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APPLICATION OF MRTMD ON HIGH-RISE PORCELAIN CYLINDRICAL ELECTRICAL EQUIPMENT

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Abstract

High-Rise Porcelain Cylindrical Electrical Equipment (HRPCEE) is playing increasingly important role in the power supply system and is essential to its safe operation. Earthquake damage investigations show that HRPCEE is vulnerable during earthquakes because of its structural features and material characteristics. This paper aims on inventing a type of shock absorption device using multiple ring tuned mass dampers(MRTMD). Two types of typical HRPCEE are chosen as research objects. Seismic performance of the two objects are studied and relevant damping devices using multiple ring tuned mass dampers (MRTMD) are designed. The influence of MRTMD on HRPCEE is investigated through finite element analysis using ANSYS. For the first equipment, optimal installation location and damping ratio of ring tuned mass dampers (RTMD) are discussed. The effects of RTMD frequency offset, MRTMD damping and MRTMD control of higher modes are also studied. For the second equipment, acceleration, displacement and stress response among structure without control, with RTMD and with MRTMD control are compared. Results show that the vibration of HRPCEE could be attenuated by RTMD/MRTMD and MRTMD outperforms RTMD. Control of higher modes is implementable but not indispensable for type one equipment while that is irreplaceable for type two equipment.
Keywords: MRTMD, HRPCEE, Vibration control, Finite element analysis, Damping

1. Introduction

High-Rise Porcelain Cylindrical Electrical Equipment (HRPCEE), such as disconnecting switch and transformer, is playing increasingly important role in the power supply system and is essential to its safe operation. However, considering the porcelain characteristics and special structural shape, it is not easy to ensure HRPCEE safety during earthquakes. Earthquake damage investigations from both abroad and at home show that HRPCEE experienced severe damage during the past earthquakes [1-3]. The Great Tangshan earthquake made more that 58% breakers and more than 66% arrestor out of work. During the 1994 Northridge earthquake, more than 50% HRPCEE experienced unrecoverable damage. Finding proper damping methods to attenuate the seismic inner-force and displacement response of HRPCEE is of great urgency.

Most HRPCEE is cantilever shape and some facilities even have heavy heads, such as big combined arrestors. The structural characteristics made HRPCEE vulnerable during earthquakes. Besides, the natural frequencies are in resonant with the earthquake dominant frequencies. Also, most insulators are made of porcelain and this kind of material is brittle and weak at absorbing energy. Furthermore, brackets used in practical applications often have amplification effect.

Researchers have proposed many methods to deal with the disturbing problem [4-9]. For example, bracing wires and robs are used to enhance the lateral stiffness to protect HRPCEE. However, this method do need large space and may lead to new weak points. Composite materials are used to replace the traditional porcelain ones and have many advantages [4]. Besides, base isolations are also used to enhance the HRPCEE seismic performance[8, 9]. Base isolations can sharply decrease the natural frequency of HRPCEE but increase the absolute displacement of HRPCEE. Unlike buildings, HRPCEE are more likely to be influenced by the conductors and thus base isolation methods may sometimes cause serious problems. GIS enrolled all the inner parts together with metal shell. This method can obviously increase the seismic resistant ability [7]. A serious problem of GIS is the isolating gas may cause environmental problems. Metallic dampers[5, 6] have been advocated and applied in some actual cases and have achieved positive results.

Multiple tuned mass dampers [10], first been proposed in 1993 and then been used in many areas is a passive energy absorption method and has many advantages[11-15]. Considering the vulnerability of HRPCEE and MTMD damping method. This paper proposed Multiple ring tuned mass dampers according to the HRPCEE shape to decrease the adverse vibration caused by earthquakes. Comparing with tuned mass dampers, MTMD is more robust and has more obvious damping effect[16-18]. At the same time, multiple ring tuned mass dampers is designed considering the centrosymmetry of HRPCEE and can be applied to reduce arbitrary horizontal HPRCEE vibration.

