The Research Situation and Prospect of the Structural Vibration Control

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ABSTRACT: Vibration control technology has a broad application prospect in the civil engineering anti-seismic. It can be used to reduce the vibration response of structures under the dynamic loads, such as earthquake and wind, and also be used to improve the structure vibration resistance and extend the fatigue life of structure. This paper expounds the basic concept and principle of passive control, active control, semi-active control and hybrid control in structural vibration control, the comparison and analysis between them and the advantages and disadvantages of the various control methods for structure, and mainly analyzes the various form of passive control. At last the author looks forward to the development prospects and development direction of the structure vibration control theory, and indicates the direction for future research.

Keywords: vibration control; building structure; vibration reduction mechanism; development prospect

1 INTRODUCTION

Earthquake is one of the sudden natural disasters with great harm. The direct cause of the earthquake disaster is that the great destruction and collapse of buildings in the earthquake result in secondary disasters and personnel casualties. Therefore, for the research on architectural safety, economy and reliability are the main topics in the field of earthquake engineering, to effectively reduce the earthquake disaster, which has important practical significance [1]. A large number of researches of earthquake damage at home and abroad show that the effective ways to reduce earthquake disaster are scientific and reasonable seismic design methods and measures. The traditional method of resisting the earthquake effect is to increase the strength, stiffness and deformation ability of structure, but the methods above are neither economic nor effective [2]. In engineering practice, in order to reduce the seismic effect, the vibration control method is usually adopted [3]. Requiring the structure to response under seismic action does not exceed the standard limit, thus seismic energy dissipation is needed. In the past, a seismic system usually consumed most of the energy via the damage of the structures, which would produce certain damage of components and even collapse, so this method is not very reasonable and safe. Chinese-American professor Zhiping Yao put forward the concept of structure control for the first time in 1972. After decades of development, many scholars at home and abroad have obtained a lot of research results on that theory [4]. Based on whether the control measures will be adopted by the external energy, structural vibration control technology can be divided into following four categories: passive control, active control, semi-active control and hybrid control, which can effectively improve the safety of the structure, and has important practical significance.
2 THE PASSIVE CONTROL

Passive control changes the mass, damping, and stiffness of structure through device, institution or sub-structure, uses vibration isolation, vibration absorbing, and other devices to carry out energy consumption, or reduce the number of structure to absorb energy, so as to achieve the purpose of reducing vibration. Because passive control has the advantages of simple structure, low cost, reliable performance, convenient construction, and easy-maintenance without external energy support, it gets wide attention [5]. Many passive control technologies are mature, and have been applied in the practical engineering.

2.1 Base isolation

Base isolation is the isolation layer which is composed of isolation bearing and damper and set up at the bottom of the building to reach the goal of reducing the vibration of structure, and the analysis model of isolation is shown in Figure 1. Commonly used foundational vibration isolator can be divided into rubber bearing, sliding bearing and elastic-plastic bearing, which have the basic characteristics, such as bearing, vibration isolation, reset, and energy consumption. Among them, the rubber bearing structure is the simplest, which is convenient for installation and maintenance, and is widely applied in engineering. Isolation device must have three characteristics: (1) enough initial stiffness and strength; (2) large deformation; (3) provide larger damping and have larger energy dissipation capability. It is compressive but not tensile, so it is bad for vertical vibration reduction effect. Meanwhile it is a danger for horizontal resonance vibration for a long period of time, so the base isolation design for a short period of low-rise buildings in the vibration control effect should be better.

2.2 Energy dissipation and vibration reduction

Energy dissipation damper system is used to put the structure of some non-load bearing units into energy dissipation device, or install damper in some parts of the structure, to consume the earthquake energy of the input structure, so as to protect the main structure from damage in strong earthquake. Compared with traditional structure seismic systems, it has the some advantages: 1) the traditional seismic system uses the main bearing component (beams, columns, and nodes) as the energy dissipation structures, while the bearing component may damage in the earthquake, and even make houses collapse. Damping and energy dissipation system uses non-load bearing element as the energy dissipation structures, their damage can protect the main structure, so it is safe and reliable; 2) it is easy to repair or replace after the earthquake, and structures can be reused quickly; 3) the attenuation of structures of seismic response is effective. Due to the advantages above, energy dissipation damping system is widely used in high-rise building, earthquake or wind resistance of tall buildings, single industrial shelving, longitudinal seismic, etc.

