Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.VIII)

SE-R2

State-of-the Art Report
ACTIVE SEISMIC RESPONSE CONTROL

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SUMMARY

As an advanced structural design concept, "Active Seismic Response Control" is to be worthy of attention in the anti-seismic design of structures. The concept makes the structural property controllable, adapting the structural property instantaneously due to the earthquake ground motion. Both the nonstationary characteristics of the earthquake ground motion and the nonlinear structural property play an important role to achieve the self-balancing structural system. The preceding researches regarding to the "Structural Control" are reviewed from the viewpoint of the active seismic response control.

INTRODUCTION

When an earthquake occurs, and the strong motion records of the ground surface and underground layers are fortunately obtained, we seismic engineers welcome the interesting big event because it gives us opportunity to investigate, such as, why was such wave forms created and how come it was obtained in such a form? These questions are probed and analyzed by; considering the mechanism of the epicenter, the characteristics of the soil or rock medium of the wave propagation route, the local ground characteristics of the site where the records were obtained. Based on these facts, a model is assumed and the reproduction of the observed records is attempted, but in many cases a clear cut explanation cannot be found.

If a physical explanation cannot be given as to why such seismic wave form appeared on an existing observed strong ground motion record, then it would be out of question to be able to offer accurate prediction of the seismic wave characteristics that may or may not happen in the future. That is a problem. Moreover, the social needs to seismic safety should accelerate. What it amounts to is that, it will grow into what may be expressed as an extremely severe situation for engineers, that are in the position to shoulder the responsibilities pertain to safety, if left just as it is.

If so, then, such thoughts would turn ones mind to make a move towards emergence from the passive design philosophy, which is to endure the fate of an earthquake by waiting, on to challenging a design system of earthquake control in which an active seismic response control of the structure can be executed with the building side taking the initiative. It has dawned upon me that to develop the above concept, is my research theme from now.

ACTIVE SEISMIC RESPONSE CONTROL

The intelligizing of metropolises and the emergence of the intelligent building groupings which comprise the vital core, is thought to be in not too distant future, when viewed from the information oriented progress of today. And when it is realized, it is very clearly foreseen that the present design philosophy of earthquake resistant structure, which contends that even if the building loses its function due to strong earthquakes, it is permissible as long as it is not demolished, will not be acceptable any longer. My concept regarding the active seismic response controlled structure began from quite a ways back(Ref.1.2), but based on the inducements, and with the recent technology innovation I made the debut of this advanced technology system dressed in the form of the Dynamic Intelligent Building.

Recent buildings in spotlights, such as the intelligent buildings are not good enough, by only providing that the structure should not collapse. It is moreover necessary to maintain interior functions without too much vibrations, and the structure of "high supplementary valued architectural space" which was considered difficult by present conventional concept, should now become possible with the application of the seismic response control system. Well, do you think it is only a self praise, when I consider the active seismic response control structure as far superior, which can provide the " high supplementary valued architectural space", of which principle subsistence is computerized control, and consequently suppress the shaking of the building? So, under the circumstances I decided to call these buildings the "Dynamic Intelligent Buildings".

As the methods to protect buildings from the destructive forces of earthquakes, there is great history of earthquake resistance construction since the end of 19th centry. It has progressed from the rigid structure to the flexible structure against earthquakes, but as the computations became seemingly precise and complicated, such as analyzing the earthquake responses of structures, I presume that there are many who have doubts as to the rate of in-comprehensibility pretaining to input ground motion of earthquakes. Needless to say, it is "idiotic to conduct a detailed and precise calculation on unknown input factors".

Moreover, there is a general condition which requires reduction of costs arising from the sence of competitions due to the mechanism of economic society. Is it possible to ensure safety under such circumstances? Even though the calculation is thoroughly detailed, as a matter of course, the results of such calculations have aspects of being decided based on assumptions of the input earthquake ground motion. So, there may exist a constant uneasy feeling, that foregoing is not necessarily reliable. In past days, when the behavior of structural mechanics was still grasped generally, the safety factor was distributed about evenly with the degree of causes unknown. In this respect, I belive it is now about time to extricate ourselves from the ordinary science or technology long known as earthquake resistance, to which we have become familiar with.

In the ordinary earthquake resistant structure, the hysteretic plasticity of the structural element contributes to the energy absorption, and the variability of natural frequency occasionally reduces the growth of the resonant vibration, if the building structure does not collapse as the results of the plastic deformations. It was already investigated as the nonlinear transient response process, related to the nonstationarity of the earthquake ground motion and the nonlinearity of the structural response(Ref.1).

