Base Isolation Technique for Tokamak Type Fusion Reactor Using Adaptive Control

T. KOIZUMI, N. TSUJIUCHI, F. KISHIMOTO
Mistubishi Electric Corp., Amagasaki, Japan
H. IIDA
Japan Atomic Energy Research Institute, Tokaimura, Japan
T. FUJITA
University of Tokyo, Tokyo, Japan

1 INTRODUCTION

Isolation technology has been noticed recently in the field of protecting the entire heavy structures from earthquake motions, and already many aseismic structures have been constructed(1). This method is suited to isolate the heavy structures like buildings and large scale electric appliances(2)(3) because in that case the structure is relatively simple and the reliability of operation is high. In this aseismic method, however, restrictions about relative displacement between structure and ground become always subjects of question, and by taking these points into consideration, it seems possible to realize the practically reliable isolation device. Accordingly, the authors have developed an adaptive control method in which the vibration responses occurring in the structure at the time of an earthquake is continuously measured with attaching a control element of the isolation device, and changing the damping factor of the isolation device adaptively in any moment, so that the measurement may settle within a predetermined allowable range.

In this report, with the purpose of organizing the basic concept of adaptive isolation method and verifying this experimentally, as a typical example of heavy structure, the nuclear fusion reactor which required aseismic performance of high precision was selected, and fabricated a 1/29 scale model for experimental verification. It should be notified that this scale model could not perfectly follow the updated Tokamak type fusion reactor but the idea and concept of this method could be examined without any inherent differences. By proposing a newly developed control rule for limiting simultaneously both the response acceleration occurring in the structure and the relative displacement taking place between the ground and the aseismic floor with allowable values, the aseismic effect was confirmed by computer simulation and experimental verification.

2 ADAPTIVE ISOLATION CONTROL OF NUCLEAR FUSION REACTOR

2.1 Control rules and stability conditions

The following two points are particularly important for effective operation of the isolation device.

(1) Not to increase the response acceleration of the objected structure.

(2) To keep the relative displacement of ground and aseismic floor within predetermined allowable limits.

Accordingly, the object of adaptive control was determined to reduce the response acceleration and relative displacement simultaneously, and the possibility of such control rule was studied by numerical simulation. In the scale model of the object, in comparison with the natural frequency (2.8Hz) of aseismic support, since the natural frequency (14Hz) of the structural system is high, the structural system is regarded as a rigid body, and a model was set up in the system of one degree of freedom shown in Fig. 1.

As the control rule, the absolute value of the acceleration of the aseismic floor and the absolute value of the relative displacement to the ground were compared with the respective target values, and a control gain was continuously calculated from them, and the damping factor was automatically adjusted on the basis of this signal.

The equation of motion of the system of one degree of freedom shown in Fig. 1 may be expressed as follows by ignoring the damper for controlling.

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = -m\ddot{z}(t) \tag{1}$$

where,

m :mass of objected structure,

c :damping constant of isolation device,

k :spring constant of isolation device,

$x(t)$:relative displacement of objected structure to ground,

$\ddot{z}(t)$: input earthquake acceleration.

By making equation (1) dimensionless by employing $\zeta = c/2\sqrt{mk}$, $\omega = \sqrt{k/m}$, and introducing the controllable damping factor $mC(t)$, the equation of motion considering the control rule becomes as follows.

$$\ddot{x}(t) + 2\zeta\omega\dot{x}(t) + C(t)\dot{x}(t) + \omega^2 x(t) = -\ddot{z}(t) \tag{2}$$

$$C(t) = AG(t) = A[\frac{|\ddot{x}_{abs}(t)|}{\ddot{x}_{absl}} - W\frac{|x(t)|}{x_l}]$$

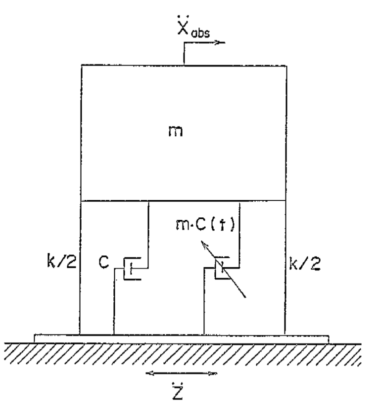
$$\ddot{x}_{abs}(t) = \ddot{x}(t) + \ddot{z}(t)$$

where,

A : control gain amplification factor (< 0),

$G(t)$: control gain,

W : relative weighting factor between normalized absolute acceleration and normalized relative displacement (> 0),



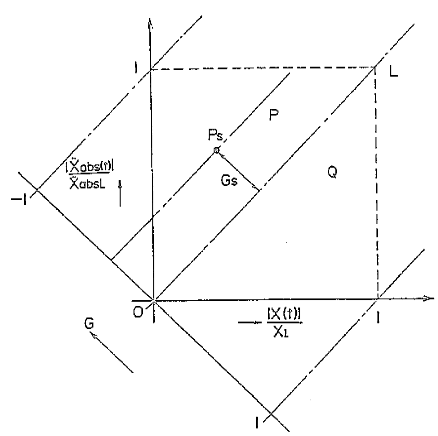


Fig. 1 Simulation model of adaptive isolation system. Fig. 2 Calculation method of adaptive control gain.

