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A PROPOSAL OF NEW ANTI-SEISMIC STRUCTURE WITH ACTIVE SEISMIC RESPONSE CONTROL SYSTEM -DYNAMIC INTELLIGENT BUILDING-

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SUMMARY

A "Dynamic Intelligent Building (DIB)" is proposed as a dynamically controllable structural system against the severe earthquakes. This DIB aims at the earthquake-proof structures. The theoretical control concept for the DIB comes from the transient seismic response process. An Active Adjustable Stiffness System is analytically simulated, and the basic control effect is certified from the results. An Active Mass Driver System is simulated in the experiment, and the artificial unresonant process is confirmed.

INTRODUCTION

A new structural design concept against the destructive earthquake is proposed in this paper. This basic concept has been derived from the study of nonlinear random vibration by the first author in the 1950's.

First, the ordinary structural restoring property was modeled as the poly-linear hysteresis model which was referred to as the natural nonlinearity (Ref.1). This nonlinearity is related to the accumulation of an irreversible damage. In the dynamic response process, as the growth of plasticity makes the natural period longer, consequently, the growth of resonant vibration is suppressed for the earthquake ground motion with narrow-band-width power components. This occurrance was explained as the unresonant property of the nonlinearity.

Next, the artificial nonlinear property which depended on the inherent element property, such as the hardening property of steel wire, was analyzed aiming at the efficient unresonant vibration state without irreversible damage (Ref.2). This sequence of researches produced the basic concept of the active seismic response control (Ref.3) as follows:
1. Shut off the input energy from the earthquake ground motion.
2. Isolate the natural period from the dominant seismic power components.
3. Adjust the dynamic property to hold the unresonant state.
4. Adopt an efficient energy absorption mechanism.

The superior feature of this structural design concept was to use the dynamic response process, in which the unresonant process was intentionally realized without the structural damage. In the 1950's - the 1960's, this concept was shelved as being just a theoretical, since there existed insufficient fundamental technology and scarce social needs for this concept.

PROPOSAL OF DYNAMIC INTELLIGENT BUILDINGS

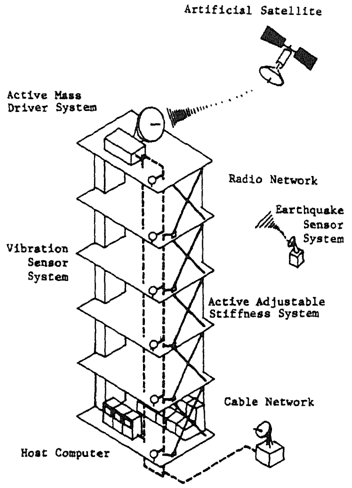


Fig.1 Basic Concept of DIB

In the coming information age, the data communication system will cover the widespread information. Actually, some artificial satellites are already utilized for the emergency data network system. The Intelligent Buildings (Smart Buildings) are designed to use efficiently these network systems.

The higher the serviceability of the advanced information society is, the greater becomes the reliance on these functions. As a result, the importance and the vulunerability of this function are rising, therefore, careful maintenance is required for the installed system.

From the viewpoint of the structural engineering, this request needs a complete shelter that keeps the nondestructive state even after the severe earthquake.

In reply to these social needs, a "Dynamic Intelligent Building (DIB)" is proposed as the building system with the active seismic response control using the central processing unit and data network system in the Intelligent Buildings (Fig.1). It goes without saying that the recent innovation in the advanced technology will be useful to realize the structural concept which is considered as the self-balancing system against the earthquake.

The DIB is aiming to supply a high quality environment even when subjected to severe earthquakes. Therefore the DIB imposes the strict design criteria on itself as follows:

1. To suppress the structural vibration to remain below the allowable threshold of the installed equipments. (Vibration-free structure : Serviceability)
2. To keep the structural soundness during and after the severe earthquake. (Damage-free structure)

In order to achieve these criteria, the dynamically controllable nonlinearity is the progressive answer, in which the controlled structure possesses self-balancing functions against the nonstationary earthquake ground motion. This function is realized as an automatic structural control system.

