

Study of Fuel Tank Sloshing Noise Prediction

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ABSTRACT

The development of technology to predicting sloshing noise from a fuel tank was approached from the aspects of simulation and experiment. First, an acceleration and deceleration from a vehicle was applied to a bench-mounted fuel tank containing fuel to generate a sloshing noise, and the physical parameters that were closely correlated with the sloshing noise were extracted. Next, computer simulation using an explicit transient solution method was performed to reproduce the fluid motion behavior in the tank, and a study was performed whether or not the physical parameters obtained from the experiment was useful for predicting sloshing noise. As a result, it was confirmed that the sloshing noise was caused by fuel striking localized areas of the inside wall of the tank. It was found that the occurrence of sloshing noise could be predicted by analyzing the impulsive pressure rise at the inside wall of the tank. A comparison of the computer simulation results with the experimental results showed that the experimentally observed impulsive pressure rise could be accurately reproduced by simulation as well, thus enabling the occurrence of fuel sloshing noise to be predicted.

1. Introduction

In order to enhance quietness inside a passenger vehicle, it is important to address noise reduction of all the relevant functional parts, including the fuel tank. For this reason, demands for reduced fuel sloshing noise are increasing year by year.

The conventional fuel tank made of steel sheet has baffles spot-welded to it for reducing sloshing noise. The specifications of the tank were determined by trial and error through evaluation using an actual vehicle. However, along with the increasing use of plastic fuel tanks that are difficult to install with baffles, it has become necessary to consider the basic profile of the tank that minimizes the occurrence of sloshing noise, at the initial stage of development. In addition, efforts are being made to reduce the number of prototype vehicles and shorten the development period by using a computer, so simulation technology for predicting the occurrence of fuel sloshing noise is being increasingly demanded.

In order to predict sloshing noise, it is necessary, first of all, to reproduce the fluid motion behavior of the fuel in the tank using a computer. This was previously considered to be extremely challenging because the behavior of the fluid is complicated. However, along with the evolution of analysis technology in recent years, several analysis codes which can handle the behavior of a fluid that has a free surface have become commercially available, and there are also reports of cases of analysis^{(1),(2)}. These reports state that by using simulation to visualize the flow inside the tank it is possible to acquire general guidelines for reducing sloshing noise. However, there is little mention of technology for directly predicting the occurrence of noise by simulation. The reason for this is that because the understanding of the phenomenon is insufficient, the mechanism whereby the motion of the fuel in the tank generates sloshing noise has not been adequately investigated. In this research, first a bench test was performed to extract the physical parameters that are closely correlated with the generation of sloshing noise, and then these physical parameters were

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reproduced by computer simulation, and finally the two sets of results were compared with each other in order to develop technology for predicting the occurrence of sloshing noise by computer simulation.

2. Mechanism of Generation of Sloshing Noise

The following two hypotheses concerning the mechanism of generating of sloshing noise are conceivable. One is that the air in the fuel tank vibrates due to agitation of the fuel, generating noise which passes through the wall of the tank to the outside, and the other is that the surface of the inside wall of the tank vibrates when struck by the fuel, causing noise to be generated. Both of these phenomena coexist, however, from the viewpoint of simulation it is very important to establish which of them is dominant. If the former is dominant, it is necessary to simulate the process where the fluid is agitated causing the air in the vicinity to vibrate. In this case, however, it is difficult to predict the vibration of the air due to the interaction between the air and the liquid. Conversely, if the latter is dominant, it is possible to perform simulation by calculating the pressure rise when the fuel in the tank strikes the wall of the tank.

3. Bench Test

3.1. Test Equipment

A bench test was carried out to determine which of the above two phenomena has the greater effect. Figure 1 shows the concept of the test equipment.

Microphones were installed at a point 300 mm above the tank and also inside the tank, in order to compare the level of the noise inside and outside the tank. In addition, pressure sensors were installed at 10 points inside the tank in order to measure the pressure when the fuel in the tank strikes the tank wall, and also acceleration sensors were installed on the outside of the tank in order to measure the vibration of the wall surface.

The test equipment for applying motion to the tank consisted of a frame made of steel pipes suspended by a wire. The tank was mounted on this frame and rocked back and forth. Figure 2 shows the overall construction of the equipment.

