Compact Damping Element for Response Control in Light-Weight Structure

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SUMMARY
The aseismic construction, seismically isolated and response control structure have been applied to the several structures. However, the quake-proof technique for the smaller scale structure such as a detached house, server rack and work of art has not yet been in the development stage until now, and especially there is a problem in the damping element in the practical use stage because the downsizing of damping element is often difficult to be adapted to design specification such as a performance, a cost, a mechanism and so on. In this study, a response control system for light weight structure with low cost, simple mechanizm and high vibration reduction ability. This paper describes the effectiveness of two types of new damping devices from several analytical and experimental results. One is the polyurethane elastomer material for detached house, and the other is magnetic damper using Eddy-current damping effect for server rack.

Keywords: Response control, Damping Element, Seismic Safety, Litght Weight Structure

1. INTRODUCTION

Many response control techniques have been researched and developed in several areas, and the damper with greater performance has been practically used more and more. Since a damping effect is one of most important element for vibration system as with a spring element, it has been required further upgrading from a view point of performance, function, environment resistance, cost and so on. Especially, Niigata Chuetsu earthquake in 2004 caused the serious damage not only architectural and civil structures, but also personal computer and sever rack in the office. Such damage in information and communication machinery is very serious problem because it is highly information-intensive society now. In recent years, the application of base-isolation technique to the information and communication machinery including server rack has been performed positively. However, there is the problem that the vibration after seismic input is not decrease immediately, and also the maximum stroke in the device is not enough. From these problems, it is expected that the development of an efficient damping element for base-isolation device in a lightweight mechanical structure.

On the other hand, the detached houses designed by the old building standards act in Japan were suffered enormous damage from the Great Hanshin-Awaji Earthquake and the Great East Japan Earthquake, and are about 50% in total detached houses even now. The upgrading for seismic safety such detached houses is urgent duties because the occurrence of huge earthquake is expected in an extremely high probability. Response control technologies are one of the efficient method to up grade the structural safety.

In this study, a response control system for light weight structure with low cost, simple mechanizm and high vibration reduction ability. This paper describes the effectiveness of two types of new damping devices which was considered above design specifications. One is the polyurethane elastomer material to the detached house not only for upgrading the seismic safety element but also for increasing the energy absorbing element for structural response control. The mechanical characteristics are investigated from several loading tests, and it is also confirmed that the test specimen using polyurethane rubber material indicates a high linearity in the mechanical characteristic and high damping performance. The other is magnetic damper using Eddy-current damping effect to be realized a damper without any contact, stroke limitation, maintenance and strong nonlinearities on damping effect. In recent years, the permanent type magnets such as a samarium-cobalt magnet or neodymium-iron-boron magnet has been able to use as a practicable damping element with comparatively low cost. The basic damping characteristics using the prototype model had confirmed in several experimental and analytical investigations.

2. NEW DAMPING MATERIAL FOR RESPONSE CONTROL USING URETHANE RUBBER

2.1. Urethane elastomer

Urethane material is collective term of rubber-like elastomer obtained by the reaction of the polyol (Polyester polyol or Polyether polyol) and isocyanato, and is also called urethane elastomer. Material properties are located in the middle characteristic of the traditional rubber and plastic. Main excellent features of urethane material are durability, wear resistance, ozone resistance and modeling. On the other hand, weakness are allowable temperature limit, water resistance and resistance property of organic solvent, strong acid and alkali. Moreover, urethane material is divided into the ether and ester type in generally. The former one has the feature of cold resistance and highly elasticity compared with the later one, and also hydrolysis does not occur in material structure. The later one is high mechanical strength, but hydrolysis occurs in ester connected part. Furthermore, very great advantage of material in a manufacturing process is to be shaped with several forms by using a cast molding. The manufacturing time can significantly reduce compared with a general rubber material.

The urethane rubber has a small nonlinearity of the dynamic characteristic, and also the molecule design that accepted a performance demand is easily possible compared with a visco-elastic material such as high-damping rubber that has been used as vibration absorbing material in generally. From such reasons, the urethane rubber has the possibility that may be able to realize a characteristic as the vibration reduction materials which has not been in practical used so far.

The material has been used in a solid tire of forklift or a wheel of a roller coaster, a pulley, an anvil and a cable tray as an industrial article, and various rollers or cleaning blades as OA machinery. In addition, there is the example of use for blades of the road surface contact part of snowplow.