Followed by introduction, damping effect of two types of HRPCEE is discussed in section 2 and 3, respectively. After that, a conclusion and required future work is given.

Fig. 1 –High-Rise Porcelain Cylindrical Electrical Equipment (HRPCEE)

2. Damping effect of type I equipment

Current transformer LVQB6-220 is chosen as a prototype in this section. The equipment is about 3.63m high. The weight is about 760kg. The finite element analysis is carried out with ANSYS/LS DYNA. The numerical model is shown in far left of Figure 2

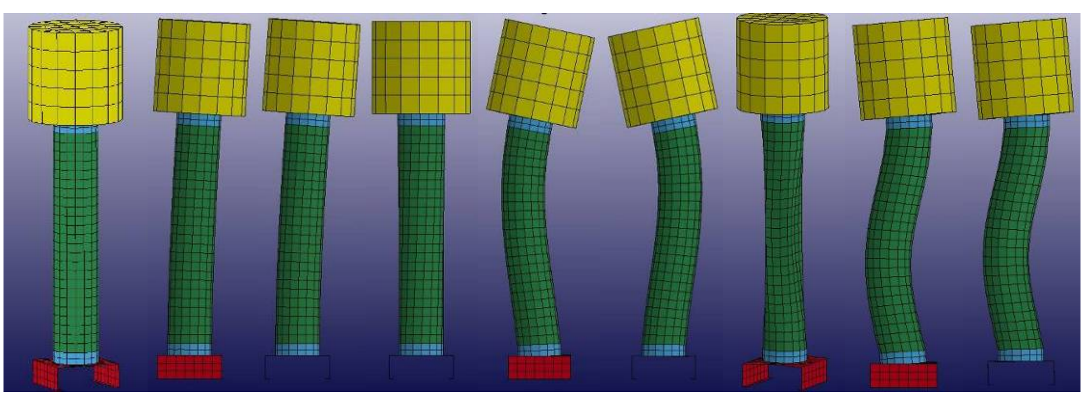


Fig. 2 – Type I HRPCEE and relevant modes

2.1 Modal analysis

It is necessary to analysis the modal information before carrying out other time history analysis. Table 1 gives the first 15 modes of the transformer. It can be drawn from Table 1 that although the equipment in the two perpendicular horizontal direction is not totally the same at the bracket position, the natural frequencies in the two horizontal are really close. Mode 1 and 2 refer to the fundamental modes while Mode 3 refers to the fundamental torque mode. Mode 4 and 5 refers to second order modes in x and y directions, respectively, while mode 13 and 14 are even higher modes. The rest are all local modes.

Table 1 – Modal information of type I HRPCEE

Mode	Period	Mode	Period	Mode	Period
1	0.393	6	0.037	11	0.019
2	0.377	7	0.037	12	0.018
3	0.089	8	0.035	13	0.018
4	0.051	9	0.019	14	0.018
5	0.049	10	0.019	15	0.017

2.2 Best TMD mounting position

In the finite element analysis, the mass ratio is set as 0.1. the damping ratio is set as 0.1. The TMD control frequency is set in accordance with the equipment natural frequency. An sine beat excitation is given and the TMD mounting position changes from the transformer bottle to top. The acceleration response of transformer top part is chosen as a reference. Dynamic responses of the transformer at different TMD mounting positions are listed in Table 2. It can be drawn from the table that as the mounting level increases, the damping effect increases, too. It is beneficial to mount TMD at the maximum displacement position of control mode.