2.2.1 Viscous fluid damper

Viscous fluid damper uses liquid viscous to provide damper for vibration energy dissipation. Nonlinear fluid viscous damper does not provide stiffness, and its damping force is only related to the speed. Damper output force:

\[ f_d(t) = C(n)^\alpha \]  

(1)

In the formula: C is a generalized damping coefficient; n is the relative horizontal velocity at the ends of the damper; \( \alpha \) is speed index. When \( \alpha = 1 \), damper performance is linear; When \( \alpha < 1 \), damper performance is nonlinear. Obviously, when \( \alpha \) is smaller, the sensitivity of the damper on speed is higher. For a very low relative speed, it still can output a lot of damping force to effectively reduce the structural dynamic response. In addition, the hysteresis curve of the linear damper is akin to ellipse; nonlinear damper with \( \alpha \) is smaller, hysteresis curve is closer to the rectangle, which means that the nonlinear damper has more excellent energy dissipation capacity [6], and the damper hysteresis curve comparison is shown in Figure 2.

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Figure 1. The analysis model of isolation.

Figure 2. Damper hysteresis curve comparison.
In engineering practice, the energy dissipation performance of viscous fluid damper is related to the support form and layout. Common forms of support are three kinds: single diagonal, double inclined rod, and “people” glyph, and the damper layout diagram is shown in Figure 3. When using diagonal strut, the damper’s energy dissipation efficiency increases as the angle reduces, so the angle should not be too big, and the general angle is 25° to 45°; because the damper and brace are linked together, it will inherit the shear and bending moments caused by own and brace self-respect, which has an adverse effect on the service life of the damper, so the brace length should not be too big.

2.2.2 Viscoelastic dampers
Viscoelastic damper is generally made up by constraint steel plate and viscoelastic material. Its working principle is that viscoelastic material does reciprocating motion with constraint steel, producing shear deformation for energy dissipation, and the viscoelastic material is generally adopted by the polymer or vitreous material. The main advantages of viscoelastic damper is that it can work under the condition of major earthquakes and small earthquakes, so it not only can be used in aseismic, but also can play a role in tall building wind resistance. However, the properties of viscoelastic materials were evidently affected by the temperature, so the temperature needs to reasonably consider in the process of design and use.

To describe the mechanical properties of the viscoelastic damper, put forward the following four main calculation models:

(1) Maxwell model
The constitutive relationship of the model that viscoelastic dampers can be equivalent to a spring and a damping element in series is:

\[ \tau + p_1 \ddot{\gamma} = q_1 \dot{\gamma} \]  

(2)

In the formula, \( \tau \) and \( \gamma \) represent shear stress and shear strain of the viscoelastic material respectively; \( p_1 \) and \( q_1 \) represent the coefficients determined by the properties of viscoelastic materials respectively. Maxwell model can well reflect the relaxation phenomenon of the viscoelastic damper and the energy storage modulus on frequency change trend, but it can’t reflect the slight creep property of viscoelastic damper and loss factor along with the change of frequency characteristics, and it even can’t reflect the temperature influence on the parameters of viscoelastic damper.

(2) Kelvin model
Kelvin model is composed of elastic element and damping elements paralleling to each other, and its constitutive relationship is:

\[ \tau + q_0 \gamma = q_1 \dot{\gamma} \]  

(3)

In the formula, \( q_0 \) and \( q_1 \) represent the coefficients determined by the properties of viscoelastic materials respectively. Kelvin model can well reflect the creep and relaxation of the viscoelastic damper phenomenon, but it cannot reflect the viscoelastic dampers of the energy storage modulus and loss factor along with the change of temperature and frequency characteristics.

