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STUDY ON THREE-DIMENSIONAL SEISMIC ISOLATION SYSTEM FOR NEXT GENERATION NUCLEAR POWER PLANT: ROLLING SEAL TYPE AIR SPRING

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SUMMARY

This is to present the results of four tests using the three-dimensional (3D) seismic isolation device to be used for a heavy building like a nuclear reactor building to confirm its applicability. The device developed is the 3D seismic device that consists of a laminated rubber bearing and rolling seal type air spring placed in series.

In this study, the following four tests are carried out to examine the performance of the 3D base isolation device using a 1/12-scaled model.

1) The pressure resistant ability test for the air spring is performed under the pressurization by water. It is confirmed that air spring strength can evaluate from the shape and a diameter of roll part, reinforced fiber strength. It is recognized that the strength of the air spring is considered to have sufficient margin against the operating condition of an actual plant.
2) The accelerated aging test for air spring is examined. There is no influence in the characteristic as the air spring and the strength of the accelerated aging air spring bellows is not reduced compared with a new one. The long-term reliability of the air spring is confirmed.
3) The performance of the device by the horizontal and vertical dynamic force is confirmed in Dynamic vertical and horizontal test.
4), It is confirmed that vertical damping performance depends on the orifice between the air cavity and the air tank inside the cylinder in the orifice-damping test. It is recognized that the theoretical formula can correctly evaluate the orifice damping with nonlinear characteristic depending on the frequency and amplitude.

As the results said above, the developed 3D seismic isolation device is confirmed to be applicable to a nuclear power plant.

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INTRODUCTION

The 3D seismic isolation device is developed to use for the base isolation system of the heavy building like a nuclear reactor building. The 3D seismic isolation device that consists of a lead rubber bearing and rolling seal type air spring placed in series.
As the lead rubber bearing and the air spring are separately widely used with the general buildings and industrial structures, their reliability is high. However, the following problem is generated when these two pieces of equipment are combined.

1) Capability for supporting excessive weight.
2) Damping performance to reduce the earthquake response.
3) Performance of the part, which acts vertical force and horizontal force simultaneously.

In this research, the prospect of the technical feasibility of the device has already been acquired by feasibility test [1]. In this report, in order to evaluate the applicability of the 3D seismic isolation device to the actual plant, four tests are carried out.

ACTUAL THREE-DIMENSIONAL (3D) SEISMIC ISOLATION DIVICE

Outline of actual device

The outline of the proposed 3D seismic isolation device is shown in Fig. 1, and the dynamic properties and device specification are shown in Table 1.

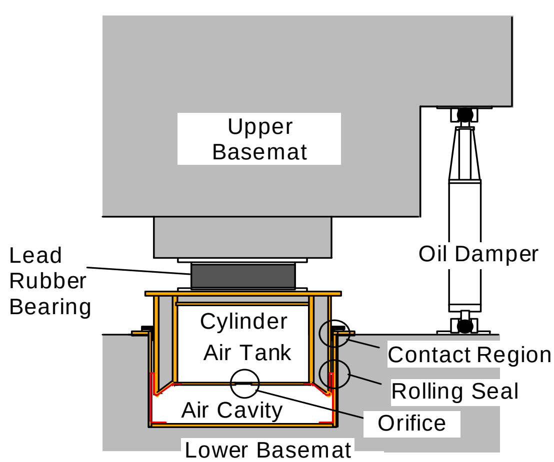


Fig.1 Three-dimensional isolation device

Table 1 Outline of 3D device

Dynamic Properties	Horizontal Initial Period	1.0 s
	Horizontal Isolation Period	2.8 s
	Horizontal Yield Coefficient	0.1
	Vertical Isolation Period	2.0 s
	Vertical Damping Factor	0.2
Specifications	Supporting Load	9.8MN
	Diameter of Rubber Bearing	1.6 m
	Total rubber thickness of Rubber Bearing	0.225 m
	Diameter of Air Cavity	3.0 m
	Pressure of Air Cavity	1.6 MPa

