

An Experimental Study of Sloshing Noise in a Partially Filled Rectangular Tank

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ABSTRACT

Liquid sloshing noise from an automotive fuel tank is becoming increasingly important during frequent accelerating/decelerating driving conditions. It is becoming more apparent due to significant decrease in other noise sources in a vehicle, particularly in hybrid vehicles. As a step toward understanding the dynamics of liquid sloshing and noise generation mechanism, an experimental study was performed in a partially filled rectangular tank. A systematic study was performed to understand the effects of critical parameters like fill level and acceleration/deceleration magnitude. Response parameters like dynamic pressure, dynamic force, dynamic acceleration and sound pressure levels along with high speed video images were recorded. The proposed experimental setup was able to demonstrate major events leading to sloshing noise generation. These events in the sloshing mechanism have been analysed from the dynamic sensor data and correlated with high speed video images.

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INTRODUCTION

Liquid sloshing can be defined as the movement of liquid free-surface inside a partially filled container due to any external disturbance [1]. Sloshing has been an important area of research in various engineering fields like transportation of liquid by all major modes of transportation [2, 3, 4, 5, 6, 7], safety of structures against seismic loading [8, 9], vehicle stability for aerospace application [10, 11], etc. More recently, slosh noise generation under sudden acceleration/deceleration condition is getting increased research attention for premium and hybrid vehicles [12, 13]. In automobiles, sloshing noise in a fuel tank can be radiated as structure borne noise and air borne noise. Structure borne noise is generated due to wall vibration (Fluid-structure interaction) and Air borne noise is radiated due to fluid-fluid interaction inside the tank. The generated vibrations propagate through mounting attachments to the passenger cabin. As a result of advancements in automotive technology, noise radiation from engine, driveline, tires, brakes, and wind sources has considerably reduced. Hence sloshing noise has become as one of the major noise source in a vehicle for particular operating conditions.

A number of experimental studies has been performed to investigate sloshing phenomenon in tanks. Ibrahim et al [14] have reviewed several engineering applications where liquid sloshing dynamics is an important engineering consideration. Theories based on non-linear dynamics is being extensively used to understand the complex behaviour during sloshing. However, a majority of studies are related to work towards understanding dynamic loading and stability of structures. Since this review, several other studies have been reported in open literature on sloshing dynamics. Lugni et al [15] performed experiments to study the behaviour of flip-through events generated upon a vertical rigid wall when subjected by impact waves. Effect of

baffles on sloshing dynamics has been studied both using experimental and numerical techniques by several groups. Akyildiz and "U" nal [16] studied sloshing in a rectangular tank with varying exciting parameters to analyse the effects of baffles and fill levels on impact pressure and fluid flow inside tanks. Liu and Lin [4] and Cho and Lee [17] numerically investigated the effect of baffle height on sloshing dynamics. Rebouillat and Liksonov [18] reviewed different numerical techniques that are being used to study sloshing dynamics and the associated fluid-structure interaction.

As mentioned before, effect of liquid sloshing in an automotive fuel tank is gaining importance as it contributes to overall vehicle noise level. Noise generation and radiation within a vehicle due to liquid sloshing inside a tank is quite complex. Researchers till recently have typically relied on experimental measurements of such noise characterization [19, 20]. Wachowski et al [13] concluded on the basis of experiments that sloshing noise can be classified into three categories: Splash, Hit and Clonk noise and the three were differentiated on the basis of their dominant frequency range. Kamei et al [21] experimentally determined a correlation that relates fuel tank, body parts and tank mounting structure to slosh noise. The tank mounting structure, which is related to both the fuel tank and the body parts has the largest contribution to sloshing noise.

However, with the advent of powerful computational tools, researchers are now trying to develop computational based methodologies for noise estimation which can then be used in early design phase of a fuel tank. Wiesche [12] performed experiments and numerical simulations of sloshing in automotive fuel tanks. He reported a correlation between slosh noise and dynamic pressure fluctuations. Additionally, he used two-phase Computational Fluid Dynamics (CFD) to track liquid interface within a realistic tank.

geometries to determine these pressure fluctuations. Park et al [22] have studied a vibration of automotive floor panels due to sloshing loads using Fluid - Structure Interaction (FSI) analysis. Vaishnav et al [23] used Eulerian based Computational Fluid Dynamics (CFD) and Arbitrary Lagrangian-Eulerian (ALE) based vibrational analysis to perform FSI studies of fuel tank sloshing. Similarly, Marriott et al [24] have used FSI based computational methods to study fuel tank sloshing behaviour.

