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Development of Flexible Liquid Damper

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ABSTRACT

The “Flexible Liquid Damper” (FLD) is a new concept of a vibration control device. The damper is composed of only two parts, a flexible ball and liquid filling in the flexible ball. The damper design is simple, but the mechanism underlying its significant damping capacity has not been clarified. Two kinds of tests are conducted to investigate the characteristics of the damper in this study. One is the sinusoidal sweep test, while the other is the free decay test. First, several parameters of the damper are investigated, such as its size, material and the properties of the liquid itself. As a result, it is found that the case of around 50% volume is the most effective rather than the case where the ball is 100% filled with liquid. Moreover, other conditions have some effect, such as the wall thickness of the ball, and the liquid viscosity. Both the free vibration and the sinusoidal sweep tests show its great damping capacity. The damping effect obtained in free vibration tests is higher than that by the sinusoidal sweep tests. In some test cases, two dominant peaks are observed; the peaks only appear in the case of some combinations of the damper parameters. An attempt is made to analyze the damping mechanism using the general-purpose computational tool "ANSYS", by creating an analytical model of the damper to simulate the test results. From the numerical results, it is found that the vibration control mechanism of this damper is mainly similar to the mechanism of the dynamic vibration absorber. However, the numerical results also show that the damper is not a simple dynamic vibration absorber and may include some other energy dissipation or energy transfer mechanism.

1. INTRODUCTION

In recent years, seismic activity has been more vigorous around the world. To counter earthquakes, various methods of reinforcement have been adopted for large and critical facilities. There are also ongoing efforts to improve the performance of large buildings such as high-rise buildings and apartment buildings by some reinforcement methods such as bracing and so on. Seismic strengthening by bracing is conventional for individual homes, but the development of a general method for aseismic performance improvement for private homes is difficult due to cost. This is the motivation for the development of the FLD.

The FLD is a new concept vibration control device which consists of a liquid-filled flexible ball as shown in Figure 1.

Figure 1 Flexible Liquid Damper

The FLD is under development for the prevention of mechanical vibrations. The FLD is most effective for shock type excitation. It is therefore considered useful for transient vibrations such as during earthquakes. The merit of this damper is its simplicity and low cost. The damper has a damping effect when installed on the top of the structure. The damping effectiveness has been investigated in several previous studies, but the mechanism has not yet been fully clarified. This study is therefore required to understand the mechanism of this new damper. This paper summarizes the present results of our efforts to understand these mechanisms.

2. EXPERIMETAL WORK

2.1 Test apparatus

The test apparatus is designed for two kinds of tests in the same system. The two test methods employed are “the free decay test” and “the sinusoidal sweep test”. The free decay test measures the response of the freely decaying wave from a given initial displacement. The sinusoidal sweep test measures the vibration response to a sinusoidal excitation force.

Figure 2 shows the test system. The system base plate is set on two blocks, A and B. The test part is set on block A, while the vibration exciter is set on block B. Rubber tubes are set on block A to reduce the effect of sympathetic vibrations between the two blocks. A board set on the rubber tubing supports the movable frame. The vibration plate is connected to this frame by a spring. The frequency of the vibration plate is controlled by the rigidity of the spring. As the vibration plate and the frame vibrate due imbalance, a fixed frame is built on block A to restrict the direction of vibration, with wires between the vibration plate and the frame.

