Title: **Hybrid Mass Dampers for Canton Tower**

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"The Hybrid Mass Damper (HMD) system possesses multiple security measures, which can ensure the safety of HMD under major typhoons or earthquakes…The proposed HMD system is fail-safe, signifying its robustness."

This paper presents an analysis of the design and application of novel Hybrid Mass Dampers (HMD) for Canton Tower in Guangzhou, China. The HMD is composed of a passive Tuned Mass Damper (TMD) with two-stage damping level, and a compact Active Mass Damper (AMD), which is driven by linear induction motors mounted on the TMD. In case of a failure in HMD control system, the system would become a passive TMD.

Introduction

During the last three decades, the technology of active structural control has become a significant research focus in the field. There are a lot of successful examples of AMD or HMD application for tall buildings, TV towers, bridge towers, etc.; to attenuate the wind-induced vibration. As early as 1987, Aizawa conducted a shaking table test of a four-story frame in Japan and his test verified that an AMD can reduce the seismic responses of the structure (Aizawa et al. 1990). Spencer presented a benchmark model of AMD control for a three-story steel frame (Spencer et al. 1998). After several years of experimental and theoretical studies, this technology was applied in a "real world" venue and achieved remarkable success. To date, many practical engineering projects worldwide have implemented AMD control systems, and many of them have withstood the test of typhoons and earthquakes. The real-time monitoring results have shown that AMD or HMD can achieve a preferable degree of vibration suppression (Ou 2003, Shizhu et al. 1999 & Hongnan et al. 2008).

A novel HMD is proposed herein to stabilize Canton Tower against movements caused by major typhoons, which would be composed of: a passive TMD with two-stage damping level and a small AMD driven by linear induction motors mounted on the TMD. This paper introduces the design of the device composition, i.e., water tank, bi-directional rail roller bearing, laminated rubber bearing, oil viscous damper, AMD, and anti-torsion bearing as well as multiple security measures of a HMD system. A numerical simulation of Canton Tower with various control systems was carried out to investigate the advantages of the proposed HMD system over other control systems. Simulation results were compared with the passive and full-active various control systems. The three most unfavorable wind attack angles were also considered in the numerical simulation.

General Description of Canton Tower

Canton Tower is a landmark of the city center business area of Guangzhou, China with a

Figure 1. Canton Tower, Guangzhou © EERTC

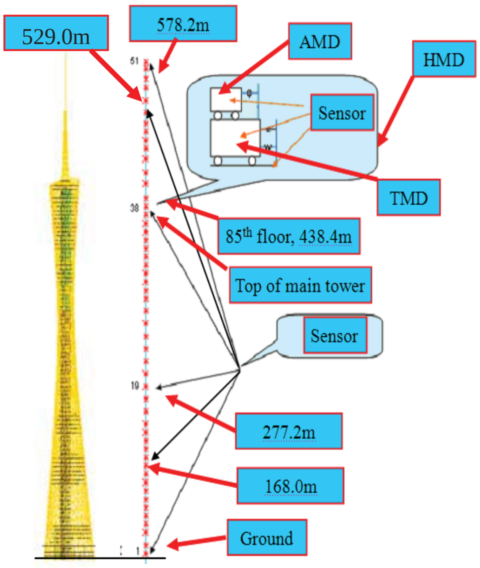

Figure 2. HMD control system © EERTC

total height of 600 meters (1,969 feet) (see Figure 1). It houses a restaurant, observatory and telecommunications facilities. The main tower is 454 meters (1,490 feet) tall with a 146-meter (479-foot) tall antenna on top. The total weight is around 194,000 tons. The fundamental period of Canton Tower is 10.01s as indicated by three-dimensional finite element analysis of ANSYS. According to the code for seismic design of buildings in China, Canton Tower is a Class A building based on its design classification.

