Design of a fuel tank in Volvo front loader L120
Effects of the baffles on reducing liquid sloshing

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Abstract

Sloshing phenomena could seriously damage tank structures and reduce its lifetime. On the one hand, studies directly recommend the use of baffles to solve these problems, nevertheless on the other hand the existence of small tanks or plastic tanks without baffles confuse and complicate the case.

The first aim in this thesis is to clarify the necessity of baffles for a particular diesel tank L120 H-Generation in Volvo front loaders. Then, the second aim is to improve the existing design.

Four configurations are proposed and checked independently. Experiments in the lab, FEM static stresses analyses and vibrational simulations are done in order to fulfill the requirements.

The conclusion of this thesis is that the dissipation of energy is highly recommended, so having an oblique baffle with holes could be a good way to reduce the sloshing and extend the lifetime of the tank.

Key words: Sloshing phenomena, baffles, steel tank, front loader, vorticity, hydroimpact, fuel trap.
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1 Introduction

Front loaders could be considered as construction equipment with several usages, for instance heavy construction, agriculture, material handling and mining industry. The modular design and the amount of additional equipment make them usable to any kind of construction.

Driving up, backwards, braking in a sudden manner or accelerating are some of the activities that these front loaders must stand during operation time that result in extreme movements of the fluid inside the tank. The fluid’s impacts in the walls generate stresses that could damage the structure of the tank. This problem not only happens in front loaders, but also in other vehicles such as aircrafts or ships.

1.1 Background

Nowadays Volvo manufactures two different kinds of tanks for the L120 H-Generation front loaders (Yang Shin, 2013). Although the main difference between them lies in the material, plastic or steel, many other features make them behave in a completely different way.

A 270 liters steel tank is screwed to the rear frame under a diesel engine. It generates severe vibrations that affect the whole rear frame structure and the tank as well. The tank is very long and wide although not too high. Such configuration could generate large waves that shake the fluid, which leads to several problems and could cause unexpected deformations or leaks in the tank structure.

Plastic tanks despite not having any partition or baffle inside, can perfectly bear the sloshing phenomenon, while a steel tank, with their corresponding baffles installed, can crack. Some laboratory vibrational tests demonstrate that a steel tank has fatigue problems in the corners, where the fuel suction trap is located.

Cracking is a very serious problem that could lead to leakage and even make the machine stop working. Even being safer and cheaper, due to customer’s requirements the use of plastic tanks is not possible everywhere.

The case of this study consists of a 270 liters steel tank, resting on a skid plate thanks to longitudinal edges that leave a gap of 10 mm between them. In contrast to the plastic tank which is fastened by strings to the structure, the steel one is assembled to the skid plate by four screws. The tank originally had one longitudinal baffle and a fuel sump, supposedly used to avoid sloshing, reinforce the structure and stabilize fluid movements.
To increase the lifetime of the tank, studies about sloshing phenomenon must be done. Therefore, the first step in this thesis work is to determine whether the baffles are needed or not. After this, the appropriate H-Generation fuel tank should be redesigned and tested.

1.2 Purpose and aim

The general purpose of this thesis is to improve the current steel tank used in H-Generation front loaders in Volvo Construction Equipment. It is necessary to determine the need of baffles, study the effect of vertical baffles on liquid sloshing in this particular tank and find out the best configuration to reduce the sloshing phenomenon as much as possible.

Then the subtasks to fulfill the aim of this thesis are:

- Define the necessity of baffles in the L120 tank.
- Make three different baffles by applying the scientific knowledge acquired.
- Test in the lab the three baffles proposed by combining them into four different configurations.
- Finite element design and analysis of the stresses.
- Vibrational tests.
- Compare all the results and give a conclusion.

1.3 Hypothesis and Limitations

In this study there are several limitations to consider. The first limitation is that the tank contains diesel. Nevertheless, for the experiments made in the lab, the tank was filled with water. The purpose of the lab tests is just to understand the behavior of the liquid sloshing without any kind of numerical results, therefore filling it with water is good enough for this aim (Yang Shin, 2013).

Another limitation is that the external shape of the tank cannot be modified at all, because no changes will be done to the surroundings. In the experiments, the tank tested was L150, whose shape is quite similar but 100 liters bigger than the real one L120. For the aim of these tests which is mainly to observe the fluid behavior, the similar shape of both tanks makes the tank L150 good enough for this purpose. The differences between both tanks are shown in appendix A.
1.4 Reliability, validity and objectivity

Tank tests carried out in the laboratory are not as restrictive as the real front loaders work conditions. As the purposes of the laboratory tests are just to understand the behavior of the liquid inside the tank, check the differences generated by changing the baffles and evaluate the best configuration of them, the visual results obtained are good enough to fulfill these requirements.

The fluid movement will be recorded with a high speed GoPro camera installed in the modified tank and the vorticity and dissipation of kinetic energy will be studied. Nevertheless, no further fluid calculations will be computed.

Baffles should be welded to the tank, but to simplify the study and make repetition of the tests possible using different baffles, they will be fixed to the structure with screws.

Weldings are not modeled so the results will not take this feature into consideration.
2 Theory

2.1 Hydroimpact

Hydroimpact is the physical phenomenon that occurs when a vehicle with a certain speed suddenly stops causing a stoppage of liquid mass. Due to the loss of kinetic energy, firstly the liquid pressure will increase along the tank and the amplitude of these movements could be quite large (Shimanovsky, 2012). After some time, the pressure will slowly start to decrease and oscillatory movements will appear in the liquid.