$\ddot{x}_{abs}(t)$: absolute acceleration of objected structure,

x_{absl} : maximum limit set value of $x_{abs}(t)$,

x_l : maximum limit set value of $x(t)$.

Referring now to Fig. 2, the setting method of control gain is described below. In Fig. 2, the axis of abscissas and the axis of ordinates respectively denote the normalized relative displacement and normalized absolute acceleration, both normalized by the maximum limit set values. Since the relative displacement and absolute acceleration possess mutually contradictory properties, let us suppose here that the optimum value of the dynamic characteristics of the isolation device be confined on a straight line L on which the normalized relative displacement and normalized absolute acceleration are showing similarly coincident values in any moment. However, for example, if the normalized absolute acceleration is large and the normalized relative displacement is small, the response comes in a region P shown in Fig. 2, and in the inverse case the distribution is in a region Q. Supposing the response to be Ps as shown in Fig. 2, the distance from the line L is delivered as control gain signal Gs. The sign is decreasing direction (minus) of the damping factor when the normalized absolute acceleration is greater than the normalized relative displacement, and increasing direction (plus) of the damping factor in the inverse case. According to this control rule, in this isolation device, when the relative displacement between the ground and the aseismic floor is too large, the damping factor is increased to reduce the isolation effect, and to the contrary when the absolute acceleration of the structure is too large, the damping factor is decreased to enhanced the isolation effect. A control block diagram used in this adaptive isolation concept is shown in Fig. 3.

The stability condition is discussed below. In order that equation (2) would be stable, it is required that the following formula should be imposed.

$$2\zeta\omega + C(t) > 0 \tag{3}$$

Supposing $\ddot{z} = 0$ for the convenience sake, the stability condition for the control gain G(t) is shown in equation (4) because the control gain amplification factor A is negative.

$$\frac{|\ddot{x}_{abs}(t)|}{\ddot{x}_{absl}} < W\frac{|x(t)|}{x_l} - \frac{2\zeta\omega}{A} \tag{4}$$

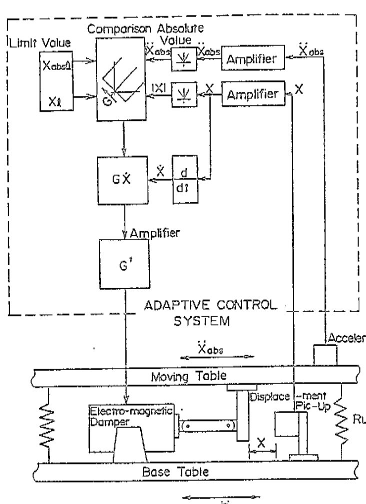


Fig. 3 Block diagram of adaptive isolation system.

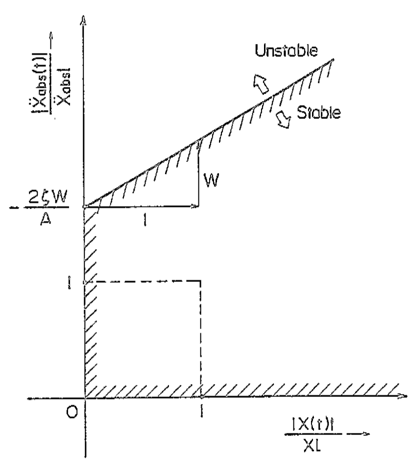


Fig. 4 Stability chart for amplification coefficient of adaptive control gain.

This condition is illustrated in Fig. 4. Hence, when the control region is in the stable region, that is, as far as the following relation is satisfied, the system is stable.

$$-2\zeta\omega < A < 0 \tag{5}$$

2.2 Evaluation of control characteristics

The characteristics of the control rule applied in this adaptive isolation concept were studied by simulation by employing the analysis model shown in Fig. 1. The constants used in the simulation are listed in Table 1. As compared with the damping ratio without control, when the amplification factor of the control gain was changed, the effects on the absolute acceleration and relative displacement are shown in Fig. 5. According to the diagram, there is a contradiction between the absolute acceleration and relative displacement, and by varying the amplification factor of the control gain, it is recognized that the damping ratio can be adjusted as desired. However, the sensitivities of the absolute acceleration and relative displacement to change the damping factor are not equal, and in order to design the isolation device as expected, it is necessary to study the effect of the relative weighting factor W between the two. Accordingly, using the values in Table 1, the effect of the relative weighting factor W was investigated by setting the amplification factor of the control gain at -11.6 so that the damping ratio may be variable from zero to 0.66. The results is shown in Fig. 6. As clear from Fig. 6, by the relative weighting factor W, the absolute acceleration and relative displacement can be weighted, and it is possible to add the limits suited to the desired isolation device.

