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AMD control analysis and parametric optimization for a wind excited tall building structure

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Abstract

Under the background of one large scale high-rising reinforced concrete structure located in Dalian city, the AMD active control analysis and design against wind loading is carried out. First, the structural computation model and loading modal are established according to the engineering background and design requirement. Then, the parameter optimization for AMD subsystem is conducted under wind excitations. At last, numerical simulation for the structure controlled by AMD system is carried out. The numerical results show that the AMD system with the optimized parameters can achieve a significant effectiveness on suppressing wind induced structural acceleration response, which will also be in favor of addressing occupant comfort issues. In addition, the control effect of Root Mean Square (RMS) response is generally higher than that of the peak response, which may have implications on structural functionality and reliability during its service life span. The analysis and optimum approaches for AMD control analysis as well as corresponding results can also be applicable to similar control problems.

Keywords: high-rising building structure; AMD control; parameter optimization; wind induced vibration control

1 Introduction

In 1972, J.T.P. Yao introduced the modern control theory into vibration control of civil structures (Yao, 1972), which started the new era of research on structural active control in civil engineering field. During the development of nearly 40 years, Active Mass Driver/Damper (AMD) control, with the better control effect and cheaper control cost, has taken the lead in various active control occasions, becoming the most extensively used and researched control systems in lots of practical applications (Soong, 1990; Housner et al., 1997; Spencer et al., 1997; Ou, 2003). Several important journals in civil engineering field, such as ASCE Journal of Engineering Mechanics (issue 4th, in 2004), ASCE Journal of Structural Engineering (issue 7th, in 2003), Earthquake Engineering and Structural Dynamics (issue 11th, in 2001 and issue 11th, in 1998), reviewed the-state-of-the-art in research and engineering applications of semi-active control and active control, especially AMD control. In addition, Spencer and Nagarajaiah (2003) systematically overviewed the applications of active control in civil engineering, more than 50 high-rising buildings, television towers and about 15 large-scale bridge towers have been equipped with AMD control systems for reducing wind-induced vibration or earthquake-induced vibration of the structures. Zhang (2005) made a systematically comparison for different control schemes under the background of the Benchmark control problem, and disclosed that the AMD control was the best control scheme due to these merits, such as the best ratio of control effect over control effort, simple and easy to be implemented etc. Moreover, through analysis of typical important large-scale structures subjected to different excitations, the effectiveness and feasibility of employing AMD control for civil structures has been successfully proven (Ou, 2003; Zhang, 2005), where wind and earthquake induced vibration control of high-rising buildings and bridge towers, ice induced vibration control of offshore platforms, wind-wave-current coupling excited control of deep sea platforms are all studied.

The application of AMD active control systems to civil engineering structures has had the history of more than twenty years. In 1989, the Kajima company in Japan took the lead in accomplishing the first application of active control in the world, which is the 11 floors' Kyobashi Seiwa building located in Tokyo. Almost at the same time, in the United States, Soong (1990) at the National Centre for earthquake engineering research (NCEER) accomplished the first AMD active control experiment. Up to the present, around the world, more than 50 high-rising buildings have adopted AMD (HMD) active control systems, and more than 20 bridges also adopted AMD systems to reduce the wind induced vibration of bridge towers during construction (Housner et al., 1997; Spencer et al., 1998). For example, the Yokohama Land Mark building finished in 1993 in Kanagawa is a 70-storey high rise building which adopted two AMDs weighted 340 tons, and the total mass of this structure is about 260000 tons (Spencer and Michael, 1997), which is similar to the structure discussed in this paper. The most recently completed Canton Tower, 600m high, has also adopted two innovative AMD control systems (Xu et al, 2013).

2 Structural models

This structure is located in the coastal area of Dalian city, and the main body is divided into three towers with a total building area of 254,000 square meters, among them northern building is a five-star hotel (in the following abbreviated as building “A”). In the following, control design of building “A” according to the engineering requirement will be carried out. Building A is a board-like building and its plane is rectangular with the transmeridional length of 73.34 meters and north-southern length of 25.20 meters, and the total height of main tower is 173 meters, which sits above the 6 floors of skirt house terrace, and the terrace is 29 meters high. Therefore, the height to width ratio is 144/25.2=5.7 which is close to the limit value 6.0 by design code. This structure is the type of frame-shear wall composited structure with CFST columns, which falls between concrete structures and steel structures, and according to the designing code its height restriction should be 180 meters, with the height to width ratio limit is 6.0, thus this building is not beyond the code limit. Building A has 46 floors above the ground, and 4 floors being 20 meters deep beneath the earth surface. The seismic fortification intensity in Dalian is 7 degrees, and the standard wind pressure is 0.72 kilo-Newton per square meter. Because the Dalian district is near to the sea and the wind force is much bigger. In addition, the height to width ratio of building A is 5.7, the structure is so slim that the lateral vibration is more obvious according to preliminary dynamic analysis. In order to reduce the horizontal amplitude of vibration as well as the acceleration response, and to enhance the safety of the whole structure and human comfort of habitants on top floors, an AMD active control system is being proposed for controlling its wind induced vibrations.