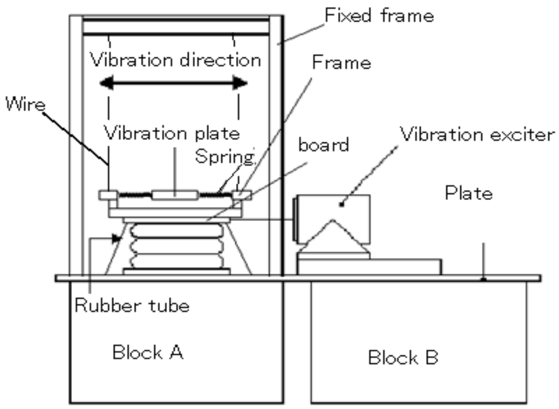


Figure 2 System of test apparatus

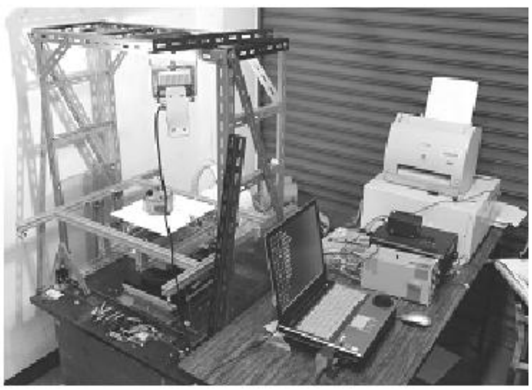


Figure 3 Picture of test apparatus

Figure 4 Rubber Ball

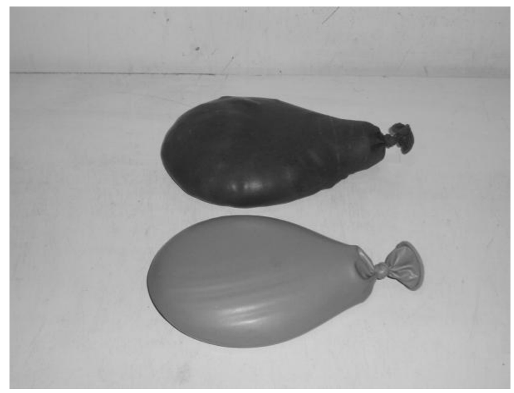


Figure 5 Rubber balloon

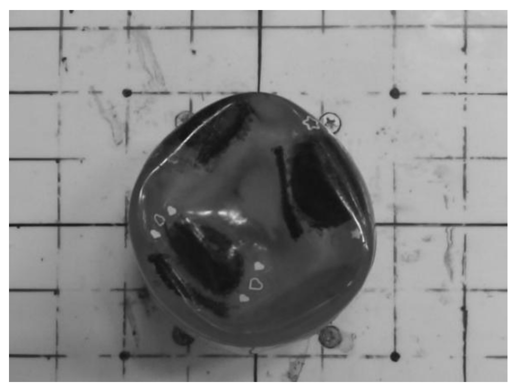


Figure 6 PVC ball

2.2 Test models

The models tested in this study are rubber balls, rubber balloons and PVC balls. The rubber ball and the rubber balloon are used for the comparison of different of stiffness. The PVC balls are also used to compare the effect of material.

The diameter of the rubber balls is 150mm, while the four PVC balls have diameters of, 75mm, 127mm, 152mm, and 172mm. These diameters are measured when the ball is completely filled with liquid.

The rubber balloon is the most flexible, while the PVC ball is the most rigid among the test balls.

2.3 Test patterns

Two conditions are considered. In condition 1, the mass of the vibration plate is fixed. In condition 2, the mass ratio μ is fixed. The mass ratio μ is defined in equation (1).

$$\mu = \frac{\mathbf{m}}{(\mathbf{M} + \mathbf{m})} \qquad (1)$$

m: Mass of the damper
M: Mass of the base

From these tests, the damping ratio is measured for two test conditions; one is “vibration plate only”, and the other is with the “damper placed on the plate”. The damper induced damping ratio is obtained by calculating the difference between the damping ratios of these two cases.

The tests are also divided into two types. The first type is the basic test, while the second is the design improvement test. The first type of test is used to investigate the basic characteristics of the damper. The second test type investigates damper improvement. The following are further details on the two test types:

Basic tests

- Comparison of material

The effect of damper material is examined by comparing dampers developed using the rubber ball and the rubber balloon. Each damper is filled with water and the test method is the free decaying test. The test condition is 1.

- Fluid volume

The damper is filled with liquid in different levels. This test investigates the effect of the amount of liquid. The amounts of liquid are changed in 12.5%, 25%, 37.5%, 50%, 75%, 82.5% and 100%. Water is used as the liquid and air is evacuated from the ball. In these cases, the natural frequency of the vibration plate controlled by springs is fixed in a certain value. The rubber ball is used in this test, and the test method is the free decaying test. The test condition is 1.

- Ball stiffness

The effect of the stiffness of the damper is investigated. In this test, three stiffnesses are examined, soft, standard and rigid, by changing the thickness of the ball. Water and the rubber ball are used in the test. The test method is the sinusoidal sweep test and the free decaying test. The test condition is 1.

- Effect of Viscosity

The effect of the liquid viscosity is investigated. In this test, three types of liquid are examined, silicone oil, water, and alcohol. The rubber ball is used. The test methods are sinusoidal sweep and free decay. The test condition is 1.

- Comparison of mass ratio

In this test the effect of mass ratio is investigated. The three mass ratios considered are, 0.14, 0.2 and 0.43. Test condition is 1. The PVC ball is used as the test piece. Test method is sinusoidal sweep test.

Design Improvement tests

In these tests the number and the combination of dampers in an array configuration are investigated as shown in Figure 7. The test condition is 2. The PVC ball is used and the test method is sinusoidal sweep test. The mass ratio μ is fixed at 0.43.

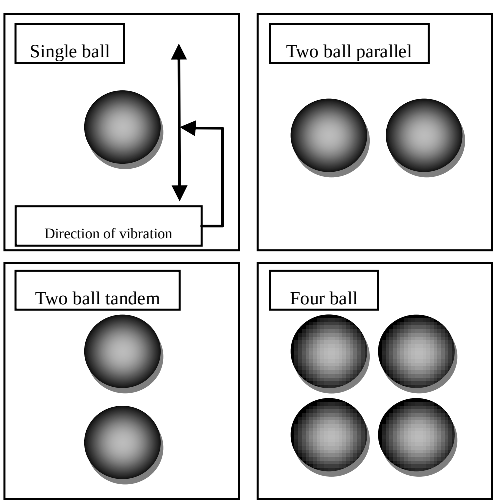


Figure7 Array test pattern

3. TEST RESULTS

The test results are shown below according to each test condition.

