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Study on Soil-Pile-Structure-TMD Interaction System by Shaking Table Model Test

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Abstract: The results of a shaking table model test for the soil-pile-structure-TMD (tuned mass damper) interaction system are presented in this paper. It has been testified that the TMD effectiveness to control the seismic responses of the structure, which is built on soil site, is much lower than that at the situation if the controlled structure constructed on rigid site due to the effect of soil-structure interaction. Some test results also show that TMD device might be harmful to the controlled structure if the soil- structure interaction is not considered in the TMD design when the structure is built on the soft soil site. For the structure constructed on soil foundation, this research verifies that the SSI effects must be understood carefully before the design of the TMD control, to determine if the control is necessary and soil-structure interaction must be considered in choice of the reasonable parameters of the TMD device.

Key words: soil-pile-structure interaction; TMD's performance; shaking table model test

1 Introduction

In the various types of structural control system developed, TMD is a more practical type due to its simple mechanism, reliability and low maintenance. However, its effectiveness to suppress vibration is generally dependent on the parameters of the ratio of its designed frequency to the fundamental frequency of the controlled structure and the vibration damping of the structure. It means that the exact evaluation of the modal characteristics, especially the fundamental frequency of the controlled structure is a very important factor for the design of the TMD device. Therefore, the SSI effects, which affect the dynamic characteristics of the structure, must be considered when the controlled structure is constructed on soil layer. This problem has arised the interesting of many researchers. Many studies[1-4] have been done on the effects of SSI on the TMD's performance under the excitation of earthquake or wind in detail. It was concluded from their works that strong SSI effects could greatly modify the damping characteristics of the structure, which in turn affect the performance of a damper system mounted on top of the structure under the seismic excitation. The damper's effectiveness rapidly decreases, as the soil medium gets softer due to the significant contribution to the damping of the soil-structure system from soil material hysteresis and radiation effect. For structures resting on very soft soil, SSI effects can make a damper on the structure totally ineffective. In order to reasonably evaluate the feasibility of using dampers to control the maximum structural responses, SSI effects must be taken into account. The numerical results also show that SSI has some influence on the effectiveness of TMD performance to mitigate the wind response of the structures, but the effect is not as strong as on TMD performance to mitigate the seismic response of the controlled structures. It is especially important for TMD application to mitigate wind-induced response of structures with structural damping that TMD must be tuned to the fundamental frequency of the soil-structure system instead of the structure alone.

However, all the studies in structural control with considerations of the SSI effects were conducted analytically or numerically. It is imperative to verify the research results mentioned above with small-scale model test in laboratory or ultimately with full-scale structure tests in field conditions. In order to better understand the effects of SSI on TMD's performance and verify the research results derived from numerical computation, a shaking table model test on soil-structure-TMD interaction system is presented in this paper.

2 Modeling of test

The soil-pile-structure interactive system used in this model test is composed of three parts, namely superstructure, TMD device installed on the top of the structure and group-pile foundation which is embedded in finite-size horizontal soil layer, as shown in Fig.1 and Fig.2. The five-storey structure is a steel frame with 1.5 meters high in all and 0.3 meter for each storey. Its planar dimension is 0.3m×0.3m. Seismic motion is input in single horizontal direction. The steel frame in the perpendicular direction of seismic excitation is designed very strong, to ensure the structure only can vibrate along the direction of seismic excitation during the test. The fundamental frequency of the model frame can be modulated through changing the number of horizontal link rods along the seismic excitation direction. There are two types of the superstructure adopted in the test, with the fundamental frequency 5.86Hz and 6.64Hz, for convenience of expression, denoted as A1 and A2 frame respectively. A special electromagnetic TMD vibration control device with two horizontal oscillators is designed for this test[5]. The fundamental frequency of TMD device can be tuned to some extent through changing the stiffness of the oscillators. Group-pile foundation with four piles is used in this test. Each single pile is 0.5 meter long. The cross section for each single pile is square with dimension 0.03 m×0.03 m. The foundation is made of reinforced concrete, in which reinforcement steel bar is simulated by iron wire.