Nonstationary Seismic Characteristics

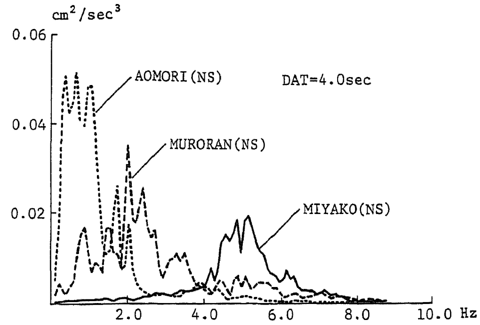
A running power spectrum is so efficient to investigate the nonstationary seismic characteristics. For example, three acceleration records of the Tokachi-oki earthquake (1968) are analyzed, and they are representing the typical three classes of soil condition in Japanese Building Code.(Fig.1)

The frequency components and the occurence times of the dominant power components can be observed from these results. And these show the individual dominant power frequencies which reflect the soil characteristics of site where the records were obtained.
The remarkable point of these records are the difference of the duration time and the dominant power frequencies, though they were recorded at the same earthquake event.

The difference of duration time is caused by the interaction between the velocity of earthquake wave propagation and the velocity of the destruction in the soil mechanism at the epicenter. In this reason, the record of Miyako which locates in the opposite direction with the destructive direction, has long duration time compared with that of Muroran which locates in the coincident direction.

And the difference of dominant power frequencies is mainly caused by the soil condition of each site. Especially, the result of Aomori, which is the record of soft soil site, shows the typical time varing of the dominant power frequencies from 1.0Hz to 0.4Hz. This will be explained as the nonlinearity of site soil, such as the plasticity or the liquifaction.

In the study of the active seismic response control, this nonstationarity of earthquake ground motion is positioned as one of the important design criteria for the control system. Regarding the dominant power components, the width and the duration time are also included as the necessary conditions in the active controller. Therefore, more detail research on the earthquake ground motion is essential in order to make clear the characteristics of the nonstationarity.



Maximum power spectra
in the running power spectra,
Tokachi-oki earthquake 1968

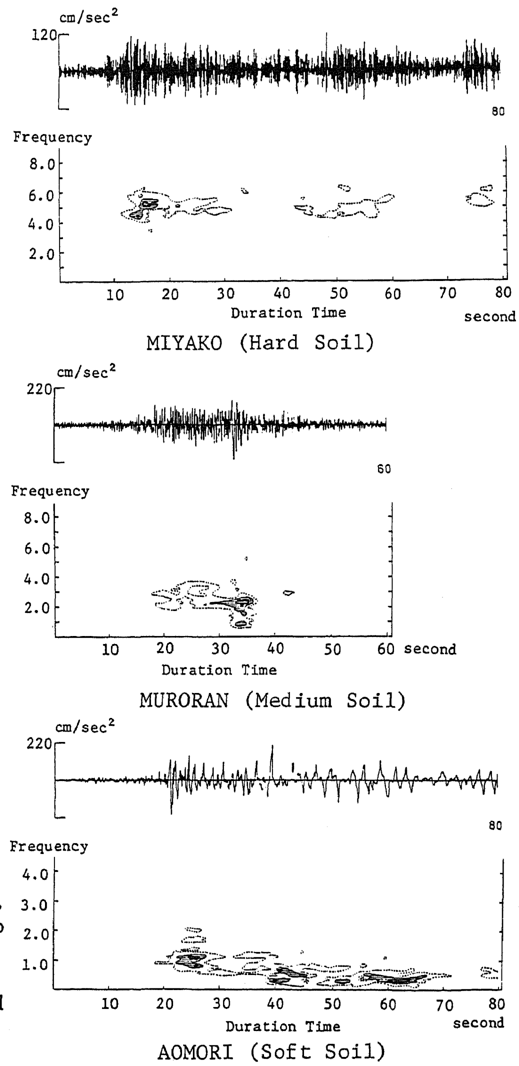


Fig.1 Running Power Spectra

Notion of Active Seismic Response Control The typical feature of seismic structural response process is considered as a sequence of transient response. The seismic response process is described using the asymptotic motion equation (1).