Table 2 – TMD damping effect at different levels (mm, mm/s^2)

	Mounting Position	Acceleration Max	Displacement Max	Acceleration Reduction Ratio	Displacement Reduction Ratio
With TMD	0.05	3.1	12.5	-0.42%	1.20%
	0.14	3.1	12.4	0.91%	1.67%
	0.22	2.8	11.4	9.41%	10.0%
	0.30	2.4	9.56	23.5%	24.3%
	0.39	2.1	8.28	31.2%	34.5%
	0.47	1.9	7.76	37.8%	38.6%
	0.56	1.7	7.05	43.6%	44.2%
	0.73	1.7	7.62	45.0%	39.7%
	0.82	1.4	6.34	55.7%	49.9%
	0.90	1.0	4.46	66.1%	64.7%
	0.98	0.8	4.33	72.9%	65.7%
Without TMD		3.1	12.6		

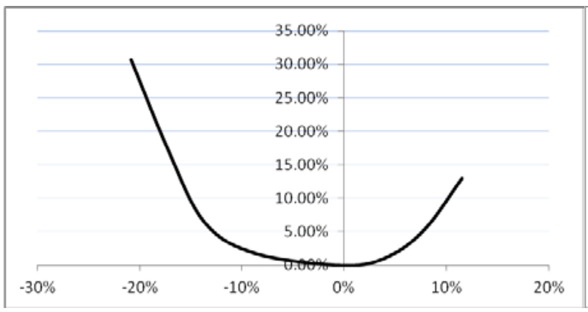
2.3 TMD detuning effect

In actual cases, the dynamic characteristics of research equipment may differ from the design values. This may thus lead to deviation from TMD actual control frequency to theoretical best value. So it is meaningful to discuss the TMD detuning effect. It can be foresee that the damping effect will decrease as the detuning level increases. The exact damping effect will be discussed in this section.

In the finite element analysis, the TMD control frequency changes from 2.2Hz to 3.1Hz. Three different ground motions, artificial, El Centro and Wolong natural ground motion records, are chosen and the maximum acceleration and displacement responses are defined as reference and compared. It can be concluded that the acceleration response is more sensitive to the deviation compared with displacement. Besides, the damping effects differ when TMD facing sine beat excitation and natural ground motion records. Compared with natural ground motion record, TMD performs better patterns. At the same time, TMD does not perform best at the best TMD control values because of the input frequency band. However, this phenomenon cannot be treated as negative only. Numerical simulation results show that TMD show more stability facing natural ground motions rather than sine beat excitation.

Table 3 – Detuning effect for acceleration and displacement

Freq.	Deviation	Acc(+)	Deviation	Acc(-)	Deviation	Dis(+)	Deviation	Dis(-)	Deviation
2.20	-21%	1037	30.61%	-1019	30.36%	4.1	18.00%	-3.3	18.29%
2.30	-17%	931	17.29%	-949	21.37%	3.9	13.24%	-2.9	3.88%
2.40	-14%	845	6.39%	-887	13.45%	3.7	8.41%	-2.8	-0.87%
2.54	-9%	808	1.77%	-812	3.86%	3.5	2.08%	-2.7	-2.58%
2.78	0%	794	0.00%	-782	0.00%	3.4	0.00%	-2.8	0.00%
2.90	4%	805	1.35%	-796	1.87%	3.6	5.51%	-2.9	3.60%
3.00	8%	838	5.47%	-838	7.25%	3.9	12.99%	-3.0	7.03%
3.10	12%	897	12.97%	-891	13.95%	4.2	21.86%	-3.2	16.39%



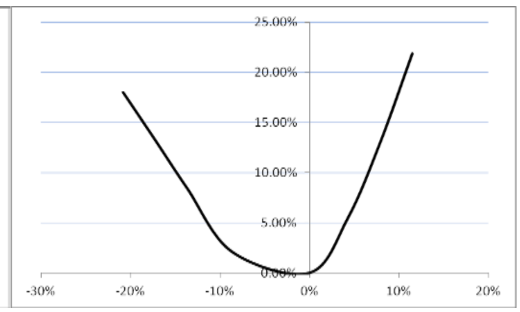


Fig. 3 – Detuning effect curves for acceleration and displacement

2.4 MRTMD damping effect

MRTMD are used to replace TMD to enhance the damping effect and robustness. El Centro and Wolong ground motion records are used [19] and relevant time histories are plotted. The number of MRTMD unit is set as 3. The total mass of is 10% of the transformer and corresponding control frequencies are set as 2.3Hz, 2.5Hz, and 2.8Hz. Results show that MRTMD shows much better damping effect.