Fluid movements in a tank have an infinite number of natural frequencies. When the frequency of the tank motion is close to one of the natural frequencies of the tank fluid, large sloshing amplitudes can be expected and resonance will occur (Akyildiz, 2005). As the sloshing phenomenon is nonlinear, resonance will not appear exactly at the natural frequency, but at a frequency close to that value. The waves created will hit the tank’s walls, increase the pressure and can damage the structure.

Depending on the liquid depth and frequency of oscillations, different kinds of waves will appear (Akyildiz, 2005). For a shallow liquid oscillating at a frequency much lower than its resonance frequency, a standing wave will be formed. This wave will become a train of travelling waves when the frequency increases. Hydraulic jump will take place due to a small disturbance and appear over a range of frequencies near the resonance frequency. If the frequency keep rising, the jump will become a solitary wave. In case of deeper liquid, large amplitude standing waves will appear if sloshing is close to the resonance. These waves are asymmetric and, at large amplitude tank excitations may be combined with traveling waves.

2.2 Water and diesel properties

Liquid is one of the three known physical states and one of the main features is that they have a certain volume but not a certain shape. All liquids can be characterized as almost incompressible, thus even applying a large pressure the liquid will not change its volume. Because of this property, high pressure and stresses are generated when liquid is stopped by the baffles (Eswaran, 2009).

Liquid sloshing is one of the problems of great practical importance regarding to the safety. It is known that partially filled tanks are prone to violent sloshing under certain motions. Therefore, one of the main causes that justify the use of water instead of diesel in the lab experiments is the fact that the diesel can easily evaporate and mix with the air generating high explosive mixture.
The sloshing problem depends heavily on the properties of the fluid. In table 1, two important properties of liquids are compared.

The first property shown is the density, which is a physical unique property of matter that measures the mass per unit volume (RAE, 2014). As it is possible to observe, although densities of both fluids are comparable, water is denser than diesel, so stresses generated in the tank will be greater and the results more restrictive.

The second property that should be taken into account is the viscosity of the fluid. This property could be defined as the quantity that describes a fluid's resistance to flow. In other words, it is the ratio of the shearing stress to the velocity gradient in a fluid. Fluids resist the relative motion of immersed objects through them, thus a shear layer is created and the energy could be dissipated by viscous action (Elert, 1998–2014).

As it is shown in table 1, fuel viscosity is greater than water viscosity, which means that the dissipation of energy using fuel will be greater as well. Therefore, it is possible to assume that the results using water instead of fuel in the experimental case would be more restrictive.

<table>
<thead>
<tr>
<th>Density [kg/m³]</th>
<th>Viscosity [cps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>1000</td>
</tr>
<tr>
<td>Diesel</td>
<td>850</td>
</tr>
</tbody>
</table>

The third property that deserves to be mentioned is the free surface. It can be defined as the surface that is subjected to a constant perpendicular normal stress and no parallel shear stress, such as the boundary between two liquids or a liquid and a gas (Myasuda, 2014). Any motion of the free liquid surface inside its container caused by any disturbance is called sloshing, and generates a nonlinear wave.

The more stable the free surface is, the less sloshing problems will appear. The critical baffle height is one of the main factors that will affect the movements of the fluid inside the tank since the roof of the tank should never be reached.

2.3 Physical phenomena

Several physical phenomena occur inside the tank when the vehicle suddenly stops. As has been explained before, due to the hydroimpact, an increase of the pressure travels along the tank. Depending on the nature of the pressure,
two different kinds of dynamic pressures can be distinguished, impulsive and non-impulsive (Akyildiz, 2005). The first pressures, localized and extremely high, are caused by rapid pulses due to the impact between the tank surface and the liquid itself. They are associated with hydraulic jumps and travelling waves. Nevertheless, the non-impulsive pressures result from standing waves. In this case, the pressure varies slowly being neither harmonic nor periodic, even though the external oscillation is harmonic. According to the sloshing phenomena, impulsive pressure which strongly varies with time has to be taken into account.

To proceed with the phenomena that occur inside the tank, hydrodynamic damping should be described. When a baffle is placed inside the tank, its blockage effect increases, which results in a decrease of the liquid sloshing and leads to energy dissipation. A vortex between the baffle tip and the liquid surface is created and it becomes weaker and smaller as the height of the baffles is increased. This causes a reduction of the damping effect of the tip vortex on the liquid sloshing (Jung, 2012).

Figure 1 shows the vortex created at the upper part of a baffle in a rectangular tank. As has been already explained, the higher the baffle is, the smaller the vortex.

![Vortices for 20% and 80% baffle's height respectively (Jung, 2012)](image)

2.4 Finite Element Method

Nowadays, the Finite Element Method (FEM) is one of the most powerful widely used numerical methods to solve arbitrary differential equations which approximates the real solution by dividing the whole body into a finite number of small elements.

Bodies are assumed to be continuous and two different forces could be considered, surface forces (forces per unit area) and body forces (forces per unit volume).
Firstly, the equilibrium of the body should be established. For a three dimensional elasticity case, the equilibrium equation is presented below.

\[ \nabla^T \cdot \sigma + b = 0 \]

where \( \sigma \) is the stress tensor and \( b \) is the body force.

Some mathematical operations lead to obtain the weak formulation, presented as follows.

\[ \int_V (\nabla v)^T \sigma \, dV = \int_S v^T t \, dS + \int_V v^T b \, dV \]

where \( v \) is an arbitrary weight vector, \( V \) is the volume, \( t \) is the traction vector and \( S \) is the surface. This weak form is very important in the field of solid mechanics and it is often named as virtual work principle.