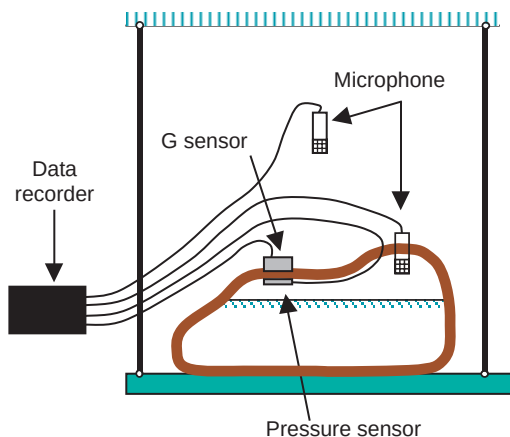


Fig. 1 Concept of equipment

The following procedure for applying acceleration and deceleration to the tank was set. First, the tank is pulled to the rear until it touches the stopper of Fig. 3, and is then left motionless until the surface of the liquid in the tank comes to rest. Next, the tank is released, causing it to move forward while accelerating. It continues to move forward past the bottom center position. A rope is tied to the rear of the frame supporting the tank in order to regulate the stroke of the frame. Consequently, when the tank moves forward and exceeds a certain limit, this rope becomes taut, applying a deceleration to the tank. When the rope is stretched to its limit, the tank starts to move backward. The length of the rope has been adjusted in advance so that the maximum deceleration reaches 0.3 G, enabling the same deceleration to be generated repeatedly.



Fig. 2 Laboratory equipment

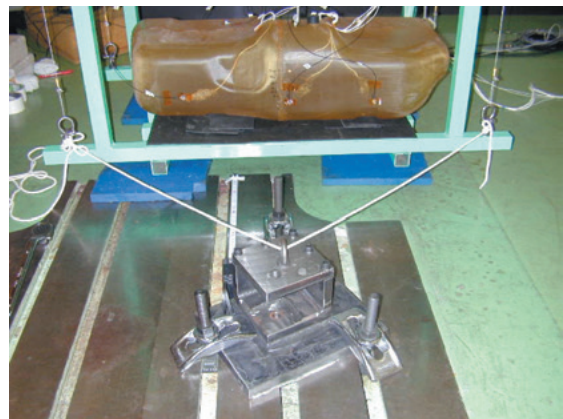


Fig. 3 Stopper

3.2. Test Results

Figure 4 shows a graph of the noise measured from a height of 300 mm above the tank (hereafter called “evaluation point noise”). The level of the fuel in the tank at this time is 40 liters. The graph has five large peaks that correspond to the timing at which the surface of the sloshed fuel alternately reaches the front and rear walls of the tank.

Here, a detailed study of one of these peaks is carried out. Figure 5 shows the evaluation point noise, Fig. 6 the noise inside the tank, and Fig.7 the vibration of the tank wall at the location nearest the evaluation point. In each of these graphs, attention is focused on the instant at which the peak rises, and the time axis is indicated in enlarged form. In all three graphs, one graduation along the horizontal axis is 0.05 second. By comparing these three graphs

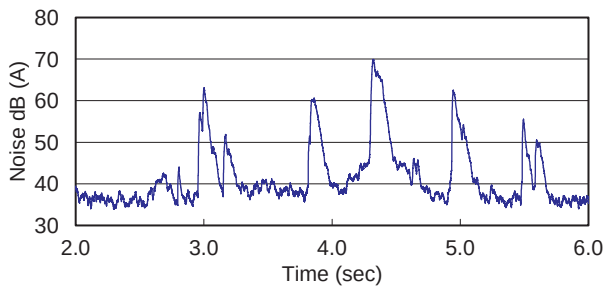


Fig. 4 Sloshing noise at evaluation point

with each other, it can be seen that there is strong correlation between the evaluation point noise and the vibration of the surface of the tank wall, but that there is no correlation between the noise inside the tank and the other two graphs. For this reason, it can be considered that the noise inside the fuel tank has little effect on the evaluation point noise. In the case of both of the hypotheses mentioned in Section 2, noise generated due to vibration of the inside of the tank wall is ultimately transmitted to the evaluation point, so it follows as a matter of course that there is correlation between wall surface vibration and the evaluation point noise. However, because no correlation with the noise inside the tank can be seen, it can be considered that the cause of vibration of the tank wall surface lies elsewhere.

