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VIBRATION ISOLATION USING ACTIVE CONTROL SYSTEMS FOR CIVIL ENGINEERING STRUCTURES

by

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SUMMARY

The active control of structural systems arises from the need for reducing the response of a system under the influence of dynamic loads by continuous modification of the inherent characteristics of the system and the impressed excitation. The concept if implemented in practice opens up immense capabilities for the standardization of design of structural systems and their portability to differing loading environments. A review of basic concepts, the analytical work done, the Experimental studies and the implementation in practice has been presented in this paper together with the problems which need to be yet overcome.

1. INTRODUCTION

1.1 Civil Engineering Design : Objectives and Philosophy

Civil Engineering structures play a dominating role in almost all spheres of life and with the increase in the technological levels that need to be housed and protected the role of the strcuctures becomes even more critical. It therefore becomes imperative to accurately assess the loads, which the structural systems will be required to withstand, and appropriately design the systems for a specified life span.

The structural systems are in general, subjected to a number of loads, both static and dyamic in nature. The dynamic loads such as seismic ground motion, the action of mild and severe winds, and the wave action along with their variants are primarily environmental loads over which man has absolutely no influence. On the other hand dynamic loads due to moving vehicles, rotating and reciprocating machinery are those over which man can exercise a control to the required extent. The design of a structural system subjected to the influence of dynamic loads is therefore required to maintain structural integrity during the

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course of the loading periods due to short or long term environmental effects and beyond, at least upto the useful life of the structure. It is also implied that the design would provide for the safety and comfort of the human inhabitants during the occurrence of the dynamic loading phases.

The constraints are severe and the task requires a cost effective solution without sacrificing reliability. The responsibility entrusted to the designer is enormous and is subsequently reflected in the conservative designs that are finally evolved.

1.2 Objectives of Seismic Isolation

The dynamic loads on a structural system are invariably responsible for setting it into a state of motion. The duration of the vibrations induced, the amplitudes and the frequency content of motion are dependent on the dynamic characteristic of the structural system and the excitation process. In a seismic environment the ground acceleration is the predominating feature defining the excitation. The requirements to be considered for the design of structural systems subjected to the action of seismic loads are discussed in the following paragraphs.

Integrity of the structural form and its components such that the damage that actually takes place due to dynamic loading is non-structural in nature and does not in any way impede the basic functions for which the structure was originally provided. This criteria can be satisfied provided that the internal forces in each structural component are within specified limits. The process of repair of the damaged non-structural elements should be fairly straightforward, simple and at nominal cost which should be a negligible fraction of the cost of the structure.

Safety of the inhabitants should additionally be ensured, even when the damage is non-structutal, as it has often been found, that lack of careful detail in the design of non-structural components does lead to loss of life and property.

Comfort of the inhabitants is also an important feature and this has assumed greater importance because of the trend towards high rise construction. The skyscrapers of today are fairly flexible and the absolute dynamic displacements are of the order of meters. This large displacement does not necessarily pose a threat to the structural integrity, or the safety provided by the structural system but acts as a possible psychological deterrent towards the inhabitation of such structures. It is quite well established that the prolonged exposure to large vibration amplitudes, not necessarily periodic, may lead to other physical and psychological problems thus rendering the level of dynamic responses generated may also be detrimental to plant and equipment housed at various levels within the structural complex.

Prohibitive costs in the consideration of the above mentioned features, even for a limited design period, lead to designing intentionally for certain levels of anticpated damage. It need not be emphasized that the design is such that within the acceptable service life of the system the probabiliy of a catastrophic failure is reasonably small. This factor is of increasing importance with the concept of reliability based design finding wider acceptability, wherein the designer is required to design for dynamic forces in such a manner that there are chances, however small, of internal forces exceeding the prescribed threshold values for structural integrity.

The objectives of seismic isolation for a structural system are the reduction of internel stresses in component units and the confinement of the dynamic responses within acceptable limits as may be prescribed from the various considerations.

