

# STUDY ON THREE- DIMENSIONAL SEISMIC ISOLATION SYSTEM FOR NEXT-GENERATION NUCLEAR POWER PLANT: HYDRAULIC THREE-DIMENSIONAL BASE ISOLATION SYSTEM

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# SUMMARY

In Japan, a number of three-dimensional base isolation systems have been studied for application to new nuclear plant concepts such as the FBR, but these efforts have not so far yielded practically applicable results. The impeding factor has been the difficulty of obtaining an adequate capacity on the vertical isolator for supporting the mass of an actual structure and for suppressing rocking motion. In this paper, we propose a new three-dimensional isolation system that should solve the foregoing problem. The system is constituted of a set of hydraulic load-carrying cylinders connected to accumulator units containing compressed gas, a set of rocking-suppression cylinders connected in series, and a laminated rubber bearing laid under each load-carrying cylinder. The present paper covers a basic examination for applying the proposed system to a FBR plant now under development in Japan. In order to verify expected system performance, the load-carrying cylinders were first tested independently of rocking-suppression cylinders, and this was followed by integrated dynamic test of the system incorporating both load-carrying and rocking suppression cylinders. Response analysis reflecting the test results has indicated the proposed system to be well applicable to the envisaged commercialized FBR. The study was undertaken as part of a research and development project sponsored by the government for realizing a three-dimensional seismic isolation system applicable to future FBR.

# **INTRODUCTION**

The three-dimensional seismic isolation system is a means of isolating a structure from seismic movement in vertical as well as horizontal direction. In Japan, the relevant technology has been the subject of active research and development for its being considered an indispensable asset for letting nuclear installations combine the properties of earthquake resistance and economic viability. Other buildings and structures of more general nature also are considered to have potential need for this technology [1]. The current status of this technology, however, is that three-dimensional seismic isolation has been realized for application to floor level, but coverage of the entire building including the upper stories has been awaiting development. A structure or mechanism needed to be found that would, white carrying a load of several hundred tons, present a flexible property against vertical movement (e.g. possessing a natural frequency above 1 see). Another difficulty was suppression of rocking response to seismic movement.

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As a means of overcoming the foregoing obstructions, the present authors have proposed[2] a threedimensional seismic isolation system incorporating hydraulic mechanism that will permit a compact, large-capacity facility to be realized, combined with an independently functioning rocking-suppression device. So far, demonstration tests on reduced-size model, together with modelized analysis, have been conducted on the vertical isolator, which have given assurance of practical application in fast breeder reactor installations [3,4].

With the aim of approaching a step closer to practical application, the next step envisaged is to advance into verification of long-term reliability, of performance through further tests and analyses, and examination of design problems.

The present paper takes up the performance aspect of the system, with a description of experiments using models covering (a) independent test on load-carrying cylinders alone, and (b) integrated test combined with rocking-suppression cylinders using shaking table. Also described are the results of evaluation analysis on the performance of full-dimensioned practical equipment under actual earthquake condition.

# NOMENCLATURE

A: area load-carrying cylinder  $d_{eq}$ : equivalent orifice diameter h: damping ratio of rocking  $V_1$ : volume of gas in accumulator  $V_2$ : volume of gas in backup bottle  $\gamma$  poly-tropic index  $\zeta$ : damping ratio on vertical isolation  $X_0$ : amplitude of vertical ground excitation  $X_c$ : amplitude between both ends of damping element m: supported mass  $\omega$ : angular frequency of excitation  $k_0$ : spring constant of gas in accumulator

 $k_t$ : spring constant of gas in backup-bottle

# SYSTEM OUTLINE

Key components constituting a three-dimensional seismic isolation system for application to a fast breeder reactor plant are illustrated in Fig. 1 (a) - (c); Fig. 2 depicts the arrangement of the components in the system. Key performance values envisaged for the system are presented in Table 1.

Isolator	Supported Mass 9.8MN per a isolate				
	Number	270			
Harizontal Direction	Period	2.8 [s]			
Horizonial Direction	Damping	0.20			
Vertical Direction	Period	2 [s]			
	Damping	0.20			
	Stroke	$\pm$ 200 [mm]			
Supplementary Device		Rocking-Suppression unit			

# Table 1 Main Isolation Specification for Commercialized FBR



(a) Isolator (load-carrying cylinder and accumulator unit)



(b) Rocking suppression cylinders Fig. 1 Main components of three-dimensional isolation system



The vertical isolator functions on the principle of air cushion. The weight of the plant structure is supported by a load-carrying hydraulic cylinder connected to a gas accumulator via a rocking-suppression cylinder, which absorbs pressure fluctuations of inverse phase with vertical motion, while transmitting those of coincident phase to the gas accumulator. This arrangement permits rocking to be restrained without impairing vertical isolation performance. Particulars of individual components constituting the seismic isolation system are as given below.