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

$\{x(t)\}$:Seismic Structural Response
$[E(t)] = f(M(t),C(t),K(t))$
: Transfer Function
$\{SF(t)\} = f(M(t),\ddot{y}(t))$
: Instantaneous Seismic Force
$\{RF(t-\Delta t)\} = f(M(t),C(t),K(t),\ddot{x}(t-\Delta t),\dot{x}(t-\Delta t),x(t-\Delta t))$
: Instantaneous Resonant Force

The time-varying transfer function implies the dynamically controllable property in the active seismic response control system, and it is considered as an artificial nonlinearity. This equation suggests that the current response is mathematically expressed as the result of multiplying the transfer function by the instantaneous force.

The transfer function acts as some kind of filter which has numbers of band-pass-width. The characteristic of this filtering effect is related to the current structural property. The instantaneous seismic force is caused by the ground acceleration and the structural mass property. This force component is expressed by the current time, and the basic property of this force is coincident with the nonstationarity of the earthquake ground motion. The instantaneous resonant force is related to the resulting movement caused by the previous sequence of ground motion. The resonant vibration is explained as gradual increase of this force component, which is expressed by the previous time. From this recognition, two basic control systems are obtained.

Dynamic Structural Adjustment Method In order to reduce the current response, the transfer function is dynamically controlled by adjusting the structural vibration property. The transfer function is composed of the stiffness, the damping, and the inertia property of the controlled structure. Therefore, three types of the controllable mechanical system are considered to adjust the transfer function according to the nonstationary response.

Active Adjustable Stiffness System
Active Adjustable Damping System
Active Adjustable Inertia System

The typical feature of this control concept is to make it possible that some mechanical controllers are joined in the active control system. They can provide an dynamically adjustable property with less driving energy.

These structural adjustment system can also apply to reduce the instantaneous resonant force. In the earthquake resistant structure, the hysteresis energy of the restoring property is mainly considered as the energy absorption machanism. But this results in the irreversible plastic deformation. On the other hand, the active structural adjustment system suggests the damage-free energy reducing system.

For the control algorithm of these active adjustable system, some dynamical control algorithms are requested instead of the ordinary stationary control algorithms. They will be derived from the probed investigation on the seismic nonstationary characteristics and the transient seismic response process.

Dynamic Control Force Method   This control concept was investigated in the mechanical engineering field, as an active control system, such as active damper or survo-controlled base-isolation system.(Ref.4) The advanced concept of active damper was investigated by D.C.Karnopp for the suspension system of the automobile. In this research, the optimized control force was induced to suppress the vibration, but it could not supply by the mechanical system as detected by the name, "skyhook damper", therefore, to supply the requested control force, active force generator system was adopted. (Ref.5)

Furthermore, Karnopp proposed a controllable mechanical system which was denoted as "semi-active" control system.(Ref.6) The meaning of semi-active was explained that less control energy was requested compared with the external force supplement system. Regarding this semi-active control system, several researches were continued by S.Sankar.(Ref.7) Recently D.Hrobat has applied this concept to the civil strucutres, and has made comparison of the passive, the active, and the semiactive control system.(Ref.8)

For the stationary response process, this dynamic control force system is described by means of system equation. Provided that the control force is regulated by a simple feedback control algorithm, the system matrix is rewritten as new system matrix including the gain matrix. From this equation, the dynamic control force system is considered as the structural element to improve the vibration performance.

$$\{\dot{x}\} = [A]\{x\} + [B]\{u\}$$

[A] : system matrix   {x} : state vector
[B] : coefficient matrix   {u} : control force vector

$$\{u\} = [G]\{x\}$$

[G] : gain matrix

$$\{\dot{x}\} = ([A]+[B][G])\{x\}$$

For the transient response process, this control force aims to cancel the instantaneous force according to the structural response. This type of the active controller is considered as an energy transducers, therefore, the energy supplement system is essential to realize this concept. For the civil structure the massiveness of the controlled structure occurred a critical problem in the energy source.(Ref.9)

These approaches make the uncertainty clear as possible as we can, in other words, more actual modelling is aiming in the loading and the structures. In this sense, the DIB system will be able to adopt the reasonable safty facter without a loss of the structural safety.(Fig.2)

