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# STRUCTURAL DESIGN OF A LINEAR-MOTION TYPE SEMI-ACTIVE DAMPER BY FINITE ELEMENT METHOD

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## ABSTRACT
*The purpose of this study is to design a structure of a linear-motion type semi-active damper which can reduce the vibration caused by an earthquake. This paper proposes the more effective structure of the linear motion semi-active damper by magnetic-structure interaction analysis of finite element method using ANSYS. The semi-active damper has a simple structure that a linear mover, a magnet bar, reciprocates in coils of a stator. The size of the coils and the size of the magnetic material cover which can produce the maximum damping force are simulated under the condition that the size of the mover is fixed. The electromotive force is calculated based on the change of the produced magnetic field according to the change of the given velocity of the mover in a short time. The damping force is calculated according to the electric current which the electromotive force supplies to the connected resistance. By the simulations, more than 120 [N s/m] of the maximum damping coefficient is acquired in the case that the coil is wound up from 28.0[mm] of the inner diameter to 60.0 [mm] of the outer diameter.*

**Keywords:** Semi-active damper, Finite element method, Magnetic-structure interaction analysis, Viscous damping coefficient.

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## 1. INTRODUCTION

Earthquakes are recently showing a tendency to increase in the world [1]. Reconstruction is being promoted in the earthquake-stricken region by massive magnitude earthquakes [2].

In 1995, a lot of houses were collapsed by Great Hanshin-Awaji Earthquake in Japan. One of the causes of the house collapse was poor earthquake resistance strength [3]. Because reinforcement of houses was not taken in Kyushu area adequately, many houses collapsed in 2016 Kumamoto Earthquake again [4]. Therefore, the development of an earthquake countermeasure system is required for a small and weak house such as a house partitioned into several units.

To improve earthquake resistance, for example, Yanagi et al. proposed a vibration isolation/vibration-proofing laminated rubber which improves the earthquake-resistant safety of the building [5]. Moritani et al. developed a new-type MR damper that placed a spring in an MR fluid, and confirmed its effectiveness [6].

Generally, the seismic strengthening construction raises the strength of a building for the earthquake, but it may degrade the strength depending on materials and the ground of the building [7]. And an earthquake countermeasure system which needs large power consumption is not suitable for a small and weak house.

Takahara [8]; Kubo [9] studied the structure and characteristics of a linear generator which can convert vibration to electrical energy. It is a linear-motion type generator having simple structure and produced inexpensively. The motion of the mover of the prototype linear generator changes according to the connected resistance. The authors confirmed that the linear generator can be used as a variable force damper [10].



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This paper redesigns the linear generator to increase a viscous damping force more as a variable damping force device. Specifically, the size of the linear generator that produces the maximum viscous damping force is determined by the simulation of a finite element method (FEM).

## 2. FUNDAMENTAL STRUCTURE OF A LINEAR-MOTION TYPE DAMPING DEVICE

Figure 1 shows the fundamental structure of the linear-motion type damping device. It has a cylindrical structure. Nd Fe-B magnets in the mover are placed so that the same magnetic poles face each other, in order to make the large change of magnetic flux in the coils of the stator. The coils are wound in opposite directions to each next coil and are connected in a series. The stator was covered with a magnetic material cover, so that the magnetic flux is extended through the cover and reduces cancellation of the flux in the coils of the stator.

When the mover reciprocates in the coils an electromotive force is generated. The electric current in the circuit changes according to the resistance connected to the device. The velocity of the mover changes according to the magnetic field induced by the electric current. Because the maximum electric current flows when both ends of the device are shorted, the viscous damping force is maximum. The maximum damping force is changed according to the size of coils, the size of magnetics, the magnetic path, and so on. Therefore, the change of the viscous damping force is simulated by varying the values of the size of the coils and magnets as the parameters. The next chapter describes the simulation to determine the size of the proposed damping device by the FEM.