2.2. Loading test for evaluation of mechanical characteristic

2.1.1. Experimental method

Figure 1 shows the schematic view of experimental specimen which puts two layer of urethane rubber of 40*40*15mm by steel plate of 10mm thickness as a sandwich type. The experimental condition is shown in Fig.2. The loading test apparatus is hydraulic servo actuator (maximum load: 30kN and maximum stroke: 200mm). The test parameters are shaking frequency and amplitude from 0.1 to 2.0 Hz shaking frequency and from 6.7 to 100% shear strain. Moreover, in order to investigate the amplitude dependency on excessive displacement area, the loading test until 200% shear strain was conducted in the test at shaking frequency 0.1Hz. Besides, the environmental temperature in experimental laboratory was controlled to be about 20°C.

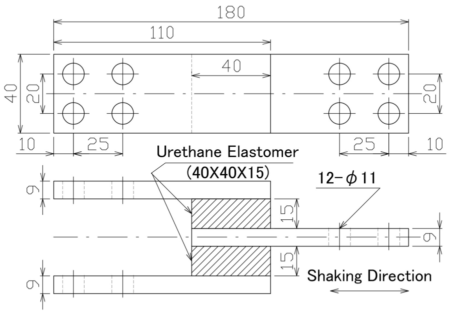
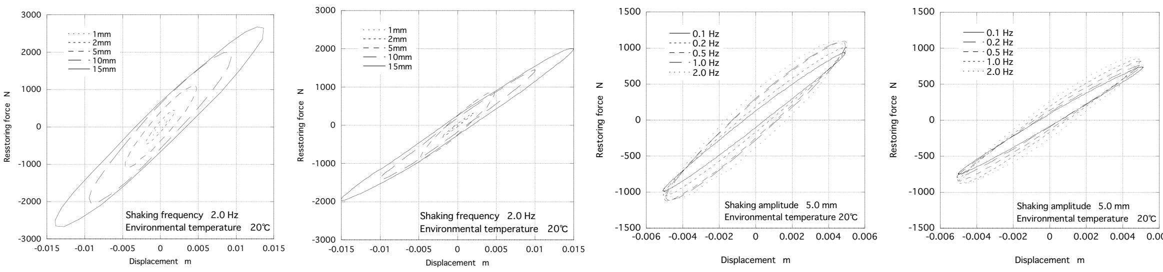


Figure 1. Experimental specimen used for loading tests

2.1.2. Experimental result

Figure 2(a) and 2(b) show the damping force characteristic in which shaking frequency is 2.0Hz to compare the both characteristics definitely. It is confirmed that the energy absorption of damping force characteristic of test specimen A which was combined by emphasizing a damping performance increases compared with specimen B. Moreover, the inclination of loop in each specimen is almost constant without a dependency on shaking amplitude. From this result, it is indicated clearly that the amplitude dependency on mechanical characteristic is an independent to the damping performance.

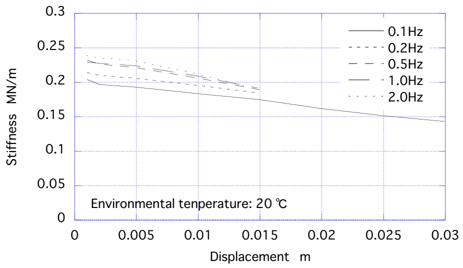
Figure 2(c) and 2(d) summarizes the damping force characteristics in 5 mm amplitude on each shaking frequency to confirm a dependency. It is confirmed again that the test specimen A improves a damping force performance compared with test specimen B. Moreover, a strong nonlinearity which is generally caused by increasing a damping ability in a high-damping rubber doesn't appear, though there is a dependency on shaking frequency. As the results, it was clarified that the damping material with various characteristic features is realized by a design of material combination.