Basic tests

- Comparison of material and volume of fluid

Figure 8 shows the results. The rubber ball has a higher damping effect than the rubber balloon. When the amount of liquid is 50 percent in the rubber ball, the damping ratio is the highest. Optimal conditions are found from these results. I.e. the amount of liquid should be 50% and the ball material should be rubber. These conditions are used in all tests that follow.

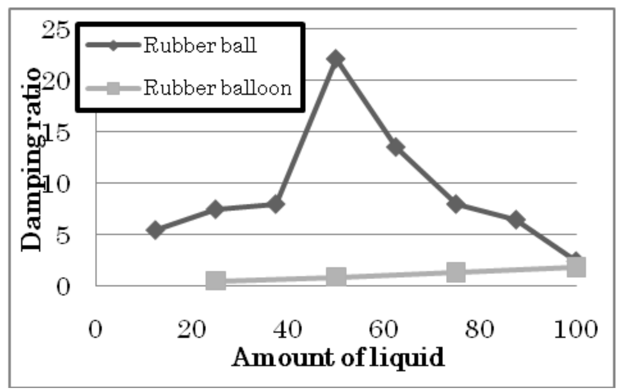


Figure 8 Comparison of material and volume of fluid

- Ball stiffness tests

Figure 9 and Figure 10 show the results. The soft ball shows somewhat higher damping, while the stiff ball shows lower damping. The soft ball has two peaks, while the standard ball has one peak. The stiff ball does not show a clear damping peak. In addition, the sinusoidal sweep tests yields lower damping values than the free decay tests.

- Fluid viscosity tests

Figure 11 and Figure 12 show the fluid viscosity test results. In the free decay test, the damping effect with water is the highest. Silicon oil and alcohol give low damping ratios, although alcohol shows the higher damping effect in sinusoidal sweep tests. Two frequencies of peak damping are confirmed when water is used.

- Comparison of mass ratio

Figure 13 shows the results of the mass ratio test. The higher mass ratio gives the higher damping ratio. But high mass ratio may cause structural overload. 10% mass ratio is the maximum value recommended.

Design Improvement tests

Figure 14 shows the design improvement test results. One damper is found to have the highest damping effect than that of the damper arrays. This is presumably because of the combined mass ratio. Several peak damping values are confirmed in the different array patterns.