For certain equipment, several basic modes, not only the first one, account significantly for the equipment vibration. So this paper tries to achieve better damping effect through control higher modes of the equipment. In this case, the second mode in horizontal direction is 20.45Hz. The total mass of MRTMD remains 10%. Two units are used to control the first mode and the third unit is used to control the second mode. The mass ratio between the first and the second is determined by the model effective mass ratio, which is 48.6:7.7. The Fourier spectrum of the transformer under El Centro with control of the first mode only and control of first two modes are compared in Figure 4. From the right figure it can be clearly seen that the frequencies around the second mode has been totally diminished. In this case, the second mode does not contribute much to the vibration caused by earthquake, the advantage of control of higher modes does not perform significantly. But it can be anticipated that control of higher modes will be of benefits under conditions which higher modes contributes much to the equipment vibration.

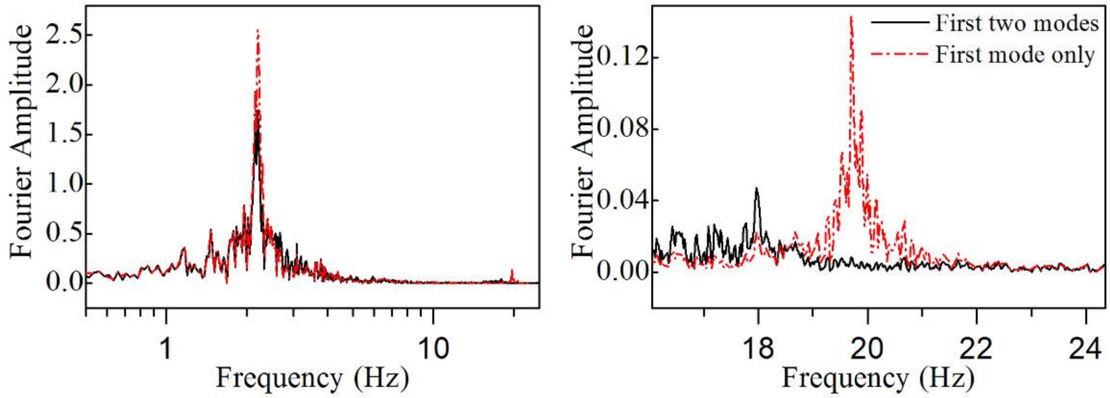


Fig. 4 – Fourier spectrum of HRPCEE under El Centro

Table 4 – Vibration reduction ratio under El Centro (mm、mm/s^2)

Type	Acc(+)	Reduction Ratio	Acc(-)	Reduction Ratio	Dis(+)	Reduction Ratio	Dis(-)	Reduction Ratio
RTMD	-9780	0.16	8064	0.21	-42.08	0.05	46.62	0.01
MRTMD	-8828	0.24	7186	0.30	-36.90	0.17	41.37	0.12
Non-control	-11575	0.00	10201	0.00	-44.33	0.00	47.06	0.00

Table 5 – Vibration reduction ratio under Wolong（mm、mm/s^2）

Type	Acc(+)	Reduction Ratio	Acc(-)	Reduction Ratio	Dis(+)	Reduction Ratio	Dis(-)	Reduction Ratio
RTMD	-50138	-0.02	46910	-0.02	-234.25	-0.01	244.5	0.03
MRTMD	-40009	0.19	38178	0.17	-189.37	0.18	199.6	0.20
Non-control	-49268	0.00	45911	0.00	-232.13	0.00	250.9	0.00

3. Damping effect of type II equipment

A 550kV breaker, manufactured by Siemens, shown in top left corner of Figure 5, is chosen as a object in this section. The voltage class of this equipment is higher than the one discussed in section 2. The porcelain shape of this breaker is much different with the transformer discussed in section 2.