1.3 The Choice of Strategy for Seismic Isolation

The choice of a proper strategy for the Seismic Isolation of structures depends upon a number of factors which would also include the designer bias and expertise in addition to the financial constraints on the implementation, maintenance and repair of the adopted system. In princicple then, the strategies that can be adopted are as follows :—

(a) Identifying and nullifying or destroying the sources of seismic energy and other dynamic excitation. This may seem to be the most obvious and attractive alternative but can never be practically realized.

(b) Use of energy absorbing devices either as structural components or as external devices.

(c) Modifying the dynamic characteristics of the structural system so that there is nominal energy transfer to the system.

(d) Providing additional control to the system so that only non-stationary and non-resonant states of vibration are produced.

Of tne above strategies the most popularly adopted are those which deal with the absorption or dissipation of energy. If the significant modes of the structure can be relocated so as to be codsiderably removed from the predominant frequency range of the seismic excitation then only the non-response will occur because of the nominal transfer of energy to tne structural system. The above could also be achieved by introducing an element of non-linearity in an otherwise linear structural systsm or by introducing the non-linearity at the boundaries/supports of the system. Alternatively non-resonant states can be achieved by means of continuous modification of the structural characteristics or the excitation in real time. The modification of the excitation process implies an additional component of excitation superimposed over the seismic component and acting in a manner to so-as-to counter the effect of the seismic forces on the system response. The practical aspects of the above strategies are outlined in the next section.

1.4 Past Implementation

The first few attempts at minimizing the seismic hazard date back to the late twenties and early thirties [1] when the "soft or flexible first storey" concept was originally introduced. However, this concept attracted greater attention in the late sixties [2], and then it was established that though the concept actually leads to a reduction in the dynamic shears, it also causes large dynamic displacements while not entirely eliminating the risk of total collapse in the case of a large event. Later structures were designed to rest on slip pads [3,4] to achieve the isolation. Ellipsoidal bearings [5], laminated rubber bearing pads [6], rubber bearings in combinatioh with energy absorbers relying on the plastic deformations of metals [7, 8], design of systems using nonlinear optimization techniques to the plastic design of the entire frame without the provision of external energy dissipating devices [9] followed in due course of time. All the above discussed attempts to mitigate the effect of seismic excitation, relied on passive control devices to limit the response and keep internal forces within specified bounds.

1.5 Current Trends in Seismic Isolation

The present trend is towards the use of active control to suppress the response parameters when the system is subjected to seismic excitation. There are a number of possible approaches with a sound theoretical basis, some of them have been experimentally verified and actually implemented in practice. The application areas range from very high structures subjected to wind, to deep water offshore structures. Some of the notable installations of active control systems are the Citicorp Building in New York city [10], the John Hancock Building in Boston [11], and the Canadian National Towers in Toronto [12], The underlying principles and concepts are outlined in the next section.

2. ACTIVE CONTROL SYSTEMS

2.1 Components and Devices

Active control systems depend on the superimposition of additional energy to the structural system so as to counteract the effect of dynamic disturbances and minimize the response parameters. An element of continuous data acquisition and processing in real time is necessary to achieve the desired results. A typical configuration of an active control system consists of the following component units :-

(a) Sensors to monitor the external excitation or system response parameters or both.

(b) Microprocessors to effect the data acquisition and processing in real time.

(c) Software for the computation of the control forces that need to be input to the system in order to minimize the response parameters and for the control of hydraulic actuators.

(d) Hydraulic actuators, interfaced to the microprocessor, to generate the requisite control forces for the minimization of the responses due to the external excitation.

The devices suggested for active control systems are as follows:-

(a) Active tendon control systems consisting of tendons connected between electro-hydraulic servo-mechanisms and suitably located within the structural system.

(b) Active tuned mass dampers connected to devices such that the control and the inertia forces reduce the dynamic response.

(c) Aerodynamic appendages which are dynamically regulated in real time to reduce the responses due to winds in the case of high rise structures.

(d) Gas pulse generators activated at discrete time intervals and providing pulses of magnitude as determined by the control algorithm.