#### **Isolating support**

The isolating support combines the toad-carrying cylinder with a laminated rubber bearing. The loadcarrying cylinder has its connecting piping mounted on the same base plate as the rocking-suppression cylinder, so as to prevent piping connections from being distorted by the movement of the rubber bearing. The load-carrying cylinder is designed with a piston diameter such that its pressure rises to about 25 MPa when supporting a vertical load of 9.8 MN, with account taken of the sealing performance of sealing and the surface pressure of swivel joint incorporated in the system. Design pressure resistance is set at 50 MPa, considering the pressure fluctuations brought by the vertical and rocking motions.

### Accumulator unit

The content of gas in the accumulator unit determines the natural frequency and damping ratio of the vertical isolator. The target values of the isolator are 0.5 Hz natural frequency and 25% damping ratio [4]. This damping force is generated by inserting an orifice in the channel connecting the main accumulator and back-up bottle constituting the gas accumulator system.

### **Rocking-suppression cylinders**

For efficiently mitigating rocking motion, the load –carrying cylinders are divided into groups of 4 cylinders with each group connected collectively to the hydraulic fluid space on one side of the rocking-suppression cylinder, the other side space being connected to a group of 4 accumulators. The rocking-suppression cylinders have rods inserted from both ends, the rods being connected to the adjacent cylinder through swivel joint. Rod stroke is designed to adequately accommodate hydraulic fluid flow to and from 4 load-carrying cylinders.

# **DESIGN OF ISOLATION FUNCTION**

#### **Restoring force**

The vertical position restoring force characteristics --- being determined by the polytropic change of gas condition --- is expressed by the function

$$\Delta F = \left\{ \left( 1 - \frac{A\Delta x}{V_1 + V_2} \right)^{-\gamma} - 1 \right\} F_0 \tag{1}$$

where the amount of gas compression  $A\Delta x$  --- being adequately small compared with the initial gas volume  $V_1 + V_2$  ---- is permitted linear approximation in the vicinity of origin, so that the natural frequency f can be expressed by

$$f = \frac{1}{2\pi} \sqrt{\frac{\gamma g A}{V_1 + V_2}} \tag{2}$$

provided, however, that the orifice inserted between the main accumulator and backup bottle provides adequate pressure loss, inasmuch as the extent of throttling will affect the natural frequency, as it win be mentioned further on.

It is seen from Eq.(2) that assuming  $\gamma$  to be 1.6 (somewhat greater than for ideal gas), it should suffice to have a total accumulator volume of around 640 liters in order to attain the target value of 0.5 Hz natural frequency cited earlier.

# Damping

Damping is ensured by the provision of an orifice between main gas accumulator and backup bottle, as mentioned earlier. Provided ideal conditions, the damping ratio induced by the throttling will be:

$$\zeta = \frac{1}{2\left(1 + 2\frac{V_1}{V_2}\right)}$$
(3)

which means that the damping ratio is precisely determined by the ratio of gas volumes between those of the main accumulator and back-up bottle. The target damping ratio of 25% cited earlier will call for letting  $V_1/V_2=1/2$ . In actual arrangement, the main accumulators have been designed to be of bladder type with 250 liters capacity, and the backup bottles of 210 liters to be of bladderless type.

## **Rocking-suppression performance**

Rocking-suppression performance is determined by the rigidity of the train of components that transmits the pressure fluctuations generated by the rocking motion. In the present instance, the factors that played are: (a) the bulk modulus of hydraulic fluid, (b) rod rigidity, and (c) piping structure rigidity. For (a), the value adopted assumed 3% air immixture of gas in the hydraulic fluid.

# DEMONSTRATION TESTS TO ASCERTAIN PERFORMANCE

Tests were conducted for ascertaining the performance (a) of load-carrying cylinders alone applying oscillated vertical force and static horizontal force and (b) of the integrated system incorporating also the rocking-suppression cylinders, so as to apply oscillating force in both vertical and horizontal directions.

The models used for the tests were sized in scale assuming a supported structure with mass of 25 tons, and were made to call for performance data on oscillation frequency and damping to be derived on the same scale as the fun-size equipment. The foregoing prerequisites resulted in designating the test model dimensions to the scales listed in Table 2.