The modal information is listed in Table 6 and plotted in Figure 5. The dominant frequency band of most earthquake is 1-10Hz. It can be found that more than one modes are in the coverage which means that not only the first modes, but also higher modes will contribute significantly to the equipment vibration.

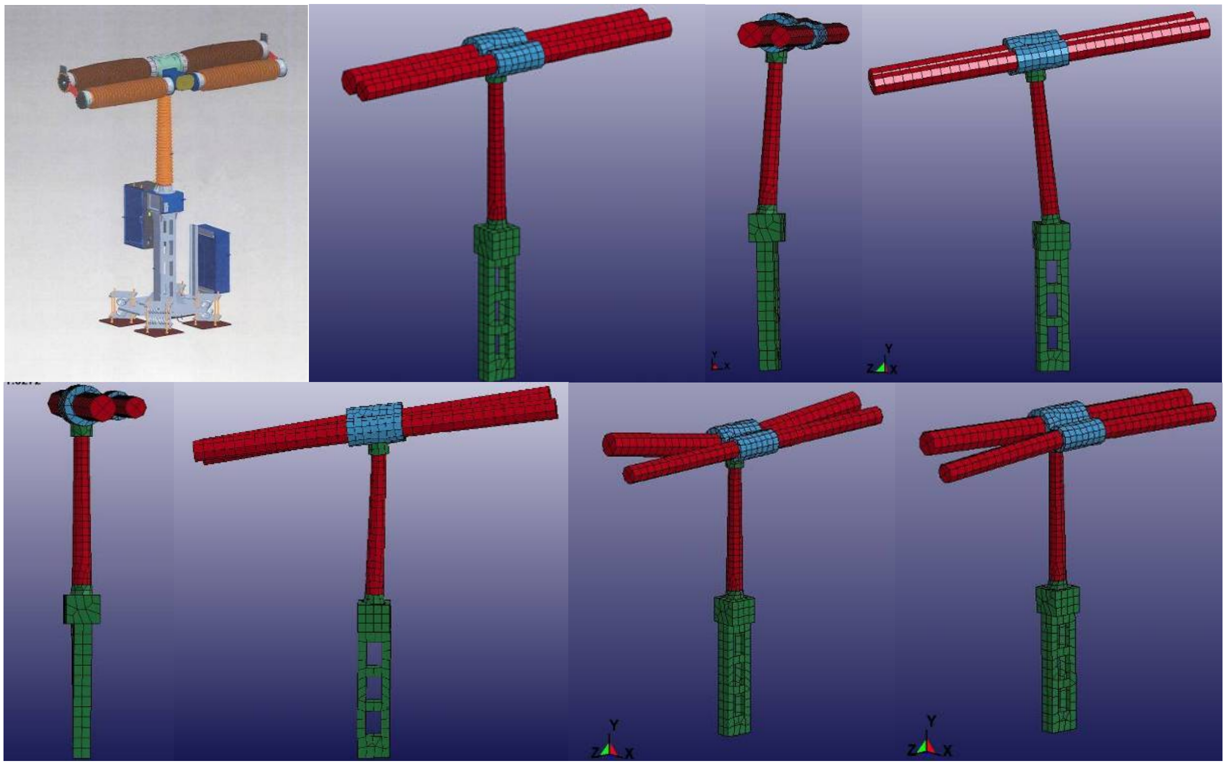


Fig. 5 – Type II HRPCEE and relevant modes

Table 6 – Modal information of type II HRPCEE

Mode	Eigenvalue	Radians	Cycles	Period
1	2.37E+01	4.87E+00	7.75E-01	1.29E+00
2	3.38E+01	5.82E+00	9.26E-01	1.08E+00
3	1.32E+02	1.15E+01	1.83E+00	5.47E-01
4	4.18E+02	2.04E+01	3.25E+00	3.07E-01
5	1.27E+03	3.57E+01	5.68E+00	1.76E-01
6	1.85E+03	4.31E+01	6.85E+00	1.46E-01
7	2.25E+03	4.74E+01	7.54E+00	1.33E-01
8	2.89E+03	5.38E+01	8.56E+00	1.17E-01
9	3.18E+03	5.64E+01	8.98E+00	1.11E-01
10	9.19E+03	9.59E+01	1.53E+01	6.55E-02
11	1.16E+04	1.08E+02	1.72E+01	5.83E-02
12	1.70E+04	1.30E+02	2.08E+01	4.82E-02
13	2.43E+04	1.56E+02	2.48E+01	4.03E-02
14	3.39E+04	1.84E+02	2.93E+01	3.41E-02
15	6.59E+04	2.57E+02	4.09E+01	2.45E-02

3.1 MRTMD parameters setting

One RTMD unit is installed at top of the vertical insulator to control the first mode. Four RMTD units are installed at each end of the horizontal insulators to control the higher modes which also contribute significantly to equipment vibration. The total mass of the MRTMD is set as 10% of the equipment. The mass ratio among each RTMD unit is determined by the mode effective mass ratio. The damping ratio is set as 10%. At the same time, the equipment with Single TMD is also simulated as a comparison. Three indexes are chosen to evaluate the damping effect of MRTMD. 