

The Prediction of Fuel Sloshing Noise Based on Fluid-Structure Interaction Analysis

2011-01-1695

Published
05/17/2011

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doi:[10.4271/2011-01-1695](https://doi.org/10.4271/2011-01-1695)

ABSTRACT

Fuel sloshing noise is involved with flow motion inside fuel tanks as well as structural characteristics of vehicles. Therefore it is necessary to introduce Fluid-Structure Interaction (FSI) analysis to predict sloshing noise phenomena more accurately. Purposes of this paper are to verify the reliability of the FSI method and suggest new CAE analysis processes to predict fuel sloshing noise. The vibration of floor panels induced by sloshing impact is evaluated through FSI analysis. A series of tests is carried out to validate simulation results. The numerical optimization of parameters is also carried out to reduce computation time. In addition, effects of sloshing noise factors are discussed based on simulation and test results. Lastly, a method to predict fuel sloshing noise by exerting sloshing load on a vehicle is suggested.

INTRODUCTION

Recently, the reduction of fuel sloshing noise became one of crucial NVH issues as the overall noise level of vehicles has been decreased. Fuel sloshing noise induced by flow motion in fuel tanks usually occurs as fuel fills more than 75% of a fuel tank and a vehicle stops abruptly in a slow driving condition. Generally, fuel sloshing noise is divided into three categories according to its occurrence mechanism. They are bubble noise, waving noise and impact noise. First two are known as air-born noise and closely related with flow motion itself inside fuel tanks. On the other hand, the last one is structure-born noise and it is generally understood that both vehicle structure and fuel flow motion are connected with this phenomenon [1].

It is well known that a number of design factors other than fuel filling levels and driving conditions are involved with the occurrence of fuel sloshing noise. However, most of works to reduce sloshing noise are carried out after these various design factors have been already fixed. It happens because the confirmation of a fuel sloshing noise level is totally relied on driving tests which are usually available at the late stage of vehicle development processes. Therefore, in order to consider design factors in advance for reducing fuel sloshing noise, it is highly demanded to develop a new method of CAE analysis which can predict a noise level at an early design stage.

In order to enhance the accuracy of CAE analysis regarding impact sloshing noise, it is necessary to reflect interactions between fluid and structure as detail as possible considering its close connection to physical properties in both areas. However, the application of Fluid-Structure Interaction (FSI) analysis has not been practically available since it takes too much computation time and the accuracy of analysis has not been verified. Instead, CAE analysis regarding sloshing noise has been carried out for a structure and a fluid part separately. For example, the stiffness of floor panels and mounting parts are examined and proper locations of pads are suggested based on the static analysis of structure. However, the amount of load exerted on mounting structures by sloshing motion is ignored in this approach. On the other hand, pressure on tank surface due to fluid motion is predicted using CFD analysis and it determines if baffle configurations are acceptable. In this case, however, it is impossible to present effects of fluid motion transmitted to vehicle vibration since typical CFD analysis assumes a rigid wall for tank surface. As a result, various design factors related with fuel sloshing noise have not been considered comprehensively, possibly leading to over design of subsystems.

Purposes of this paper are to show the reliability of FSI analysis and build new CAE analysis processes to predict fuel sloshing noise, while computation time is kept within a certain limit for practical applications in vehicle development processes. In order to achieve these purposes, firstly, fluid motion inside a flexible tank is calculated and compared with results of a series of experiments. Secondly, values of floor panel acceleration caused by fuel sloshing are evaluated and the reliability of them is investigated based on the correlation with tests. Thirdly, the optimization of various numerical factors is carried out to reduce computation time within practical limit without sacrificing its accuracy. Additionally, effects of sloshing noise factors on panel vibration are discussed in order to suggest a guideline to reduce fuel sloshing noise. Lastly, a new method to predict fuel sloshing noise based on sloshing load from FSI analysis is suggested, then its validity is discussed.

