Active seismic response control systems for nuclear power plant equipment facilities

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1. INTRODUCTION

The original concept of an "Active Seismic Response Control System" has been presented by the first author in the latter half of the 1950's, when the nuclear power plants were just going to be adopted into Japan. While the earthquake-resistant approach to them, in the field of civil engineering, had still important problems then, the first author(1957) proposed several kinds of the supporting systems for the reactor and the steam generater. These ideas were deduced from his investigations on the non-linear vibration theory in which the characteristics of the non-linear hardening restoring force emphasized the efficiency for suppressing the nonstationary resonant responses of structures. In consequence of the theoretical and analytical researches, the four principles were proposed (Kobori 1960);

P1.cut off the seismic energy transmission source, if possible.
P2.use an energy absorption mechanism.
P3.isolate the natural frequencies of a controlled structure against the dominant frequencies of seismic disturbance as possible.
P4.control a structure to cause nonstationary and unresonant states by applying its variable non-linear property actively.

These principles do not only classify the ordinary anti-seismic structures, but also discriminate the active controlled structures.

In succession of the afore-mentioned concept, the research as to Dynamic Intelligent Building (DIB) System was started again based on the innovation of technology for the last 30 years (Kobori 1986). This concept is adaptable not only to the ordinary buildings but to the equipment facilities installed therein. In this paper the basic concept of DIB System is generally explained, and it must be consequently shown that these active seismic response control system have remarkable possibility as an active supporting system for the equipment facilities.

2. BASIC CONCEPT OF DYNAMIC INTELLIGENT BUILDING SYSTEM

In Japan, the research on earthquake resistant structures has been continued for more than one hundred years, and has contributed to the improvement of structural soundness when subjected to severe earthquakes. This anti-seismic design philosolphy has been definitely systematized by the concept of seismic safety factor for the statistically fluctuated characteristics of the restoring force and the earthquake loading. These ordinary earthquake resistant structures should be categorized as passive anti-seismic structures. The various kinds of anti-seismic structural elements regulated by this design philosophy have been extensively developed, (Fig.1).

Meanwhile, the concept of structural control was first in U.S.A. proposed as a technical introduction from engineering mechanics (Yao 1972). In the field of engineering mechanics, the modern control theory has been dominantly developed in accordance with the progress of digital computers. J.N.Yang (1975,1985) started his research based on the modern control theory, and could discribe the optimal control scheme. And he recently presented the possible application of the active tendon and active mass damper control system to buildings excited by strong earthquakes. T.T.Soong (1976, 1986) has also studied on the modal control scheme, and indicated the feasibility of his scheme by experimental results. S.F.Masri (1985) started his research about the passive impact damper, and recently showed experimental results of the active pulse control for flexible structures.

As an active anti-seismic structure, the authors (1986) proposed the Dynamic Intelligent Building System,which has two active anti-seismic concepts;

C1. Reduction of input energy

The dominant frequencies of earthquake do not continue so long, and each width in frequency domain is not so wide. If the natural frequencies of structures can be changed dynamically not to pass through the peak power of seismic disturbance, then as a result, the reduction of input energy might be achieved.

C2. Artificial unresonant state

In the transient process of seismic response, the effect of previous deformed motion is defined as a "resonant force", hence the resonant state is caused by the growth of this force. If a counter force can cancel this resonant force, then an unresonant state might be artificially accomplished.

The development of DIB System requires the linkage of widespread researches, such as seismological, structural, mechanical, and electrical engineering. Then the proposal of DIB System leads to the establishment of a new paradigm in the structural engineering.

3. ANALYTICAL SIMULATION OF DIB SYSTEM

In order to verify the efficiency of DIB System, the authors have developed the DIB simulator program. As a preliminary stage, DIB System is composed of four sub-units.

1 Outer earthquake sensor unit

The far sensor network arranged surrounding the predicted epicenter, can transfer the preceding information as to the arrival of the actual earthquake waves.

2 Inner vibration sensor unit

The data from this unit is analysed to obtain the natural frequencies of the controlled system, and is used as a material of command signal for active anti-seismic controller.

3 BRAIN unit

This unit acts as an artificial intelligence, such as the sequential data analysis to grasp the property of disturbance, the decision of command for active anti-seismic controllers, and the recognition of aging effect in vibration mode and natural frequency.