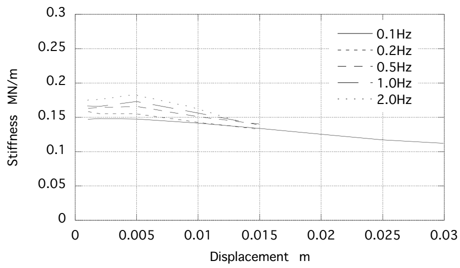
(a) Test specimen A (b) Test specimen B (c) Test specimen A (d) Test specimen B

Figure 2. Displacement and frequency dependency on restoring force characteristics

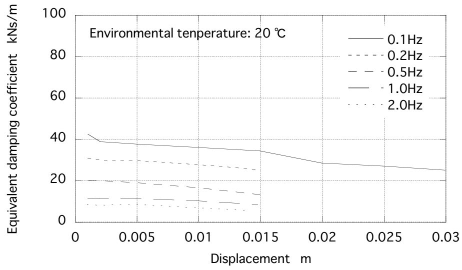
Figure 3(a) and 3(b) show the displacement dependency on stiffness in each specimen. Although the quantitative characteristics is not equal in each other, the displacement dependency on stiffness has a very small in a deformation area as different as 30 times because the rate of change with stiffness stayed about 70 % in the specimen A, and is about 75 % in the specimen B. The frequency dependency on stiffness is also a very small, and moreover, the dependency decreases as the shaking amplitude increases. It was confirmed that the stiffness of the urethane elastomer used in the loading test is not so much affected against a shaking displacement and velocity regardless of the damping performance. Figure 3(c) and 3(d) show the displacement dependency on equivalent damping coefficient. It is shown that an steady damping effect is expected from small displacement and the displacement dependency is low similar to the stiffness, though the damping coefficient of test specimen A is higher quantitatively than the specimen B because of enhancement on damping performance. Moreover, it is considered that the frequency dependency on damping coefficient is not so much strong as discuss in detail in next chapter but there is a weak dependency.



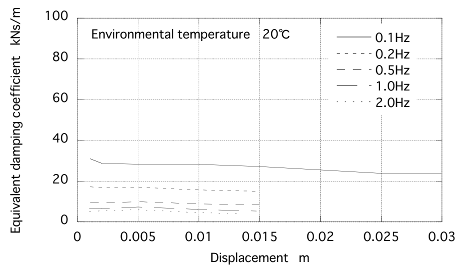
(a) Test specimen A



(b) Test specimen B



(c) Test specimen A



(d) Test specimen B

Figure 3. Displacement dependency on stiffness and damping coefficient

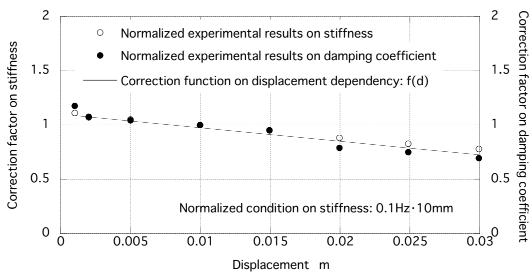
2.3. Preliminary analysis for vibration control effect

The vibration control effect is examined by using the numerically modeled mechanical characteristics of test specimen A. Two kinds of numerical model are examined. One is the identification model using the experimental result in loading test directly, and the other is four element model (Ito, 1999) which is composed of Voigt and Maxwell model using stiffness and damping element of the material.

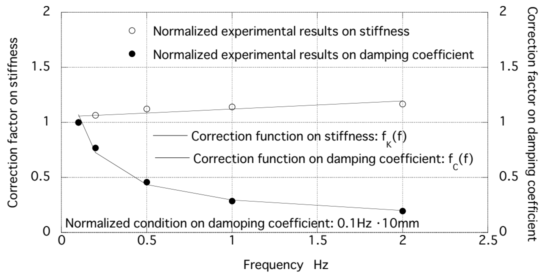
2.3.1. Modeling of mechanical characteristics for urethane rubber using experimental identification

The dependency on mechanical characteristic of the urethane rubber obtained from loading test is normalized by any experimental item and is evaluated the qualitative tendency. Figure 4(a) shows the normalized displacement dependency on each mechanical characteristic by the stiffness and damping coefficient at 0.1 Hz shaking frequency and 10mm shaking amplitude. From the result, the displacement dependency on stiffness and damping coefficient equal qualitatively and quantitatively, and then the same correction factor for the dependency was used for the preliminary analysis. Figure 4(b) shows the normalized frequency dependency on each characteristics by the stiffness and damping coefficient at 0.1 Hz shaking frequency and 10mm shaking amplitude as the same on stiffness, but the different correction factors for damping coefficient was examined as appropriate. The numerically modeled characteristics of test specimen A is as follows. Besides, the model does not include the correction element for a shape factor and a temperature dependency which is future subject.