FSI ANALYSIS MODELS

In general, FSI models for simulations are consisted of a Lagrange domain, an Euler domain and a coupling surface between these two domains. Fluid belongs to Euler meshes and structure such as tank surface, sub-tank and baffles are modeled in Lagrange meshes. FSI analysis is implemented by solving both equations of motion for structure and fluid at each time step. Structural motion of Lagrange material is considered as a moving boundary to fluid in the Euler domain, and Euler fluid pressure is considered as an external load on Lagrange structure. In this study, MSC Dytran is used for FSI simulations and the general coupling method is selected to define coupling surfaces since it is known to provide faster solutions than the ALE method without the appreciable degradation of simulation results [2].

It is well known that various design factors are related with the occurrence of fuel sloshing noise. For example, a baffle configuration and a fuel tank shape are clearly related with flow motion inside tanks. In addition, the stiffness of a fuel tank and floor panels affect the level of impact sloshing noise. Moreover, binding conditions of a fuel tank to a vehicle such as locations of pads, the compressed rate of pads are also known as critical factors of sloshing noise. These design factors above are also called fuel sloshing noise factors. It is required to reflect physical properties of sloshing noise factors into FSI models as much as possible for improving the accuracy of simulations. However, the usage of a whole BIW is excluded since computation time is expected to increase abruptly. In addition, the weight capability limit of test facilities prohibits the employment of a whole BIW. Instead, the usage of a BIW buck is newly suggested for both simulations and tests as shown in [Figure 1](#). It is consisted of a fuel tank, a vehicle structure cut under a rear floor panel and tank mounting parts such as straps and pads, which can represent crucial sloshing noise factors as they are.

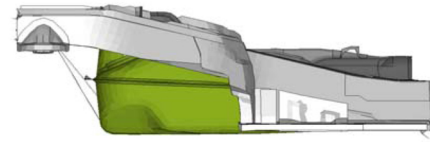


Figure 1. The side view of a FSI model combining a BIW buck and a fuel tank

THE RELIABILITY OF FSI ANALYSIS

THE PREDICTION OF SLOSHING MOTION IN FSI ANALYSIS

The flow motion inside a fuel tank is the first thing to confirm when the accuracy of simulations is concerned since it works as a source of fuel sloshing noise and vibration. The main difference between FSI and conventional CFD is whether the flexibility of structure is considered. CFD predicts flow motion assuming a rigid body for a tank wall. In this chapter, effects of flexibility on flow motion are investigated by comparing flow motion results obtained by each method.

First, a series of fuel sloshing tests and simulations is carried out for a fuel tank. The fuel tank is filled with water to 7/8 of its capacity and fuel sloshing motion is induced by following a given acceleration condition in [Figure 2](#). Observed sloshing motion inside the acrylic tank is compared with FSI simulation results in [Figure 3](#) at the moment of 0.5, 0.7, 0.9, and 1.2 sec after the tank starts to decelerate. It is noticed that there is an excellent agreement between numerical predictions and corresponding test results, which verify the accuracy of the FSI method on sloshing motion prediction.

Next, a series of simulations is carried out for a plastic fuel tank in order to examine the effect of flexibility on sloshing motion. Fluid motion inside the tank is obtained for rigid and flexible structure, respectively and simulation results are shown in [Figure 4](#). Clear differences in sloshing motion between FSI and conventional CFD are observed as marked with circles in [Figure 4](#). It confirms that the source of fuel sloshing noise is clearly influenced by the interaction between fluid and structure.

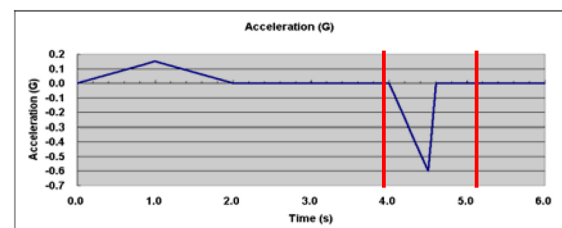


Figure 2. The acceleration condition to induce fuel sloshing motion in a BIW buck state.