There are other systems also under investigation such as the active member and joint system and the gyroscopic system. The principle of each does not differ from what has been earlier outlined, i.e. the reduction in response can be achieved by the dynamic modification of system behaviour or the excitation to which the system is subjected.

2.2 Definition of the Problem

The active control basically depends on the supply of external energy for minimizing the structural response under the influence of dynamic loads by dynamically modifying the system characteristics. This can best be appreciated by examining the equation of motion for a single degree of freedom system

$$m\,\ddot{Y}(t) + c\,\dot{Y}(t) + k\,Y(t) = -m\,\ddot{X}(t) + U(t) \qquad (1)$$

in which Y (t) is the relative displacement of the mass 'm' with respect to the ground displacement, X (t); 'c' and 'k' are the damping and stiffness respectively; and U (t) is the active force from the controller.

Further if U (t) is defined as a linear combination of the relative motion of the structural system then

$$U(t) = a_1\,Y(t) + a_2\,\dot{Y}(t) + a_3\,\ddot{Y}(t) \qquad (2)$$

The substitution of equation (2) in equation (1) leads to

$$(m - a_3)\,\ddot{Y}(t) + (c - a_2)\,\dot{Y}(t) + (k - a_1)\,Y(t) = -m\,\ddot{X}(t) \qquad (3)$$

which indicates the dynamic variation in the system characteristics i.e. the mass, damping and the stiffness.

2.3 Solution for Optimal Control

The classical formulation of the optimal control problem for a system idealized in one dimension and subjected to a single component unidirectional base acceleration, $\ddot{X}$

$$M\ddot{Y}(t) + C\dot{Y}(t) + KY(t) = HU(t) + G\ddot{X}(t) \tag{4}$$

where M, C, K have the usual meaning, Y is the relative displacement vector of the structural system with respect to the base, and H is the location vector of controllers. The state vector can then be expressed as

$$\dot{Z}(t) = AZ(t) + BU(t) + W\ddot{X}(t) \tag{5}$$

The performance index can then be defined as

$$J = \int_0^{t_f} [Z^T(t)\, Q\, Z(t) + U^T(t)\, R\, U(t)]\, dt \tag{6}$$

Where t_f is a duration defined to be longer than that of the earthquake. The performance index J can be minimized subjected to the constraint of the equation of motion, to arrive at the so-called classical optimal closed-loop control [Fig. 1], classical open-loop control [Fig. 2]. and classical optimal closed-open-loop control [Fig. 3] depending upon the type of control algorithm adopted.

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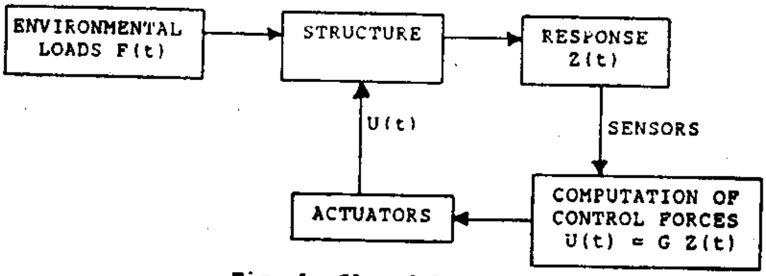