Items	Actual system	Test model	Scale factor					
Supported mass [ton]	1000	12.5	12.5/1000					
Piston area of load-carrying cylinder [m <sup>2</sup> ]	0.667	0.005	12.5/1000					
Gas volume of accumulator [liter]	215	2.5	12.5/1000					
Gas volume of backup-bottle [liter]	420	5.3	12.5/1000					
Period [s]	2	2	1/1					
Fluid pressure [MPa]	25.0	25.0	1/1					

 Table 2 Scale factors between test model and actual system

# INDEPENDENT TEST ON LOAD-CARRYING CYLNDERS ALONE

The key factors affecting the isolating performance in this instance were:

- Restoring force characteristics determined by the compressed gas

- Characteristics of oscillation damping induced by the orifice inserted between main gas accumulator and backup bottle

-Characteristics of mechanical friction made to act against oscillation.

The foregoing characteristics were taken into account in evaluating the test data.

The arrangement of testing apparatus is as sketched in Fig.3. In the experiment, external force from actuator imparts displacement oscillation on the load-carrying cylinder. The resulting cycles of loading force and cylinder piston displacement are recorded, together with the pressures of hydraulic fluid and of gas.



Fig.3 Testing arrangement

Inasmuch as the oscillation amplitude and frequency are dependent on the damping function determined by the extent of opening of the orifice inserted in the gas accumulator system, these oscillation variables were systematically varied in operating the actuator. Also, since the sliding friction against vertical motion varies with horizontal load, the vertical oscillation was imparted while applying by means of manuallyoperate jack a static load corresponding to the horizontal oscillation response.

# **TEST RESULTS**

### Sliding friction resistance characteristics

Representative data from the test are reproduced in Fig.4 (a), showing hysteresis curves from runs at 0.06 Hz frequency and  $\pm 90$  mm amplitude applying static horizontal loads corresponding to 0.0, 0.2 and 0.4 G. The broken line in the figure represents the theoretical value of restoring force --- neglecting friction--- calculated using Eq. (1).

It is revealed from Fig.4 (a) that sliding friction is generated even in the absence of horizontal load, and increases with its addition. The test data of Fig.4 rearranged to present sliding friction as function of horizontal load yields the line drawn in Fig.4 (b).



#### **Damping force characteristics**

To evaluate the damping force characteristics, the throttling force generated by the orifice was derived by multiplying by cylinder bore the orifice-induced loss of pressure. An example of resulting data is presented in Fig.5, showing hysteresis curves of damping force generated by throttling. The symbol  $d_{eq}$  appearing in the inscription of the drawing represents the orifice diameter assuming a cylindrical orifice inserted in a pipe of 9 mm bore. It is calculated applying the orifice characteristics.



The damping performance with gas throttling was evaluated applying a model such as depicted in Fig.6. In calculating the vertical isolation performance, the bulk modulus of hydraulic fluid is neglected, since it is amply greater than that of gas. The damping generated by gas throttling consequently becomes proportional to the square of gas velocity.



Fig.6 Analysis model to evaluate the vertical damping characteristics

Assuming the damping generated by orifice to be viscous damping brought by the damping coefficient ceq, the frequency response from the base excitation displacement to the two extremities of the damping element is calculated from

$$\left|\frac{X_{c}}{X_{0}}\right|^{2} = \frac{m^{2}\omega^{4}k_{0}^{2}}{\left\{m\omega^{2}(k_{0}+k_{t})-k_{0}k_{t}\right\}^{2}+\omega^{2}c_{eq}^{2}\left(m\omega^{2}-k_{0}^{2}\right)^{2}}$$
(4)

For evaluating data from excitation test, it suffices to substitute the supporting mass by infinity in Eq.(4) to yield

$$\left|\frac{X_c}{X_0}\right|^2 = \frac{k_0^2}{(k_0 + k_t)^2 + \omega^2 c_{eq}^2}$$
(5)

We next consider the instance where the damping element provides damping proportional to the square of the velocity  $c_2$ . Assuming the equivalent viscous damping to equal  $c_{eq}$  when the relative displacement amplitude between the two extremities of damping element is  $X_c$ , there will hold between  $c_2$  and  $c_{eq}$  the relation

$$c_{eq} = \frac{8}{3\pi} X_c \omega c_2 \equiv B X_c \omega c_2 \tag{6}$$

The energy consumed per cycle by the damping element will be, from the area of ellipse in Fig.5.

$$U = \pi c_{eq} \omega X_c^2 \tag{7}$$

Substituting Eq.(6) into Eq.(5) to derive Xc, and further substituting the derived Xc into Eq.(7) will yield the energy consumed per cycle in the form

$$U = \frac{\pi}{8} \frac{\left\{-2(k_0 + k_t)^2 + 2\sqrt{(k_0 + k_t)^4 + 4B^2c_2^2\omega^4k_0^2X_0^2}\right\}^{3/2}}{B^2\omega^4c_2^2}$$
(8)

Applying the above treatment to all instances, the dissipated energy derived from the area enclosed by the different ellipses yields the data presented in Fig.7, where the curves have been derived applying Eq.(6).