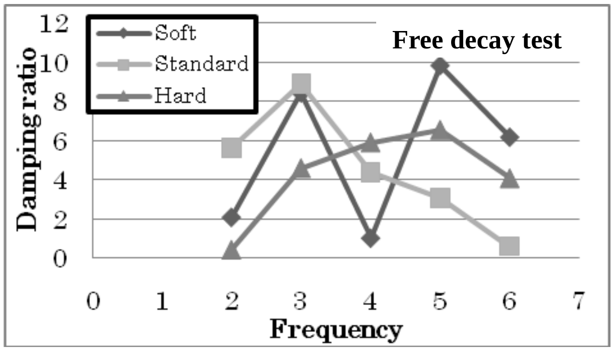


Figure 9 Effect of ball stiffness

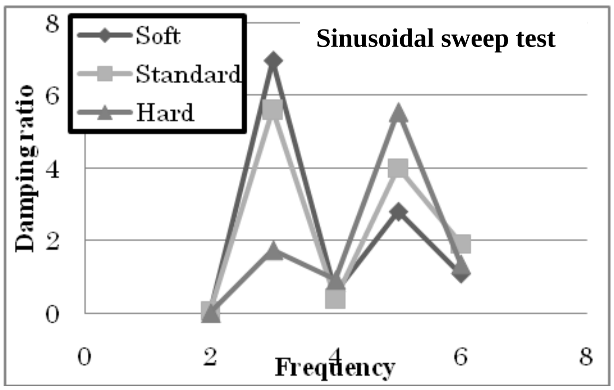


Figure 10 Effect of ball stiffness of ball

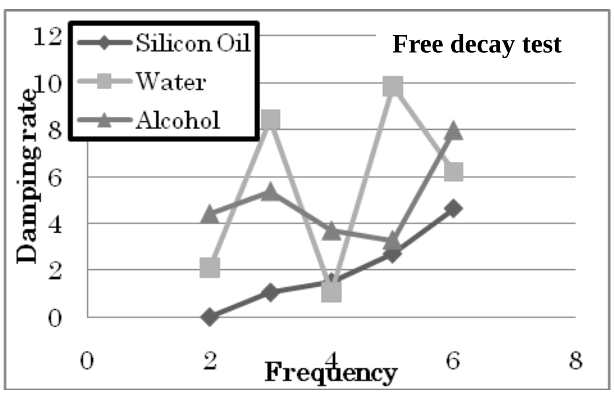


Figure 11 Viscosity of liquid

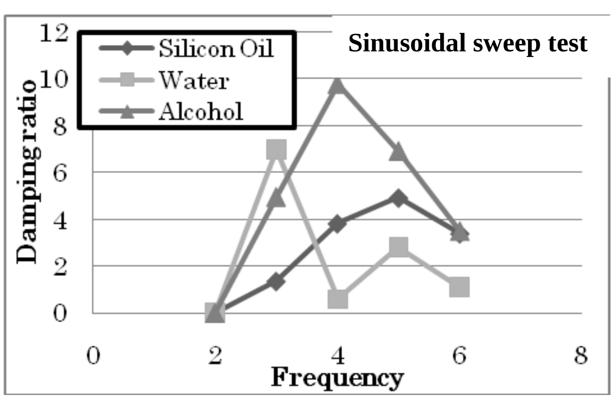


Figure 12 Viscosity of liquid

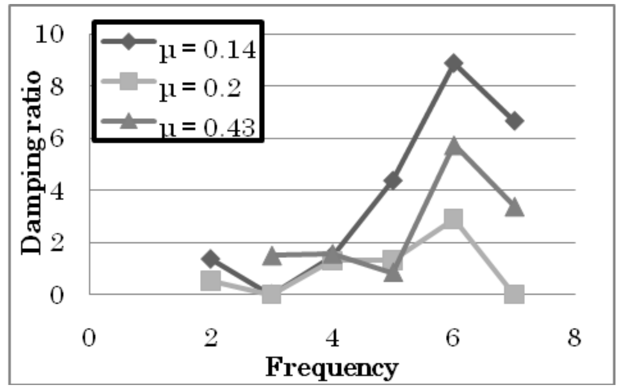


Figure 13 Result of comparison of mass ratio

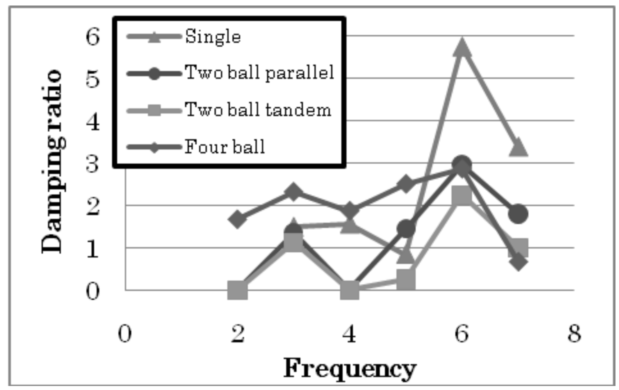


Figure 14 Result of improving test

4. DISCUSSION

4.1 Characteristics of the damper

It is found that the damping effect of the rubber ball is higher than the rubber balloon from tests on the comparison of materials. In the tests, the rubber balloon vibrates with the vibration plate. The rubber balloon and the vibration plate vibrate as one body. The damper therefore needs a certain level of stiffness. In addition, the damper filled to 50 percent with liquid shows the highest damping effect. But the reason for this cannot be determined simply based on this test.

Next, by the test of the comparison of materials, it is concluded that a certain level of stiffness is important. From the test on ball stiffness, the damping effect drops to a low value when the stiffness is too high. An index quantifying this stiffness effect should be formulated in the future.

From the test on the effect of fluid viscosity, the damping effect is found to be high when the viscosity of the liquid is low. When water is used in the tests, two peak damping levels are found. This phenomenon appears only for the water case. The viscosity is important for the effectiveness of the damper.

A definition of a proper FLD is created from these basic tests as follows:

Definition of proper FLD:

(a) Moderate flexibility
(b) Material should maintain the damper shape
(c) Significant liquid density for inertia

From the mass ratio comparison test, it is found that the higher mass ratio shows the higher damping ratio. But if the mass ratio is (too) high, the damper is also easily damaged. Thus mass of the damper must be carefully optimized.

From the design improvement tests, it was found that the effect of a single damper is higher than multiple damper arrays. The reason may come from the fact that multiple dampers interfere with each other. The FLD should therefore have a simple configuration.

In addition, the rubber balloon is more effective than the PVC ball. This is because the PVC ball is stiffer than the rubber ball. The stiffness of the damper must therefore be moderately soft.

4.2 Additional tests

In the foregoing tests, the characteristics of the damper were examined. But the damping mechanism of the damper is not understood. Then, from the definition of the proper FLD, (b) "Material should maintain the damper the shape", the damping mechanism is strongly dependent on the shape of the damper. Figure 15 shows the shape of the damper filled to 50%, 40% and 30%.

The main damping mechanism may come from the vibrating part in Figure 15. Therefore, trapezoidal pedestal set under the damper of 40%. Thus shape of the damper of 40% is copied from shape of the damper of 50%.

If the damping mechanism of the damper has no relation with amount of liquid, the mechanism depends on the shape of the damper. Sinusoidal sweep test and the free decaying test results are shown in Figures 17 and 18.

These results show that the damper with 40% liquid volume shows similar trend as 50% filled damper. Thus the result suggests that the damping effect mainly comes from the indicated vibration part.