(3) Standard linear solid model
The model is the simulation of viscoelastic dampers by making elastic element and Kelvin element in a series, its constitutive relationship is:

\[ \tau + p_1 \ddot{\gamma} = q_0 \dot{\gamma} + q_1 \dot{\gamma} \]  

(4)

In the formula, \( q_0, q_1 \) and \( p_1 \) represent the coefficients determined by the properties of viscoelastic materials respectively. Standard linear solid model can not only reflect the performance of the viscoelastic damper on frequency change trend, but also can reflect the viscoelastic damper relaxation and creep characteristics of mild. However, it can’t reflect the temperature effect on the properties of viscoelastic dampers.

(4) Finite element model
The model is put forward by Tsai, who thinks the stress-strain relationship of viscoelastic damper for:

\[ \tau(t) = G_m \gamma(t) + G_n D^{\alpha}[\gamma(t)] \]  

(5)

In the formula, \( D^{\alpha}[\gamma(t)] \) is a specific function, \( G_m \) and \( G_n \) are the basic model parameters. The model takes the influences of temperature, frequency and strain amplitude on the properties of viscoelastic damper into account, which is relatively accurate, but is very complex and difficult for application.

2.2.3 Tuned vibration energy dissipation device
Tuned vibration energy dissipation device is mainly divided into tuned mass damper (TMD) and tuned liquid damper (TLD). They use additional subsystem absorption in the body of the main structure of the vibration energy and make the main body structure vibration reduce.

Tuned mass damper (TMD) is a vibration system composed of mass, spring and damper, and the calculation model of TMD-structure system and the application of TMD in engineering drawing examples are shown in Figure 4 and 5. TMD is one of the earliest
structure passive control device currently used in the vibration control of high-rise buildings and towering structure\(^7\). The vibration control mechanism of TMD for structure is: when the structure produces vibration, and drives the TMD system vibrate under the action of outer incentive, the relative motion and inertia force of the adverse effect of TMD system to the structure tune the inertia force, and make its effect on structural vibration control, so as to achieve the purpose of reducing vibration response. It has the advantages of simple structure, convenient installation and maintenance, and low cost. The damping effect is the best when the vibration frequency of TMD system is consistent with that of the structure\(^8,9\).

![Figure 4. The calculation model of TMD-structure system.](image)

Tuned liquid damper (TLD) is equipped with a liquid and a rigid container fixed on the structure, and the model of the TLD system is shown in Figure 6. The structure equipped with the tuned liquid damper (TLD). When it is subjected to vibration, the liquid in TLD sloshing, uses the inertia force and damping energy so as to achieve the purpose of reducing vibration, by adjusting the size and depth of the liquid to control the liquid sloshing frequency. Tuned liquid damper (TLD) has the advantages of low cost, simple installation, convenient maintenance, no pollution, etc. TLD also can be used as a water storage device.

3 ACTIVE CONTROL

Active control is the application of modern control technology, to realize online real-time tracking and prediction for the input ground motion and structural response\(^10\). The actuator is applied on the structure control system to change the characteristics of the structure, and make the structure and performance of the system satisfy certain optimization criteria, placing certain external force on the structure to reduce the dynamic responses of structures under vibration\(^11,12\). Because the real-time control force can change with the input of seismic characteristics, its control effect basically does not depend on the seismic wave, which is better than passive control. Active control is a technology which needs additional energy, and its fundamental difference with passive control is whether it needs extra energy consumption and has the complete feedback control loop. Compared with the passive control, active control technology is complex and expensive, which has high maintenance requirements, but for high-rise buildings or high seismic fortification buildings, active control has better control effect\(^13\).

Active control device is composed of the instrument measurement system (sensor), control system (controller), power drive system (actuator), etc.

3.1 The damping mechanism of active control

The equation of motion for structure under control of the external force and the interaction force:

\[
M \ddot{x}(t) + C \dot{x}(t) + K x(t) = -M \ddot{X}_g(t) + EU(t)
\]  

In the formula, \(M\), \(C\), and \(K\) are structural mass, stiffness and damping matrix; \(x\), \(\dot{x}\), and \(\ddot{x}\), are structural displacement, velocity and acceleration vectors; \(I\) is for single row vector; \(\ddot{X}_g\) is the acceleration of ground motion; \(E\) is active control force position matrix; \(U\) is active control force vector.