The excellent agreement between the theoretical curves and the empirical square plots substantiates the adequacy of the present method for evaluating orifice damping.



**TEST OF INTEGRATED SYSTEM INCLUDING ROCKING-SUPPRESION CYLINDERS** 

Using a shaking table, integrated tests combining vertical and horizontal dynamic forces were conducted to verify the integrated performance of the system incorporating with rocking-suppression as well as the load-carrying cylinders. The items verified were:

- (a) Frequency and damping characteristics in vertical direction
- (b) Rocking-suppression performance
- (c) Performance under earthquake condition.

#### **Testing Arrangement**

The equipment used in the integrated test is illustrated in Picture.1. The test model of 25 tons mass simulating the plant building is supported by two load-carrying cylinders. The rocking-suppression cylinders and gas accumulator unit are installed as part of the supported mass.



Picture-1 Scale-down model of vertical base-isolation and rocking suppression system

This test did not include examination of the horizontal isolation performance, and hence, one of the Loadcarrying cylinders was firmly fixed to the oscillating table. The other cylinder was mounted with swivel, to prevent inordinate distortion of the load-carrying cylinder brought by rocking movement.

The items examined and the means adopted for their implementation are summarized in Table3. Shown in Fig.8 are the forms of the external waves imparted to the model in the tests under item (c) in Table 3.



Items verified	Implementations		
(a)	[parameter] gas volume of accumulators and backup bottle		
Performance of vertical isolation	[exciting motion] sinusoidal sweep up in vertical direction		
(b)	[parameter] equivalent orifice area		
Performance of rocking suppression	[exciting motion] sinusoidal sweep up in horizontal direction		
(c)	[excitation]		
Performance under seismic excita-	reduced seismic wave in horizontal and vertical direction		
tion			

# Table 3 Examined items on shaking table test

Limitation of shaking table capacity led to adopting 2/10 excitation amplitude for the vertical waves compared with the original wave as given <sup>[3]</sup>. For horizontal excitation, the corresponding response to be expected with use of the laminated rubber bearing was calculated in advance, and in experiment the excitation was varied in the range from 1.5 to 10 times the calculated values of response expected to occur in actual equipment.

# Model for Analyzing Shaking Table Behavior

For the purpose of evaluating the validity of the modeling technique adopted to simulate the actual structure, a model for analyzing the technique was drawn up, which is shown in Fig.9.



Fig.9 Analysis model of shaking table test

The supported mass is assumed to be a rigid body. Orifice-induced damping is modeled identically to the case of the preceding independent test. To avail of the results obtained from the independent test, a contact element ensuring bestowal of a friction dependent on horizontal force was applied to the load-carrying cylinder (right-hand side in Fig.1) fixed on the shaking table. Furthermore Fanning's equation was applied in deriving the viscous resistance acting on hydraulic oil in the piping between load-carrying cylinder and gas accumulator, while that in the piping components --- elbows, couplers etc.--- were derived applying the damping element  $c_{2d}$  proportional to the square of flow velocity.

In the present testing model, the parts situated above the swivel joint behave rigidly in respect of seismic isolation, so that the center of rotation coincides with the swivel center. In the analytical model, conse-

quently, the vertical distance between contact point that constitutes the center of rotation and the center if gravity (height of the gap element in Fig. 9) has been matched to that of the test model.

# TEST RESULTS

## Vertical isolation performance

In Fig.10 are shown the frequency response curves obtained from a sweep test performed with vertical exciting acceleration set at 50 gal, using a set of large and small gas accumulators to represent the main accumulator and backup bottle. The lines drawn in this figure represent the measured data, and the plots the analytical results.

The resonance frequencies deriving from test and the corresponding values obtained from analysis are cited in Table 4, together with the design values. The excellent agreement of the empirical data with the analytical as well is with the design values well substantiates the validity of the present procedure of frequency evaluation.



lator units

Table 4 Resonance frequency								
		Accumula-	Tested / designed	Analysis				
		tor unit size						
Resonance	Vertical direction	Large	0.46 / 0.50	0.46				
frequency [Hz]		Small	0.68 / 0.73	0.68				
	Rocking		2.9/3.0	3.1				

Fig.10 Frequency response in vertical direction

Similarly good agreement between empirical and analytical data was seen for the variations with orifice bore brought on the trend of change in response curves and on response ratios, thus evidencing the validity of the present procedure also for damping performance evaluation.