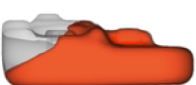
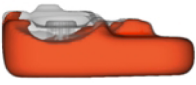
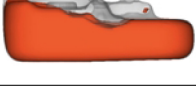
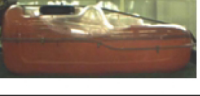
Time	FSI Analysis	Test
0.5s		
0.7s		
0.9s		
1.2s		

Figure 3. The comparison of sloshing motion between FSI simulations and verifying tests.

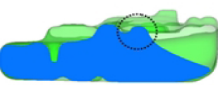
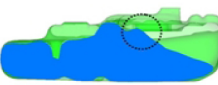
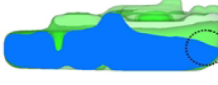
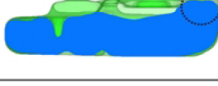
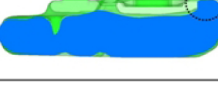
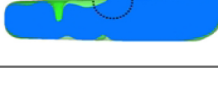
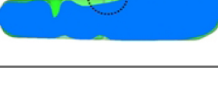
Time	Rigid Tank (CFD Analysis)	Flexible Tank (FSI Analysis)
0.5s		
0.7s		
0.9s		
1.2s		

Figure 4. The comparison of sloshing motion between conventional CFD and FSI simulations.

THE PREDICTION OF SLOSHING-INDUCED ACCELERATION IN FSI ANALYSIS

It is known that impact sloshing noise occurs as vibration due to sloshing transmits to a vehicle body. In order to investigate this type of sloshing noise, sloshing-induced vibration on a fuel tank and floor panels is evaluated in simulations. Values of acceleration are calculated at given locations on a BIW buck of a mid-size sedan vehicle, which is shown in [Figure 5](#). The same fuel amount and sloshing inducing conditions in the previous chapter are applied for simulations.

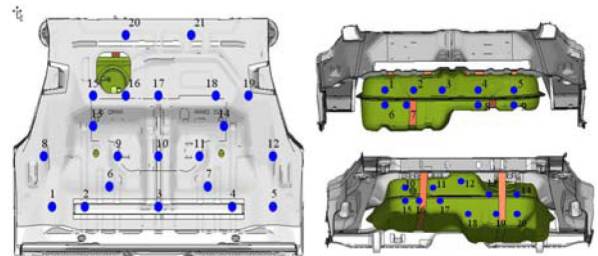


Figure 5. The location to measure sloshing-induced acceleration on the floor panel (left) and the tank surface (right)

In addition, the validity of FSI analysis regarding sloshing-induced acceleration is examined through verifying tests. These tests are carried out with a BIW buck fixed on a plate as shown in [Figure 6](#). The plate moves along rails following same conditions used in simulations. Sloshing noise is also measured through whole series of tests in order to examine the correlation between sloshing noise and floor panel vibration. Predicted values of acceleration on the floor panel are compared with test results in [Figure 7](#). Peaks due to sloshing impact are observed at around 0.5 sec in transient responses of acceleration on the floor. The maximum amplitude of acceleration is observed at the same location for both simulation and test results as marked in [Figure 7](#). Examining the complete set of acceleration estimation, it is found that general agreement is observed considering peak distribution and the amplitude of acceleration. Excessive peaks at the initial stage of simulations should be ignored because they are numerical noise due to external load such as gravity and belt tension in FSI models.

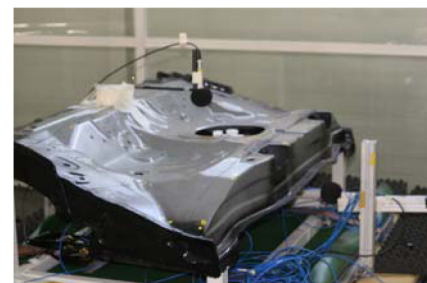


Figure 6. The BIW buck with a fuel tank for verifying tests of FSI simulations