The concept of the DIB stimulates the widespread future needs, namely, the construction of infrastructure (earthquake sensor system, energy storage system, and data network system) and the academic research (control theory, active controller). In this way, from the practical point of view, the DIB opens up an immense market for the advanced high technology. And from the academical viewpoint, the active seismic response controlled structures will be the new paradigm in the field of structural mechanics.

THEORETICAL CONCEPT OF DIB

The theoretical control methods and the classification of the active seismic response control are explained using the transformed motion equation. The structural response subjected to earthquake motions, can be expressed by means of motion equation (1).

$$[M]\{\ddot{x}(t)\} + [C]\{\dot{x}(t)\} + [K]\{x(t)\} = - M\{\ddot{y}(t)\} \quad (1)$$

This equation is transformed into asymptotic equation using trapezoidal rule.

$$\{\ddot{x}(t)\} = [E(t)]^{-1}(\{SF(t)\} + \{RF(t-\Delta t)\}) \quad (2)$$

$[E(t)] = [M] + 0.5*t*[C] + 0.25*t^2*[K]$: Transfer Function

$\{SF(t)\} = -[M]\{\ddot{y}(t)\}$: Instantaneous Seismic Force

$\{RF(t-\Delta t)\} = -[G1]\{\ddot{x}(t- t)\} - [G2]\{\dot{x}(t-\Delta t)\} - [G3]\{x(t-\Delta t)\}$

: Instantaneous Resonant Force

$[G1] = 0.5*t*[C] + 0.25*t^2*[K]$

$[G2] = [C] + 0.5*t*[K]$ $\quad$ $[G3] = [K]$

The meaning of equation (2) is explained that the current acceleration is obtained by multiplying the transfer function by the instantaneous force. Therefore two basic control methods can be considered.

Dynamic Pole Assignment Method The nonstationary seismic property and the transient response process are peculiar problems from the viewpoint of structural control. Therefore it needs the dynamic pole assignment method instead of the stationary pole assignment method. In order to change the pole position dynamically, the constitutive elements of the transfer function are the target, namely, the mass, the damping, and/or the stiffness property.

And to decide the suitable pole position, it is necessary to foresee the dominant power frequencies in the coming earthquake. The earthquake sensor system which transmits the signal of coming earthquake from near epicenter, will be valuable to create an anticipation time for the feedforward control algorithm. By this control algorithm the input seismic energy is shut off, isolating the natural frequency from the dominant power frequencies. Therefore the advantage of this control concept is that less external energy is needed to control the structure besides the driving energy for the active controller.

Dynamic Counter Force Method There are two kinds of control concept to reduce the instantaneous force. The first is the usage of the external counter force to cancel the instantaneous seismic force (Feedforward control) or to cancel the instantaneous resonant force (Feedback control). Some types of energy transducer are proposed as the active controller to generate the counter force.

The second is the adjustment of the structural property, such as mass, damping, and stiffness. In this control process, the phase-modulation of the structural response can cause the cancellation of the instantaneous resonant force countering the coming seismic force. Therefore, no external control energy source required. This control algorithm needs also the information of the coming earthquake, in order to use the seismic force as the counter force.

ACTIVE ADJUSTABLE STIFFNESS SYSTEM

As the typical active controller, the Active Adjustable Stiffness System (AASS) is adopted in this paper. Three types of the AASS are presented, namely, active bracing system (Fig.2), active hinge system, and active base system. These controllers are realized as the mechanical controller.

They have respectively primary control procedure dependent on the dynamic response characteristics. As a typical primary control procedure, the active length bracing system can adjust the length only in the slacking state. This primary control procedure makes it possible to respond quickly with less external energy.

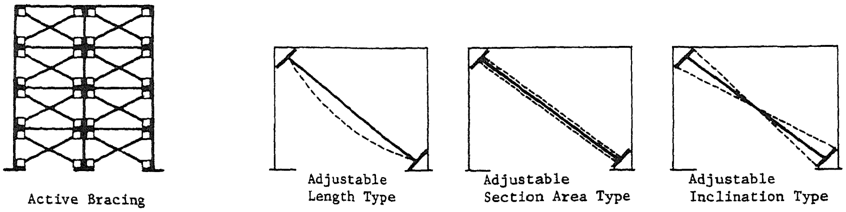


Fig.2 Active Adjustable Stiffness System

In the control technology, the adaptive control algorithm is designated as the advanced feedforward control for the automatic control system subjected to the nonstationary disturbance (Ref.4). In this paper, the identified analytical model (predictive observer) is adopted to predict the vibration in the transient structural response (Fig.3).