Fig.1 Steel frame structure and TMD device

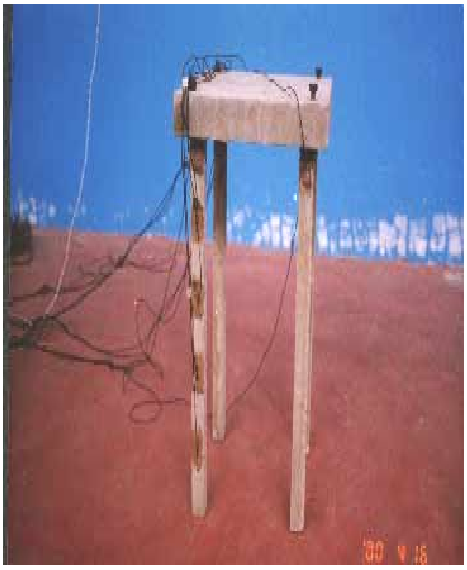

Fig.2 Group-pile foundation

Three different seismic waves are considered in order to investigate TMD's performance in a more realistic environment in the test. They are El Centro wave, Shanghai wave and artificial wave, in which Shanghai wave is produced according to the characteristics of soil layer in Shanghai region, while the artificial wave is created according to the characteristics of test model. Fig.3 and 4 give acceleration time histories of Shanghai wave and artificial wave, respectively. For above three seismic waves, the input peak values of acceleration are 0.1g and o.2g, respectively. According to the purposes of the test, there are 12 test cases of different combination of different foundation, superstructure and TMD system, as listed in Table 1. In the test, an acceleration sensor is fixed at the top of the frame to measure the seismic acceleration response. Meanwhile four strain sensors are set at the base of four columns of the frame to record the seismic strain responses. The planer dimension of elliptic shaking table is 4m×3m. Its work frequency ranges from 0.1 to 80.0 Hz. The model of soil-pile-structure interactive system is shown in Fig.5.

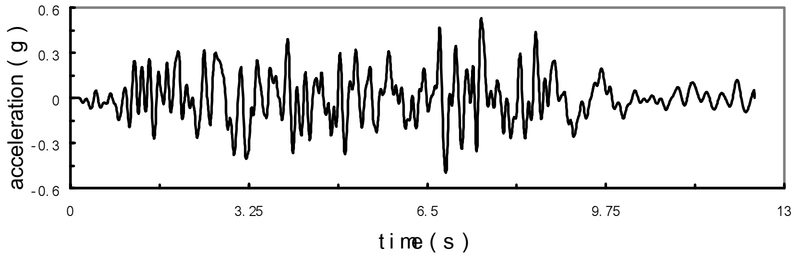

Fig. 3 Acceleration time history of Shanghai wave

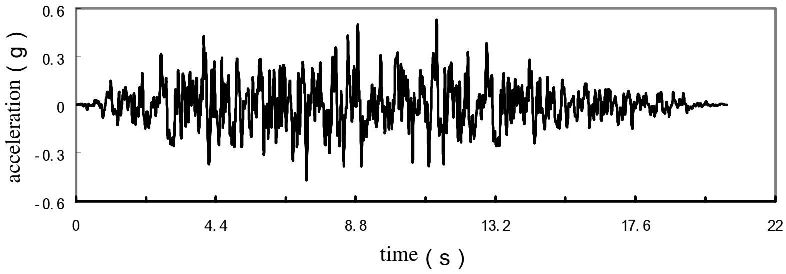

Fig.4 Acceleration time history of artificial wave

Tab.1 The combination of foundation-structure-TMD system and their code

Foundation Type	A1 frame			A2 frame		
	No TMD	TMD (f_a)	TMD (f_b)	No TMD	TMD (f_a)	TMD (f_b)
Rigid Foundation	A1N0	A1T0a	A1T0b	A2N0	A2T0a	A2T0b
Pile Foundation	A1N4	A1T4a	A1T4b	A2N4	A2T4a	A2T4b

The following compares the seismic responses of the frame resting on rigid site and group-pile foundation in order to investigate the effects of SSI on TMD's performance under different earthquake excitations.

Fig.5 Soil-pile-structure interactive system

3. Model test results

For comparing the seismic responses of the frame with and without TMD control, a control effectiveness α of TMD device is defined as below.

$$\alpha = (c - c^{'})/c \qquad (1)$$

In which c and $c^{'}$ are the absolute values of the seismic peak response of the frame without and with TMD control, respectively. They can represent any seismic responses of the frame. In this paper, the acceleration at the frame top and dynamic strain at the structural base are examined. From the formula, if α is a positive value less than 1, it indicates that TMD device can performance the function of reducing the seismic response of the structure. When α is a negative value, it means that TMD can't reduce the seismic responses of the structure but increase them. Under this circumstance, the TMD has negative effects on the structure rather than positive effects.

In the test, the first natural frequency of the TMD devices mounted on the top of A1 and A2 frame is tuned to 5.76Hz and 6.60 Hz, respectively.

3.1 Seismic response control of the frame on rigid site

The effectiveness of TMD for controlling acceleration and dynamic strain response of the frame, which is fixed on the rigid site are listed in Tables 2 and 3. When the structure is built on rigid site, it means that SSI effect doesn't exist. It is shown in Tab.2 and 3 that TMD device can decrease seismic responses well, including acceleration and strain responses both for A1 and A2 structures.