3 EXPERIMENTAL VERIFICATION BY SCALE MODEL

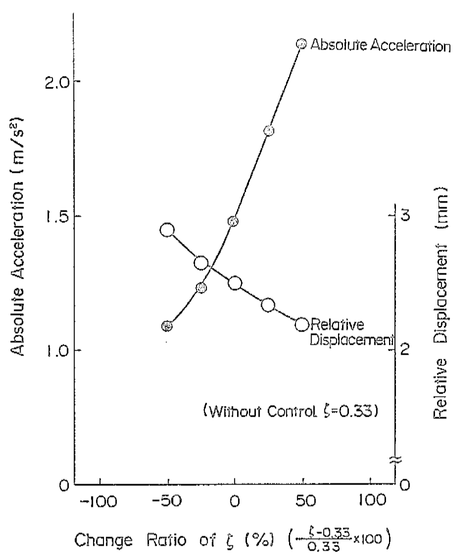


Fig. 5 Influence of absolute acceleration and relative displacement for amplification coefficient.

Table 1 Condition of numerical simulation.

Input wave		El-centro, 1940,N-S
Input acceleration	$\ddot{z}$	9.371 m/s^2 (937.1 gal)
Natural frequency	ω	2.8 Hz
Damping ratio	ζ	0.33
Maximum limit set value of $\ddot{x}_{abs}(t)$	$\ddot{x}_{absl}$	0.8525 m/s^2 (85.25 gal)
Maximum limit set value of $x(t)$	x_l	1.51 mm

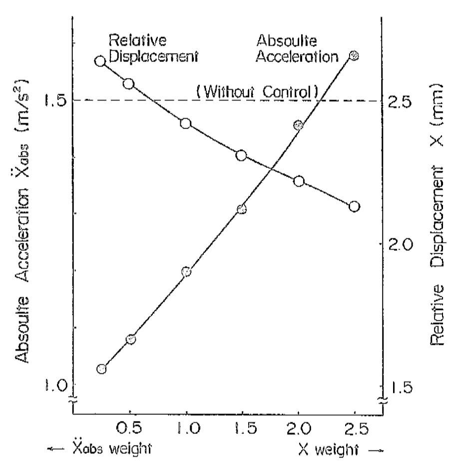


Fig. 6 Influence of relative weighting factor W

3.1 Sample and experimental procedure

Fig. 7 shows a 1/29 scale model of Tokamak type fusion reactor fabricated for the study of the adaptive isolation device. The aseismic floor employed in this model is a structure of supporting from the ground by using six rubber bearings. This rubber bearing is a kind of laminate structure composed of 41 pieces of 0.8 mm thick rubber and 0.3 mm thick steel plate, and the stiffness ratio of vertical direction to horizontal direction becomes up to about 500 as a result of this formation [4]. As aseismic elements, there are also oil dampers and electromagnetic dampers. The electromagnetic damper is installed for the purpose of adaptive control by changing over the damping factors, and is capable of generating damping force due to eddy current loss with respect to the relative speed of the aseismic floor and ground. As the vibration control signals, the outputs of the accelerometer, displacement sensor, and force sensor were used. The accelerometer measures the absolute acceleration of aseismic floor, ground and coil parts, the displacement sensor measures the relative displacement between the aseismic floor and ground, and the force sensor measures the vibration control force generated in the electromagnetic damper.

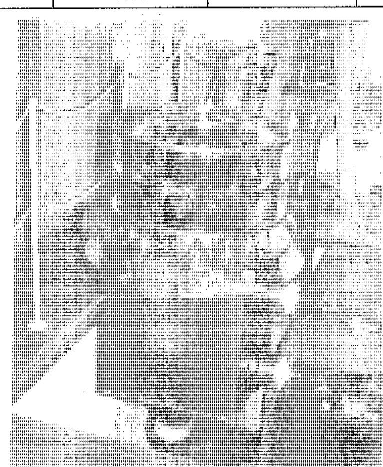
The modal constants of the scale model were identified, and the results are shown in Table 2. It is known from Table 2 that this isolation device can adaptively control the damping ratio in the range of $0.16 < \zeta < 0.46$. The control effect was verified by comparing the time history response results by the input of El-centro earthquake waves (N-S, 1940) in non-control case, constant gain (max. damping factor) control case, and adaptive control case.