Owing to this engineering structure adopting frame-shear wall with CFST (concrete filled steel tubes) columns, the structure belongs to super high-rising buildings, so the bending-shear model is considered in the calculation model. Here we take the calculation formula for lumped-mass system with the structure simplified as 50 degree of freedoms of sugar-coated haws on a stick (Wang, 1978). The flexibility matrices of this model is established according to the bending-shear model formula, and the global stiffness matrices is deduced by solving the inverse of the flexibility matrices, and the damping matrices adopts Rayleigh's diagonal intersection damping hypothesis supposing that the damping ratios of the first two vibration models are both 5%. The difference of the structural stiffness in the two planar directions is so big, that the difference is more than 3 times, so it is feasible to carry out the single directional response control analysis according to the weak direction. The intrinsic frequencies of first three lateral vibration modals of the primary structure are 2.38, 10.36 and 22.10 radian per second, and the corresponding damping ratios are 5.00%, 5.00% and 9.11% respectively.

According to standard wind pressure $w_k = 0.72kN/m^2$ in Dalian area, which has already considered the structure importance coefficient and applying the sampling method based on stochastic process theory incorporated with the widely used Davenport's wind speed spectrum, the computational program for acquiring wind load has been worked out, which will be used in structural dynamic analysis in the following. Samples can be generated to simulate the gust wind effect on the structure. As a result of all the previous samplings, one representative wind sample which is close to the 20 samples' average values is chosen to carry out the following control analysis of the structure under gust wind excitations. Time history of the wind force at the tower top of the structure by this wind sample is shown in figure 1 with a 10 minutes period is illustrated.

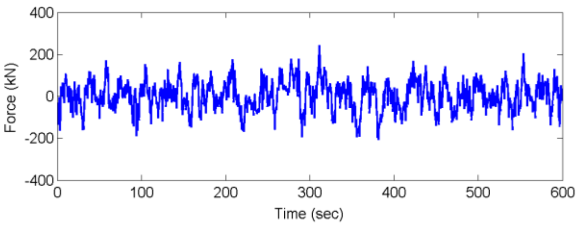

Figure 1. Time history of wind gust force at the top floor

The relation of wind control effect under AMD between average value of the 20 samples and each single sample is shown in figure 2, and therefrom No.1 wind sample can be chosen as a representative wind input case for the following parameter optimization procedure. What needs to be explained is the wind induced displacement can be divided into two parts, i.e. the stationary displacement caused by average wind, and the vibration displacement caused by wind gust. The calculated stationary displacement at the tower tip is 13.6cm according to the wind sample No.1, which is uncontrollable by means of any vibration control system. As a result, the relative displacement mentioned in the following in this paper indicates the gust displacement, namely deducting stationary displacement from total displacement.

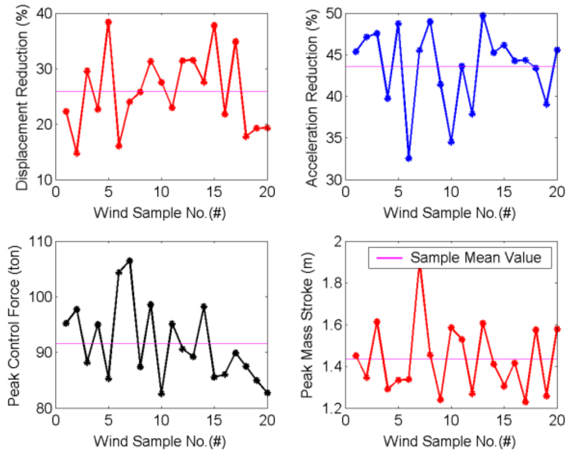

Figure 2. Control results between each sample and mean value

3 Control analysis and parameter optimization

The AMD subsystem parameter optimization of this paper will be faced with two challenges. In addition to wind, earthquake is also necessary to be considered. Secondly, the tactics on choosing physical parameters and weight parameters of control algorithms for AMD system. However, considering the special location of the structure nearby the coastal areas, optimization and physical parameters of AMD subsystem are determined primarily based on wind excitation analysis. While, for the earthquake induced vibration control case, physical parameters can be chosen the same as wind input case analysis, the difference is to choose different weight parameters for analysis, thus to reach different active control tactics according to different input.