$$\begin{cases} K_A = K_{1.0Hz\_10mm} \times f(disp) \times f_K(freq) \\ C_A = C_{1.0Hz\_10mm} \times f(disp) \times f_C(freq) \end{cases} \tag{2.1}$$



(a) Displacement dependency



(b) Frequency dependency

Figure 4. Correction function of mechanical characteristics

2.3.2. Modeling of mechanical characteristics of urethane rubber using four elements model

Four elements model has been generally applied to numerical model for mechanical characteristics of visco-elastic material such as a stress relaxation, creep and visco-elasticity. Although linear Voigt model is manageable on vibration analysis, the model can not express frequency dependency on elasticity. On the other hand, Maxwell mode composed linear element can indicate visco-elastic characteristic, but the application region is used to a limited extent. In here, the four element model is composed from Voigt and Maxwell model which are placed in parallel each other, and also the nonlinear four element model used for displacement dependency on each element is examined as shown in following. Besides, the identification in each element is set from initial value based on recurrence characteristic on damping force of Voigt model. Moreover, each stiffness and damping coefficient are regulated by trial and error using the displacement dependency function which is normalized by the experimental results at 0.1Hz shaking frequency and 10 mm amplitude. Figure 5 show regulated results used for the four element model in the range from 1mm to 15 mm shaking amplitude and from 0.1Hz to 2.0 Hz shaking frequency. As shown in the figures, it is confirmed that the good identification is obtained by using nonlinear four elements model.

$$K_e = \frac{\omega^2 C_1^2}{K_1^2 + \omega^2 C_1^2} K_1 + K_2 \tag{2.2}$$

$$h_e = \frac{\omega}{2} \frac{K_1^2 \left(C_1 + C_2\right) + \omega^2 C_1^2 C_2}{K_1^2 K_2 + \omega^2 C_1^2 \left(K_1 + K_2\right)} \tag{2.3}$$

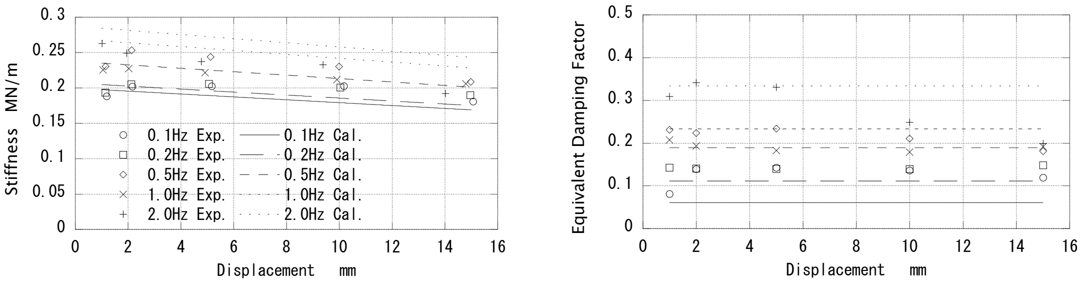


Figure 5. Correction function of mechanical characteristics

2.3.3. Time response analysis for evaluation of effectiveness of urethane damper

In a preliminary analysis, the time response analysis using 2 DOF shear deformation type model which was assumed a two-storied detached wooden house is examined, and the vibration control effect is estimated in case that the urethane elastomer damper using the material of test specimen A is applied a detached house. The analytical model is as follows; Mass of 1st storey: 14,000 kg, Mass of 2nd storey: 8,000 kg, Stiffness on 1st floor: 12.8 MN/m, Stiffness on 2nd floor: 7.84 MN/m, 1st modal damping ratio: 0.01. Besides, The stiffness and damping coefficient is composed by the identification model of experimental loading test mentioned above. Therefore, since the seismic response analysis becomes nonlinear simulation, Runge-Kutta-Gill method is used as numerical integration method in this time. The acceleration and displacement responses in each floor are evaluated with damper case and without damper case. Besides, the analytical parameter is the frame with dampers, and also one frame has 4 dampers. In the analysis, the case without dampers, with 2, 4 and 6 flames in 1st floor are examined. As the 2nd floor, the half damper quantity is installed. Input wave is JMA Kobe NS 818 gal used for the seismic response analysis.