Fig. 1. Closed-Loop Control

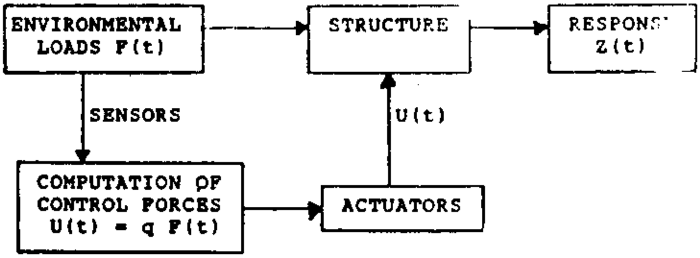

Fig. 2. Open-Loop Control

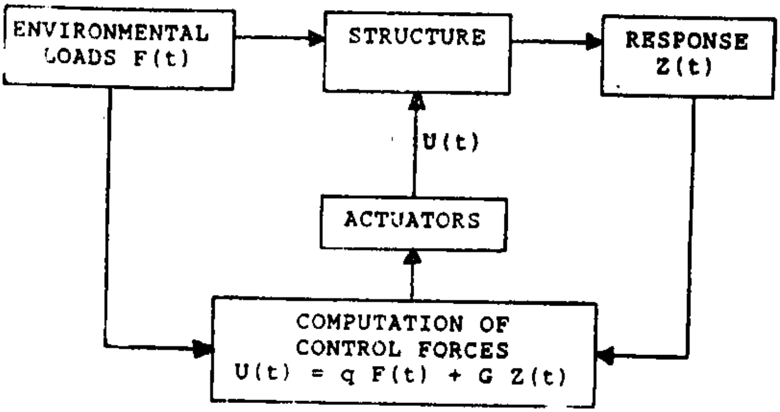

Fig. 3. Closed-Open Loop Control

However these three classical optimal control algorithms require a prior knowledge of the earthquake base excitation history X (t). Unfortunately, many environment loads, including the earthquake ground acceleration, wind gusts, wave loads, etc., are not known as a priori. Therefore, these three classical optimal control algorithms are not applicable under random environmental loads. However, if the earthquake base acceleration, X (t) is disregarded, then the closed-loop control is referred to as the Riccati closed-loop control. The Riccati closed-loop control, however, does not satisfy the optimal condition, and it is inferior to classical optimal contral, because the earthquake ground excitation is disregarded. While the earthquake ground motion is not known a priori, the base excitation of the building can be measured on-line in real time by installing sensors on the basement floor. This important information can be utilized to develop instantaneous optimal control algorithms. The performance index can then be established as a time dependent parmeter,

$$J\,(t) = Z^{T}(t)\,Q\,Z\,(t) + U^{T}(t)\,R\,U\,(t) \tag{7}$$

and the excitation history upto all t between 0 and t_f can be used to minimize the performance index at that instant. This new approach of ensuring instantaneous optimal control led to the development of algorithms to provide :—

(a) Instantaneous optimal open-loop control

(b) Instantaneous optimal closed-loop control

(c) Instantaneous optimal closed-open-loop control

2.4 Evaluation of Active Control Systems

2.4.1 Analytical Studies

Numerical simulation studies on the application of instantaneous control algroithms to structural systems have confirmed their efficiency in controlling and reducing structural response and preventing potential structural damage due to the action of environmental loads [13, 14, 15,].

2.4.2 Experimental Studies

Early experimental tests were performed on series of small scale structural models as reported in 1980 [16]. The structural models included a simple cantilever beam, a king-post truss and a free standing column while control devices varied from tendon control with manual operation to tendon control with servo-valve-controlled actuators. The possible use of gas pulse generators as active control devices, which produce servo-controlled pulses (forces) resulting from the release of air jets, has also been investigated experimentally on a six storey building scaled model [17] More recently, experiments on active mass damper systems have also been carried out in the laboratory by placing an active mass damper on the top floor of a four storey model frame whose motion was linearly related to the instantaneous state of the system [18].

A comprehensive expeimental study of tendon control was also recently carried out using a standardized structural model (a three storey steel frame, which was made to behave dynamically similar to a prototype structure by means of artificial mass simulation) under base excitation supplied by a shaking table. Control algorithms tested in this series of experiments include the classical control algorithms and the instantaneous optimal contral algortihms described earlier [19, 20, 21, 22]

While it is not psssible to reproduce the vast amount of analytical and experimental data available, it may however suffice to state that the results are encouraging and they show great promise of active control concepts.

2.5 Active Control Systems : The Problems

Having examined the efficiency and applicability of active control systems for the reduction of vibration levels in structural systems the problems associated with active control systems need to be examined closely. The problems basically relate to the power supply to the system and the reliability of the system as an entity or of component units taken individually.