1) The acceleration and displacement response of the horizontal insulator root part. 2) The stress response of lower part of the vertical insulator. 3) The stress response of the horizontal insulator.

3.2 Damping effect

Acceleration response of the end part of horizontal part under El Centro and Wolong earthquake is plotted in Figure 6. Maximum acceleration response in given in Table 7. It can be observed from the table that MRTMD reduced the vibration significantly. The acceleration vibration reduction ratio under El Centro is 42% while that under Wolong and Qianan is 35% and 34%, respectively. Compared with Single RTMD, MRTMD shows superiority in both effectiveness and robustness.

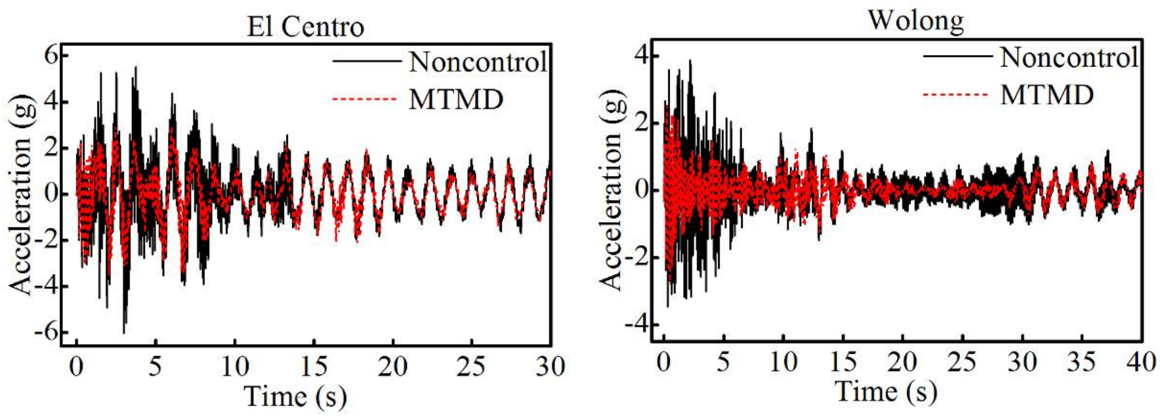


Fig. 6 – Acceleration response of HRPCEE under El Centro and Wolong

Table 7 – Acceleration reduction ratio for type II HRPCEE (m/s^2)

	EICENTRO		Wolong		Qianan	
	Acc.Max	Reduction ratio	Acc.Max	Reduction ratio	Acc.Max	Reduction ratio
Noncontrol	6.05	0%	3.88	0.00	4.24	0
RTMD	5.15	14%	3.99	-3%	4.08	4%
MRTMD	3.50	42%	2.53	35%	2.80	34%

For clarity, time history of displacement and stress response is not given in this paper. Relevant maximum values are listed in Table 8 and 9. The peak displacement reduction ratio under El Centro is 19% while that under Wolong and Qianan is 21% and 41%. The peak stress reduction ratio under El Centro is 39% while that under Wolong and Qianan is 38% and 39%. Performance of MRTMD is much better on both effectiveness and robustness than RTMD under same mass ratio.