This device realizes a 3D isolation by the lead rubber bearing as horizontal isolation system and the air spring as vertical isolation system independently. The specifications of lead rubber bearing are determined by the previous research to reference [2]. The air spring is set up in the lower basemat. By adopting a rolling seal type air spring, the device can be in operated even under large vertical deformation. The contact region should be designed so that the horizontal force can be transmitted with almost no friction to realize the smooth move in vertical direction. The pressure of an air spring is 1.6MPa in the normal condition, which is relatively high compared with the pressure (about 0.3-0.9 MPa) of an ordinary air spring. For this reason, the long-term reliability of the air spring using high pressure is an examination subject. Horizontal damping performance is considered by the lead rubber bearing. The air tank is placed inside the cylinder. Vertical damping performance is considered by the orifice between the air tank and the air cavity and the oil damper that operates in the three directions. The oil damper is set up around the plant perimeter.

Evaluation of the lower basemat

In an actual plant, the pits of the same number of 3D isolation devices are made to the lower basemat. For this reason, the concrete between pits and the reinforcing bar are checked. Stress analysis is carried out using the 3-dimensional FEM model. An analysis model is shown in Fig. 2.

An analysis result is shown in Fig. 3. Consequently, it is confirmed that the stress of concrete is below allowable stress, and the reinforcing bar could be arranged at the lower basemat.

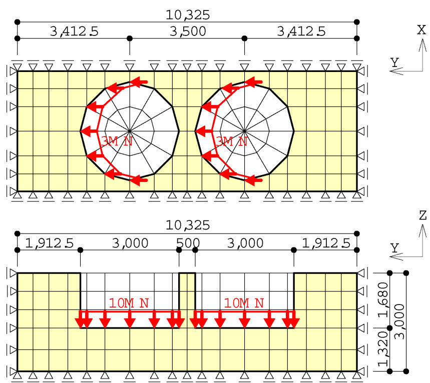
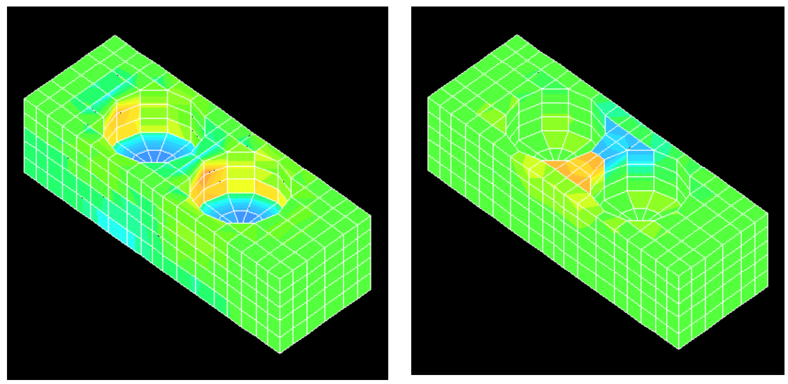


Fig. 2 Analysis model



(a) Stress of the Z-direction (b) Shear stress

Fig. 3 Stress analysis result

TEST RESULTS

Outline of test

The following four tests are carried out to examine the performance of the 3D isolation device.

1) The pressure resistant ability test for the air spring is performed under the pressurization by water.
2) The accelerated aging test for air spring is examined and durability for air spring is also examined.
3) In Dynamic vertical and horizontal test, the performance of the device by the horizontal and vertical dynamic force is examined.
4) In the orifice-damping test, vertical damping performance depending on the orifice between the air cavity and the air tank inside the cylinder is examined.

Similarity law

The scale ratio of the model to an actual prototype structure is 1/12 and both acceleration and stress are equal to those of the prototype. The similarity law is shown in Table 2.