4 Active seismic controller

Adjustable stiffness devices, aiming at C1 concept, act to change the natural frequency of controlled system. Active Mass Driver creates the counter force to cancel the resonant force.
These sub-units are expressed as mathematical models and analytical procedures, and are combined in dynamic response program,(Fig.2). In this simulator, the state variable is sequentially obtained, then the property essential for active anti-seismic controllers is obtained.
The physical meaning of C1 and C2 concepts are explained by using the transformed motion equation.

$$\{\ddot{x}\}_i = [E]^{-1}(-[M]\{\ddot{y}\}_i + \{CF\}_i - [G1]\{\ddot{x}\}_{i-1} - [G2]\{\dot{x}\}_{i-1} - [G3]\{x\})_{i-1} \qquad (1)$$

$$[E] = [M] + 0.5*Tau*[C] + 0.25*Tau*Tau*[K]$$

The object of control is considered to reduce the value of $\{\ddot{x}\}_i$,then C1 concept aims to change the transfer function; $[E]$,and C2 concept aims to reduce the summation value of each force.

3.1 Feedforward Control of Adjustable Stiffness Devices

The C1 concept is confirmed by the feedforward control of Adjustable Stiffness Devices. In this control scheme,there are two important points to change the natural frequency. First,it is essential to recognize the non-stationary dominant frequency of earthquake wave, then the typical earthquake waves, such as El Centro and Taft are analysed by using running power spectra. The results of both earthquake waves show the expectant dispersion property of dominant frequency,(Fig.3). Second, the adjustable stiffness devices are supposed as the active controller to change the natural frequency.
Two cases of one degree of freedom model are analysed, in each case, the standard frequency is respectively 1.25Hz and 3.0Hz,and variable stiffness range is half through twice of the standard stiffness. As the input wave, EW component of Taft earthquake, is normalized to the maximum acceleration value of 100gal. The selected frequency is shown as the tajectory on the running power spectra of input wave,(Fig.5). The displacement and shear force response results show respectively reduction in all duration time, and 35% through 40% of reduction in the maximum response value,(Fig.4). In addition to this, the value of accumulated input energy is deducted about 75%. These results confirm the validity of C1 concept. From this concept it is found that no external energy is needed to suppress the structural vibration.

3.2 Feedback Control of Active Mass Driver

The C2 concept is confirmed by feedback control of Active Mass Diver, which can generate the counter force in accordance with the command signal. There are several definitions of counter force to reduce the summation of each force in equation (1). In this case, the counter force is defined proportional to the relative acceleration of the previous step. Only one Active Mass Driver is arranged at the top floor of an eight-storied controlled building,(Fig.6). As the earthquake wave, E-W component of Taft earthquake is normalized to the maximum acceleration value of 350gal. More than 50% of reduction is achieved at the maximum response value of acceleration,(Fig.7). The accumulated inner energy is deducted more than 80%. The response spectra of the top floor acceleration response,(Fig.8) indicates the elimination of first mode vibration. It is efficiently pointed out that no troublesome analytical procedure is demanded for the control, namely, the inherent filtering effects of the controlled system are used as the material of command signal.

4. APPLICATION OF DIB SYSTEM TO NUCLEAR POWER PLANT FACILITIES

Upon designing the equipment facilities, assuming the no interaction effect between the building and the plant equipment contained therein, the seismic load for equipment is evaluated from the seismic response value of building model without the equipment. In this process, the indefinite feature of the ground motion is treated by an envelope response spectra, and that of structural modelling is evaluated by the shift spectra. In this process the resonant vibration of building is unfavorable as the seismic load for the equipment. The basic concept of DIB System can be applied to an active supporting system or an active vibration controller for equipment facilities. These systems have two advantage points.

1. Both the basic concepts of DIB system cause unresonant state to the controlled system, and the predominant control effect is attained when dominant frequency of seismic disturbance are so sharp and narrow in the frequency domain. Therefore, the resonant vibration of building is not unfavorable as the seismic load for equipment contained therein
2. The transfer function of building is available to get a preceding information of earthquake loading for equipment,since its transfer function acts as the amplifier of ground motion with some time lag.

In addition, less size of controlled system gives more feasibility to realize these basic concepts.

5. CONCLUSION

Active anti-seismic structure is distinguished from ordinary anti-seismic structure, and the demand for anti-seismic controlled system will stimulate the research activities of ordinary structural control. This concept of active anti-seismic structure should arouse widespread researches, and consequently a new paradigm would be established in structural engineering. Dynamic Intelligent Building System is proposed as an active anti-seismic structure. DIB System has two basic concepts, such as reduction of input energy(C1) and artificial unresonant state(C2). The feasibility of these concepts are respectively verified by using DIB simulator program.