2.5 Vibrations

Sometimes vibrations could be a disadvantage, therefore great efforts should be done in order to reduce them. Every machine that tends to do work by reciprocating or rotating induces vibrations due to its own characteristics which can be measured or calculated (Kaarthic, 2008).

Vibrations can be classified in four types:

1. Free Vibration: appears when no external loads act on the system. If damping occurs the motion will vanish, otherwise, the body will tend to vibrate forever.

2. Forced Vibration: occurs due to the forces acting on a structure, although they tend to be damped or stopped due to the system nature.

3. Damped Vibration: forced vibration or a self-induced vibration is damped or stopped from causing further inconvenience.

4. Random Vibration: these occur very rarely and randomly and are hence very difficult for controlling.

When the vibration frequencies are close to one of the natural frequencies, resonance could occur, which can lead to serious damages making structures collapse.
3 Literature review

3.1 Baffled and unbaffled tanks

In this subchapter the need of baffles is discussed. Large oscillations and large impact pressures created by hydroimpact can damage the walls of the tank and welds could crack. Figure 2 shows the results of a 2D analysis of liquid sloshing in rectangular tank with and without baffles (Akyildiz, 2012). The blue arrows describe the direction and the value of the velocity and the red lines indicate the liquid free surface.

![Comparison of 2D sloshing free surface in the tank without baffles and with baffles at time 15 sec (Akyildiz, 2012).](image)

As it is shown before, the difference between the baffled and the unbaffled case is critical. The baffle installed inside the tank reduces dramatically the free surface displacement and the velocity of the fluid. The height of the baffle in this case is 75% of the total height.

3.2 Features to consider while designing baffles

Through numerical and experimental investigations and analyses, it is possible to consider some factors that severely affect the design of a tank. Although the tank geometry and the fill depth percentage could be considered as main features, the oscillation amplitude, the acceleration of the vehicle, the properties of the fluid (density, compressibility or viscosity) and some other factors must be taken into consideration (Zheng, 2013).

As has been explained before, longitudinal sloshing inside an unbaffled partially filled tank could cause extreme degradation, becoming highly recommendable to install transversal baffles inside the tank to avoid these damages. A vortex is originated near the baffle tip and a flow separation is generated before and behind the baffle when liquid sloshing occurs.
The shape, height, position and number of baffles have a great impact on the antisloshing effect. In order to understand the behavior of the liquid inside the tank, some investigations comparing different baffles are presented as follows.

3.2.1 Height of the baffles

To obtain the interaction between fluid and baffles further studies have been considered. The following study presents how the height of the baffle could affect the fluid movement when the structure is excited (Jung, 2012). The case of study consists of a 160 liters tank with a filling level of 70% of the tank height. The height ratio between the baffles, $h_b$, and the free surface of the liquid, $h$, ($h_b/h$) is evaluated in steps of 0.2 from 0 to 1.2.

The measurement of the free surface elevation, figure 3, $E_{\text{max}}$, was tested and the results are presented in the following diagram.

![Figure 3. Maximum elevation of the free surface as a function of the baffle height (Jung, 2012).](image)

According to this study, the critical baffle ratio is 0.3 and below it, the baffle does not affect the fluid movement. Over ratio 0.3 the free surface does not reach the top wall and the pressure in the upper part of the tank drops rapidly. Ratio 0.9 is the most effective one to stabilize and over 0.9 no considerable differences are observed. The 3D simulation of the effect of the baffle height on fluid movement is attached on figure 4. Time sequences are shown in each column increasing the height of the baffle in each row respectively.
The simulation presented above demonstrates the big influence of the baffle height ratio and the behavior of the fluid. Over ratio 1.0 the fluid starts to behave as in two separated tanks and the liquid free surface does not even reach the top of the baffle. The fluid does not move between subdomains. In this research, the pressure is examined as well. The results show that the largest pressure, which appears in the unbaffle case, is above the critical height of the baffle of 0.3.

3.2.2 Shape of the baffles

Baffles could be designed in many ways, and some of the most interesting geometries will be shown in this subchapter. To begin, a drawing of a conventional baffle for a cylindrical tank is presented in figure 5.

This model, even being the most basic design, extremely decreases the sloshing phenomenon, (Zheng, 2013). However, changing the profile of these conventional baffles causes big differences while calculating the sloshing force.
The use of the baffle with corrugations, shown in figure 6, reduces by half the maximum stress and by one fourth the deformations, in comparison with the conventional one (Shimanovsky, 2012). Nevertheless, stresses in the most loaded part of the tank exceed the yield strength of the material.

Figure 6. Baffle with corrugations and its corresponding stresses (Shimanovsky, 2012).

The wavy baffle, shown in figure 7, is an improvement of the baffle with corrugations. In this case, maximum stresses are four times lower and deformations two times in comparison with the corrugated one. Moreover the mass of the partition is also reduced.

Figure 7. 3D Wavy baffle and its corresponding stress (Shimanovsky, 2012).

Another redesign that deserves to be mentioned is the so called circular or ring baffle, which is based on the conventional one, but with a hole in the center and/or more around it, as shown in figure 8, (Zheng, 2013).
It is demonstrated that the more and the smaller holes the baffle has, the better results are obtained. Having several holes not only reduces the sloshing force, the force variation is smoother as well. Sloshing force is greatly degraded when liquid flows through the holes, therefore a baffle with many small holes must have an excellent behavior on reducing liquid sloshing.