Next, attention is focused on the relationship between the pressure at the inside wall of the tank and the evaluation point noise. Figure 8 shows a comparison of the time history of the evaluation point noise and the wall surface pressure at each point. This figure shows that the pressure on the inside wall of the tank rises abruptly when the evaluation point noise rises. From this fact,

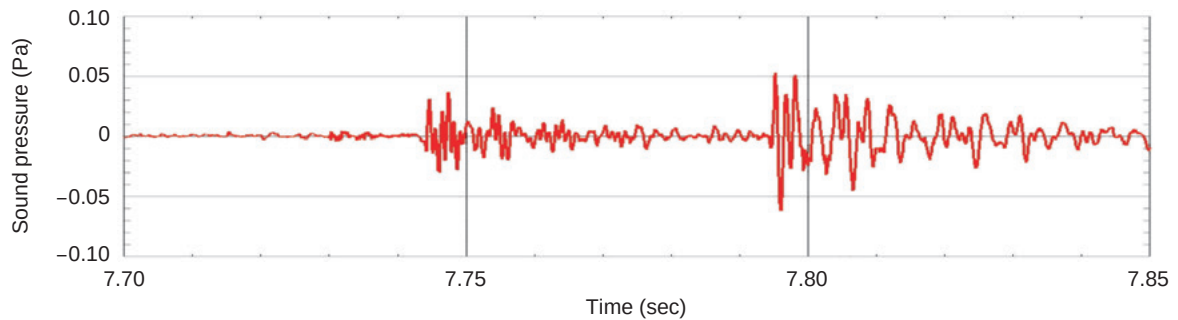


Fig. 5 Sound pressure (Outside of tank)

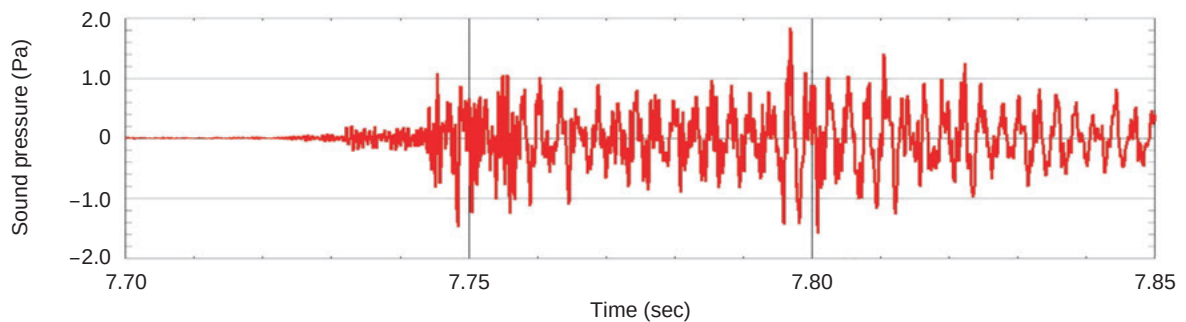


Fig. 6 Sound pressure (Inside of tank)

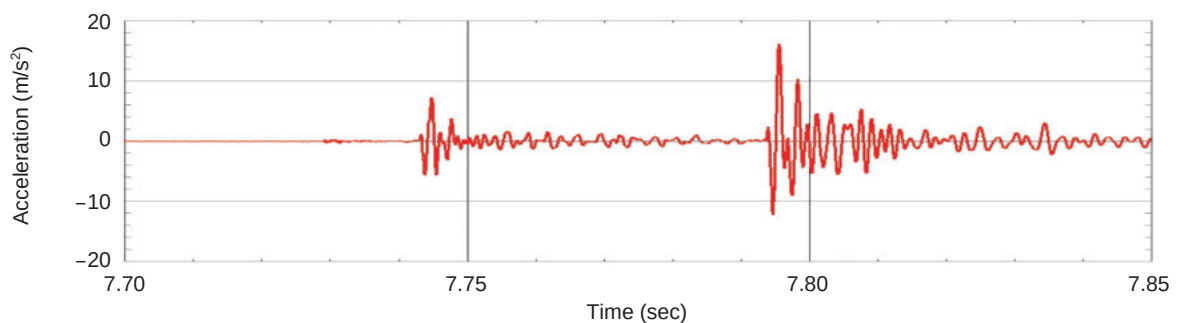


Fig. 7 Vibration (Tank surface)

it can be inferred that evaluation point noise occurs when the tank wall surface is vibrated as a result of the liquid in the tank striking the wall surface. The difference in the detected pressure rise from one measurement point to another indicates that the phenomenon whereby the liquid strikes the inside wall of the tank is extremely

localized. In the simulation, when the motion of the liquid surface is visualized, permitting a detailed observation of the points where the pressure rise at the wall surface can be conducted, it is possible to verify the phenomenon whereby the fuel strikes the wall surface, thus bearing out the above inference. When the pressure inside the