Table 2 Similarity law

Parameter	Similitude	$\lambda = 12$
Length	$1/\lambda$	1/12
Velocity	$1/\sqrt{\lambda}$	1/3.46
Acceleration	1	1
Time	$1/\sqrt{\lambda}$	1/3.46
Mass	$1/\lambda^2$	1/144
Stress	1	1

Test model

As the experiment equipment capability and safety are considered, air spring pressure of the test model is set to 0.8MPa. For this reason, the original prototype is to be modified so that the pressure of the air cavity is 0.8MPa. The dimension of the test model is then calculated base on the modified prototype, is shown in Table 3. In a reduction model, a rolling seal part cannot be imitated completely. For this reason, 2 models of the air spring are made. The model-1 of the air spring is fitted the volume of the air cavity. The diameter of a rolling rubber diaphragm of the model-2 is the same as the diameter of the prototype.

Table 3 Dimension of modified prototype and test model

Parameter	Prototype	Model-1
Support Load (kN)	4900	34
Horizontal Isolation Period (s)	2.8	0.81
Vertical Isolation Period (s)	2.0	0.58
Pressure of Air Cavity (MPa)	0.8	0.8
Effective Diameter of Air Cavity (m)	2.82	0.235
Diameter of RB (m)	1.6	0.133
Total rubber thickness of RB (m)	0.45	0.026
Diameter of Lead plug (m)	0.25	0.021

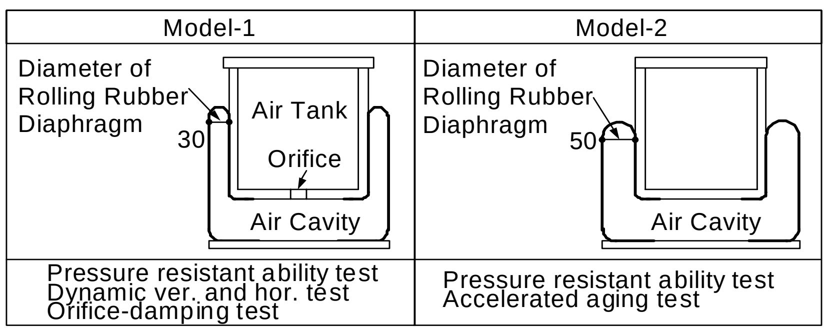


Fig. 4 Two types models with air spring

Pressure resistant ability test

Test case

To grasp the ultimate pressure and failure mode of the air spring, the water pressure resistant ability test is performed under a constant height of the air cavity. The maximum water pressure is to 10MPa, to confirm the fracture of the air spring. Two types of pressure increase are considered; 1) a monotonous increase and 2) a stepped increase (refer to Fig. 5). The difference in the ultimate pressure by the diameter of a roll part is also confirmed using the model-1 and model-2. Outline of this test is shown in Fig. 6.

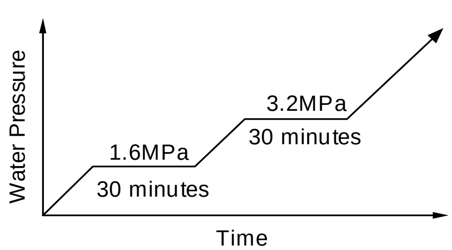


Fig. 5 Increase history (stepped increase)

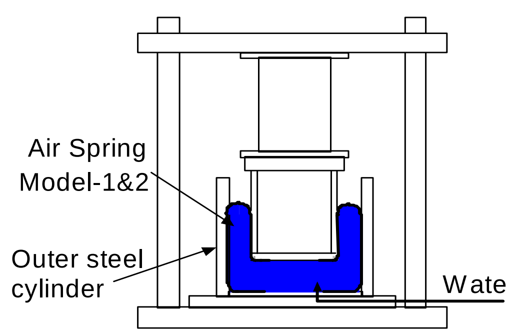


Fig. 6 Pressure resistant ability test

Test results

The results of the pressure resistant ability test are shown in Table 3. The average maximum pressure of the air spring model-1 is 5.5MPa, and that of the model-2 is more than 10.0MPa. There is no difference in the maximum pressure by the pressurization pattern. The fracture of an air spring bellows is occurred in the roll outside part. It is recognized that the strength of the air spring is considered to have sufficient margin against the operating condition (i.e. pressure 1.6MPa) of an actual plant.

In addition, it is confirmed that air spring strength can evaluate from the form and a diameter of roll part, reinforced fiber strength. The evaluation value of the model-1 air spring strength is 5.2MPa, and the evaluation value of the model-2 air spring strength is 10.3MPa.