Canton Tower is a tube-in-tube structure composed of a reinforced concrete inner structure with ellipse cross-sections of 14 and 17 meters (46 and 56 feet), and a steel lattice outer structure with its cross-section being a varying oval throughout the height of the tower. The cross section of steel lattice twists from ground level to the roof, which gives the building its unique feminine profile. The lengths of its major and minor axis are 80 and 60 meters (262 and 197 feet) respectively in the bottom layer, 27.50 and 20.65 meters (90 and 68 feet) in middle layer, and 50 and 45 meters (164 and 148 feet) in the top layer. This external frame comprises 24 inclined concrete-filled columns, horizontal ring beams, and diagonals. The antenna on the top of main tower is a steel spatial structure with an octagonal cross-section of 14 meters (46 feet) in the maximum diagonal.

Since the tower is a supertall construction with a slender profile and low damping, it is dynamically wind sensitive, which would potentially increase acceleration levels under strong wind. The persistent wind-induced vibration can not only result in fatigue damage of the tower, but also induce discomfort for occupants. It is therefore necessary to develop an effective control strategy to improve the comfort and serviceability of Canton Tower.

Proposed HMD control system

The location of sensor, the HMD, and the HMD vibration control device is at a height between 438.4 and 448.8 meters (1,406 and 1,472 feet) (see Figure 2). Our novel active-passive composite T system is a combination of a TMD with a variable two-stage damping level, and a small AMD mounted on the TMD (see Figure 3). Two symmetrical fire water tanks are designed as the tuned masses, each weighing 600 tons, sitting on the three bi-directional rail roller bearings installed on the 85th floor of the main tower. Laminated hollow rubber bearings are used to provide the stiffness of the TMD. A two-stage oil damper is designed for the TMD, which is capable of adjusting the damping level of the TMD automatically once the TMD stroke exceeds a given level. The 50-ton AMD, driven by linear induction motors, can improve the control performance and the robustness of a passive TMD significantly. The anti-torsion bearing is installed between the main tower roof and water tank to prevent the water tank from moving rotationally. The newly proposed HMD system is designed to stabilize the tower against movement; to significantly improve the structural serviceability; and to enhance occupant comfort in the event of strong winds. Because the responses of Canton Tower in the short-arm direction is much greater than responses in the long-arm direction, HMD control was employed in the weak axial of main tower, while TMD control was used in the strong axial due to the consideration of economic costs and a compact system.

Design of HMD Components

Fire Water Tank

Inertia-based dampers such as TMD commonly requires an additonal mass to provide a given damping level, which may be heavy and costly. Analysis shows that Canton Tower is sensitive to the vertical gravity load. Instead of introducing extra gravity loads, two water tanks for fire control in Canton Tower are set on the 85th level and occupy two floors, serving as the shared tuned mass of the TMD in both horionzontal directions of the main tower. It is worth mentioning that this level will be open to the public for sightseeing and for an educational exhibition of how the HMD system works.

The total weight of each fire water tank is 650 tons which is about 0.35% of the tower's total weight. Not only does the shape of the water tanks meet the demand of space, but it also offers an appropriate mass ratio to make the TMD achieve a favorable level of performance. The top of the water tanks are not

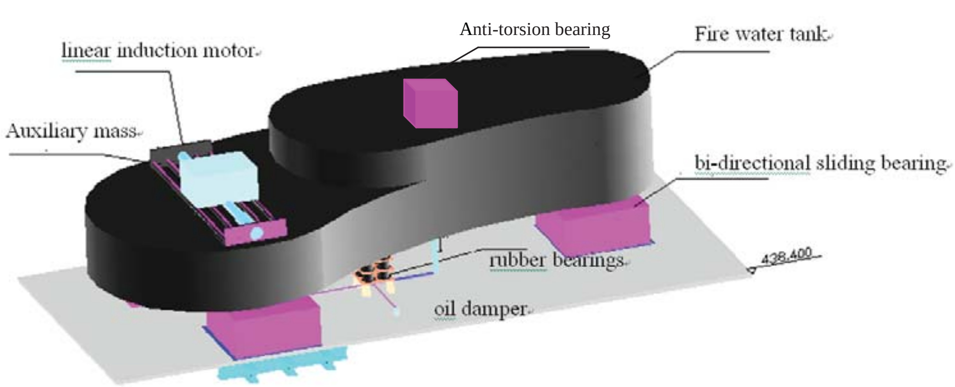

Figure 3. The proposed HMD system © EERTC

designed to be flat so as to preserve space for an AMD device. In order to restrict the influence of fire water tanks for the vibration of the main tower, two water tanks are used and placed around the core tube symmetrically (see Figure 4).