C1 concept aims to use the property of non-stationary dispersion of ground motion. This property is indicated by the running power spectra of measured earthquake waves. From this concept it is remarkably pointed out that no external energy is needed to suppress the structural vibration.

C2 concept is explained by using the transformed motion equation. This equation is very meaningful to explain the physical meaning of counter force ,and to define the decision scheme of counter force.

The adoptation of DIB System to nuclear power plant equipments should contribute to the improvement of safety of important equipments when subjected to the severe earthquakes.

REFERENCE

Kobori,T. 1957 A Feasibility Study on Vibration Control
Transactions of AIJ(Kinki Branch) Oct.1957 (in Japanease)

Kobori,T. & Minai,R. 1960 Analytical Study on Seismic Response Controlled Structures
Transactions of AIJ No.66 Oct. 1960 (in Japanease)

Kobori,T. el al. 1986 New Philosophy of Anti-seismic Design
The 7th Japan Earthquake Engineering Symposium 1986

Yao,J.T.P. 1972 Concept of Structural Control
ASCE,Vol.98,No.ST7 July 1972; 1567-1574

Yang,J.N. 1975 Application of Optimal Control Theory to Civil Engineering Structure
ASCE,Vol 101,No.EM6 Dec.1975; 818-838

Yang,J.N. el al. 1985 Active Control of Seismic-Excited Buildings
ASCE,Vol.111,No.ST10,Oct.1985; 2165-2180

Soong,T.T. & Martin,C.R. 1976 Modal Control of Multistory Structures
ASCE,Vol.102,No.EM4,Aug,1976; 613-632

Soong,T.T. et al.1986 Active Control of Structures during Earthquakes
EAEE Lisbon,Proceedings of the 8th ECEE

Masri,S.F. et al.1985 Active Vibration Control of Large Civil Structures AIAA-85-0681-CP