# **Rocking-Suppression performance**

Reproduced in Fig.11(a) are the data from test runs at constant 30 gal exciting wave acceleration in horizontal direction. Here the abscissa represents frequency and the coordinate the response ratio --- i.e. the ratio [rocking displacement / horizontal exciting displacement], where "rocking displacement' means the degree of rotation brought by rocking converted into equivalent displacement in the load-carrying cylinder.

The shift of peaks in the curves well evidence the very significant hardening of resonance frequency with application of rocking-suppression. Coincidence with empirical result is seen of the analytical result for 16% damping ratio.

With the abscissa of Fig.11 (a) altered from [rocking displacement / horizontal exciting displacement] to [rocking displacement (mm) / horizontal exciting acceleration (gal)], the curves take the form shown in Fig.11 (b), with the dwindled peaks strikingly indicating the marked rocking-suppression performance ensured by the device.



Fig.11 Frequency response curve of rocking motion

## Performance under seismic excitation

Figure 12 shows the response of rocking displacement to excited horizontal and vertical acceleration as shown in Fig.8. The solid line represents the response with rocking suppression, and the broken line represents the response without that. The response displacement with rocking suppression is only 1.4 mm, but that of without rocking suppression is 14mm. It indicates the effect of the rocking suppression is remarkable under seismic excitation.



Figure 13 shows the vertical response displacement to the same excited acceleration. In this figure, the solid line represents the response displacement obtained by the test, and the broken line represents that obtained by analysis.



Fig.13 Comparison between the test and analysis

It can be concluded from the foregoing findings that the system ensures good agreement with analyses, and that the analysis technique used above is appropriate to evaluate the performance of actual system.

# PERFORMANCE ANALYSIS OF ACTUAL FULL-SIZE EQUIPMENT UNDER EARTH-QUAKE CONDITION

### Model adopted for analysis

the foregoing method of performance analysis was applied to estimating the performance of the threedimensional seismic isolation system proposed in this paper to the most recent design of a FBR plant under development today in Japan. The envisaged seismic input wave pattern is as indicated in Fig.14. The load-carrying cylinders are envisaged an arrangement such as presented earlier in Fig.2, with the system characteristics of vertical oscillation frequency and damping, and of friction force dependent on horizontal excitation, all modeled on the analysis pattern of Fig.9.



As regards the load-carrying cylinder connected to the rocking –suppression cylinder, the model assumed the springs representing the bulk modulus of hydraulic fluid and rigidity of piping to be linked to the spring representing the rigidity of the rocking-suppression cylinder rod as schematized in Fig.15.



In respect of horizontal movement, the system was assumed to incorporate a laminated rubber bearing with lead plug as shown in Fig.1 (a). The restoring force characteristics of this bearing would be represented by yield seismic intensity  $\beta = 0.1$ , pre-yield frequency T<sub>1</sub>=1.0 sec, and post-yield frequency T<sub>2</sub>=2.8 sec.

# **Results of analysis**

The analyzed results are presented in Fig.16, which indicates that the response acceleration would be reduced to 1/2 in vertical direction (drawing(a)) and to1/3 in horizontal direction (drawing(b)), thus predicting good seismic isolation performance. Vertical displacement of the structure induced by rocking would be suppressed to the well-acceptable value of 12.7 mm (drawing(c)).





(c) Vertical displacement periphery of upper structure generated by the rocking motion Fig.16 Results of the analysis for actual isolation system

# CONCLUSION

Reduced size model tests on the independent load carrying cylinders alone and integrated system combined with rocking suppression cylinders have been performed to verify the expected performance of a three-dimensional seismic base isolation system, as proposed by the authors, incorporating hydraulic mechanism to ensure adequate isolation performance.

In the independent tests, the results have proved good agreement between theoretical calculation and test data in respect of restoring force and damping characteristics.

In the integrated system test, the results have proved good agreement of performance between analytical results and test data in respect of natural frequency and damping ratio in terms of frequency response and seismic response.

In addition, the transient analyses of actual size isolation system under earthquake condition were performed using characteristics obtained by the tests. It can be found that marked rocking suppression performance and applicable vertical and horizontal isolation performance in these results.

It can be confirmed that the performance of entire three-dimensional isolation system is applicable to FBR power plants.

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