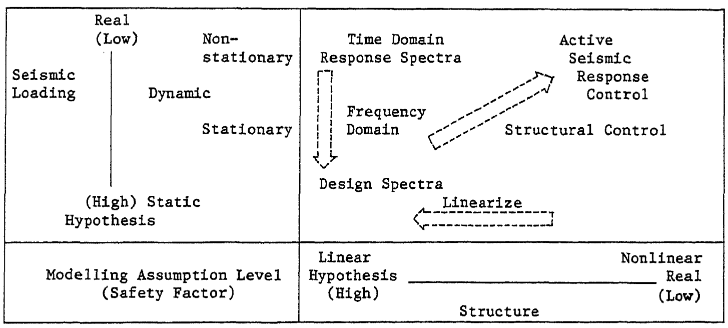


Fig.2 Active Seismic Response Controlled Structures

TREND OF ACTIVE SEISMIC RESPONSE CONTROL

Background of Control Technology The concept of "control" was started from the development of the mechanical engineering, such as James Watt's "Governer" for the steam engine in the 1780's. From the engineering stand point, the meaning of "control" is explained as "the means by which machines are directed and made to operate". As the progress of industrial innovation, the complex system needs more precise control beyond the human operation. And to reply these request, the research field was extended to the mechanical and electrical engineering, and this engineering field has established itself as a cross-disciplinary research, named the control engineering, or mechatronics.

The ordinary control theory was systematized in the 1950's, in which the property of the controlled system was expressed using Bode diagram or phase-plane locus. This control concept was mainly adopted for the adjustment to obtain some suitable controlled state, or the control system had some restricted controllable range around the basically designed system, in the meaning of "adjustment".

The modern control theory was also systematized in the 1960's. This control theory gave a closed-form conclusion for the linear optimal control. This optimality was also studied in the mathematical field, and precise description for the optimum conditions was derived.(Ref.10) R.Bellman published the progressive control theory as "Dynamic Programming", in which the basic concept of the performance function was extended as a combined form with the control state and the control cost.(Ref.11)

R.E.Kalman described the controlled system as the system equation, in which the control force was obtained to be optimizing the performance function of a quadratic form.(Ref.12) And this modern control theory became popular due to the progress and the spread of the digital computers after the 1960's.

This trend of control engineering became big stream in the progressive developement of the automobiles, aeronautics, and aerospace engineering, and the control technique extended from the stationary control process to the dynamic control process. This influenced the civil engineering field as well.

Structural Control J.T.P.Yao proposed the concept of "Structural Control" in 1972. In this paper, the ordinary building was metamorphosed into the self-vibration control system. And four types of control algorithm were explained for the civil structures. And the highest level of control systems were designated as the multivariable automatic adaptive control systems which existed in most biological system such as the human brain.(Ref.13) And typical control system was explained using a thruster engine and feedback control with decision logic.

J.N.Yang started a theoretical research based on the modern control theory. In this research, the active mass damper and the active tendon system were adopted as active controllers, and the optimal critical-mode control for tall buildings has been presented. As a result, it was concluded that the spillover effect of modal control is negligible since a few lowest modes dominate the seismic response of a tall building.(Ref.14) J.N.Yang has verified the feedback control algorithm using the acceleration, velocity, and displacement sensor. This control algorithm was designated as semi-active control in the sense of the needless of on-line computation to regulate the active control forces.(Ref.15) J.N.Yang had also extented his research to the nonstationary earthquake, in which Monte Calro simulations have been performed.(Ref.16) A sensitivity study has been carried out to determine the effect of uncertainties involved in estimating structural characteristics on the results of optimal control.(Ref.17)

T.T.Soong aimed to control the dominant modal component based on the ordinary pole assignment method using the modern control theory.(Ref.18) In this control algorithm, the performance function was composed as the square term of the control force to optimize the energy criterion. And the importance of the controller placement was suggested.(Ref.19) Furthermore, the optimal locations of a limited number of controllers were explained for the minimization of total energy requirement.(Ref.20)

And A.Rohman investigated the control performance by the pole assignment method.(Ref.21) This research made clear the possibility of vibration control for the civil structures. In these preliminary state, the interest of the researchers was concentrated on the application of the control theory to the structural control, and not much attention was paid to the peculiar characteristics of the seismic disturbance.

Active Seismic Response Control S.F.Masri has been continued the study on impact damper from 1960's, and as the advanced study of structural control, a distinguished experimental research was conducted in the laboratory.(Ref.22) As an active controller, a thruster pulse generator was adopted and the control pulse force was triggered when the structural response exceeded a certain threshold (Bounded State). This control algorithm was explained that the gradual rhysmic build-up of the structural response can be destroyed by applying a pulse of suitable magnitude in the proper direction.