(a) Power requirements for active control systems can be quite high when large structural systems are subject to active control. In the case of general vibration control (low amplitudes and large duration of time) the 'power would be required continuously for the generation of smaller forces for fairly large durations of time. Whereas extreme events, seismic or otherwise, will require the generation of larger control forces, thought for a shorter duration of time. This aspect of power reqirement need fo be considered from a financial point of view.

(b) Availability of uninterrupted power has to be considered. For general vibration control, to reduce the effects of moderate to severe winds, or continued wave action, uninterrupted power supply may not be a problem. However, power supply in the case of a seismic event may not always be guaranteed, since there would be shutdown of power generating equipment for safety and other reasons. In the extreme case there would be failures affecting transmission lines and distribution systems and once again there is an element of uncertainty regarding the supply of power to the control system. Therefore, adequate provisions for alternative sources of power need to be made for the case of vibration control against seismic events. This again may involve a very heavy financial investment.

(c) Financial implications for the standby mode need also be considered since the active control system would in most practical application be in a standby mode for prolonged periods. The duration of intervals between the active states of the control system is largely governed by the local environmental features and the threshold structural response parameters, beyond which the vibration suppression mechanism is required to be activated. The periods in question could vary from a few days to a large number of years and the financial outlay on the control system would then represent dormant capital. This would be the case till such time that municipal regulations or other statutory bodies make provision of control systems mandatory for certain categories of structures, residential or otherwise.

(d) Serviceability and reliability of the control system will again be adding to the already high installation costs of active control systems with its diverse constituent elements. Periodic inspection of the hardware facilities and functioning ot both the hardware and the software will be critical. Preventive and corrective maintenance as may be necessitated from time to time will be required to ensure the reliability in the functioning of the control system, The integrity of the software for optimizing the structural response and driving the servo-actuators of the control system is also critical to the effective functioning of the hardware components and the system as an entity.

CONCLUSIONS

Based on the information presented above with regard to active control systems and the analytical and experimental studies, the following conclusions emerge :—

(a) The theoretical and experimental investigations indicate immense potential for the application of active control systems for the suppression of vibration due to both short and long term environmental effects.

(b) The successful implementation of active control systems on prototype structures would create an element of standardization in the construction of civil engineering structures, since the critical element would not be the design but the control system and its efficiency. This feature would also be reflected in the portability of the designs in as much as the same design being used for different geographical locations have diverse climate and seismic zones.

(c) Active control systems are ideally suited for low amplitude vibration control due to environmental loads, other than of seismic origin, wherein uninterrupted power supply can be assured. For vibration control due to seismic activity, the power problems and the detrimental effects of the standby mode of operation, may create some hinderance in the practical implementation of the active control systems on large structures. The foregoing compounded with the fact that the power supply through public utility lines may not be available at the time of a seismic event may create problems regarding the acceptability of the active control systems. Alternative sources of the large amount of required power may not necessarily help to provide the acceptablity by the engineering community unless supported by experimental tests on full sacle structural systems and data obtained from implementation of active control on existing structues.

(d) Application areas in which active control can be easily introduced using low-power devices will emerge and this concept would be most favourable for the protection or sensitive equipment and instruments against damaging vibrational amplitudes.

(e) In practice the most desirable way of introducing a control on the response of structural system, due to the effect of environmental loads, seismic and otherwise, would be a combination of both passive and active control systems such as to effect an economically feasible and reliable solution.