Bi-directional rail roller bearing

A bi-directional rail roller bearing was developed to withstand the gravity load of the whole HMD and allow the water tank to move freely (see Figure 5). Each water tank sits on three bi-directional rail roller bearings, whose geometry center is the same as the mass center of the water tank. The guide rail directions are parallel to both-axis directions of the main tower. Considering that the required stiffness of the TMD in the weak-axis and strong-axis directions are quite different, restoring springs are installed in the rail roller bearing to obtain additional stiffness needed for TMD in the strong-axis direction. A spherical bearing is equipped on top of bi-directional rail roller bearing to accommodate deflection of the water tank, whose allowable swing angle of the spherical bearing is set to be 3°.

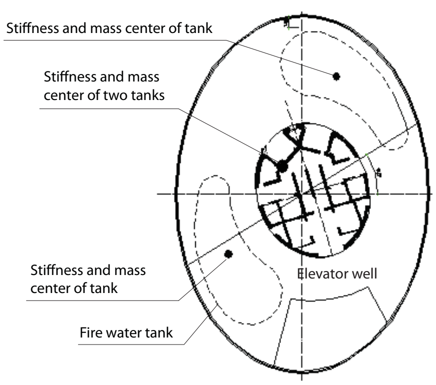

Figure 4. Stiffness and mass center of fire water tank © EERTC

Three security measures were designed to ensure the safety of the TMD. The first safety measure is taken by using oil buffers in both directions as soft collision devices (see Figure 6). The oil buffers were designed to restrict the excessive velocity of the TMD, while it absorbs the kinetic energy. Four restoring force springs are installed parallel to the oil buffer in order to restore the deformation of the buffer.

The second security measure is the locking device (see Figure 7). When the impact force of the TMD is very large, the tongue will lock into a groove causing the TMD to be locked.

The third security measure is a steel baffle designed to absorb vibration impacts due to major typhoons or earthquakes.

Rubber bearing

The lower TMD of the proposed HMD system is designed to control the tower in both horizontal directions. Because of their ideal isotropic linear stiffness and low cost, laminated rubber bearings are used to provide necessary stiffness for the TMD. As the fundamental period of the tower is as long as 10.01s, the desired stiffness of the TMD is less than the lateral stiffness of a single small rubber bearing. Moreover, the TMD stroke required is too much for a single laminated rubber bearing. A strategy of using three layer rubber bearing successively is designed to meet the requirement of allowable stroke and desired stiffness of the TMD. In order to provide preferable linear lateral stiffness and favorable durability, laminated hollow rubber bearings are developed and investigated systematically. The hollow rubber bearing are not designed for holding pressure, which is different from the widely used natural rubber bearing in seismic isolation.

Oil damper

Mass, stiffness and damping are the three main properties of a TMD. An ingenious passive oil damper with built-in control valve is designed for the TMD. The oil damper offers a two-stage damping characteristic – a high and a low damping. The relative displacement of the TMD to the tower is small under small and moderate wind, and the oil damper provides an optimal TMD damping force. However, in case of a hurricane or typhoon, this innovative oil damper can passively shift to a high damping level once the TMD displacement exceeds a given level, while the AMD mounted on the water tank is automatically trigged. In this way, the HMD system under strong wind still achieves a satisfactory performance while the TMD stroke is within an acceptable level.