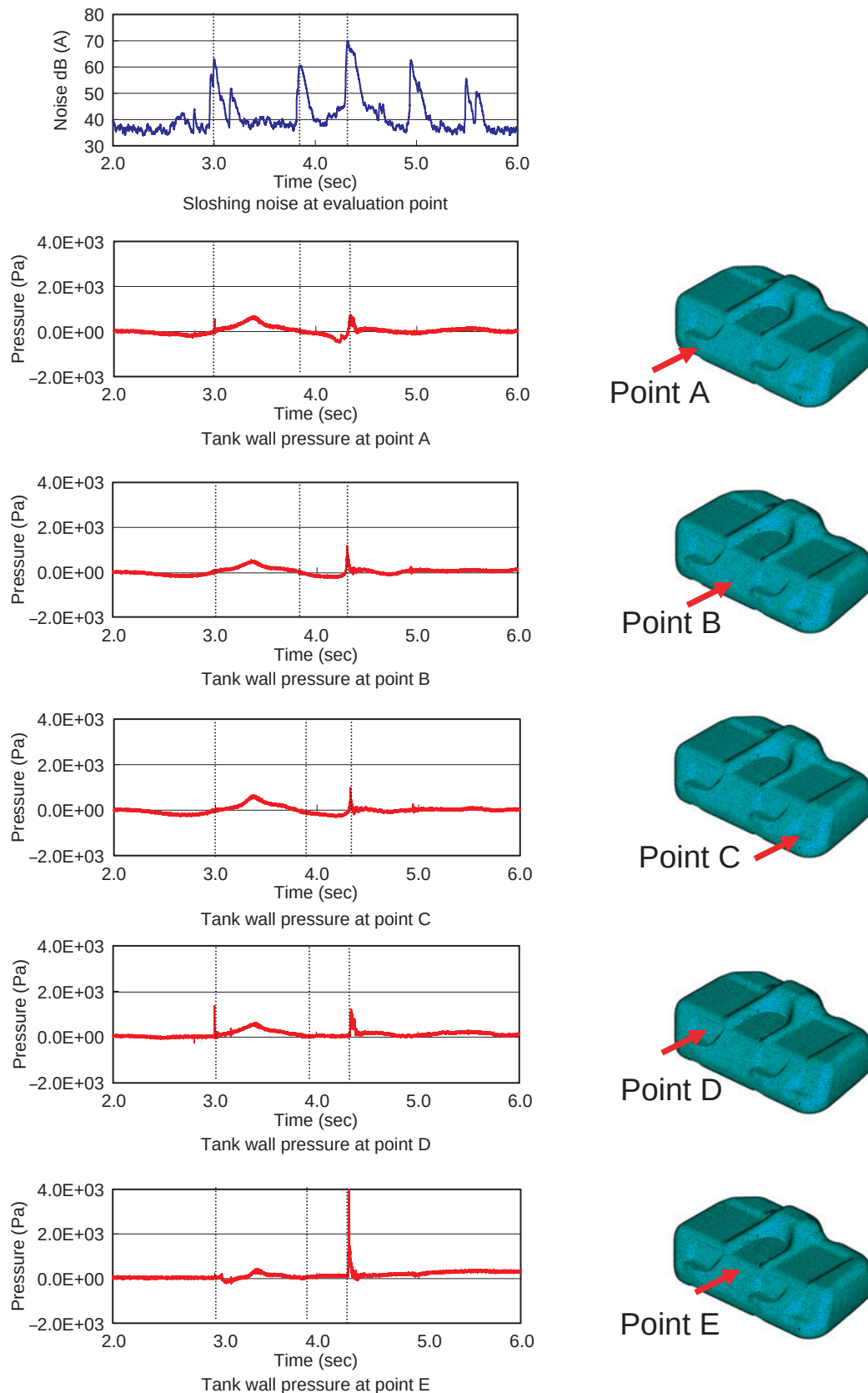


Fig. 8 Measured tank wall pressure

tank rises slowly, the phenomenon whereby the evaluation point noise reaches a peak corresponding to the pressure rise is not seen, so it can be considered that the sloshing noise is generated only when the pressure rises impulsively over a short period. Incidentally, a pressure peak, such as that corresponding to the second noise peak, sometimes fails to appear at any measurement point whatever when the evaluation point noise is generated. It is thought that this is due to the occurrence of a pressure rise at a point other than the measurement point.