To finish with this subchapter a different baffle’s shape is briefly presented, the staggered baffle, in figure 9, which is divided in two parts, located in two different vertical planes.

Several studies changing the angle in these two configurations demonstrate that the reverse staggered baffles with an inclination of 20° reduce the sloshing force dramatically making at the same time the variations of this force much smoother than those generated in tanks with other staggered baffles.

3.2.3 Position of the baffles

The position of the baffles severely affects the reduction of the sloshing phenomenon. Some years ago, a very complete experiment to study the pressure distribution in a tank due to the liquid sloshing was carried out.
(Akyildiz, 2005). A rectangular, 263 liters tank was tested. A total of 145 tests were done by varying different features, as the level of liquid, excitation amplitude, frequency of oscillation and the baffles’ position. To be focused only in this characteristic, it has been taken into consideration only the tests that present all features constant, except for the position. Thus, 25% fill depth, 8° amplitude, 2 rad/s roll frequency tests have been analyzed.

As it is possible to observe in figure 10, baffles reduce dramatically the pressure on the sides of the tank. A shear layer is created and the energy is dissipated by the viscous action.

![Figure 10. Variation of the pressure for a tank with no baffles, with a vertical baffle and with a combination of vertical and horizontal baffles (Akyildiz, 2005).](image)

The experiment shows that the traveling characteristics of the sloshing wave are improved by using horizontal baffles which also creates a hydraulic jump and a breaking wave that dissipates the energy. It can be noticed that the use of both baffles reduces the pressure more than the use of just a vertical one.

By analyzing these results it is possible to reaffirm that the use of baffles is highly recommendable as presented before (Akyildiz, 2005). Although the combination of horizontal and vertical baffles is the best option, the difference in the results is not that significant. This means that in a real case, the use of only vertical baffles could be good enough to reach the objectives and the costs of manufacturing and materials would be lower.

Figure 11 shows a graph that compares the unbaffled case, the tank with horizontal and vertical baffles and the tank with a ring baffle, which consists on a vertical baffle with a hole in its center (Eswaran, 2009). The decrease of the pressure by using baffles is obvious, but here it is possible to observe that ring baffles are the best option because they reduce the pressure to the maximum extent.
The velocity motion of the liquid at the walls is suppressed, as well as the wave amplitude, and the vertical motion of the liquid near to the walls is retarded. Vertical baffles suppress the horizontal component of the velocity while the horizontal and ring baffles decrease the vertical component. Stresses on the walls are reduced thanks to the turbulence created in the sharp edges that dissipates the energy.

To proceed with this subchapter, another research deserves to be mentioned (Zheng, 2013). The case of study consists of a cylindrical tank with four conventional baffles inside, which means that it is divided into five spaces, with six possible walls that could be affected by the sloshing phenomenon. The sloshing force was studied in relation to the angle that conventional baffles had with the y-axis, see figure 12, (Zheng, 2013).

In order to investigate the influence of the baffle installation angle on liquid sloshing reduction, different oblique angles were configured. The oblique angle was set to be 0° (vertical baffle), 5°, 10°, 15° and 20° degrees. The corresponding baffles were labeled N0, N5, N10, N15, and N20.

Taking as an example the sloshing force acting on the third wall, i.e. the second baffle, it can be observed in the graph below that having a baffle with any kind of inclination could derive in greater results when a 40% of the tank is filled.
This study confirms that the 20° angle baffle is the best choice although the results differ very little between tanks equipped with different angled baffles at the same liquid fill level. When the level of liquid inside the tank is higher than a 40%, the inclination of the baffle scarcely affects the sloshing force.

Nevertheless, the larger the oblique angle is, the heavier the baffle will be, then the structural tank’s mass will be increased and the useful load capacity of the tank will be decreased. Therefore, the 5° baffle could be the best option because as it was explained before, the sloshing force is quite the same for every angle baffle, but this one is at the same time the lightest one.

A brief explanation of the place that baffles should have in a tank depending in their shape is presented as follows (Zheng, 2013).

The distribution of the baffles in the tank should fulfill specified requirements. In case of conventional and ring baffles, the distribution in a cistern deposit should be the one presented below in figure 13, which divides the deposit into five parts.

![Figure 13. Distribution of conventional and ring baffles (Zheng, 2013).](image-url)
In contrast to the conventional and ring baffles, staggered baffles, shown in figure 9, are divided into two parts, located in two different vertical planes. The longitudinal distance between them is shown in figure 14.

![Figure 14. Distribution of staggered baffles (Zheng, 2013).](image)

The second configuration needs eight baffles that divide the tank into nine parts, therefore more cost on manufacturing will be needed.

After this literature review chapter, it is possible to conclude that the design of the baffles inside the tank depending on the height, shape and position, leads to great differences regarding the sloshing phenomenon. Therefore detailed studies to select the baffle or baffles that fulfill specific requirements, should be done in order to avoid this phenomenon.
4 Method

After all the theory and studies presented, the clear approach of the necessity of baffles has been established. First of all the original design is shown in figure 15 and then, the position of the baffle and the fuel trap is presented in figure 16.

Figure 15. 3D View of the original design

Figure 16. Original position of the baffles
The tank has 270 liters and it originally had one longitudinal baffle which was welded to one of the walls of the tank and to the floor as well. There was also a fuel trap welded to the baffle to reinforce the structure and stop the fluid movement. Higher stresses and cracks appeared exactly in this part, where the fuel trap was located. As it is possible to observe in figure 17, the original baffle was completely flat, which means that energy was not well dissipated and high stresses appeared due to the sloshing phenomenon.