Anti-torsion bearing

In order to prevent torsional motion of the huge water tank, an anti-torsion bearing was developed (see Figure 8). The anti-torsion bearing is composed of a lower and upper guide rail beam, guide rail and cross anti-torsion linking. The top of anti-torsion bearing

Figure 5. Bi-directional rail roller bearing © EERTC

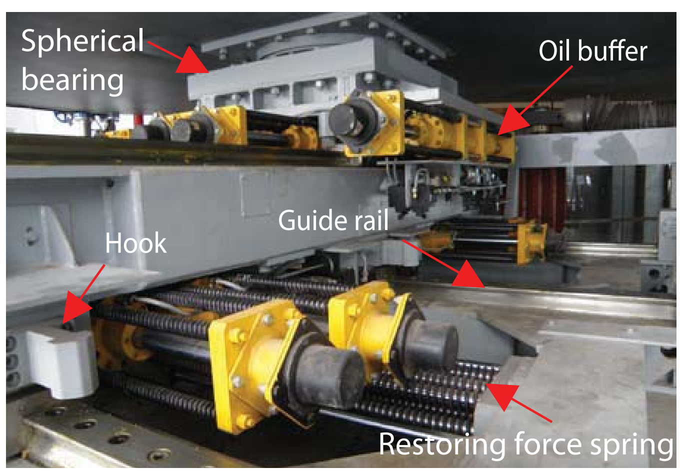

Figure 6. Soft collision device © EERTC

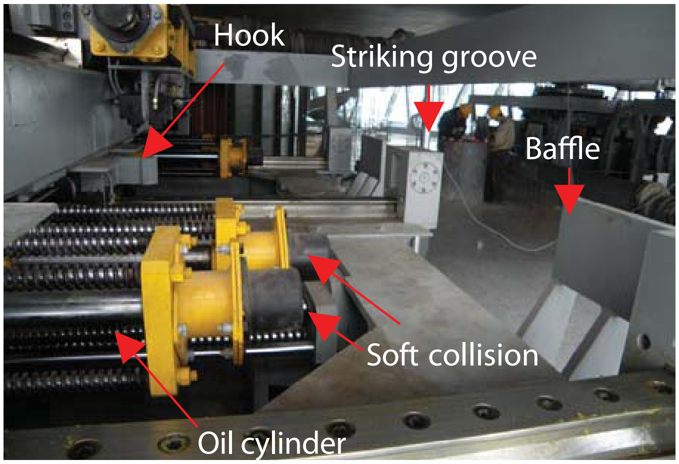

Figure 7. Locking device © EERTC

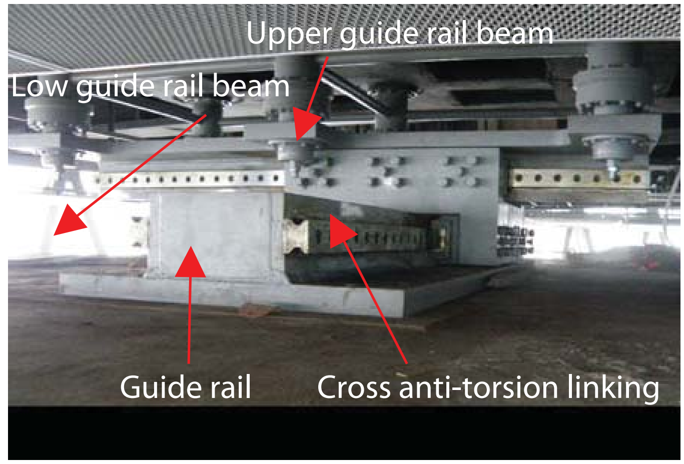

Figure 8. Bi-directional rail roller bearing © EERTC

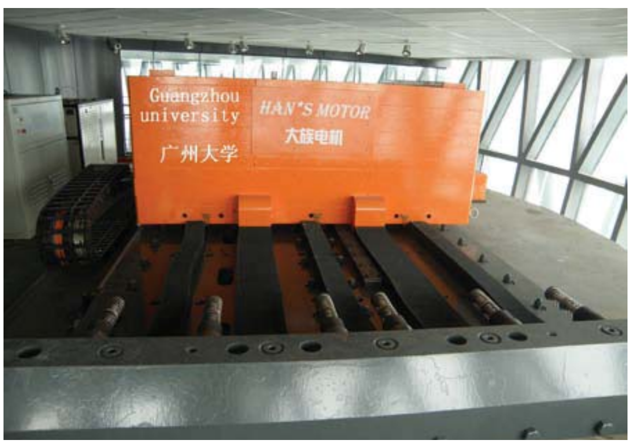

Figure 9. AMD driven by linear induction motors © EERTC

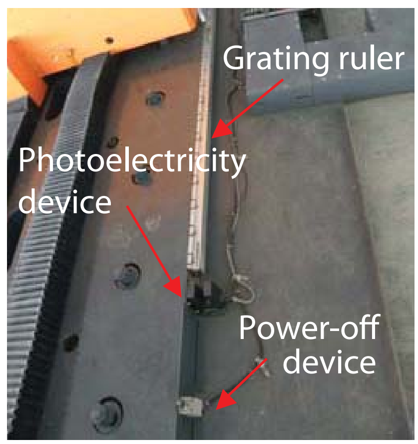

Figure 10. Collision device © EERTC

Figure 11. Collision device © EERTC

attaches to the floor beam of the main tower, and the bottom of anti-torsion bearing connects to the top of fire water tank. Two groups of linear guide rails can control the motion of cross anti-torsion linking in both the transverse and longitudinal direction independently.

Active mass damper

An AMD system is installed on top of the water tank to improve the performance of the TMD in the case of strong gusts. The moving mass, weighing 50 tons , is supported by a linear guide in weak-axis direction. Therefore, the control system works as a hybrid mass damper in the weak-axis direction and as a simple passive mass damper in the strong-axis direction. Figure 9 shows the AMD on the Canton Tower. Linear induction servomotors are used as an actuator to drive the 50-ton active mass. When this new actuator is adopted, transmission devices are not necessary and no friction is induced by the presence of a transmission device. The AMD has the advantages of low noise, high precision, quick response and easy maintenance. The relative displacement of AMD is measured by a grating ruler. The allowable stroke of an AMD is ± 2 meters (6.5 feet) and the peak speed