Table 8 – Displacement reduction ratio for type II HRPCEE (mm)

	EICENTRO		Wolong		Qianan	
	Dis.max	Reduction Ratio	Dis.max	Reduction Ratio	Dis.max	Reduction Ratio
Noncontrol	150	0%	78.6	0%	65.8	0%
RTMD	127	15%	64.5	18%	42.8	35%
MRTMD	122	19%	62.2	21%	39	41%

Table 9 – Sress reduction ratio for type II HRPCEE (MPa)

	EICENTRO		Wolong		Qianan	
	Stress max	Reduction Ratio	Stress max	Reduction Ratio	Stress max	Reduction Ratio
Noncontrol	17.5	0%	17.5	0%	17.3	0%

RTMD	11.9	32%	11.4	35%	11.4	34%
MRTMD	10.7	39%	10.8	38%	10.5	39%

From Figure 7 it can be drawn that not only the first mode, but also the second mode, have significant impact on equipment vibration. So it is reasonable to control higher modes and finite element analysis does show the superiority of MRTMD.

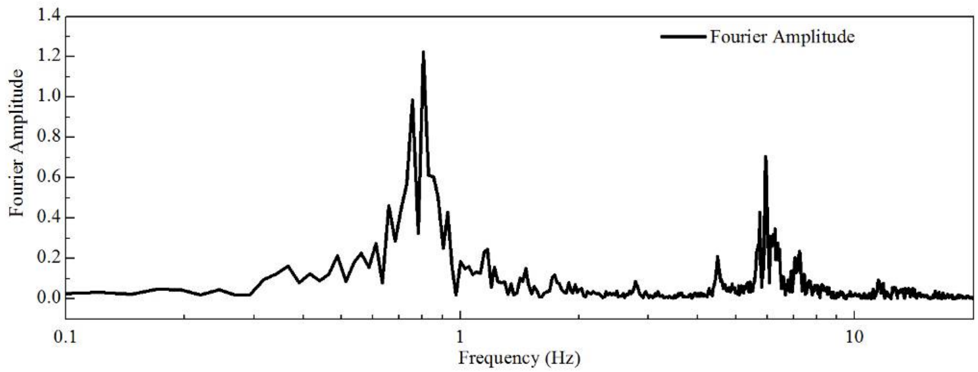


Fig. 7 – Fourier Spectrum of type II HRPCEE under white noise

4. Conclusions

This paper introduced a new damping method for HRPCEE based on tuned mass damping theory. Two typical types of HRPCEE are choen and discussed in this paper. Best TMD mounting position is researched and TMD detuning effect is studied. Seismic responses of the each HRPCEE chosen in the paper with and without control are compared.Besides,damping effect between RTMD and MRTMD is compared. Furthermore, as to a specific HRPCEE, whether to control the first mode only or together with even higher modes are also researched. Numercial Results show that for the 'I' type equipment chosen in the paper, MRTMD,which involves three damping units,consitituing 10% of the total facility mass, can reduce the peak acceleration and displacement response to about 80% compared with non-control. For the 'T' type equipment used in this paper, which involves six damping units, consitituting 10% of the total mass, can averagely reduce the peak acceleration and displacement response to about 60% compared with non-control. The shake table test carried out in this paper does verify the effectiveness of the damping method advocated in this paper.

In future works, more emphasis should be paid on the might exist influence on the HRPCEE function caused by the damping device.

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6. References

[1] Qiang, Xie, and Zhu Ruiyuan. "Damage to electric power grid infrastructure caused by natural disasters in China." IEEE Power and Energy Magazine 9.2 (2011): 28-36.