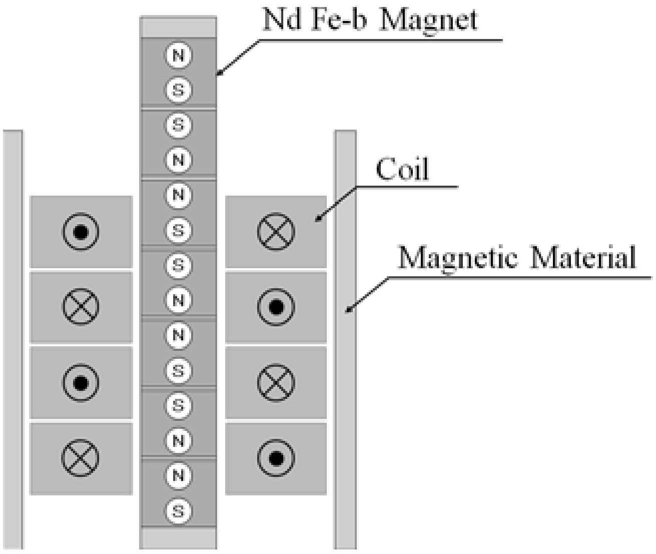


**Fig-1.** Fundamental structure of the linear-motion type damping device

## 3. DESIGN BY FEM SIMULATION

The dynamic characteristics of the linear-motion type damping device are analyzed by a maginetic-sturacture interaction analysis using FEM software ANSYS (CYBERNET SYSTEMS Co. Ltd.). The analytic model includes the linear-motion type damping device, a resistance connected to the device, and a spring and a damper connected to the mover.

The analytical model and the calculated magnetic configuration is shown in Fig.2. Figure 2 (a) shows the axisymmetric model of the linear-motion type damping device. Seven inside rectangles are magnets of the mover, and four outside rectangles are coils, respectively. The magnetic field of the linear-motion type damping device is shown in Fig.2 (b). The magnetic path is extended to the magnetic material cover placed outside the coils. Figure 2 (c) illustrates the connection of the device and resistances, which are the internal resistance and the connected resistance.

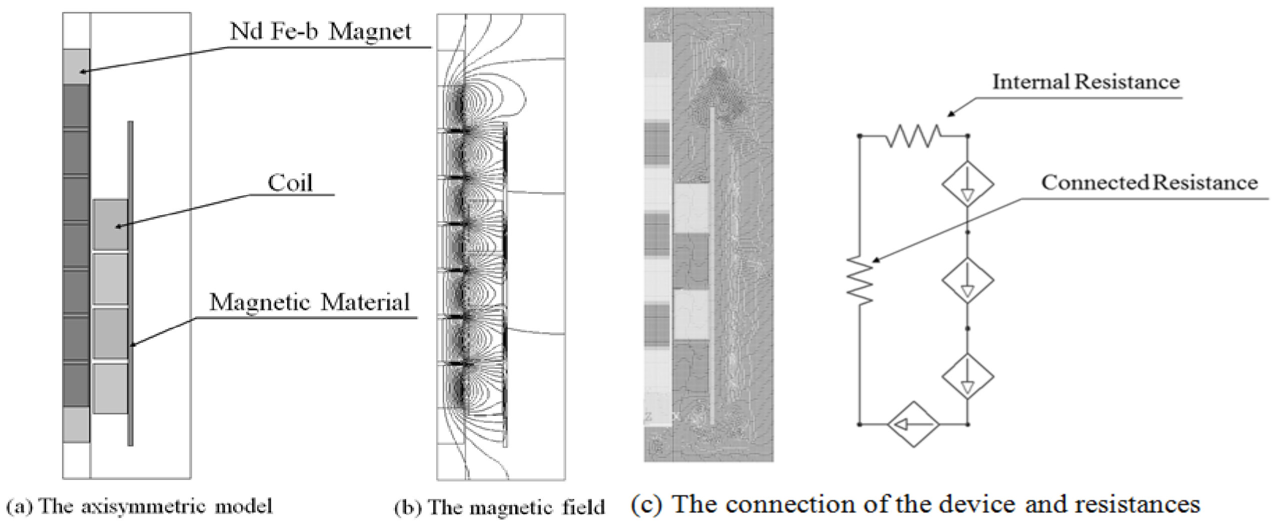


**Fig-2.** Analytical model and calculated magnetic configuration by ANSYS (CYBERNET SYSTEMS Co. Ltd.)

The vibration characteristics when a weight is dropped on a board connected to the mover with the spring are calculated. Here, the weight is 15[kg] and the spring constant is 6584.375[N/mm]. The mover is driven by step load with step size of 3.3 [ms]. The displacement of the mover is determined by architectural analysis. The load current and the induction magnetic field are calculated by the displacement of the mover by electromagnetic field analysis. Because the motion of the mover is impeded by the force produced by the induction magnetic field, the displacement of the mover is afresh calculated by structure analysis by adding the step load including the increased force. The series of calculations are repeated until the displacement of the mover converges. The viscous damping coefficient is evaluated from the calculated responses.

## 4. SIMULATION RESULT

Takahara et al. designed the same type device as a linear generator to acquire electricity from mechanical vibration [8]. Its structure is suitable as a generator, but it is not confirmed whether it is suitable as a damper. Here, the linear-motion type damping device is redesigned based the linear generator.