Table 4 Maximum pressures

No.	Pressure pattern	Model	Maximum pressure
1	Monotonous increase	Model-2 (5cm)	5.4MPa
2	Monotonous increase	Model-2 (5cm)	5.2MPa
3	Stepped increase	Model-2 (5cm)	5.9MPa
4	Stepped increase	Model-2 (5cm)	5.5MPa
5	Monotonous increase	Model-1 (3cm)	< 10MPa
6	Monotonous increase	Model-1 (3cm)	10.2MPa

( ): Diameter of rolling rubber diaphragm

Accelerated aging test

Test case

Accelerated aging tests are performed using the model-2 of air spring. After the aging tests, the dynamic vertical response test and the water pressure resistant ability test are performed, and the durability of the air spring is evaluated. The air spring holding the pressure of 0.8MPa is placed into the oven of 80 degrees centigrade. The accelerated period is evaluated from the material examination results of rubber (Activation energy = 20.75 kcal/mol, period = 30 years, 45 years, 60 years).

Test results

The dynamic vertical test is performed with the heat accelerated aging air spring bellows. The result of case-5 (60 years) is shown in Fig.7 as compared with the result of the new bellows. Both of results are very similar. All of the results of the pressure resistant ability test are shown in Table 5. The strength of the accelerated aging air spring bellows is not reduced compared with a new one (refer to Table 4). Hardening of rubber is found in the heat accelerated aging bellows (refer to Photo 2). However, there is no influence in the force-displacement relationship and the strength as the air spring.

Photo 1 Accelerated Aging Test

Table 5 Maximum pressures

Case	Accelerated age	Maximum pressure
1	30 years	6.0MPa
2	30 years	5.4MPa
3	45 years	6.5MPa
4	45 years	7.4MPa
5	60 years	5.3MPa
6	60 years	6.4MPa

60years 30years new

Photo 2 Accelerated aged air spring bellows

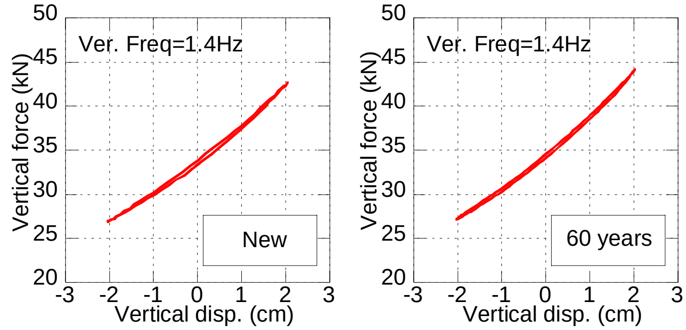


Fig.7 Vertical force-displacement relationship (Vertical amplitude: ±2cm)

Dynamic vertical and horizontal test

Test case

The dynamic vertical and horizontal tests are performed using the model-1 of air spring. The performance of the device subjected to the vertical and horizontal excitation is examined. The following three cases of tests are performed. Outline of this test is shown in Fig. 8.

Case1: dynamic vertical property tests by sinusoidal wave

Case2: dynamic vertical property tests with constant horizontal force

Case3: dynamic property tests subjected vertical and horizontal sinusoidal wave simultaneously

Test results

The relations between the vertical force and the vertical displacement under the sinusoidal vertical force (amplitude: 40mm, frequency: 1.5Hz) are shown in Fig. 9(a) as compared with the theoretical formula. The theoretical formula of the restoring force-displacement relationship of the air spring is shown below.

$$W = P_r A_{r0} \tag{1}$$

$$P_r = (P_{r0} + P_0)\frac{V_{r0}{}^{\gamma}}{(V_{r0} - A_r x)^{\gamma}} - P_0 \tag{2}$$

W: Support load, P_r: Pressure of air spring, A_{r0}: Effective area of air spring,
A_r: Vibration area of air spring, P_{r0}: Initial pressure, γ: Polytropic index,
P_0: Atmospheric pressure, V_{r0}: Initial volume

It is recognized from Fig. 9(a) that the theoretical formulas well predict the examination result is almost in agreement with. The relations between the vertical force and the vertical displacement under the constant horizontal force (horizontal displacement: 20mm) are shown in Fig. 9(b). It seems that there is a little friction in the contact region under the constant horizontal force, but the device worked smoothly in the test.