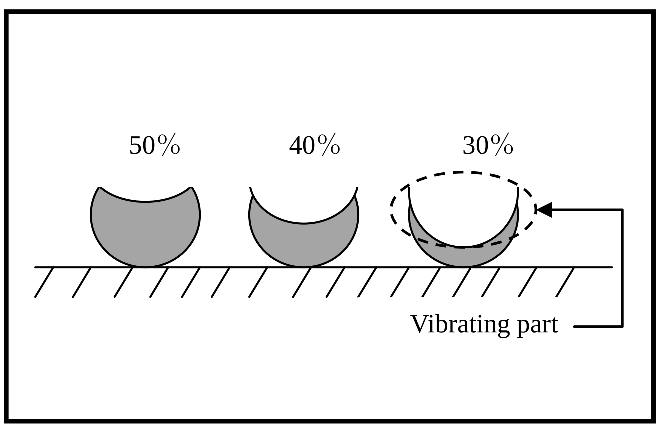


Figure 15 Shape of Damper (50%, 40%, and 30%)

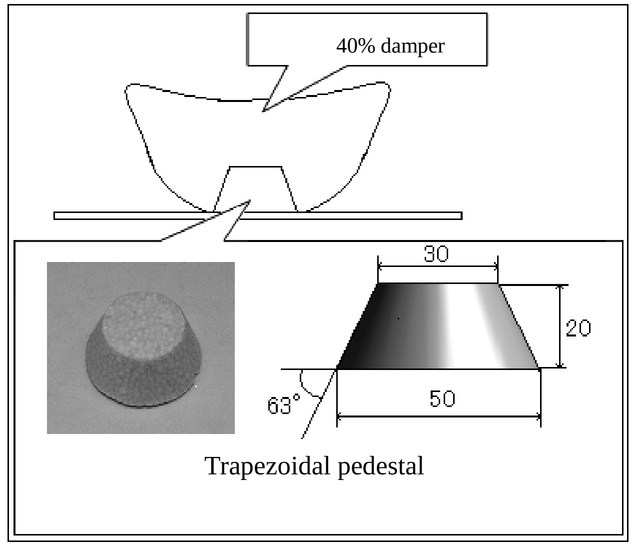


Figure 16 Trapezoidal pedestal

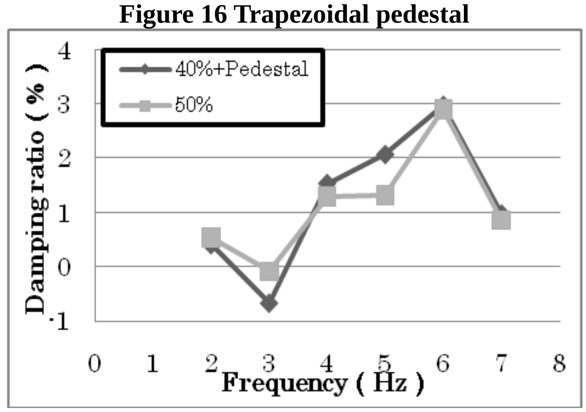


Figure 17 Result of free decaying test

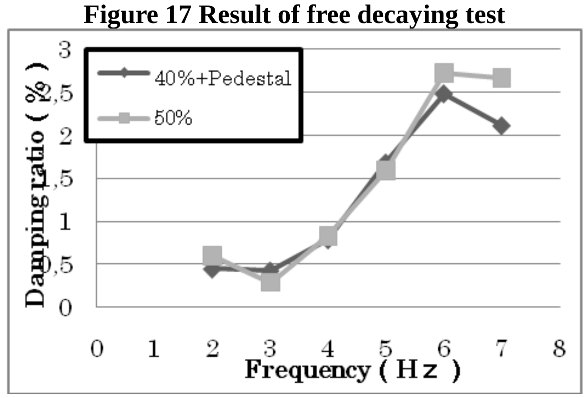


Figure 18 Result of sinusoidal test

4.3 Analytical approach

By the basic tests and the design improvement tests, the characteristic of the damper is examined. However, the mechanism of damping needs further analysis since it has many unclear points.

In this analysis, a general purpose block simulator "Simulink" is used at first. In Simulink, a two-DOF system model is built for the calculations. Figure 19 shows the analytical model. Figure 20 shows the Simulink block diagram.

Data of the free decay test when mass ratio μ =0.2 and frequency is 6 Hz is the input to Simulink. Figure 21 shows this result.

An animation is created to compare the simulation result with a movie of the real damper. Fig.22 shows an example of the animation. In comparison with the movie of the real damper, the animation of the analytical result shows very similar movement. Therefore it is concluded that the damping mechanism of the damper is not simply the mechanism of a dynamic absorber.