Furthermore, the advantage of this bounded control algorithm was detected as the applicability for the nonlinear structural system by reason of the simplicity of the control algorithm and the independence of vibration characteristics of controlled structure. And the stability of this control method was studied by means of Liapunov's direct method.(Ref.23)

Some fundamental experiments were conducted by J.Roorda, in which the characteristics as the active controller were verified. The electro-hydraulic devices had difficulties which came from the inherent complexities of such system. From this results, much more study for this control system was recommended to apply this in the practical systems. On the other hand, the electro-magnetic devices had high responsibility, which was explained as the simplicity of mechanism for the force generation. It was concluded that the phase relationship between the control force and the structural motion was of paramount importance.(Ref.24)

L.Meirovich described the independent modal control method for the complex structure based on the linear control theory.(Ref.25) Martin-Sanchez obtained U.S. patent regarding predictive control system for the active seismic response control.(Ref.26,27)

T.Kobori proposed a concept of Dynamic Intelligent Building from the stand point of the active seismic response control.(Ref.28) The term of active seismic respons control was derived from his basic anti-seismic structural concept. In this concept, the research field covers entire seismic structural mechanics not restricted to the development of the control devices.

Recently J.N.Yang has proposed the instantaneous optimal control algorithm for the seismic response control to improve the classical optimal control algorithm in the condition that the entire earthquake ground acceleration history was not known a priori.(Ref.29) This control algorithm was certified in the experimental research by T.T.Soong.

T.T.Soong explained the results of experimental research on the structural control using an active tendon, in which instantaneous optimal control algorithm was attractively described.(Ref.30,31) As an active controller, a servo-controlled hydraulic actuator was adopted to generate the control force which was transmitted through a tendon system. And several control algorithms were compared their control efficiency, in which the instantaneous optimal closed-loop control has best feasibility for active structural control. Furthermore, the time delay compensation for the state vector was taken into account as a feedback gain.

From the viewpoint of the practical application, S. Baba proposed the digital active optimal control algorithm.(Ref.32) M.Kawahara also presented the application of dynamic programming method, in which a short anticipation time of the seismic loading was assumed for the optimization process. And the short anticipation time for seismic loading had almost equivalent control efficiency compared with the optimal control in which the entire seismic loading was known a prioi.(Ref.33, 34)

In the mechanical engineering field of Japan, various researches have been continued regarding the vibration control.(Ref.35,36) T.Shimogo and K.Yoshida conducted some experimental research using the Active Dynamic Vibration Absorber System, in which a digital control algorithm was adopted and a linear moter was used as the active force generator.(Ref.37)

In this way the first research stream of the active structural control in the civil engineering, started as the application of the control technology which was developed in the mechanical engineering. Therefore the controlled process was restricted to the stationary process, and the controlled structure was restricted as a linear model.

The second research stream started from the experimental research in which the nonstationary characteristics was taken up as the problem of the active seismic response control. And this trend joined with the previous theoretical stream, aiming at the practical application of the active structural control. The active seismic response controlled structure is positioned as one category of the ordinary seismic response control (Fig. 3).

Integrated Level	Anti-Earthquake	Anti-Wind	Anti-Vibration
Low Basic Elements	Earthquake Resistance Structure *Beam, Column *Shear Wall, Bracing	Wind Resistance Structure *Aerodynamic Measures Structural Shape Flap, Slot	Vibration Control *Structural Measures Isolation from Resonant Frequency
	STRUCTURAL CONTROL		
Mechanism Devices	Passive Seismic Response control *Base-Isolation *Viscous Damper *Mass Damper(Absorber)	Passive Vibration Control *Aerodynamic Measures Flap, Slot *Viscous Damper *Mass Damper	*Vibration & Shock Isolation Isolators Isolated Foundation
System High	Active Seismic Response Control *Active Force Controller Active Mass Driver Active Tendon *Active Stiffness Adjustable System	Active Vibration Control *Aerodynamic Measures Active Appendage Active Slot *Active Force Controller *Active Tendon	*Active Force Controller

Fig. 3 Classification of Structural Countermeasures for External Loadings

FUTURE SCOPE

The study of the active seismic response control covers widespread research fields, such as, the engineering seismology, the structural mechanics, and the system mechanics. In other words, the viewpoint of active seismic response control will give us the new aspect for the ordinary seismic structural mechanics. And this will enlarge the scope of activities as the cross-disciplinary research.