Another detail that deserves to be mentioned is the welding problem, which aggravates the cracking in the area where the fuel trap is located. Generally, more than two welded joints should not interfere, but in the original design the fuel trap shown in figure 18 is welded to the ground of the tank, hence the intersection line leads to high stresses. Figure 19 shows an example of the welding problem.
After considering the known effects of the different features of the baffles, presented in the previous chapter, a new design of the baffles has been proposed in order to solve all the problems. Figure 20 and figure 21, show a 3D view of the new design and the position that the baffles have respectively. The new baffles will be able to avoid sloshing and welding problems and the structure will not need an extra reinforcement, then the fuel trap is not needed anymore, so it has been deleted. Detailed drawings are presented in appendixes.
The predominant movement of the liquid is forwards and backwards, so the longitudinal baffle does not really have to support very high stresses, but it serves as a reinforcement of the structure itself. In order to check the influence of this baffle, figure 22 and figure 23 show the two different baffles that have been proposed for the longitudinal position, one of them with holes and the other one without. Due to the welding process no holes exist where the two baffles are connected.

Another improvement that deserves to be mentioned is the removal of the material in the lower corners, which is not only because of the welding technology principles but also to allow the liquid go through different subdomains.
As has been explained before in the theory chapter, having certain angle between the baffle and the vertical plane could positively affect the sloshing phenomenon, figure 12, therefore for the transversal position, only one baffle with several holes, figure 24, has been proposed. It has been tested in two different positions: totally vertical and 5° inclination in respect to the vertical.

To select the optimal design and position of the baffles, stress analysis, vibrational analysis and laboratory experiments have been carried out and explained as follows. For each of the three tests, four different configurations have been checked, see table 2.

<table>
<thead>
<tr>
<th>CASE</th>
<th>LONGITUDINAL (always 0°)</th>
<th>TRANSVERSAL (always with holes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>with holes</td>
<td>0°</td>
</tr>
<tr>
<td>2</td>
<td>with holes</td>
<td>5°</td>
</tr>
<tr>
<td>3</td>
<td>without holes</td>
<td>0°</td>
</tr>
<tr>
<td>4</td>
<td>without holes</td>
<td>5°</td>
</tr>
</tbody>
</table>

Show Figure 23. Longitudinal baffle without holes

Show Figure 24. Transversal baffle with holes
4.1 Experimental methodology

To achieve a better understanding of the fluid motion inside the tank, and confirm the theory studied in this thesis, experiments have been carried out in the lab. The tank used for the experiment was L150 instead of L120, which means that the tests have been performed using a bigger tank. Figure 25 shows the original tank used for the experiments, and the baffles have been designed proportionally and placed with the same distribution. Baffles were screwed instead of welded, to make possible the replacement after each of the four cases. Drawings are shown in appendixes.

All tests have been done using water instead of diesel.

![Figure 25. Tank L150](image)

To make the observation of the fluid easier, the top wall of the tank was removed. After that, the inner part of the tank was painted in white to increase the brightness. Finally, some colorful particles (glitter) were added to the water to reflect the light.

After all these preparations, the tank was placed in a trailer and fixed with stripes, see figure 26 a). Fluid motion was recorded using a high speed GoPro camera, shown in figure 26 b), while the car was driven in order to simulate the front loader behavior.
4.2 Stresses methodology

The three baffles proposed have been modeled and statically analyzed using Catia V5R19 software and placed in the existing model of the tank L120 H-Generation. The model has been treated as one part to make the calculations simpler.

The entire tank including the baffles is made of steel and properties are presented below, table 3.

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young Modulus</td>
<td>210 GPa</td>
</tr>
<tr>
<td>Poisson Ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Yield strength</td>
<td>140 MPa</td>
</tr>
<tr>
<td>Density</td>
<td>7850 Kg/m³</td>
</tr>
</tbody>
</table>

The global model has been meshed using 3 mm tetrahedron elements with linear approximation. The baffles have been modeled with a 1.5 mm mesh to obtain more accurate results in the area of interest. To simplify the calculations and to decrease the meshing time, the accuracy of the elements’ geometry has been defined as 10%.

Due to real conditions, the tank has been clamped with four holes where the screws are located and supported on the two longitudinal edges that rest on the skid plate, see figure 27. Gravity has been applied to the whole mesh.
The pressure changes with the height of the liquid, so it will not have the same value in the bottom than in the upper part of the tank. As this is a conservative study and baffles are not that high, it is considered that the pressure is equally distributed along the baffles. To simulate the fluid behavior, distributed loads acting on the baffles and walls of the tank have been considered. The formula used to calculate the forces is the following:

\[ F = \rho \cdot V \cdot (\ddot{x} + g) \]

where \( F \) is the distributed load, \( \rho \) is the density of the diesel, \( V \) is the volume of the liquid acting on the corresponding wall or baffle, \( \ddot{x} \) is the acceleration of the front loader and \( g \) is the gravity. Values of acceleration are shown in table 4.

<table>
<thead>
<tr>
<th>AXIS</th>
<th>ACCELERATION</th>
<th>DECELERATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>X (longitudinal)</td>
<td>15.7 m/s²</td>
<td>19.62 m/s²</td>
</tr>
<tr>
<td>Y (transversal)</td>
<td>1.57 m/s²</td>
<td>1.962 m/s²</td>
</tr>
</tbody>
</table>

All calculations have been made using the values of the deceleration in x and y axis respectively, so the requirements in the worst case are fulfilled.