4. Computer Simulation

Generally, the entire internal volume of a fuel tank of an automobile is not filled with fuel, but instead is always occupied simultaneously by air and liquid. Therefore, in order to simulate the sloshing of the fuel in the tank, it is necessary to reproduce the behavior of a fluid that has a free surface. Also, because both a structure (tank) and a fluid (fuel) exist in the system, and exert an effect on each other, it is necessary to perform structure-fluid interaction analysis. In this research, MSC Dytran, which enables analysis of a fluid that has a free surface and also permits structure-fluid interaction analysis, was used.

4.1. Making a Model

In the structure-fluid interaction analysis, an Euler element was applied for the fluid part, and a Lagrange element for the structural part, and a method in which they were superimposed on each other was used. Here, an Euler element is a type of element that is fixed in a space and contains the object that moves through it. It is suitable for analyzing fluids. A Lagrange element, on the other hand, is a type of element that undergoes deformation motion according to the deformation motion of the object. It is suitable for analyzing a structure. These types of elements are coupled to each other by a method called General Coupling by MSC Dytran. This method defines each of the Euler and Lagrange elements entirely independently of each other, and then superimposes them on each other. Regarding the coupling between the Euler and Lagrange elements, the Lagrange element functions as a wall that separates the fluid, as seen from the Euler element, and the reaction from the fluid is transmitted to the structure via this boundary surface, as seen from the Lagrange element⁽³⁾.

Figure 9 shows an example of a finite element model that was used in this research. When the initial liquid surface height is specified in this finite element model, a fluid is defined in the region surrounded by the tank and the initial liquid surface, and it is possible to reproduce the way in which the liquid moves along with the motion of the tank, which constitutes the boundary surface with the fluid. By assigning the motion of the tank as time history

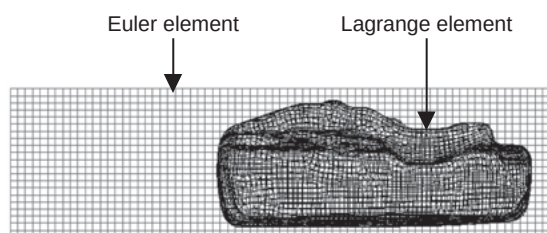


Fig. 9 Finite element model

data of the motion velocity, it is possible to reproduce any arbitrary motion.

4.2. Confirmation of Reproducibility

In order to confirm that the simulation could reproduce the motion of an actual liquid surface, the tank was made of transparent acrylic plastic to render it visible inside, and the motion of the liquid surface obtained from simulation was compared with that obtained experimentally. The results are shown in Fig. 10. It can be seen that the motion of the liquid surface can be reproduced extremely well by simulation.

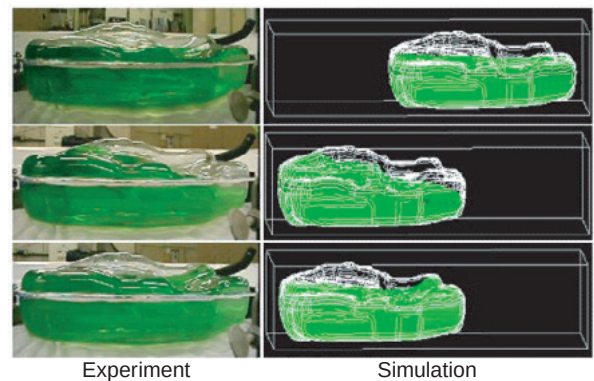


Fig. 10 Liquid surface behavior

5. Comparison with Experimental Results

A comparison of whether or not the pressure peaks observed at the inside wall of the tank during the bench test could be observed in the simulation was performed. In order to accurately reproduce the condition of the bench test, the value of the tank velocity measured during the bench test was used as the input value for the simulation. The tank inside wall pressure was output at the same points as those to which pressure sensors had been applied for the bench test, and the values obtained were compared with the measured values for the bench test. Figure 11 shows a comparison of the measured time history waveform and the results of simulation with the evaluation point noise when pressure is applied to the tank wall surface. It was found that the simulation results at point D agreed closely with the measured results, and also that the sharp pressure peak that appeared during the bench test could be observed using simulation as well. In addition, even at a point, such as point F, where no pressure peak was observed in the bench test because there were no measurement points, the pressure peak corresponding to the evaluation point noise was observed in the simulation, thus proving that the hypotheses were correct. In the simulation, it is possible to set many more measurement points within the range of the computer's ability compared to when performing actual measurement. Consequently, by appropriately allocating the measurement points, it is possible to reproduce all of extremely localized pressure peaks. This means that it is now possible to accurately predict the occurrence of sloshing noise by simulation.