As can be seen from the above literature survey, most of the research on automotive slosh noise generation is restricted to test conditions, which are very empirical in nature and therefore, do not clearly explain the mechanism of slosh noise generation and its propagation. There is a need to develop a multi-physics model to address the above lacuna. Recently, Jadon et al [25] performed an integrated study of liquid sloshing behaviour, its impact on structural vibration and noise radiation on the rectangular tank that was subjected to a sudden deceleration. They performed both experimental and computational study on this geometry. The current work is an extension of that study, and an in-depth analysis has been performed to understand various factors affecting noise generation and its radiation from a partially filled rectangular tank. Experiments have been performed under controlled laboratory conditions. An impulse based dynamic loading experimental rig was designed for this study. Parametric studies were conducted to understand the effect of fill level and vehicle deceleration on slosh noise generation. As this is the first step in a comprehensive study to understand the mechanism of slosh noise generation and its propagation, the authors have currently restricted themselves in reporting their experimental work. Numerical study is expected to be reported in near future.

EXPERIMENTAL SETUP

Test Rig

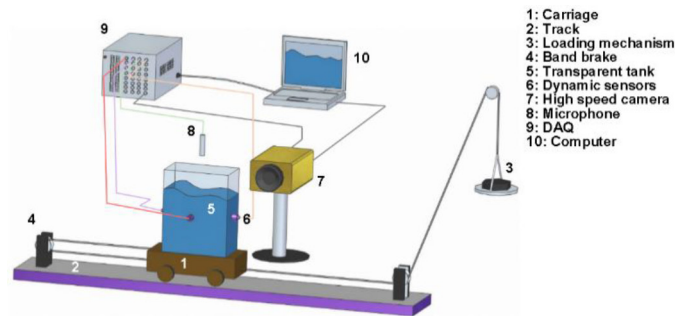


Figure 1. Schematic Diagram of Experimental Setup

Figure 1 shows the schematic diagram of the sloshing noise test rig, which simulates the sloshing phenomenon under controlled braking load to measure dynamic force and dynamic acceleration on the tank wall. It also measures sloshing noise radiated from the tank. The system consists of four major subsystems: (i) carriage and track, (ii) rectangular tank with provision for sensor mounting, (iii) loading mechanism and (iv) braking mechanism. The carriage consists of a wooden platform mounted on four polymer wheels designed for low rolling noise in order to minimize background noise. An aluminium track of approximately 1.5 m was prepared on which the vehicle

would travel. Special care was taken to minimize lateral movement of the vehicle. The track was maintained at a horizontal position with respect to the ground with the help of a spirit level. A transparent rectangular tank made of Acrylic with the dimensions of 0.238 (L) × 0.220 (W) × 0.238 (H) m³ was fabricated to perform the experiments in this study. The tank wall was 6 mm thick and it was rigidly placed on the platform to avoid any relative motion. The tank and carriage together is referred as vehicle in rest of this paper.

A three-axis linear inertia acceleration sensor (3g-ADXL335) and a line triggering sensor were mounted on the wooden platform. The line sensor was used to trigger the dynamic sensors, which include the dynamic pressure, force, acceleration and microphones. Additionally, a high speed camera, which was used to record the liquid motion inside the tank was also triggered using this line sensor.

The vehicle was accelerated when a dead weight falls under gravity. The vehicle was tethered to this dead weight by a string and pulley mechanism. A band brake was used to apply the brake when the vehicle approached the end of its traverse. The liquid inside the tank sloshes due to the sudden application of this brake. Different sensors are mounted on the vehicle to record the effect of this sloshing activity. Sensor specifications are given in Table 1. Data from dynamic pressure sensors was acquired using HBM DAQ Quantum MX410. Data from all other sensors were acquired using a NI cDAQ-9178 data acquisition system. The line sensor was activated by a change in the colour of a strip mounted along the vehicle track, which in turn triggers other sensors. Phantom V12.1 high speed camera was used to capture the liquid sloshing behaviour, which was also triggered by the line sensor. Various camera settings were used to acquire the video. The present work reports the images that were obtained with a camera frame rate of 1000 fps. This frame recording setting was chosen based on test duration and memory required for online recording. Noise radiated due to liquid sloshing from the tank was monitored using four microphones that were placed in front, left, right and top direction of the tank at a distance of 1 m from the final resting position of the tank wall.

Table 1. Sensors Specifications

Sensor Type	Make and Model	Range	Sensitivity
Inertial Accelerometer	3g-ADXL335	± 3.6g	300 mV/g
Dynamic Pressure Sensor	Dytran 2300 V3	500 psi	10 mV/psi
Dynamic Force Sensor	Dytran 1053 V3 and 1051 V4	± 100 lbf	50 mV/lbf
Dynamic Acceleration Sensor	Dytran 3055 B1		
Microphone	MPA 401		

The acceleration and deceleration of vehicle due to the loading mechanism and the band brake arrangement as described above is estimated from Eq. (1a) and 1(b) respectively

$$a = \frac{m_2 g - \mu m_1 g}{m_1 + m_2} \quad (1a)$$

and

$$d = \left(\frac{t_1}{t_2} \right) \left(\frac{m_2 g - \mu m_1 g}{m_1 + m_2} \right) \quad (1b)$$

where, m_1 is the mass of the tank with water, m_2 is the mass of the dead weight, a is the acceleration of the tank, d is the deceleration of the tank, t_1 is the time required to reach the required acceleration, t_2 is required time for deceleration, and μ is coefficient of friction.