Table 1 shows the change in natural frequency and 1st damping ratio in each analytical condition. As the results, it is confirmed that the maximum displacement response was reduced to 80 % in case of 4 frames in first floor to the detached house and 60 % in case of 6 frames, and also the maximum acceleration response was attenuated to 60 % in case of 4 frames and 40 % in case of 6 frames. Since the seismic resistant and energy absorbing performance are gradually upgrading by the increase of urethane rubber damper, therefore it is confirmed that the synthetic seismic safety of detached house improves by applying the urethane rubber damper.

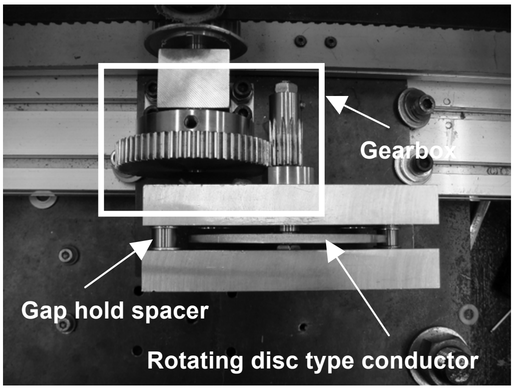
Table 1. Natural frequency and damping ratio in analytical conditions

	Without damper	2 frame unit	4 frame unit	6 frame unit
1st natural frequency (Hz)	3.4	3.6	3.9	4.2
2nd natural frequency (Hz)	7.1	7.7	8.2	8.7
Damping ratio (%)	1.0	4.4	7.4	10.0

3. PRODUCT TYPE MAGNETIC DAMPER USING EDDY-CURRENT DAMPING EFFECT AND APPARATUS FOR PERFORMANCE EVALUATION

3.1. Magnetic Damper using Eddy-Current Damping Effect

Figure 6 shows the product type magnetic damper using Eddy-Current damping effect (Seto.1979, Nagaya.1985, Matuoka.2006). and the test apparatus or performance evaluation. The damper is desired to be downsized as much as possible and also should be manufactured in the step of practical used type at the lowest possible cost. Therefore, the damper must be designed from the most basic parts with a performance based on design specification. Especially, in case of the damper for applying to a target vibration attenuation device with simple mechanism such as base isolation device for sever rack, the shape size and the constitution of the device is required careful attention.



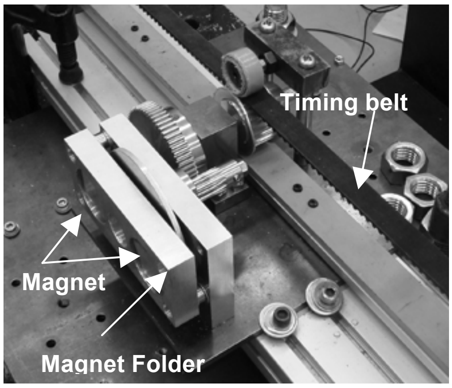


Figure 6. Production type magnetic damper used for the tests

The device used for the performance test mainly consists of neodymium-iron-boron magnet, magnet folder, aluminum rotating disc type conductor and gap holding spacer shown in Figs.7 and 8. The device converts the movement from lateral motion to rotational motion with timing belt and driving pulley, and absorbs energy by Eddy-Current damping effect which is occurred from the movement of a conductor into magnetic fields. The disk diameter is 80mm, and thickness was the design parameter to establish the design method for the damper. The disk thickness of three types is prepared for the test; 1.5 mm, 3 mm and 4.5 mm. The shape size of magnet is 24*24*12.5 mm. The magnets were combined to be a magnetic circuit of the NS pole with the opposite and translation direction in the device. In this device, two magnetic circuits were installed in total.

In general, the damping device using magnetic circuit has a problem of magnetic field especially in around information equipment. Especially, if the communication and information machine such as a server rack is super-structure on the base-isolation system, the effect of leak-age magnetic field caused by magnetic force is a severe sensitive problem generally. In Standards and Information Technology Industries Association in Japan, the ability under Class B means to allow as an well-protected environment for a communication and information machine in case under 5 Gauss. As a result, it was confirmed that it would be solved to place the damping element using magnets into the isolation device from the preliminary analysis for flux density in magnetic unit.