The active control force vector \(U\) is determined by the structure response (including displacement acceleration and seismic ground motion),

\[
U(t) = K_b x(t) + C_b \dot{x}(t) + F_b \ddot{X}_g(t)
\]

In the formula, \(K_b\) and \(C_b\) are the gain matrix of displacement and velocity responses of structures; \(F_b\) is gain vector of earthquake acceleration. Substitute formula (7) into (6), and it can get the motion equation of the active structural control system under earthquake:

![Figure 5. The application of TMD in engineering drawing examples.](image)

![Figure 6. TLD system model.](image)
\[ M \ddot{x}(t) + (C - EC_s)\dot{x}(t) + (K - EK_s)x(t) = -(\text{M} - EF)\dot{x}_s(t) \] (8)

Contrasting the formula (8) with (6), for the structure with active control system, the damping matrix and stiffness matrix of the structure and the external excitation vector have changed due to the active control force. The function of open loop control is to reduce or eliminate the extraneous force, while the function of the closed-loop control is to change the stiffness and damping parameters of the structure. So, this is the active control of structure vibration reduction mechanism that adopts the reasonable control algorithm, selects the gain matrix \( K_b \) and \( C_b \), gains the reasonable vector \( F_b \), and determines the optimal active control force, which can be achieved from attenuate or suppress the seismic response of structure.

4 SEMI ACTIVE CONTROL AND HYBRID CONTROL

Semi active control takes the passive control as the main body, which only needs a small amount of energy to change the parameters of passive control system or working condition, in order to adapt to the system of optimal state tracking. Compared with the active control, semi active control needs much smaller external energy, its maintenance requirement is not high, which is easier to implement and more economic, and the control effect is close to the former. Therefore, the development and application of semi-active control has great value, which is the focus of current research\cite{14,15}. The common semi active control devices are: the variable stiffness system, variable damping system, variable stiffness and damping system. So the magnetorheological damper and the electrorheological liquid damper are the main direction of future development.

Hybrid control is vibration control form which puts the active and passive control in the same structure. It has the advantage of two kinds of control and also overcomes their disadvantages, and only a very small energy input can achieve good control effect. In addition, put the active control and passive control at the same time in the structure, and analyze the overall response, which not only overcomes the limitation of application of pure passive control, but also reduces the control force, thus the power, volume, energy and maintenance costs of the external control equipment should be reduced, and the reliability of the system must be increased\cite{16,17}. At present, the typical mixed control devices are: active control combined with base isolation; active control combined with damping energy consumption.

5 PROSPECTS FOR THE DEVELOPMENT OF VIBRATION CONTROL

Research and application of structural vibration control have a broad application prospect, and the huge economic and social benefits have been obtained. Increase the study on the origin, and spread and the seismic principle of the earthquake, which will enable us to design more effective disaster prevention device. Comparison and optimization analysis of various energy dissipation devices get the specific calculation model and make it standardization and serialization, so it will be easy to use in design. Strengthen quantitative analysis of problems on the setting dampers and damping effect of the damper, and the research on the application technology of strengthening earthquake damaged buildings using energy dissipation technique, and add layer of existing buildings and transformation. As the development of the new functional materials, control technology and computer technology, active vibration control technology will have good prospects: 1) to determine the control algorithm which has feedback and control gain of the optimal relationship. Referring to the research achievements in the field of control, according to the characteristics of all kinds of vibration, develop a new method which is different from the traditional control theory; 2) numerical simulation, and test implementation and verification of the structure of the control system; 3) with the production of intelligent composite material, put forward the new idea of intelligent structures, integrate the sensor, actuator and controller structure together organically, and change the distribution of mass and stiffness of the structure itself, the magnitude of the damping, to achieve the goal of vibration control. Semi active control and hybrid control is an important development direction of civil engineering structure control in the future. Therefore, it is necessary to strengthen the experimental research in this area, improve the theoretical basis constantly and the reliability of the actual control effect and device, and achieve the basic requirements of practical. In addition, the time lag effect will cause the low control efficiency, which will decrease the control performance and even lead to instability of the structure. Therefore, to eliminate the delay effect is one of the topics for future research.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the Natural Science Foundation of China (National Key Project, No. 51278393).

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