According to the theory chapter, the worst case of sloshing normally appears when the tank is filled with a 70%, then to calculate the volumes acting in each subdomain, a 70% of the total capacity of the tank has been considered, see figure 28. Values of the volumes and forces applied are shown in table 5 and table 6 respectively.
4.3 Vibrations methodology

The engine, which is located over the tank, works under a frequency between 40 and 90 Hz. It is mounted on a rubber suspension to decrease the excitation, so finally the vibration transmitted to the frame is around 25 Hz. The aim of this analysis is to obtain the three lowest modes on the tank and ensure that resonance will not occur. At the same time a comparison between vibrational results in new and old tank will be shown.
Frequency analyses have been done using Catia V5R19 and in the same way as the stresses analyses, so the model was converted to one part and steel was considered in the entire tank, see table 3.

A second point to clarify is that the tank has been screwed in the same four holes and is resting in two longitudinal edges as well.

A mesh of 3 mm tetrahedron elements with linear approximation has been considered and the accuracy of the elements has been set as 10%.

To simulate the fuel inside the tank, 180 Kg were uniformly distributed in the tank.

\[ V_1 + V_2 + V_3 = 212 \, l \]
\[ 212 \cdot 0.85 \approx 180 \, kg \]
5 Analyses of the results

5.1 Experimental analyses

The main purpose of the experimental part was the observation of the fluid behavior and vorticity inside the tank to reaffirm the theory studied before. Due to the fact that the front loader moves mostly forwards and backwards, another point to discuss has been the necessity of holes in the longitudinal baffle. The influence of the transversal baffle’s inclination has been another outcome to check.

According to the theory, the worst case of study is when the tank is filled with a 70% of the capacity, then the first wave should not reach the top wall of the tank when the baffles are installed. These experiments do not study a rectangular tank with ideal excitation, in this case the geometry is more complex. After the first test, some liquid spilled out of the tank, so the decision of filling it with a 50% instead of a 70% was taken. All results were validated with this amount of liquid, and observation became easier.

Two different designs for the longitudinal baffle with and without holes were chosen to check the significance of the transversal fluid motion. For all four cases, it was possible to observe a small amount of liquid coming out of its corresponding subdomain when the first wave was created, that was due to the fact that the wave’s free surface elevation was greater than the height of the baffle. As it has been mentioned before, the transversal component of the water movement was assumed to be a 10% of the longitudinal motion. This assumption was easy to confirm in the laboratory testing because the liquid motion in transversal direction was very small and similar for every case, see figure 29 a) and b).

![Figure 29. Longitudinal baffle a) without holes, b) with holes](image)
Another feature to test was the influence of having any kind of inclination in the transversal baffle. According to the theory, the bigger angle the baffle has, the lower sloshing forces act on the baffle’s surface, nevertheless the weight of the baffle increase. To make the observation easier, a 15° angle was chosen for the laboratory tests, shown in figure 30.

![Figure 30. View of the 15° baffle](image)

The behavior of the liquid after colliding the baffles was different depending of the angle the baffle had. As shown in figure 31 a), for cases one and three, 0°, liquid went directly up after the first impact and was spread everywhere, however for cases two and four, figure 31 b), due to this inclination, waves came back to the rear part of the tank.

![Figure 31. Waves after impact a) baffle 0°, b) baffle 5°](image)

Due to the holes in transversal baffles, dissipation of the energy (vorticity) could be noticed in every case, see figure 32.
5.2 Stresses analyses

In this chapter, the results of the stresses analyses are shown and explained. Due to the steel properties, the yield strength of this material is 140 MPa, see table 3. This means that to avoid plastic deformation, stresses should not reach that value.

First of all, views of the whole tank with stresses for the four different cases of study are shown in figure 33 and the corresponding values are shown in figure 34. As it is possible to observe, in all cases the tank is mostly colored in blue, which means that the forces do not really affect the whole structure.
According to the low forces in transversal direction, y-axis, longitudinal baffles do not present high stresses. The highest stress appears where the two baffles are connected, figure 35 and values for each case are shown in figure 36. The results show very similar values of the stresses for every case, 25 MPa approximately.

Case 1)  

Case 2)  

Case 3)  

Case 4)
Figure 36. Values of the stresses

Figure 37 shows the stresses in the transversal baffle for each case and figure 38 shows the values. The transversal baffle has to support higher forces than the longitudinal one, so stresses are higher as well. In the middle of the bulkhead, around the holes, stresses have a value of 25 MPa approximately for every case. The lower edge, close to the bottom of the tank, presents punctual high stresses with a value of 45 MPa approximately for every case, nevertheless this fact could be neglected because weld joints are not modelled, i.e. in reality the baffles will be welded along the whole edges.

Case 1)

Case 2)

Case 3)

Case 4)

Figure 37. Stresses in transversal baffles for the four cases of study
To finish with this analyses’ chapter, a zoom of the stresses located where the two baffles are connected is shown for each case, figure 39, and values are shown in figure 40. This is the place where the maximum stresses appear and except for case one, in all other cases the maximum stress value is greater than the yield strength of the material. Even reaching 172 MPa for case two, these high stresses could be neglected due to the fact that this is a punctual stress and baffles will be welded in this point.

**Case 1)**

**Case 2)**

**Case 3)**

**Case 4)**

![Figure 39. Zoom of the stresses in the intersection between baffles for the four cases of study](image)
5.3 Vibrations analyses

As it is possible to observe in figure 41, the first mode for each case of study has a very similar value, around 52 Hz. Deflection occurs mostly in volume one, while the rest of the tank is almost resting. The bottom plate is moving in z direction, which means that it will move up and down.