of the AMD is set to 0.5 meter per second (1.6 feet per second). In order to ensure the safety of the AMD, five security measures for the system have been developed. The first measures are soft displacement limiting measures, whose range is 0.7 to 1.3 meter (2.3 to 4.3 feet) and -0.7 to -1.3 meter (-2.3 to -4.3 feet), and a maximum speed of the AMD varies from 0.5 to 0 meter per second (1.6 to 0 feet per second) in the range of soft limiting displacement. The

… $3 billion

“If you’re going to spend $3 billion on a building, you want someone who’s done it before.”

Carol Willis, curator at the Skyscraper Museum on the museum's latest exhibition – Supertall. From "Lunch with the Critics: Supertall," The Design Observer, October 3, 2011 second measure is the photo-electricity displacement limiting device (see Figure 10). When the AMD reaches the point of the photo-electricity displacement limiting device, the linear induction motors impose the maximal force on the AMD to arrest its motion. The third measure is the power-off device. When the AMD reaches the point of the power-off displacement limiting device, the power of the AMD will be cut off automatically. The fourth measure is the mechanical limiting displacement device (see Figure 11). This device realizes the soft collision of the AMD and absorbs its kinetic energy. The fifth measure is the hydraulic locking device. When the AMD stops moving, this device is locked-in state, and puts the AMD into a fixed state.

	UC	TMD		ATMD		HMD (LQG)	
peak roof displacement (m)	0.1898	0.1446	24%	0.0810	57%	0.1003	47%
peak roof acceleration (m/s^2)	0.0945	0.0848	10%	0.0560	41%	0.0619	35%
rms roof displacement (m)	0.0593	0.0489	18%	0.0303	49%	0.0338	43%
rms roof acceleration (m/s^2)	0.0288	0.0230	20%	0.0120	58%	0.0162	44%
peak mass stroke (m)		0.26		0.53		0.78(AMD)	0.32 (TMD)
peak active force (kN)				345		63	

Table 1. Responses at the top of main tower under ten-year wind (wind attack angle of 0°) © EERTC