The vertical and horizontal response under the sinusoidal vertical force (amplitude: ±4cm, frequency: 1.5Hz) and horizontal force (amplitude: ±2cm, frequency: 1.2Hz) are shown in Fig. 10. The vertical restoring response is almost the same as the results of the dynamic vertical force (Fig. 9(a)). As the horizontal restoring response is almost the same as the device test results of the lead rubber bearing, it is recognized that the effect of the contact region is very small.

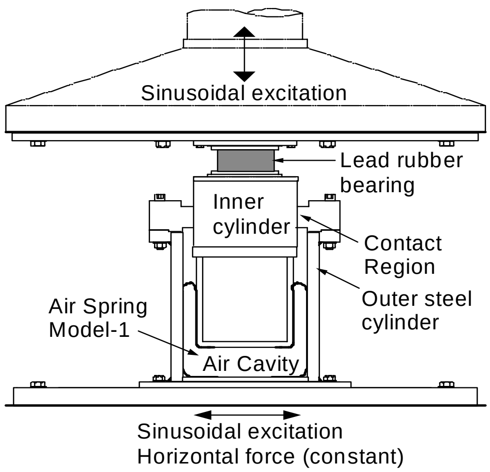
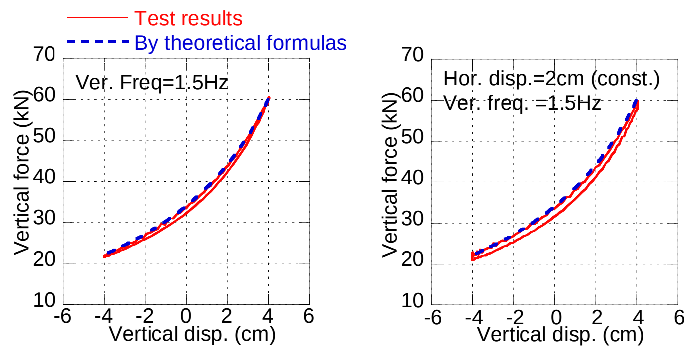
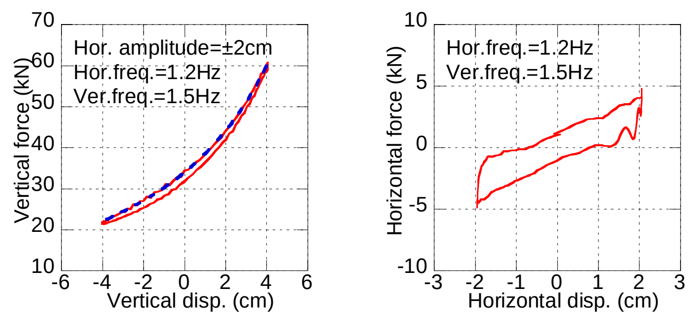


Fig.8 Dynamic vertical and horizontal test



(a) Vertical force (b) Constant horizontal disp

Fig.9 Vertical force-displacement relationship



(a) Vertical (b) Horizontal

Fig.10 Force-displacement relationship

Orifice-damping test

Test case

The Orifice-damping tests are performed using the model-1 of air spring. Outline of this test is shown in Fig. 11. The applicability of theoretical orifice damping evaluation method is confirmed by the experiments. The three diameters of an orifice are selected, 7mm, 9mm, and 11mm, and the difference in the vertical damping performance by the difference in a diameter is confirmed.