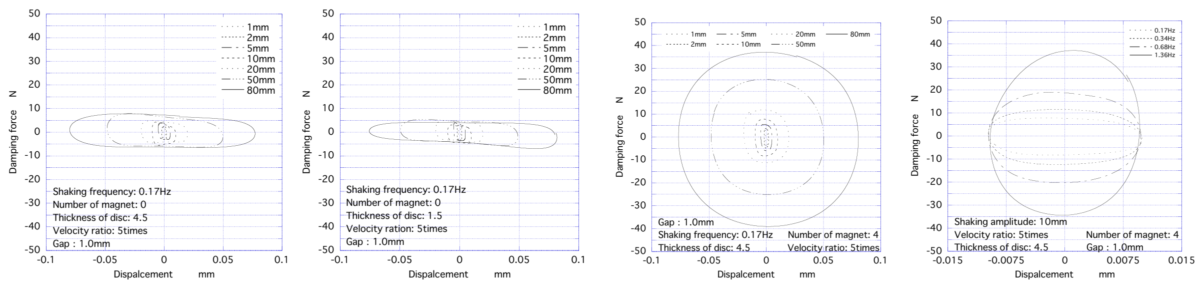
3.2. Loading test for investigation of basic characteristics of product type magnetic damper

In the loading test, four shaking frequencies from 0.17 Hz to 1.36 Hz (0.75 sec to 6.0 sec) including equivalent natural period of expected base-isolation device for applying the damping element using magnets are used for the test. Moreover, in order to confirm the amplitude dependency on the characteristics of the damping element, shaking amplitude from 1.0 mm to 80mm is applied to the test. The equivalent velocity of the test is 0.1 to 8.5kine. In addition, the number of the magnets to the damping element, the gap between the magnet and conductor, the thickness of disk and the velocity ratio are also experimental parameters in these tests. The damping characteristics of the product type damping device are investigated by using various experimental parameters.

The measured data are the displacement and the damping force of the device. Besides, the displacement is measured the movement of timing belt instead of the rotational angle. In the displacement measurement flow, the data is recorded by using the displacement transducer including into actuator, A/D converter and digital data recorder, and also the load data is recorded by using load cell, dynamic shear strain amplifier A/D converter and digital data recorder. The sampling frequency is 200 Hz in each test. As a loading method, hydraulic actuator in which the maximum load is 30 kN and the maximum stroke is 200 mm was used for the test.

3.3. Experimental results on performance evaluation for product type magnetic damper

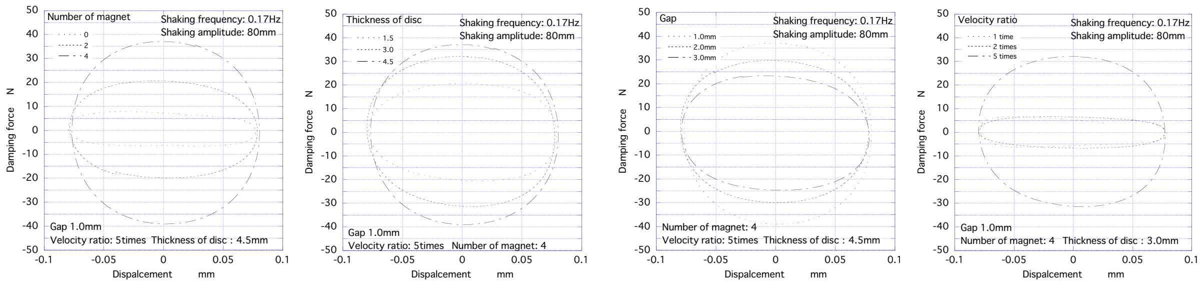
First, it is confirmed about a friction characteristic of which the device has contained since initial state, because it is should be careful about the friction force contained the damping force in the case using a lot of mechanical parts in the device like a gearbox. Figures 7(a) and 7(b) show the friction characteristics of the product type damping device without the magnet used for the test. It is confirmed that the friction force characteristics of the device is independent of shaking amplitude and frequency, gap and thickness of disc. Then, the rotational inertia force was also investigated in the same device condition using 5 times velocity ratio in the gearbox. As the results, it is confirmed that the rotational inertia force was negligibly small com-pared with the friction force in the device. Figure 7(c) and 7(d) show amplitude and frequency dependency on damping force characteristic. It is indicated that the damping force characteristic is closely similar to the characteristic of viscous damper such as shown in the results. Therefore, the damping force characteristic is proportional to the velocity, and is modelled numerically as a linear viscous damping force characteristic.