Usually the AMD mass is within 3% of total structural mass. For this structure, the auxiliary mass is designed to be 300 tons, which is about 0.14% of total structure mass or 1% of the first modal generalized mass. Control effectiveness, mass strokes and actuator forces are three uniformed indices but usually contradictory to each other. The first one is the quota standing for benefit and the latter two are considered as restriction factors. Figure 3 shows the relation between the various capacities of AMD subsystem stiffness coefficient with control effectiveness and costs.

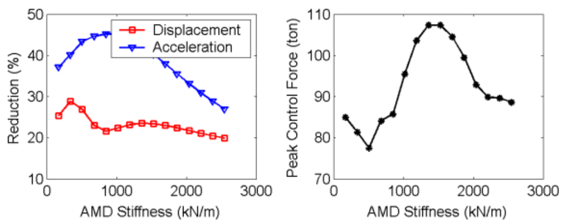

Figure 3. Optimization of AMD stiffness under wind loading

It can be seen that when the stiffness coefficient k_a is close to 1000kN/m or so, the corresponding acceleration control effect of structure has a peak value from the left picture, where $\beta = 0.6$ when $m_a = 300t$ and $\omega_0 = 2.38rad/s$. This result is far small than the optimal stiffness coefficient 0.96~1.0 of TMD which has been proposed by many researchers. This shows that relative soft stiffness can gain better control effect in reducing acceleration when adopting AMD to control structural wind response, and $\beta = 0.6$ can be viewed as the reference value based on a large number of optimization calculations. The optimization of mass parameter must be considered in two cases, firstly, the stiffness coefficient k_a is fixed, i.e. doesn't take into consideration of coupling effect between stiffness and mass. Therefore, the value $k_a = 1000kN/m$ achieved previously is considered; secondly, considering that the stiffness coefficient k_a varies with the auxiliary mass m_a, i.e. stiffness coupled with mass, and it can be divided into two sub-situations, i.e. the stiffness adjustable coefficient is set to 0.6 and 0.98, respectively. Mass optimization of AMD subsystem of the above three cases as well as TMD being tuned at the optimal stiffness are shown in figure 4.

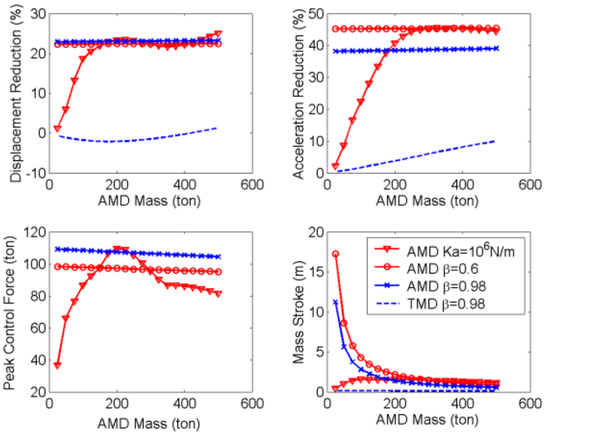

Figure 4. Optimization of AMD mass coupled with stiffness

4 Summary of AMD control design

Based on thorough analysis, physical parameters of AMD subsystem are chosen to be mass $m_a = 300t$, stiffness $k_a = 1000kN/m$ and damping coefficient $c_a = 82kN \cdot s/m$. AMD control system is proposed to be installed on the 45th floor of the structure. Owing to the situation that the stiffness of two planar directions of the structure differs significantly, which may cause unavoidable torsional effect, two AMD systems are proposed to be located at two sides of the. Therefore, each subsystem shares half mass, stiffness and damping, respectively.

Due to the active control nature, control effectiveness of AMD system is adjustable according to the control objective via weight parameters within control algorithms. The system equation of motion and AMD mass strokes and peak control forces can be considered as the constraint condition for the optimization process. In principle, AMD control can achieve any ideal control percentage at the cost of big mass strokes and control energy consumptions. Compared with AMD control, the control effect of passive Tuned Mass Damper (TMD) can only achieve a limited effectiveness provided the frequency tuning ratio should be within a narrow optimum range.

For practical consideration, the parameter optimization of AMD system will be subjected to two aspects of challenges. Firstly, wind and earthquake are two different kinds of excitations in loading characteristics and has different impact on structural response and behaviour which may target at different control emphasis; secondly, the tactics on choosing physical parameters of AMD subsystem and weight parameters of control algorithms are also different. Considering the background of this structure, it is located close to the coastal area, therefore, it is reasonable that the optimization of physical parameters for AMD subsystem is made mainly based on wind loading excitations. Whereas for earthquake loading input case, physical parameters can be adopted from wind loading case analysis, the only difference is to choose different weight parameters for control decision making, thus achieves different active control tactics according to different inputs.