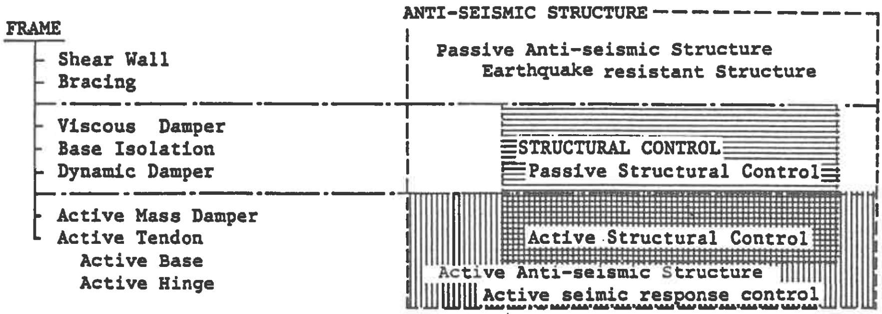

Fig.1 CLASSIFICATION OF ANTI-SEISMIC STRUCTURES

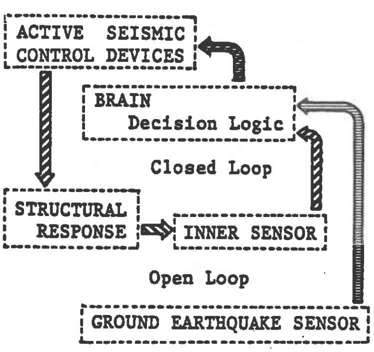

Fig.2 DIB SYSTEM FLOW

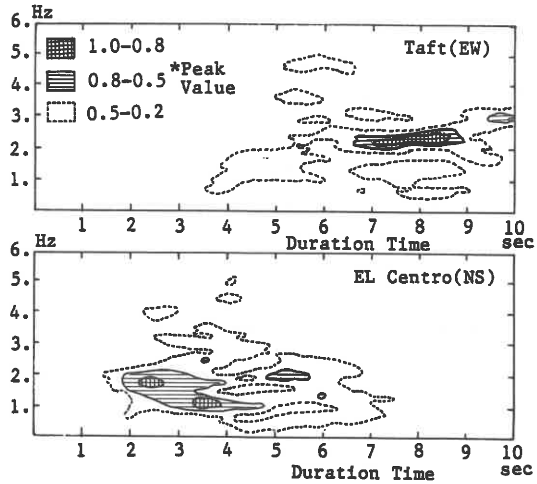

Fig.3 RUNNING POWER SPECTRA

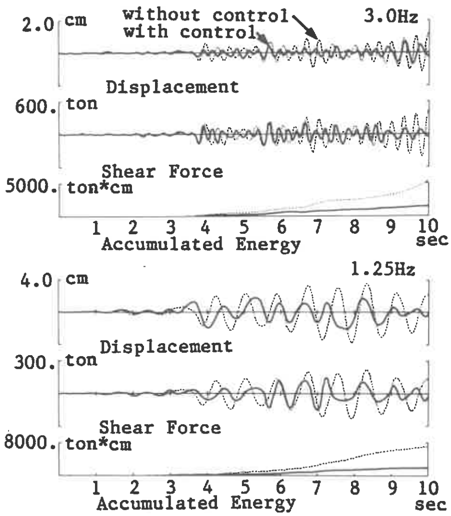

Fig.4 RESPONSE TIME HISTORY

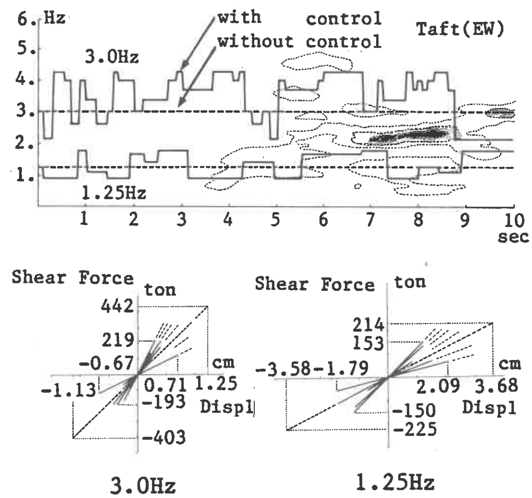

Fig.5 TRAJECTORY OF NATURAL FREQUENCY

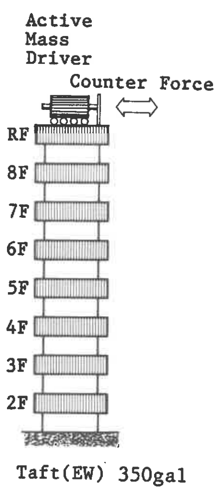

Fig.6 CONTROLLED STRUCTURE MODEL

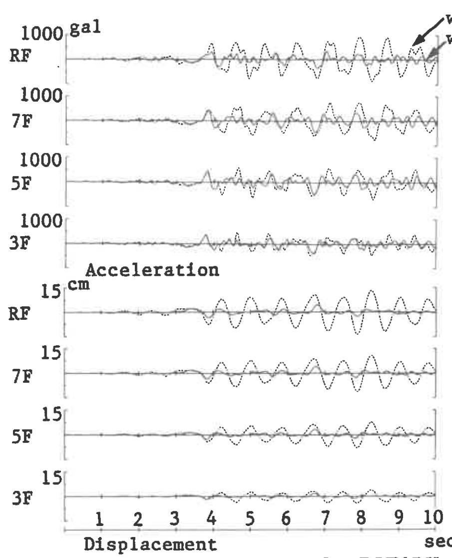

Fig.7 RESPONSE TIME HISTORY

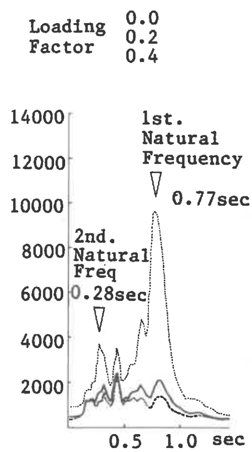

FIG.8 RESPONSE SPECTRA AT RF

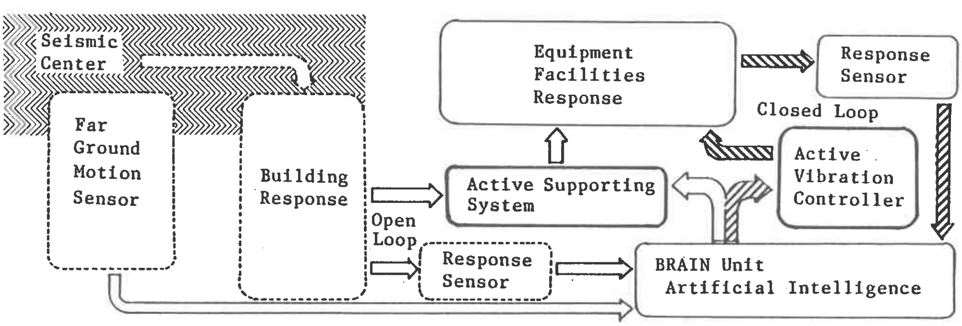

Fig.9 ACTIVE SEISMIC CONTROL SYSTEM FOR EQUIPMENT FACILITIES