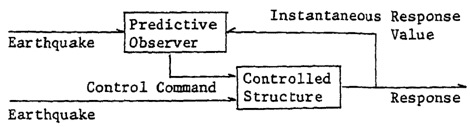


Fig.3 Adaptive Control with Predictive Observer

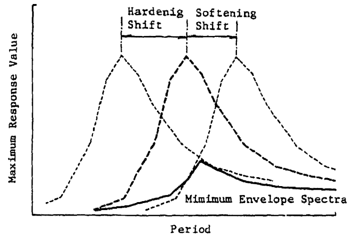
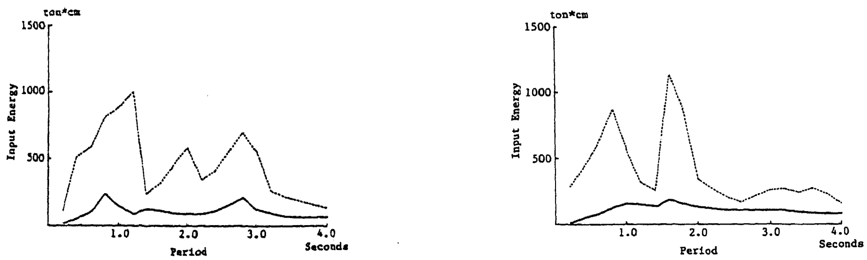


Fig.4 Basic Concept of Minimum Envelope Spectrum

The main control effect of the AASS is obtained by the dynamically isolation from the dominant seismic power frequencies at each time. This effect is evaluated as a "minimum envelope spectrum" obtained by the shift of the transient response spectrum (Fig.4). From this viewpoint, the available stiffness width is considered as one of dominant parameters to determine the maximum response value of the DIB.

A significant secondary control effect comes from the phase modulation of the resonant force which cancels the current seismic loading. This effect is sometimes experienced as an antiresonance in the seismic response process by chance, while this effect is realized intentionally in the control process.

This control system is simulated using an analytical simulator, and the results of a parametric study as to the adjustable periods produce a "DIB response spectra". The DIB response spectra for the typical earthquake certifies the unresonant feature of the controlled structure (Fig.5).



El Centro(NS) Taft(EW)

Fig.5 DIB Response Spectra

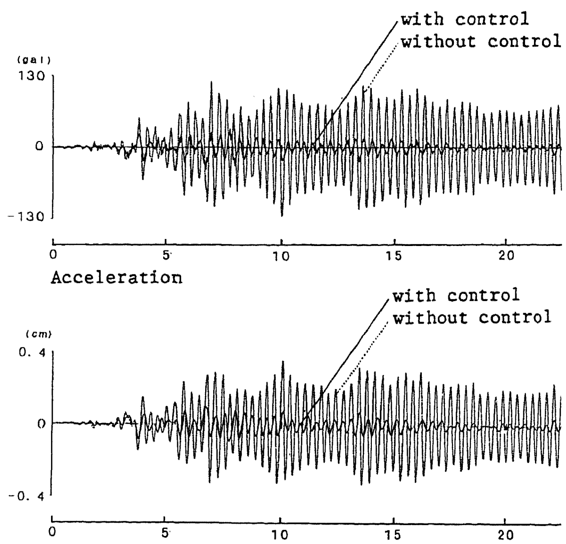
ACTIVE MASS DRIVER SYSTEM

The authors conducted some experiments to evaluate the feasibility of the concept of the active seismic response control (Ref.5).

The controlled structure was 3.0 meter-height and 0.5 meter-width, 3-story 1-span steel frame. Some of its vibration properties were as follows:
The first and the second natural frequencies were respectively 3.04, 10.0Hz, and the damping factor was approximately 0.3% for the first natural frequency.
The controlled structure was mounted on the shaking table (Fig.6).

