          |
| 30               | 8988            | 11732            | 7633                | 13087              | -15.07             | 11.55  |
| 40               | 8988            | 11732            | 8841                | 11879              | -1.64              | 1.26   |
| 50               | 8988            | 11732            | 8104                | 12616              | -9.83              | 7.53   |

Figure 11: Volume fraction of gasoline on tanker that has baffle height of 30%, 40% and 50%, liquid fluid level of 70%

The study of the effect of adding lateral baffles on the longitudinal stability of a tanker semi-trailer has been conducted by using a computational fluid dynamics approach. Lateral baffles characteristic in terms of a number of the baffle, and height of baffle have been examined to find out the appropriate baffle configuration.

It could be concluded that the simulation approach using multiphase Volume of Fluid Model in Ansys Fluent can be used to capture the air-liquid fluid interface. Analyses of the simulation results show that lateral baffles could be damping the oscillation of fluid under sloshing.

The 40% height three baffles model is the proper tanker model to resist the longitudinal sloshing in the partially filled tanker of the studied trailer. Validation on different liquids levels shows that the effectiveness of the baffle against the sloshing is high at a low liquid level. This effect reduces as the tanker is full or nearly full of liquid.

CONCLUSIONS

The study of the effect of adding lateral baffles on the longitudinal stability of a tanker semi-trailer has been conducted by using a computational fluid dynamics approach. Lateral baffles characteristic in terms of a number of the baffle, and height of baffle have been examined to find out the appropriate baffle configuration.

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The 40% height three baffles model is the proper tanker model to resist the longitudinal sloshing in the partially filled tanker of the studied trailer. Validation on different liquids levels shows that the effectiveness of the baffle against the sloshing is high at a low liquid level. This effect reduces as the tanker is full or nearly full of liquid.

LISTS OF ABBREVIATIONS

CFD: Computational Fluid Dynamics
UDF: User Defined Function
VOF: Volume Of Fluid

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.
Table 8: Effect of baffle's height on the load redistribution – fluid level of 90%

| Baffle height (%) | Static load (kg) | Dynamic load (kg) | Shifting of load (%) |
|-------------------|------------------|-------------------|----------------------|
|                   | King-pin         | Rear axles        | King-pin             | Rear axles          |
| 30                | 11556            | 15084             | 10445                | 16195              |
|                   | -9.61            | 7.37              |                      |                     |
| 40                | 11556            | 15084             | 10574                | 16066              |
|                   | -8.5             | 6.51              |                      |                     |
| 50                | 11556            | 15084             | 10790                | 15850              |
|                   | -6.63            | 5.08              |                      |                     |

Figure 12: Volume fraction of gasoline on tanker that has baffle height of 30%, 40% and 50%, liquid fluid level of 90%

AUTHOR CONTRIBUTION

The contribution of each author in this paper is listed as below:

Hong Duc Thong contributes in the supervision, project administration, and writing & editing.

Tran Minh Tai contributes in conducting the research and investigation process, and analyzing the simulation data.

Huynh Phuoc Thien contributes in the supervision, developing of methodology, and writing & editing.

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Nghiên cứu tác dụng của vách ngăn đối với sự ổn định dọc của sơми rơ-moóc chở xăng sử dụng phương pháp mô phỏng số

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TÔM TÁT
Sự sóng sánh của chất lỏng trong bồn chứa không gây tăc hại đến ổn định dọc và sự vận hành an toàn của sơми rơ-moóc bồn nhiên liệu. Khi xe chuyển hướng, tăng tốc hoặc phanh, chất lỏng trong bồn có xu hướng dao động. Kết quả là các lực và mô men thủy động sẽ xuất hiện làm giảm giới hạn ổn định và khả năng điều khiển của xe. Để hạn chế tác động của dao động sóng sánh, các vách ngăn thường được thêm vào cấu trúc của bồn. Trong bài báo này, nghiên cứu về tác dụng của vách ngăn đối với sự ổn định dọc của sơми rơ-moóc chở xăng sử dụng phương pháp số sẽ được trình bày. Một mô hình tính toán số ba chiều với các cấu trúc khác nhau của vách ngăn được xây dựng phục vụ cho việc mô phỏng. Hệ thống vi tính được mô phỏng (UDF) được sử dụng để điều khiển gia tốc của bồn chứa trong quá trình mô phỏng. Mô phỏng được tiến hành cho trường hợp xe được驾驶 tốc độ nhất định theo phương dọc với các mức tải khác nhau trong bồn chứa. Từ đó, thể hiện chất lượng của Phương (VOF) thu được từ quá trình mô phỏng được sử dụng để tính toán vị trí trong tâm của bồn chứa khi xảy ra sự sóng sánh của chất lỏng. Việc phân tích kết quả mô phỏng cho thấy các vách ngăn có khả năng chống lại các dao động sóng sánh trong bồn, kết quả là làm cải thiện ổn định dọc của phương tiện. Các kết quả tính toán cũng cho thấy ổn định dọc của xe bồn phụ thuộc vào số lượng và kích thước của vách ngăn. Mô hình bồn với ba vách ngăn có chiều cao bồn bằng 40% chiều cao bồn cho kết quả tốt nhất trong việc giảm thiểu sự sóng sánh của chất lỏng trên xe bồn khảo sát. Bằng cách thêm vào các vách ngăn, sự thay đổi tài trọng trên chốt kéo và trên trục sau có thể nhỏ hơn 5% và 2% khi mức xăng trong bồn lấn lở ở mức 50% và 70% chiều cao bồn.

Từ khóa: Vách ngăn, ổn định dọc của sơми rơ-moóc, mô phỏng sóng sánh trong bồn chứa, xe bồn

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