<table>
<thead>
<tr>
<th>Case</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1)</td>
<td>51.3 Hz</td>
</tr>
<tr>
<td>2)</td>
<td>52.2 Hz</td>
</tr>
<tr>
<td>3)</td>
<td>52.6 Hz</td>
</tr>
<tr>
<td>4)</td>
<td>53.3 Hz</td>
</tr>
</tbody>
</table>

Figure 40. Values of the stresses

Figure 41. Mode 1 for the four cases of study

Maria del Mar Diaz del Pino, Jakub Sznurowski
Figure 42 shows the result of the first mode in the original design which has a value of about 36 Hz. In this case, the whole bottom is moving up and down due to the fact that this design does not divide the tank in smaller subdomains. Furthermore, the highest deflections appear in the baffles and fuel trap. Deformations for this design become more complex in x and y direction.

As it is shown in figure 43, values for the four cases are almost the same, with a value of 78 Hz. In the bottom plate displacements appear mostly in volume three in z direction, while the longitudinal baffle is deflecting the most and the movements are located in y direction. Volume two is not really affected by the excitation.
Figure 43. Mode 2 for the four cases of study

Here, mode two for the previous design with a frequency value of 61 Hz, is presented below, see figure 44. In this case, the frequency has a value of 61 Hz. Maximum deflection in the bottom plate occurs in a different place than in the new design. As it can be observed, the baffle is deformed in y direction, while the fuel trap deforms in x and y direction becoming the part with the most complex movements.
The third and last mode is presented in figure 45. The frequency values are around 80 Hz and baffles deflect the most. For cases three and four, as the baffles have no holes, the structure becomes stiffer, and then the deformations are not really significant. In contrast, for cases one and two, higher deformations in the baffles affect the bottom of the whole tank. It can be noticed that no inclination in the transversal baffle concentrates the displacements of the bottom in volume three.

**Case 1) 80.6 Hz**

**Case 2) 80.1 Hz**

**Case 3) 80.2 Hz**

**Case 4) 80.1 Hz**

For the original design, the frequency of the third mode has a value of 65 Hz, see figure 46. Fuel trap and baffle have the highest deflections and the bottom is deformed as well.
To conclude with this subchapter, it should be noticed that the difference in frequencies values for each mode shape in the original and new tank, is always around 15 Hz, see table 7. This fact could be explained by the higher stiffness of the new design which has two connected baffles instead of one with fuel trap. Results from the previous design show that the critical part is located where the fuel trap is welded.

Table 7. Resonance frequencies in Hz

<table>
<thead>
<tr>
<th>Mode</th>
<th>CASE 1</th>
<th>CASE 2</th>
<th>CASE 3</th>
<th>CASE 4</th>
<th>PREVIOUS DESIGN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>51.3</td>
<td>52.2</td>
<td>52.6</td>
<td>53.3</td>
<td>36</td>
</tr>
<tr>
<td>Mode 2</td>
<td>78.4</td>
<td>78.2</td>
<td>77.5</td>
<td>77.1</td>
<td>61</td>
</tr>
<tr>
<td>Mode 3</td>
<td>80.6</td>
<td>80.1</td>
<td>80.2</td>
<td>80.1</td>
<td>65</td>
</tr>
</tbody>
</table>
6 Discussion

Not always big problems need big changes and this thesis could be a good example of this. Cracking could appear during lifetime and the reasons were not clear. At the beginning, several options were discussed, as fuel trap, mounting system, need of baffles, skid plate-tank interaction, etc. but only focusing on baffles the cracking problems were solved.

Baffles design did not seem to be a huge amount of work, but during paper survey the problem became more and more complex. Studies about sloshing phenomena in the area of fluid dynamics were not simple tasks to achieve and assumptions had to be made to simplify the case.

This master thesis has been based on L120 H-Generation steel tanks and just improvements for this model were studied. Although theory regarding vorticity, sloshing and energy dissipation can be applied in any kind of tank, the position of the baffles should be studied for each particular case.

Although the fact of using water instead of fuel in the experiments was not considered at the beginning, it was very helpful recommendation by Volvo experts. The properties of both liquids are not the same, but in every case, water is more restrictive than fuel, so the results are reliable.

The solution presented in this thesis for the cracking problem is not unique and some other configurations to dissipate the energy could be taken into account.

The proposal for this tank works well, but still further advanced calculations involving fluid dynamics should be made to validate the design.
7 Conclusions

Several problems could always appear while designing any kind of front loader. In case of L120, the diesel steel tank had to be improved. The problem of cracking due to the sloshing phenomenon could appear during the lifetime becoming the reason of serious damages, so it could not be neglected.

This thesis work consists of three independent approaches to examine the sloshing phenomena and the fluid behavior affected by the baffles. To start with, comparing steel and plastic tanks structures, the necessity of the baffles needed to be clarified. To explain the reasons why cracks did not appear in plastic tanks, the similarities with a balloon should be introduced. It is well known that the structure of a balloon is very flexible, so it can easily deform when the pressure varies. When sloshing happens in plastic tanks, due to material properties, the structure is able to follow in some way the liquid movements, so energy is absorbed by deformation.

In the case of steel tanks, as soon as the capacity of the tank increases and depending on the value of the vibrations, the necessity of baffles is unavoidable. The structure is not that flexible, therefore it cannot bear the hydroimpact and cracks appear.

Several analyses have been carried out in this thesis and four different configurations of the baffles have been examined. Regarding the stress analysis, very close results were obtained for every case. Thus taking into account only stress distribution, the criterion is insufficient to select the best configuration of the baffles.