	UC	TMD		ATMD		HMD (LQG)	
peak roof displacement (m)	0.4679	0.2476	47%	0.2189	53%	0.2420	48%
peak roof acceleration (m/s^2)	0.2191	0.1537	29%	0.1255	43%	0.1425	35%
rms roof displacement (m)	0.1495	0.0869	42%	0.0787	47%	0.0827	45%
rms roof acceleration (m/s^2)	0.0704	0.0390	46%	0.0304	57%	0.0371	47%
peak mass stroke (m)		0.71		0.97		1.6(AMD)	0.74(TMD)
peak active force (kN)				621		138	

Table 2. Responses at the top of main tower under ten-year wind (wind attack angle of 45°) © EERTC

	UC	TMD		ATMD		HMD (LQG)	
peak roof displacement (m)	0.4748	0.2512	47%	0.2222	53%	0.2428	49%
peak roof acceleration (m/s^2)	0.2239	0.1566	30%	0.1282	42%	0.1451	36%
rms roof displacement (m)	0.1541	0.0888	42%	0.0796	48%	0.0838	46%
rms roof acceleration (m/s^2)	0.0727	0.0399	45%	0.0311	57%	0.0378	45%
peak mass stroke (m)		0.73		1.00		1.56(AMD)	0.77(TMD)
peak active force (kN)				627		138	

Table 3. Responses at the top of main tower under ten-year wind (wind attack angle of (225°) © EERTC

Numerical Simulation

In order to investigate the effectiveness of the proposed HMD, a comparative study has been carried out between different control strategies for Canton Tower under strong wind, including a passive control system of TMD, a fully-active system of ATMD and a combining system of HMD. For convenient analysis, a simplified space model of Canton Tower was developed to reduce the size of the 3D finite element model formed in ANSYS (Tan et al. 2009). An H_2/LQG algorithm is chosen for controller designs of ATMD and HMD for its previous successful application in the real world (Skelton 1988). The active controller is designed based on a reduced-order evaluation model of Canton Tower. According to wind-tunnel experiment results of Canton Tower, the three most unfavorable wind attack angles, namely, 0°, 45° and 225°, are considered in the numerical simulation. The duration time of turbulent wind history is assumed to be 500 seconds. In order to obtain more accurate results, the calculation used is 0.001 seconds during the simulation.

Tables 1, 2 and 3 show the structural responses of the uncontrolled system, TMD, ATMD and HMD systems under ten-year return period for various wind attack angles. The utilization of three control schemes can achieve significant reduction in both peak and Root Mean Square (rms) values of structural responses, greatly improving occupant comfort and serviceability. It can be observed that the ATMD system among the three control systems offered the best performance in every case, which shows an additional 13%–26% improvement over the TMD system, at a cost of much higher strokes and active forces. In addition, the novel HMD system achieves improved performance of 5%–16% over the TMD system. The required actuator force for an HMD system is about 20% of the active control force for an ATMD, and the stroke of the fire water tank for the HMD system is comparable with the passive case and both are less than 80% of stroke for ATMD system. Since the proposed HMD combines the best features of both TMD and ATMD systems, it demonstrates significant superiority of the hybrid active-passive system over the full passive or active TMD system.

Figures 12 and 13 display the power spectra of displacement and acceleration for the uncontrolled system and the HMD systems under a ten-year return period for 0° wind attack angles at the top of the main tower in the weak-axial direction. In contrast with the spectrum of the uncontrolled case, the peak displacement and acceleration of the main tower under HMD control are clearly decreased. The displacement and acceleration of the structure was reduced in the range of 0.1 Hz and 0.35 Hz, namely, in the frequency band of the first fifty-order modal. However, the vibration absorbing frequency band of displacement at the top of the main tower is very wide, and the displacement response in full range of frequency band is reduced, which shows better displacement control effect over displacement than that over acceleration.