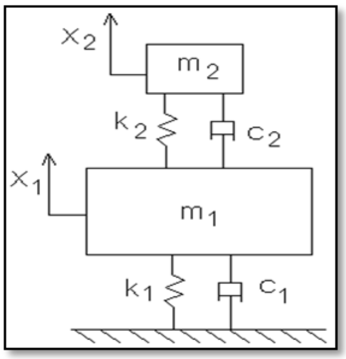


Figure 19 Two-DOF system model

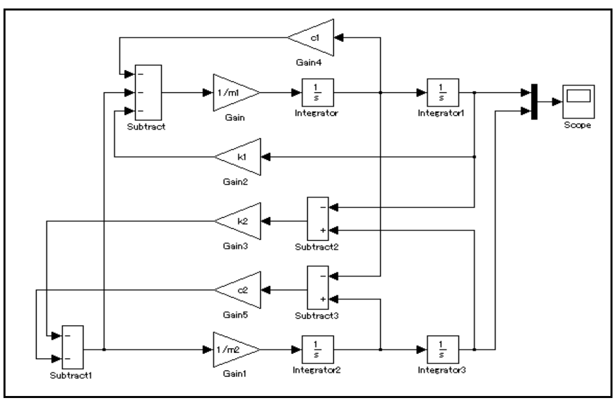


Figure 20 Simulink block diagram

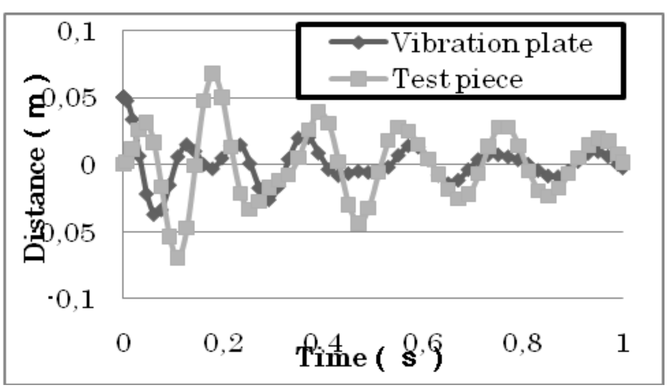


Figure 21 Waveform by Simulink

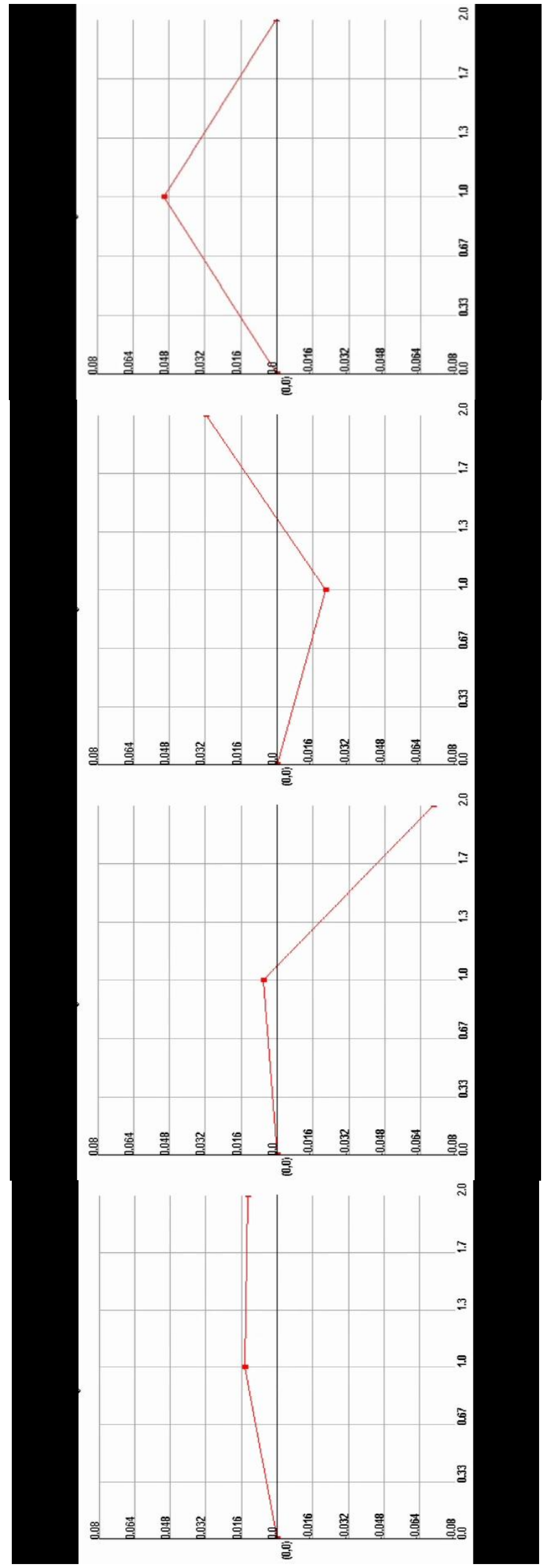


Figure 22 Modal animation

Next, a more detailed analysis is conducted based on a three dimension model using ANSYS structural elements. A model of the FLD as shown in Figure 23, where the amount of liquid is 50%, is created. It should be noted that CFD elements are not yet used in this report. However, incorporation of CFD is under way.

This model simulates the condition of the damper when it is set on the vibration plate. Damper material is PVC, and the fluid is water. The shape of this model approximates the condition when the damper set on the plate.

When the sinusoidal force is introduced, the response of the vibration plate model is confirmed in a particular range of frequencies. Figure 24 shows the case where the model of the damper is set on the vibration plate model. Parameter settings for analysis are shown in Figure 25.