1. Green, N.B (1935). "Flexible First-Story Construction for Earthquake Resistance." Trans., ASCE, 100, 645-674.
2. Fintel, M., and Khan, F.R. (1969). "Shock Absorbing Steady Sway of Skyscrapers in Wind." McGraw-Hill, New York, N.Y., 18-29.
3. Crandall, H.S., Lee, S.S., and Williams, J.H., Jr. (1974). "Accumulated Slip of a Friction Controlled Mass Excited by Earthquake Motions." J. Appl. Mech., 41 (4), 1094-1098.
4. Crandall, S.H., and Lee, S S. (1976) "Biaxial Slip of a Mass on a Foundation subjected to Earthquake Motions." Ingenieur-Archiv, 45, 361-370.
5. Matsushita, K., and Izumi, M. (1969). "Studies on Mechanisms to decrease Earthquake Force applied to Buildings." Proc. 4 World Conf. on Earthquake Engrg., B-3, 117-129.
6. Derham, C.J., et al. (1977). "Natural Rubber Foundation Bearings for Earthquake Protection-Experimental Results." Natural Rubber Technology, 8 (3), 41-61.
7. Kelly, J.M., Skinner, R.I., and Heine, A.J. (1973). "Mechanisms of Energy Absorbtion in Special Devices for Use in Earthquake Resistant Structures." Bulletin, New Zealand Nat. Soc. for Earthquake Engrg., 5 (3).
8. Robinson, W.H , and Greenbank, L.R. (1976). "An Extrusion Energy Absorber suitable for the Protection of Structures during an Earthquake." Earthquake Engrg. and Struct. Dynamics, 4, 251-259.
9. Polak, E., Pister, K.S., and Ray, D. (1976). "Optimal Design of Framed Structures subjected to Earthquake." Engrg. Optimization, 2 (1), 65-71.
10. Peterson, N.R. (1979). "Design of Large Scale Tuned Mass Dampers." Structural Control, H.H.E. Leipholz, ed., North Holland SM Publishing Co., 581-596.
11. Zuk, W. (1979). "The Past and Future of Active Structural Control Systems." Structural Control, H.H.E. Leipholz, ed., North Holland SM Publishing Co., 779-794.
12. Tucker, J.B. (1985). "Super-Sky-Scrapers: Aiming for 200 Stories." High Technology, 5 (1), 50–63.
13. Yang, J.N., Akbarpour, A. and Ghaemmaghami, P. (1986). "Instaneaous Optimal Control of Tall Building under Earthquake Excitation." Third Specialty Conf. on Dynamic Response of Structures, ASCE, Los Angeles.

14. Yang, J. N., Akbarpour, A. and Ghaemmaghami, P. (1987). "Instaneaous Optimal Control Laws for Tall Buildings under Seismic Excitations." National Center for Earthquake Engrg. Research Technical Report, NCEER-TR-87-00007.

15. Yang, J. N., Akbarpour, A. and Ghaemmaghami. P. (1987). New Optimal Control Algorithms for Structural Control." J. Engrg. Mech , ASCE, 113 (9), 1369-1386.

16. Roorda J. (1980). "Experiments in Feedback Control of structures." Structural Control, H. H. E. Leipholz, ed., North Holland SM Publishing Co., 629-662.

17. Miller R.K., Masri, S. F., Dehghanyar, T.J. and Caughey, T. K. "Active Vibration Control of Large Civil Structures." J. Engrg. Mech., ASCE.

18. Kobori, T., Kanayama, H. and Kamagata, S. (1987). "Dynamic Intelligent Building as Active Seismic Response Controlled Structure." Proc. Arch. Inst. Japan.

19. Chung, L. L., Reinhorn, A. M. and Soong, T. T. (1986). "An Experimental Study of Active Structural Control." Proc. ASCE Speciality Conf. of Structural Dynamics, L.A., CA, 795–802.

20. Lin, R.C., Soong, T. T. and Reinhorn, A. M. (1987). "Experimental Evaluation of Instantaneous Optimal Algorithm for Structural Control." National Center for Earthquake Engineering Research, Technical Report NCEER-TR–87-0002.

21. Lin, R. C., Soong, T. T. and Reinhorn, A. M. (1987). "Active Stochastic Control of Seismic Structures." Proc. of US-Japan Joint Seminar on Stochastic Structural Mechanics.

22. Soong, T. T., Reinhorn, A.M. and Yang, J.N. (1987). "A Standardized Model for Structural Control Experiments and some Experimental Results." Structural Control, H. H. E. Leipholz, ed., North Holland SM Publishing Co., 669–693.