Conclusions

1. The novel Hybrid Mass Dampers (HMD) as proposed has been applied without difficulty to Canton Tower. Considering economic costs and its compact system, the proposed HMD is feasible, effective, safe and economical.
2. The HMD system possesses multiple security measures, which can ensure the safety of HMD under major typhoons or earthquakes. In case of a failure in the HMD control system, the HMD would become a passive TMD and the control system would still work effectively. The proposed HMD system is fail-safe, signifying its robustness.
3. Simulation results indicate that the application of the HMD for Canton Tower has remarkable structural performance improvements during a strong wind. The proposed HMD demonstrates significant superiority over the full passive or active TMD system. ■

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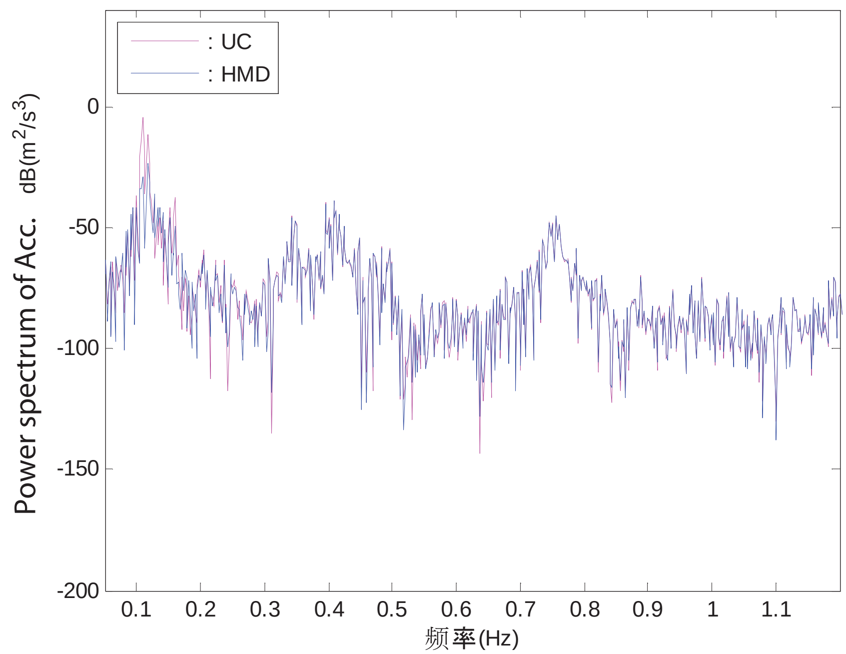

Figure 12. Acceleration power spectrum of main tower © EERTC

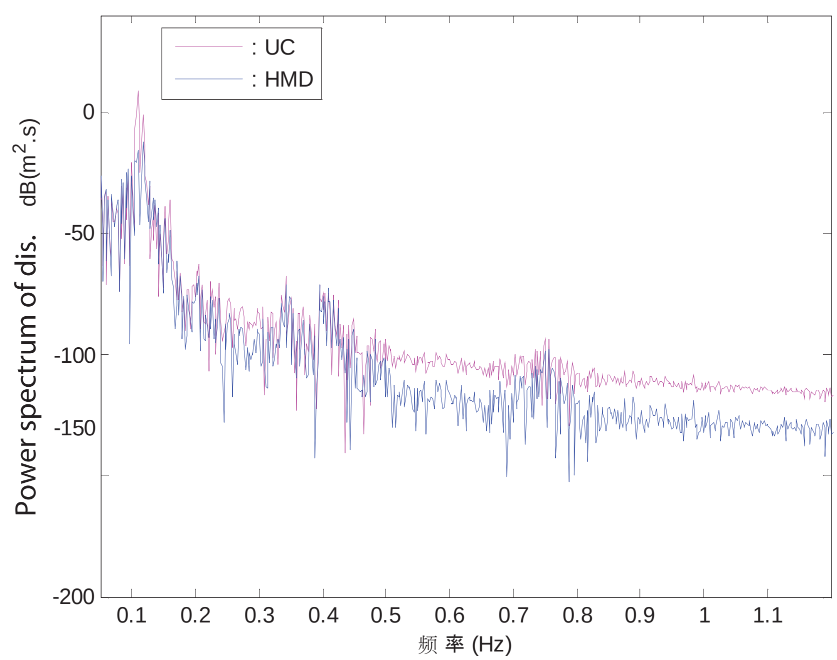

Figure 13. Displacement power spectrum of main tower © EERTC