Engineering Seismology In the earthquake resistant design, the response spectrum has less consideration as to the process of the dynamic response itself, and only maximum response values are considered as design criteria. Meanwhile, the active seismic response control aims to reduce the vibration in the process of dynamic response. For this purpose, the nonstationary characteristics of earthquake ground motion is important as the design criteria for the active control system.

Recently several earthquake observatory systems have been arranged for the practical use as well as the research purpose.(Ref.39,40) Especially some array observatory systems are activating to measure the systematic seimic records. From these records, the characteristics of wave propagation are gradually made clear in time domain as well as in the spacial domain.

From the viewpoint of the active seismic response control, these results are important to recognize the nonstationary characteristics of erathquake ground motion. Moreover, these observatory systems make us associate the prototype of the earthquake sensor system to protect an urban area.

As to the coming earthquake, uncertainty will be somewhat inevitable, but the persistent pursuit of the physical property will give us the new possibility. In the engineering seismology, the seismic occurrence mechanism and the wave propagation mechanism seem to be very important for the study of the nonstationary characteristics.

Structural Mechanics The significant feature of the seismic transient response process is dependent on the seismic nonstationarity. To compose the dynamically controllable system it is necessary to grasp the transient response process, and to use the technology suitable to reduce the vibration. These researches will increase the importance of structural dynamics in the design process.

The development of the active contoller and the investigation of the dynamic response property are essential to compose the dynamically controllable system. Regarding the practical method, the active controllers are placed as the anti-seismic element instead of the ordinary anti-seismic element, such as the shear wall or the bracing. The primary characteristics of these active controllers should be also investigated as to the dynamic responsibility. Especially, the transient responsibility of the active controllers is essential for the practical use of these devices as the active seismic response controllers.

Furthermore, in order to improve the responsibility of these devices, several new researches will be continued samely as the enormous research accumulation of anti-seismic elements in the earthquake resistant structures. These continuous research and developement will produce more efficient devices in the dynamic responsibility as well as in the cost performance. And the accumulation of the practical application will accelerate the reliance of these devices and will reduce the cost of these devices.

Based on the dynamical characteristics of the active controller, the novel control algorithm will be developed to realize the self-balancing function. And the practical application of the control system needs the cross-disciplinary research as the "mechatronics". Fortunately, the recent innovation in the control technology is to promise the progressive possibility of the active seismic response control.

System Mechanics The concept of the dynamically controllable system is as yet rather new to the structural mechanics. Especially, the practical application of the concept needs a system design process to keep the self-balancing function of the global control system. From the structural dynamics, the basic design of the control system will be derived for the individual structure. For example, the controllability and the observability conditions are necessary to decide the arrangement of the control system. From these researches we will be able to obtain the basically necessary condition for the active control system, but from the aspect of the practical application, it will be demanded to guarantee some margin in order to improve the reliance of the system.

The reliability and the maintenance are also the new design conditions for this mechanical structures. Therefore, the design philosophy of the active seismic response control needs the design concept from the system mechanics. In this research, some kinds of fail-safe mechanism and robustness for the control system will be required when developing the practical system. The improvement of the reliability for the active controller, will mitigate the necessary redundancy. Consequently it will save the initial cost of the control system, and also reduce the running cost, such as, the maintenance fee of the periodical inspection and the repairment.

CONCLUSIONS

The main problem in the active seismic response control exists is to clarify the transient response process due to the nonstationary characteristics of earthquake ground motion. Moreover, the structural nonlinearity makes the response process more complicated. Confronting this realistic phenomenon, a new solution in the structural mechanics is to establish an earthquake proof structure with self-balancing function.

As an active controller, the mechanical controllable system is intuitively contrived from the extended field of the structural mechanics. This controller is driven based on the movement of the controlled structure. And the external counter force system is an application of the control concept in the mechanical engineering.

As for the research trend of the active seismic response control, some practical approaches have started from the experimental research, in which the bounded state control algorithm and the feedback control algorithm were adopted. Recently, more advanced control algorithms are proposed, namely, instantaneous optimal control, adaptive control, and predictive control.

The research and development of the active seismic response control covers the widespread research activities. Consequently, the cross-disciplinary research will be established as a new paradigm in the seismic structural mechanics. And the practical application of this control system also needs the new design philosophy for the dynamically controllable system.

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