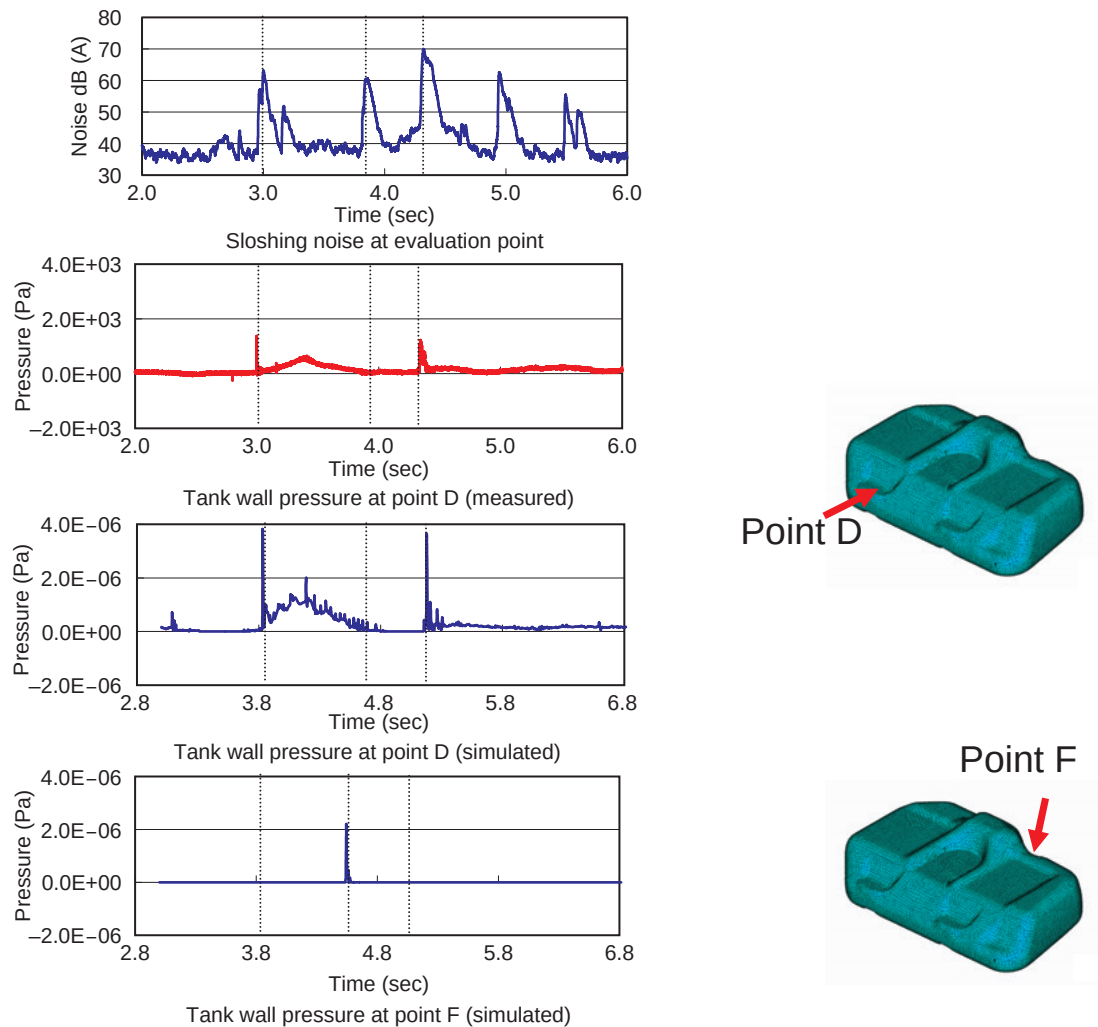


Fig. 11 Comparison between simulation and experiment

6. Conclusion

In order to develop technology for predicting sloshing noise by simulation, an experiment for extracting the physical parameters that are closely related to the occurrence of sloshing noise was performed, and the results compared to those obtained by simulation. As a result, the following facts were established.

- (1) Sloshing noise occurs as a result of the fuel striking the inside wall of the tank over a localized area.
- (2) When this happens, the pressure at the inside wall of the tank rises impulsively in a short time.
- (3) In the simulation, this sharp pressure peak could be reproduced, enabling the generation of sloshing noise to be predicted.

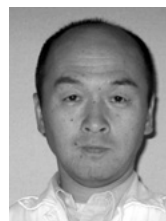
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