Under the reasonable values ranges for mass, stiffness and damping coefficients of AMD system, relation between peak control force/ mass stroke of AMD system and control effect subjected to wind loading is given in figure 5. Based on the results, once the active control force reach a certain level, there will be significant changes in the displacement control effectiveness as well as nonlinear impact on acceleration control effectiveness. Based on analysis of a large number of wind loading samples, the active control force can be determined to be 1000kN as the upper limit, and peak mass stroke is 1.5 meters, where the corresponding control effect of acceleration can achieve nearly 50%.

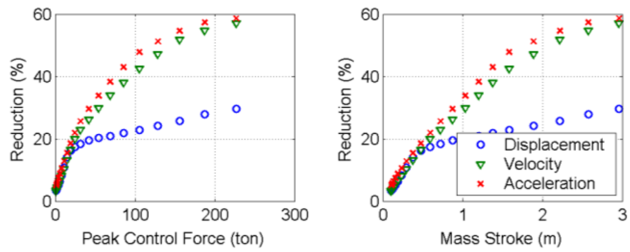

Figure 5. Relation between AMD actuator force and control efficacy under wind action

Figure 6 shows the structural global response corresponding to different levels of AMD active control forces. Based on figure 6, the acceleration control effect is obviously superior to the displacement control effect, and this meets well with occupant comfort issues (Kwok et al, 2009). For example, the controlled results of peak acceleration of primary structure may drop from over 20 gals to within 10 gals, and it will satisfy the design code requirement (Zhao, 1999). Based on the previous experience and in reference to the Benchmark problem, the control effect of peak response is usually less than the control effect of Root Mean Square (RMS) response. From the viewpoint of structural dynamic fatigue, reducing RMS response of displacement and acceleration of structure under wind loading will effectively enhance the structural functionality and reliability during its service life span.

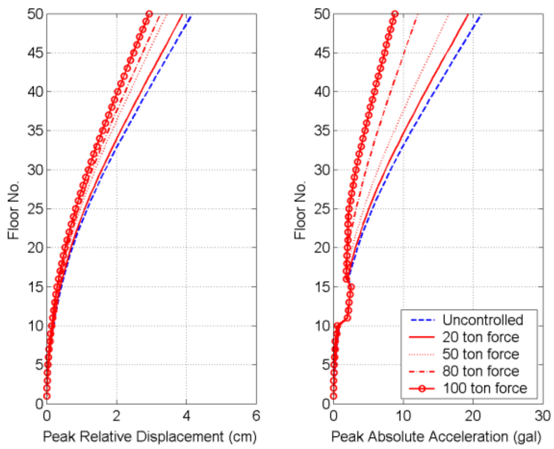

Figure 6. Relation between AMD actuator force and global control effect under wind action

Time history of structural relative displacement and absolute acceleration under one simulated wind loading is shown in figure 7 for comparison purposes, where the optimum parameters of AMD system are considered.

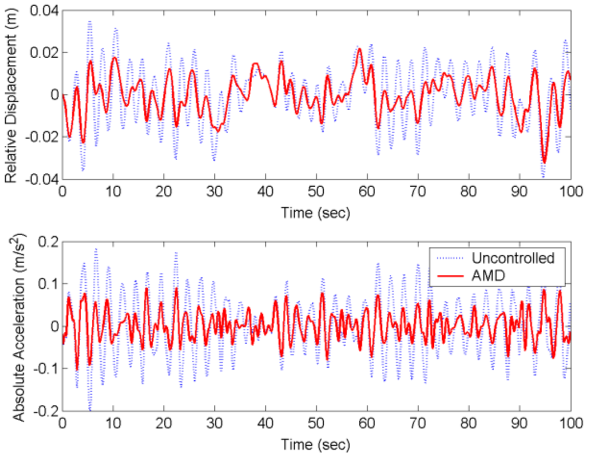

Figure 7. Time history of displacement and acceleration at the structural top floor under wind action

Conclusions

The parameter optimization procedure for AMD subsystem is conducted under the input of simulated gust wind loading, as a result, the optimal physical parameters of AMD control system has been achieved which can be applied to the design of the actual control system. Based on parametric optimization analysis, the optimal stiffness adjustable coefficient for AMD system is achieved to around 0.6, which is far lower than widely accepted optimal tuning ratios of TMD system. This indicates the optimal stiffness of AMD control system should not be necessarily the same as TMD control and a relatively soft stiffness system will be in favour of enhancing control performance while at the cost of mass displacements.

Under wind excitations, structural acceleration control effect is shown to be superior to displacement control effect, which will be in favour of addressing occupant comfort issues. For example, the controlled peak acceleration may drop from over 20 gals to within 10 gals, and thus to satisfy the design code requirement. In addition, the control effect of Root Mean Square (RMS) response of structure is generally higher than that of the peak response, which may have implications on structural functionality and reliability during its service life span.

Acknowledgments

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