As a generator, the coils are voluminously wound using a narrow line for generating higher voltage. Because the internal resistance becomes large if the number of turns in the coils are large, the circuit current becomes small. On the other hand, in order to increase the viscous damping force, because it is necessary for circuit electric currents to increase, the conducting wire of the coils must be thicker. In this study, the diameter of the conducting wire is chosen as 1.0 [mm] when the diameter of the magnet of the mover is 32 [mm] as same as the above linear generator. The diameter is the maximum value which can be obtained. The inner diameter of the coil is determined depending on the size of the magnetic. When the width of the coil is changed by 2 [mm] from 20[mm] to 40[mm], the vibration characteristics are simulated under the condition that the circuit is shunted. Here, the difference between the inner and the outer diameter of a coil is called as the width of a coil.

Figure 3 illustrated the change of the viscous damping coefficient to the width of the coil. The maximum viscous damping coefficient from the simulations is acquired as Table 1. It is 139.1[N s/m] in the case that the width of the coil is 32 [mm].

Figure 4 illustrates the change of the viscous damping coefficient according to the change of the connected resistance to the linear-motion type damping device. Here, the width of the coils is 32 [mm]. Because the viscous damping coefficient is influenced by the Lorentz force, it increases greatly with a decrease of the connected resistance. The viscous damping coefficient of the device can be varied from 0 to 89.4 [N s/m] according to change the connected resistance.

If the device is mechanically vibrated at 1 [Hz] of the frequency and 0.85 [m] of the amplitude, the proposed linear-motion type damping device will be able to generate about 152[N] of damping force.

**Table-1.** Parameters used in the simulation

| | |
|---|---|
| Diameter of the magnet | 32[mm] |
| Height of magnet | 200[mm] |
| Coercive force | 923[kA/m] |
| Diameter of the conducting wire | 1.0[mm] |
| Number of turns | 400[times] |
| Slot | 4 |
| Electric resistivity of the conducting wire | 17.0[nΩ m] |
| Internal resistance | 1.76[Ω] |
| Magnetic permeability | 800 |
| Thickness of magnetic material cover | 2[mm] |

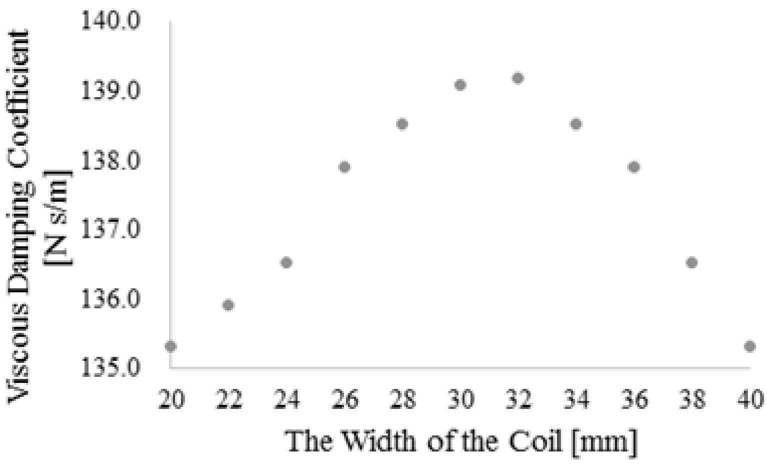


**Fig-3.** The change of the viscous damping coefficient to the width of the coil

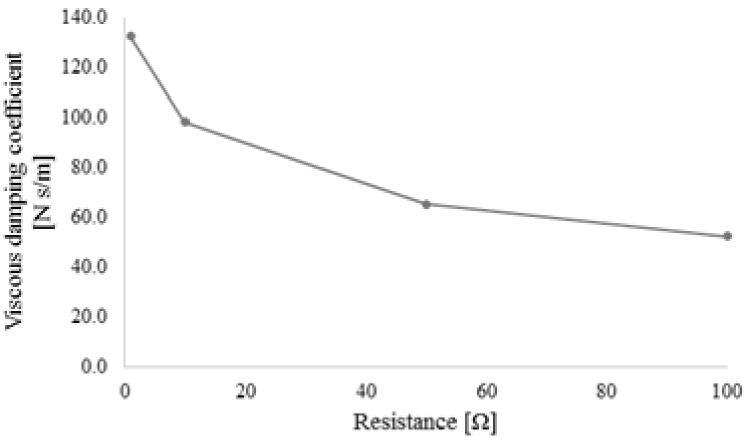


**Fig-4.** The change of the viscous damping coefficient according to the change of the connected resistance

## 5. CONCLUSION

In this paper, the size of the linear-motion type damping device is determined by FEM. It is confirmed that the viscous damping coefficient of the device can be varied from 0 to 89.4 [N s/m] according to change the connected resistance. It will change vibration characteristics of a specific place of a building by adjusting the system that will be constructed by the proposed devices individually.

The prototype will be produced and its characteristics will be measured. Furthermore, the viscous damping characteristics of the device will be controlled by PWM signals.

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