[2] Araneda, J. E., Rudnick, H., Mocarquer, S., & Miquel, P. "Lessons from the 2010 Chilean earthquake and its impact on electricity supply." Power System Technology (POWERCON), 2010 International Conference on. IEEE, 2010.

[3] Çağnan, Zehra, Rachel A. Davidson, and Seth D. Guikema. "Post-earthquake restoration planning for Los Angeles electric power." Earthquake Spectra 22.3 (2006): 589-608.

[4] Xidong, Liang, and Fan Ju. "Development of composite insulators in China." Dielectrics and Electrical Insulation, IEEE Transactions on 6.5 (1999): 586-594.

[5] ZHANG, X., DAI, Z., CAO, M., & LU, Z. "Dynamic behavior of 500 kV metal oxide arresters with a new type of lead dampers." Journal of Chongqing University 7 (2013): 013.

[6] CAO, Meigen, et al. "Study of aseismic performance and damping effects of porcelain column circuit breaker SF6." Engineering Journal of Wuhan University (2009): S1.

[7] Okabe, Shigemitsu, Sadayuki Yuasa, and Shuhei Kaneko. "Evaluation of Breakdown Characteristics of Gas Insulated Switchgears for Non-standard Lightning Impulse Waveforms-Breakdown Characteristics for Non-standard Lightning Impulse Waveforms Associated with Lightning Surges." Dielectrics and Electrical Insulation, IEEE Transactions on 15.2 (2008): 407-415.

[8] Murota, Nobuo, Maria Q. Feng, and Gee Yu Liu. "Earthquake simulator testing of base-isolated power transformers." Power Delivery, IEEE Transactions on 21.3 (2006): 1291-1299.

[9] Saadeghvaziri, M. A., Feizi, B., Kempner Jr, L., & Alston, D. "On seismic response of substation equipment and application of base isolation to transformers." Power Delivery, IEEE Transactions on 25.1 (2010): 177-186.

[10] Igusa, T., and K. Xu. "Vibration control using multiple tuned mass dampers." Journal of sound and vibration 175.4 (1994): 491-503.

[11] Rana, Rahul, and T. T. Soong. "Parametric study and simplified design of tuned mass dampers." Engineering structures 20.3 (1998): 193-204.

[12] Li, Chunxiang. "Performance of multiple tuned mass dampers for attenuating undesirable oscillations of structures under the ground acceleration." Earthquake engineering & structural dynamics 29.9 (2000): 1405-1421.

[13] De Angelis, Maurizio, Salvatore Perno, and Anna Reggio. "Dynamic response and optimal design of structures with large mass ratio TMD." Earthquake Engineering & Structural Dynamics 41.1 (2012): 41-60.

[14] Stewart, George, and Michael Lackner. "Offshore wind turbine load reduction employing optimal passive tuned mass damping systems." Control Systems Technology, IEEE Transactions on 21.4 (2013): 1090-1104.

[15] Lin, Chi ‐ Chang, Wang, J. F., Lien, C. H., Chiang, H. W., and Lin, C. S. "Optimum design and experimental study of multiple tuned mass dampers with limited stroke." Earthquake Engineering & Structural Dynamics 39.14 (2010): 1631-1651.

[16] Sauter, D., and P. Hagedorn. "On the hysteresis of wire cables in Stockbridge dampers." International Journal of Non-Linear Mechanics 37.8 (2002): 1453-1459.

[17] Zhang, Peng, Song, G., Li, H. N., and Lin, Y. X. "Seismic control of power transmission tower using pounding TMD." Journal of Engineering Mechanics (2012).

[18] Wang, Jer-Fu, and Chi-Chang Lin. "Seismic performance of multiple tuned mass dampers for soil–irregular building interaction systems." International journal of solids and structures 42.20 (2005): 5536-5554.

[19] IEEE Recommended Practice for Seismic Design of Substations, IEEE Standard 693-2005, Institute of Electrical and Electronics Engineers, 2005.