In case of vibrational analyses, the results for the four cases are very similar as well. Every case studied presents higher resonance frequencies which means that the new design is stiffer than the old one.

In contrast, experiments confirm the theory presented in this thesis. Different behaviours of the fluid could be observed depending on the baffle configuration. Regarding the transversal one, even with a small inclination, changes could really be appreciated. The wave returned to the initial subdomain instead of jumping up when it met the baffle and thanks to the slow motion camera, liquid passing through the holes is appreciated. According to the theory, this phenomenon can be explained by the dissipation of energy. The comparison between longitudinal alternatives, showed no big differences, so it can be concluded that the use of this baffle is mainly to reinforce the structure due to the small component of the velocity in y axis.

Taking into account the three independent studies within the baffles and according to manufacturing costs, case 4 (longitudinal without holes and transversal with 5° inclination), shown in figure 47, could be the best choice that fulfils the requirements of this thesis work.
Figure 47. Case 4: longitudinal no holes and transversal 5°
8 Further improvements

8.1 Design

In general, designing a tank to store the fuel in big construction machines is not a simple task. One of the main issues to study is the sloshing phenomenon, which has been the topic of this thesis, but there are several other problems to take into account while designing tanks.

Not every tank has a fuel trap located inside to stabilize the flow, so the necessity of it could be another point to discuss. For L120 H-Generation Volvo tank, this point has been solved by changing the position of the baffles inside the tank.

Volvo provides two kinds of fuel tanks that could be made of steel or plastic and each one is assembled to the whole structure in a different way. The steel tank is supported by four screws that could result in twisting problems when the rear frame twist. Thus, the use of three points instead of four to assemble the tank could be considered. The plastic tank is fixed to the structure using stripes, thus another idea could be to use the same assembling system for the steel one, reducing costs and parts in the assembling line in the manufacturing process.

The last proposal regarding the designing part could be a change of the way that the tank is resting on the skid plate. The welding process requires a tank-skid plate gap of 10 mm, so the tank is lying on two longitudinal edges instead of the whole bottom. A study of the interaction between surfaces could be done as well.

8.2 Experiments

To validate the vibrational results obtained in this thesis, further experiments in the lab could be carried out. For this purpose, the structure must be as close to the reality as possible, so the tank should be completely welded tank, with baffles included. Then, using special equipment as hammers or vibrational tables, the structure should be excited. Accelerometers should be placed strategically and finally, the data collected, should be implemented to a program to obtain the frequencies.

8.3 Calculations

In this thesis work, some assumptions for all calculations have been taken into account. Diesel has been simulated as distributed mass and corresponding forces. More accurate results could be obtained using dynamic instead of static procedures.
Computational Fluid Dynamics, commonly named as CFD, is the field that study fluids behavior using methods and algorithms to solve and analyze problems. It is commonly used for aerodynamic purposes.

This is a very complex method and calculations require the use of computers to simulate liquids and gases. First of all, physical bounds must be defined and the fluid should be meshed which could be uniform or not. Then, physical properties and boundary conditions are defined, thus all the features regarding the fluid behavior are set. Finally, during the simulation process equations of motion are solved iteratively and results are obtained.
References


Appendix A: Drawings

This appendix consists of eight drawings, four of them are for L150 and the other four are for L120 tank. Due to the fact that L150 has been the tank used for experimental tests, drawings have been made for workshop purposes.

Drawings have been made according to Volvo standards and rules for drawings, i.e. only general dimensions are included, the geometry is implemented in digital format.
Refer to the Part Version Report for the correct document issue.

Position of the baffles L150

Scale 1:6
DIGITAL SHAPE MODEL
IS BASIS WHERE DIMENSIONS ARE OMITTED
STD 101-0001

GENERAL SHAPE
± 0,5 FOR HOLE DIAMETERS

MP2
FOR HOLES

SCALE 1:4

Refer to the Part Version Report for the correct document issue
DIGITAL SHAPE MODEL IS BASIS WHERE DIMENSIONS ARE OMITTED

STD 101-0001

GENERAL SHAPE

± 0,5 FOR HOLE DIAMETERS

Φ 1 FOR HOLES

SCALE 1:4

Refer to the Part Version Report for the correct document issue

Symbols, designations and general drawing methods

STD 101-0005

View placement
Reference arrow method

ISO 128-30:2001

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Document title

... Longitudinal baffle with holes L150

... Workshop Drawing

... Diaz M., Sznurowski J.

Volvo Construction Equipment
DIGITAL SHAPE MODEL
IS BASIS WHERE DIMENSIONS ARE OMITTED
STD 101-0001

GENERAL SHAPE
± 0,5 FOR HOLE DIAMETERS
SCALE 1:4

Refer to the Part Version Report for the correct document issue

<table>
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<th>Symbols, designations and general drawing methods</th>
<th>View placement</th>
<th>Reference arrow method</th>
<th>Document release status</th>
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<tr>
<td>STD 101-0005</td>
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<td>ISO 128-30:2001</td>
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Longitudinal baffle without holes L150

At the above diagram, the following applies:

General shape

Digital shape model

Is basis where dimensions are omitted

Scale 1:4

3X R 30

3

244,7

30

R 3X

± 0,5 FOR HOLE DIAMETERS

617,8

681,1

Workshop’s Drawing

Diaz M., Szurowski J.

Construction Equipment

Format: A3
Refer to the Part Version Report for the correct document issue

Scale 1:3