(a) (b) (c) (d)

Figure 7. Friction force characteristic and rotational inertia force in damping force characteristic

Figure 8 shows the comparison of the damping force characteristic with the parameters in the design constitution of the device. In these figures, the comparison in each experimental parameter on the device construction such as number of magnet, thickness, gap and velocity ratio in lower right are indicated in each figure. Since the damping force characteristic depends on the design parameters with the characteristic of viscous damping such as shown in the evaluation test results, the damper can change the damping performance to satisfy the performance specifications in the design step. The evaluation of quantitative and qualitative tendency on each damping characteristics are indicated in following section.



(a) Magnet (b) Thickness (c) Gap (d) Velocity ratio

Figure 8. Damping force characteristics compared with design parameters in device constitution

3.4. Design formula for product type magnetic damper

From the damping force characteristics noted above, the design formula for damping force characteristics in the product type damper using eddy-current damping mechanism was considered. Table 2 shows the parameters of the formula. The formula was examined in condition with the back yoke behind the magnet unit (Sagawa. 2007). The shape size of magnet is the same in the experimental damping element, and the formula was considered that the magnets were set on the opposed side in each other. The flux density in the center of the gap in the both magnets is shown in the following equation.

$$B_g = \frac{B_r}{2\pi}\left\{\tan^{-1}\frac{ab}{2L\sqrt{4L^2+a^2+b^2}} - \tan^{-1}\frac{ab}{2(L+L_m)\sqrt{4(L+L_m)^2+a^2+b^2}}\right\} \tag{3.1}$$

in here, B_g: Flux density of center between the magnets. The distance between the surface of magnet and the centre of conductor in the product type damper is obtained from following equation.

$$L = \frac{z}{2} + gap + 1\times10^{-3} \tag{3.2}$$

in here, “gap” means the parameter in experimental condition, and the distance in between the magnet housing and the surface of magnet. Therefore, the design formula is expressed as shown bellow by using velocity ratio parameter; R_v.

$$F = \frac{knb^2 z B_g^2 R_v}{\rho} v \tag{3.3}$$

The above equation includes a unknown parameter ; k. Although the value is often obtained from the shape size of conductor and magnetic flux, the factor of the product type damper was examined from the experimental results. Therefore, the following design expression is possible to use basically within a limited extent of experimental condition. As the result, the shape factor was decided from the experimental results in all of the combination of the constitution parameters of the damper used for the evaluation tests; number of magnet unit, thickness of conductor, gap and velocity ratio. The design formula for the product type damper is set to following equation as k=0.002. By using the formula, the damping force characteristic is obtained from several design parameters of magnetic damper for the damper element in response control device.

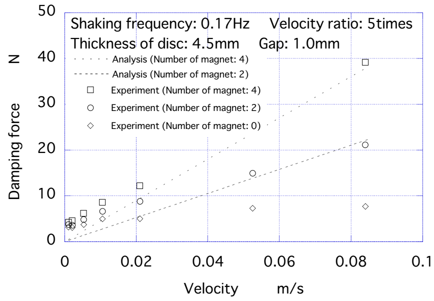
$$F = \frac{0.002 n b^2 z B_g^2 R_v}{\rho} v \tag{3.4}$$