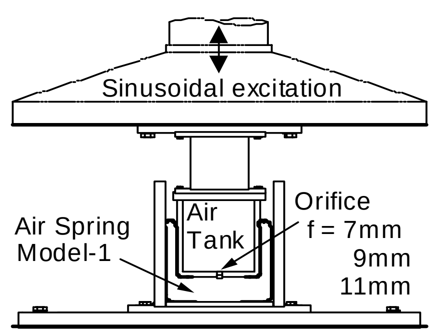


Fig.11 Orifice-damping test

Test results

The dynamic vertical test is performed and orifice damping is evaluated for three kinds of diameters of an orifice (ϕ = 7, 9, 11mm). The relation between the frequency and equivalent viscous damping factor in the case of ϕ = 7mm is shown in Fig. 12 as compared with the theoretical results. The relation between the amplitude and equivalent viscous damping factor for ϕ = 7, 9, 11mm is shown in Fig. 13. The theoretical formula, the turbulent flow theory is applied, that evaluates the orifice damping proportional to the 2nd

power of the pressure difference of the air cavity and the air tank. The damping coefficient C, under the assumption that the ratio in volume of the air tank to the air cavity is 1, is calculated based on the following formulas.
It is recognized from these figures that the theoretical formula can correctly evaluate the orifice damping with nonlinear characteristic depending on the frequency and amplitude.

$$C = K_0 \frac{\sigma}{4 + \sigma^2 \omega^2} \tag{3}$$

$$K_0 = \frac{\gamma A_{r0} \cdot A_r (P_{r0} + P_0)}{V_{r0}} \tag{4}$$

$$R_{II} = \frac{1}{2(C_d a)^2 \rho_0} \tag{5}$$

$$\sigma^2 = \frac{2}{\omega^2} \left\{ \sqrt{1 + 4\left(\frac{2}{3\pi} \frac{V_{r0} \rho_0{}^2}{\gamma (P_{r0} + P_0)} R_{II} A_r x_0 \omega^2 \right)^2} - 1 \right\} \tag{6}$$

ρ_0: Air density, a: Orifice area, C_d: Outflow coefficient

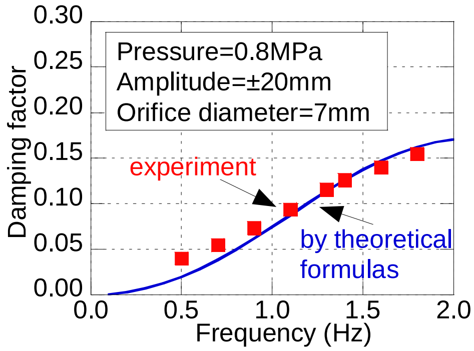


Fig.12 Orifice-damping factor (freq.-Damp.)

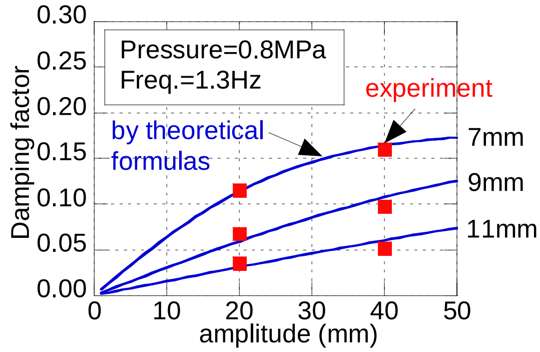


Fig.13 Orifice-damping factor (amp.-Damp.)

CONCLUSION

Four tests are carried out to examine the applicability of 3D seismic isolation device to a heavy building like a nuclear reactor building. In this study, the following four tests are carried out to examine the performance of the 3D base isolation device using a 1/12-scaled model.

1) The pressure resistant ability test for the air spring is performed under the pressurization by water. It is confirmed that air spring strength can evaluate from the shape and a diameter of roll part, reinforced fiber strength. It is recognized that the strength of the air spring is considered to have sufficient margin against the operating condition of an actual plant.
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4), It is confirmed that vertical damping performance depends on the orifice between the air cavity and the air tank inside the cylinder in the orifice-damping test. It is recognized that the theoretical formula can correctly evaluate the orifice damping with nonlinear characteristic depending on the frequency and amplitude.

As the results said above, the developed 3D seismic isolation device is confirmed to be applicable to a nuclear power plant.

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