Three natural frequencies of the vibration plate are considered, 5Hz, 6Hz and 7Hz. First, the natural frequency of the damper is set to 6 Hz, then the frequency response analysis is done. The response of the damper set on the plate and response of the plate only are shown to Figure 26.

The results of Fig.26 do not show good agreement tests. Then, the damping gives to water. Figure 27 shows the results. When the frequency of the plate is 6Hz, a similar response to experiments is obtained. But when the frequency is 5Hz, the difference from experiments is larger. When the movie of this point is shown, the damper does not move a lot and merely falls off of the vibration plate. The reason for this is that the model of the damper is expressed with FEM, and therefore, the model shows the characteristics of a solid. The current model cannot therefore be considered to express the characteristics of the FLD. But the analytical response approaches the real response when damping is applied to the fluid part. The damping mechanism is not only due to the shape of the damper but also due to the effect of the liquid inside the damper.

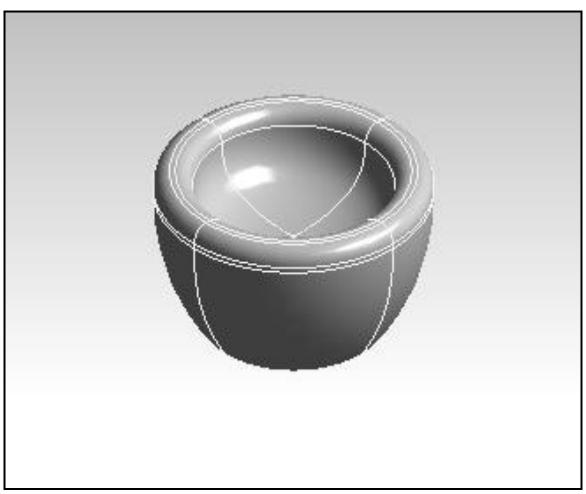


Figure 23 Analysis model

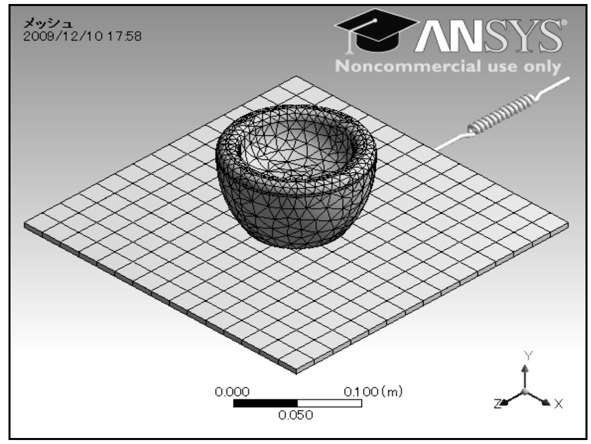


Figure 24 Model of damper set on plate

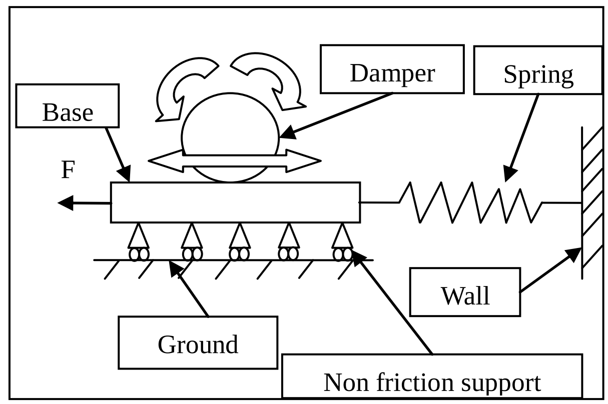


Figure 25 Setting of analysis

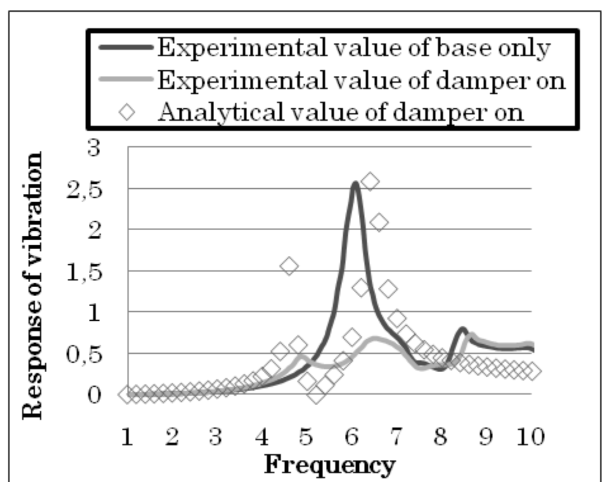
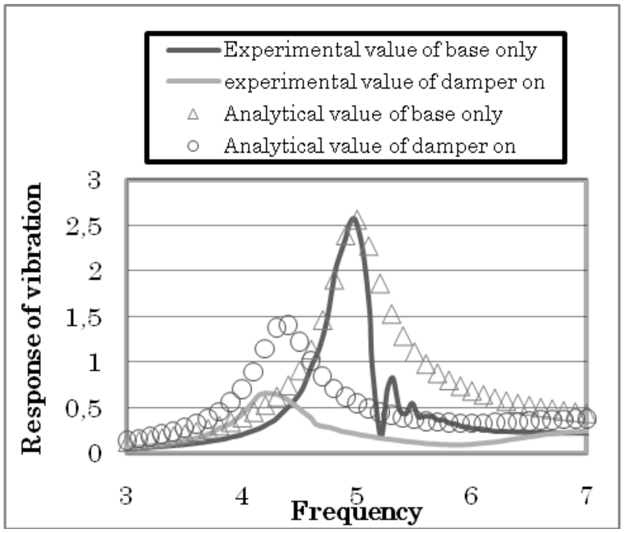
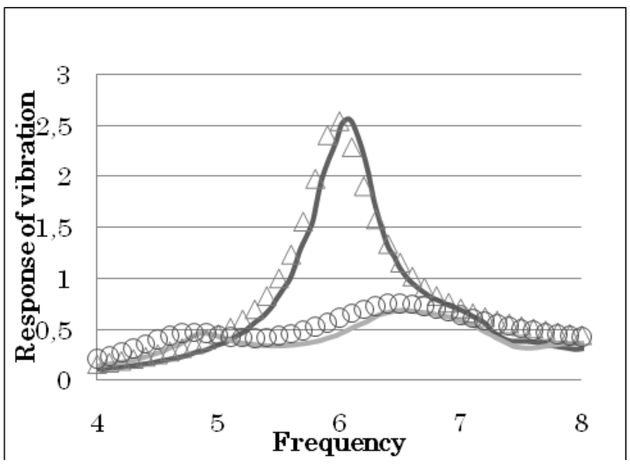


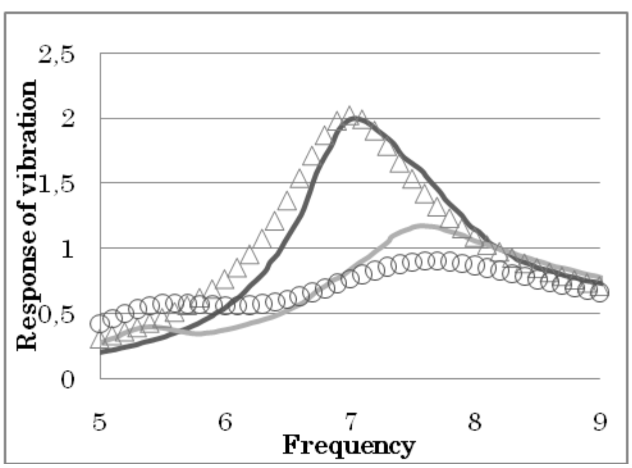
Figure 26 Result of Analysis



(a) 5Hz



(b) 6Hz



(c) 7Hz

Figure.27 Result of analysis (5Hz, 6Hz, 7Hz)

5. CONCLUSIONS

The following results are obtained:

- A conceptual definition of a FLD is obtained from basic tests. This is:
  (a) Moderate flexibility
  (b) Material to keep the shape
  (c) Significant liquid density for inertia