Data Acquisition

Figure 2 shows the mounting arrangement of the various sensors on the vehicle. The dynamic force and dynamic acceleration sensors were attached on the external wall surface of the tank. The dynamic pressure sensors were mounted such that they were in direct contact with the liquid inside the tank. The sensor mounting were so designed to avoid liquid leakage from the tank.

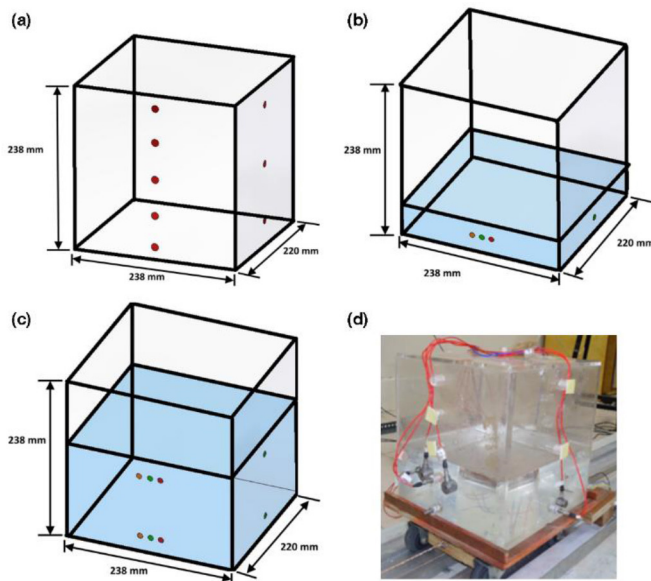


Figure 2. Tank dimensions, (b) sensors location for 20% fill, (c) sensors for 60% fill, (d) actual tank with sensor configuration

Three dynamic pressure sensors were mounted at a height of 10% below the liquid free surface. These sensors were mounted on the front, back and right walls of the tank as shown in Figure 2. Another sensor was placed at 0.1 times of the tank height and was mounted on the tank front wall. The acceleration and forces were placed on the front and back walls of the tank and are adjacent to the dynamic pressure sensor that was placed 10% below the liquid free surface. The high speed camera was placed normal to the track. The camera field of view could capture the complete tank at the time of braking.

RESULTS AND DISCUSSION

The current test setup was used to perform several parametric studies to understand the effect of tank fill level and deceleration magnitude on slosh noise generation. The effects of these parameters on fluid structure interaction of the tank was recorded using the dynamic sensors; liquid slosh visualization using the high speed video camera; and radiated sloshing noise using the microphones. A minimum of three trials on at least two different days were performed to establish the repeatability of the current test methodology.

Background Noise Measurement

Before measuring the liquid sloshing noise, a separate test was performed to estimate the background noise due to vehicle motion on the track. This background noise incorporates tyre noise, noise due to loading and braking mechanisms. Two different tests were performed to estimate the background noise: (a) tank filled with water and (b) tank filled with sand of equivalent mass. Both these tests were performed under the same loading conditions.

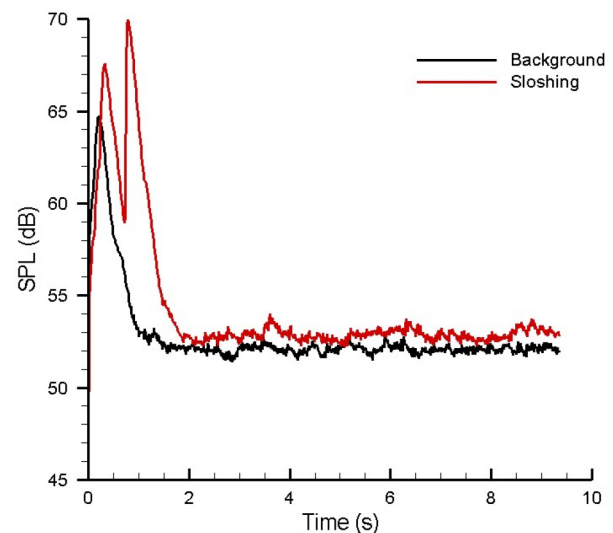


Figure 3. Estimation of Vehicle Background Noise

Figure 3 shows the recorded sound pressure levels as recorded by the front microphone. As can be seen from this figure, multiple peaks were observed for the case where the tank is filled with water. However, only one peak is observed when the tank is filled with sand. In both cases, the first peak happens at the same time and occurs before or at the time of braking. Hence, it can be concluded that the first peak is due to the background noise. Subsequent events corresponds to liquid sloshing and the effect of background noise is insignificant during these instances. High speed camera recordings were not made during noise measurements due to significant background noise contribution from its cooling fan.

Experimental Results

Table 2. Set of Experiments shows the set of experiments that was performed to understand the effect of fill level and deceleration magnitude on slosh noise radiation. As mentioned previously, one dynamic pressure sensor was placed at 0.1 times of the tank height in all the cases and all remaining dynamic sensors were placed at 10% of the tank height.