In this experiment, an electro-magnetic force generator was adopted as the active controller, and the feedback control algorithm was programmed. This control algorithm is adaptable even for the nonlinear structures. The advantage of this algorithm comes from the filtering effect of the controlled structure for the nonstationary seismic property. This definition is explained as the cancellation of the instantaneous resonant force using the counter force.

The response time history at the top floor, shows good control effect in all duration time. Especially the maximum response value is reduced to one fourth of the response without control (Fig,7).



Input Earthquake: Taft(EW) Max: 30gal

Fig.7 Response Time History

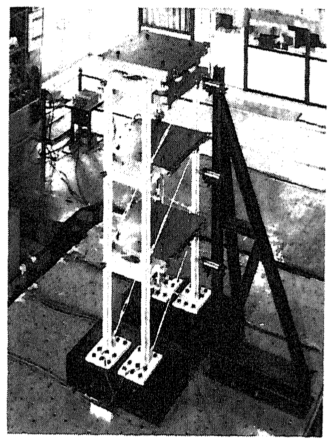


Fig.6 View of Experimental Model

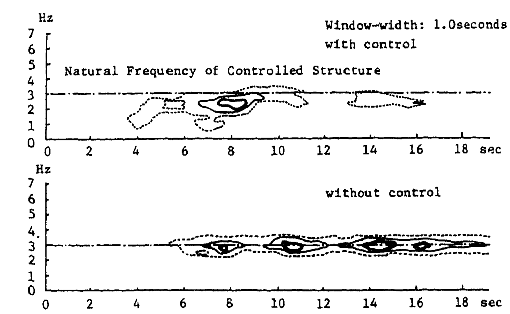


Fig.8 Running Power Spectra (acceleration)

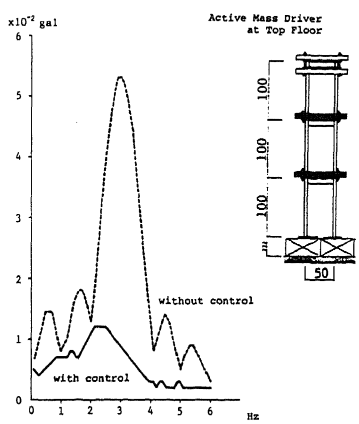


Fig.9 Running Fourier Spectra

The frequency components of the acceleration response are evaluated using running power spectra (Fig.8) and the running Fourier spectra (Fig.9). No resonant component comes out at the first natural frequency in controlled response. Meanwhile the resonant component is dominant in the response without control. This performance is explained as the "artificial unresonant control effect" by the AMD system.

CONCLUSIONS

The DIB is aiming at the earthquake-proof structure. This concept was derived from the study on the nonlinear random vibration, therefore, the inherent target of the DIB is to control the transient response process caused by the nonstationary seismic property.

In order to support the advanced information society from the stand point of the structural mechanics, the objective of the DIB is to keep the high serviceability, moreover, to realize the damage-free shelter when subjected to the earthquake.

The asymptotic motion equation suggests two basic control concepts.
C1. Dynamic Pole Assignment Method.
C2. Dynamic Counter Force Method.
The C1 control method aims to the detuning in the seismic response process, and this concept is realized as the dynamical adjustment of the structural property.

Using the analytical simulator, the Active Adjustable Stiffness System is activated according to the adaptive control algorithm. The analytical results explain the control effect as follows:

1. The natural period is intentionally selected, to isolate from the dominant seismic power component, which is based on the C1 concept.
2. The seismic force is transformed into the control force by the phase-modulation of the resonant force, which is based on the C2 concept.

In the experimental research, the Active Mass Driver System is composed from the electro-magmetic force generator with the feedback control system. The experimental results show that the resonant vibration is eliminated from the controlled vibration. The adopted feedback control algorithm is considered as the practical control algorithm.

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   Part 1. Theoretical Control Concept
   Part 2. Analytical Verification of Theoretical Control Concept
   Part 3. Experimental Verification of Theoretical Control Concept
   Part 4. Analytical Study on Japanese High-rise Building with Active Mass Driver System against Mexico Earthquake