Table 2. Parameters for design formula

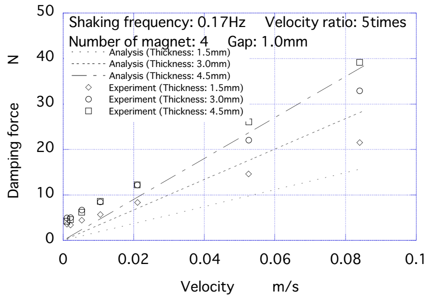
<table>
<tr><th colspan="2">Analytical parameter</th><th>Value</th><th>Analytical parameter</th><th>Value</th></tr>
<tr><td colspan="2">Residual flux density B_r [Gauss]</td><td>13.39×10^3</td><td>Distance between surface of magnet and centre of conductor: L [m]</td><td>3.5×10^{-3}</td></tr>
<tr><td rowspan="2">Shape size of magnet</td><td>Vertical width to the motion direction of conductor: a [m]</td><td>24.0×10^{-3}</td><td>Shape factor: k [-]</td><td>2.0×10^{-3}</td></tr>
<tr><td>Parallel width to the motion direction of conductor: b [m]</td><td>24.0×10^{-3}</td><td>Diameter of conductor: D [m]</td><td>80.0×10^{-3}</td></tr>
<tr><td colspan="2">Thickness of magnet: L_m [m]</td><td>12.5×10^{-3}</td><td>Velocity of conductor: v [m/s]
(V: Velocity of actuator)</td><td>$v = \frac{D}{d} V$</td></tr>
<tr><td colspan="2">Thickness of conductor: z [m]</td><td>1.5×10^{-3}
3.0×10^{-3}
4.5×10^{-3}</td><td rowspan="2">Diameter of rotating shaft: d [m]</td><td rowspan="2">80.0×10^{-3}
40.0×10^{-3}
16.0×10^{-3}</td></tr>
<tr><td colspan="2">Electric resistivity: ρ[Ωm]</td><td>2.5×10^{-4}</td></tr>
</table>

3.5. Evaluation of Damping Force in Each Parameters of Design Construction of Device

Following figures indicate the relation of the velocity dependency on the damping force with a parameter in the design constitution. All of results are compared with the analytical result using Eqn.3.4. Figure 9(a) shows the velocity dependency on the damping force in case of the parameter of the number of magnet to the device. It is confirmed again that the damping force is proportional to the velocity. Besides, since there is friction force in the device, the damping force includes almost constant force into the damping force, and the tendency of friction force is the same in the all following results quantitatively. Moreover, effectiveness of the design formula in Eqn.3.4. is verified in the comparison between the analytical and experimental result, because the analytical results obtained good agreement with the experimental one. Figures 9(b) and 10(a) are almost the same results qualitatively and quantitatively such as shown in the comparison results. However, there is a slightly difference between the relation of the damping force and the velocity ratio such as shown in Fig. 10(b), although the qualitative tendency agrees well with experimental characteristics. It is considered that the design formula will effective in all of the parameters in design constitution of the device, because the analytical result becomes in safety side as a design condition.

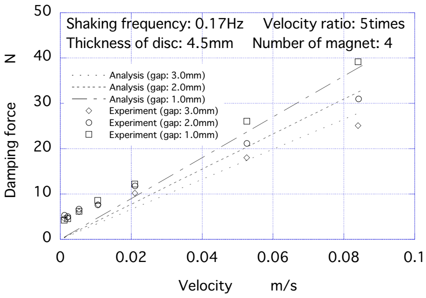


(a)

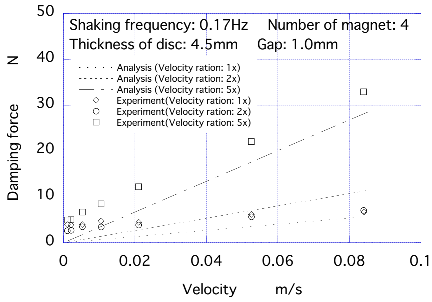


(b)

Figure 9. Relation of damping force, number of magnet and thickness of conductor



(a)



(b)

Figure 10. Relation of damping force, gap and velocity ratio

4. CONCLUSIONS

This study has been investigating a response control system for light weight structure with low cost, simple mechanizm and high vibration reduction ability. This paper describes the effectiveness of two types of new damping devices from several analytical and experimental results.

In the study on urethane rubber material, as the results, the urethane rubber indicates high linearity in mechanical characteristics and deformation performance in condition with the test parameters of shaking frequency and amplitude. Moreover, the attenuation effect of seismic response control was confirmed against huge earthquake input from the time response analysis in condition with that the urethane rubber damper applied to the detached house. It was confirmed that the maximum displacement response was reduced sufficiently. It is confirmed that the synthetic seismic safety of detached house improves by applying the urethane rubber damper.

In the study on the damping element applying Eddy-Current damping mechanism which has been practically expected the damping ability in recent years, as a result, it was considered that the damping force characteristic of the device is almost equivalent to a viscous damping force characteristic because the damping force is proportional to the velocity, and also the characteristic was independent from the parameters of design constitution of the device in the experimental range used for the loading tests. Moreover, the effectiveness of the proposed design formula was confirmed from the comparison with the experimental and analytical results.

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