3.2 Results of experiment

Vibration response results in various excitation test conditions are summarized in Table 3. The vibration response was evaluated by the peak to peak amplitude of vibration. According to Table 3, in the case of constant gain control, as compared with the case of without control, the response acceleration increased up to 13%, while the relative displacement decreased down to 11.5%. In the case of adaptive control, on the other hand, the response acceleration was 22.3% up and relative displacement was 21.3% down, and the control effect as expected was obtained.

Table 2 Modal parameter of scale model.

Condition	Without control	With control	
		Heavy damping	Light damping
Natural frequency Hz	2.8	2.4	2.9
Damping ratio	0.33	0.46	0.16



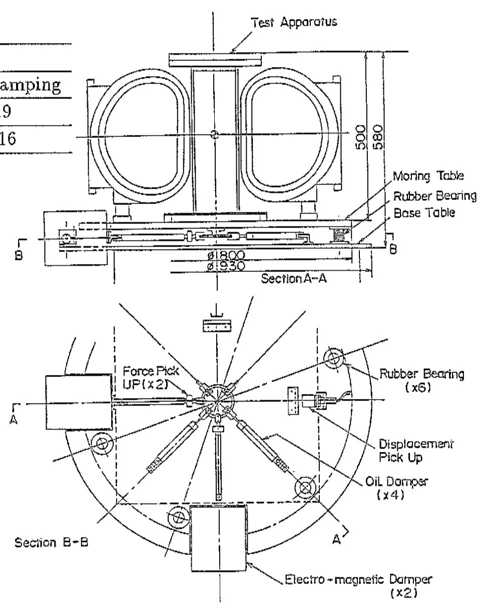


Fig. 7 Experimental setup of adaptive isolation system.

Table 3 Vibration control results for earthquake motion

Condition	Input acceleration m/s^2	Response acceleration m/s^2	Relative displacement mm
Without control	9.25	3.63	5.2
With control (Heavy damping)	9.0	3.99 (+13.0%)	4.5 (-11.5%)
With control (Adaptive)	9.5	2.9 (-22.3%)	4.2 (-21.2%)

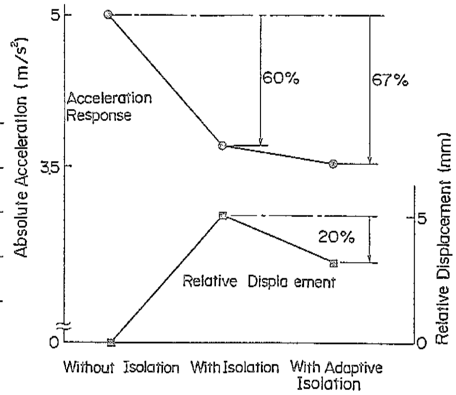


Fig. 8 Effect of adaptive isolation control.

In order to study the effect of the adaptive aseismic control, three cases, without isolation, with isolation, and with adaptive isolation, were compared, and the results are shown in Fig. 8. It is known from these results that the absolute acceleration of a structure can be reduced at least 40% by isolation only, and additionally another 33% by adaptive control. At the same time the relative displacement can be effectively reduced to about 80% by adaptive isolation control.

4 CONCLUSIONS

In this paper relating to the isolation device of heavy structure such as nuclear fusion reactor, a control rule for reducing the response acceleration and relative displacement simultaneously was formulated, and the aseismic performance was improved by employing the adaptive control method of changing the damping factors of the system adaptively every moment. The control rule was studied by computer simulation, and the aseismic effect was evaluated in an experiment employing a scale model. As a results, the following conclusions were obtained.

(1) By employing the control rule presented in this paper, both absolute acceleration and relative displacement can be reduced simultaneously without making the system unstable.

(2) By introducing this control rule in a scale model assuming the Tokamak type fusion reactor, the response acceleration can be suppressed down to 78% and also the relative displacement to 79% as compared with the conventional aseismic method.

(3) The sensitivities of absolute acceleration and relative displacement with respect to the control gain are not equal. However, by employing the relative weighting factor between the absolute acceleration and relative displacement, it is possible to increase the control capability for any kind of objective structures and appliances.

5 REFERENCES

(1) (1988). Vol.26. No.12. Aseismic Techniques : New urban development.
(2) Koizumi,T. et al.(1989). Trans.JSME. Vol.55-C. No.515 : pp.1602-1608.
(3) Tsujiuchi,N. et al.(1991).Active Control of Structural Vibration by an Active Mass Damper. Trans.JSME. Vol.57-C. No.536.
(4) Fujita,T. et al.(1984). Trans.JSME. Vol.50-C. No.545 : pp.933-939.