- If the damper conforms to this definition, the FLD generates a damping effect. The FLD has an advantage not to depend on the particular material used.
- Based on the basic tests, the FLD takes shape as a damper but these tests did not elucidate the mechanism of damping.
- Analysis to investigate the damping mechanism was also done. Two inferences are confirmed, (1) “the FLD is a simple dynamic absorber”, and (2), the “damping effect is due to the internal liquid”.
- In the present model there still remains the problem that the liquid is modeled with FEM structural elements. The model of damper should be developed using CFD.
- In the future, the model of the FLD incorporating a CFD fluid model will be developed. It is expected that the resulting FSI will shed light on the damping mechanism of the FLD.

6. ACKNOWLEDGEMENT

This report is a kind of summary of a five year project. Many students have contributed to this research. The authors hope to introduce their great effort. Especially the authors felt grateful of help of Nobuaki Tamamoto.

[References]

[1] Tomomichi Nakamura, Kouzou Sugiyama, “study on development of Flexible Liquid Damper” (in Japanese), JSME annual meeting, 2007

[2] Tomomichi Nakamura, “Development of a Damper based on a New Concept: Development and study on flexible liquid damper” (in Japanese), Journal of Osaka Sangyo University. Natural sciences, 2009

[3] Changcheng Shao “*Kihon kara Wakaru Yuugenyousohou* [Finite element method that understands from basis]” (in Japanese) morikita syuppan 2008

[4] JSME, “JSME Textbook Series Mechanical Vibration” (in Japanese), JSME, 2005,

[5] Nihon Gomu Kyoukai[The Society of Rubber Industry, Japan], ”*Gomu Gijutsu Nyumon*[Technological introduction to rubber]” (in Japanese), Nihon Gomu Kyoukai, 2004

[6]Seiichi Honma, “Plastic Handbook”(in Japanese), Kougyou Tyousakai, 2003

[7]Takanobu Aoyama, “*Tsukaeru! MATLAB/Simulink Programing*[It is possible to use it. MATLAB/SIMULINK Programing]”, Koudanya Scientific, 2007