Tab.2 Maximum acceleration response and control effectiveness of TMD (rigid site)

Earthquake Motion		Peak value（g）		α(%)	Peak value（g）		α(%)
		A1N0	A1T0a		A2N0	A2T0a	
El Centro Wave	0.1g	0.193	0.118	38.8	0.181	0.136	24.9
	0.2g	0.547	0.340	37.8	0.520	0.413	20.6
Shanghai Wave	0.1g	0.336	0.157	53.3	0.272	0.200	26.5
	0.2g	0.618	0.404	34.6	0.707	0.428	39.5
Artificial Wave	0.1g	0.254	0.150	40.9	0.263	0.154	41.4
	0.2g	0.473	0.358	24.3	0.567	0.356	37.2

Tab.3 Maximum strain response and control effectiveness of TMD (rigid site)

Earthquake Motion		Peak value（g）		α(%)	Peak value（g）		α(%)
		A1N0	A1T0a		A2N0	A2T0a	
El Centro Wave	0.1g	15.7	9.0	42.7	12.1	10.5	13.2
	0.2g	43.2	25.2	41.7	35.1	33.4	4.80
Shanghai Wave	0.1g	25.8	12.4	48.1	21.1	18.1	14.2
	0.2g	50.7	33.6	33.7	49.6	39.7	20.0
Artificial Wave	0.1g	20.6	14.0	32.0	18.3	13.3	27.3
	0.2g	36.2	29.7	18.0	37.4	30.6	18.2

Time histories of seismic responses are shown in Figs.6 and 7. In each figure the dot and solid line recorded by acceleration sensor installed at the top of the frame represent the acceleration responses of the structure with and without TMD device, respectively. It's shown clearly in Figs.6 and 7 that the TMD device performances very well for reducing the seismic responses of the structure with rigid site. The TMD device greatly decreases the seismic responses of the structure for almost all the time histories, except one case in which α is only 4.8%. The conclusion is as same as in many papers mentioned above for TMD's performance studies.

From the model test results, most of which are not shown in this paper, it's can be concluded that the vibration control effectiveness of TMD mounted on the top of the frame with rigid site is obvious. TMD greatly reduces peak acceleration response and dynamic strain response of the frame. Several test results for rigid site case are listed here in order to compare with those of for pile foundation.

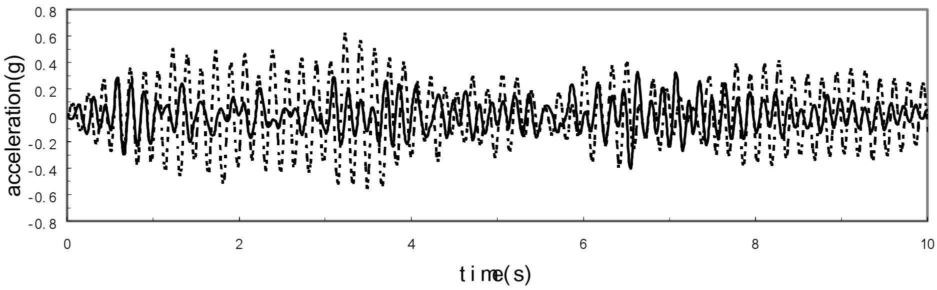

Fig.6 Acceleration time history at the top of A1 structure (Shanghai wave, 0.2g)

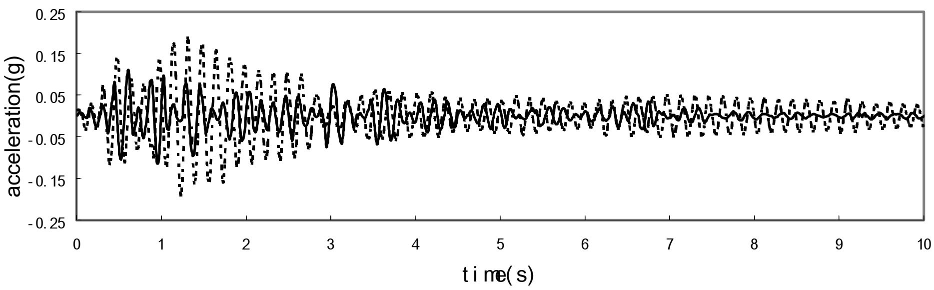

Fig.7 Acceleration time history at the top of A1 structure (El Centro wave, 0.1g)

3.2 Seismic response control of the frame on pile foundation

It's well known that the interaction of soil-pile-structure changes dynamic characteristics of the structure such as frequency, damping, mode shapes etc. The dynamic characteristics of the structure with pile foundation are different from that of the structure built on rigid site. Meanwhile seismic input motion at structure base is 'filtered' and 'magnified' by the soil site and the foundation. As we know, the control effectiveness of TMD device is closely depended on dynamic characteristic of the controlled structure. In order to better understand the effects of SSI on the frequency design of the TMD device, in the tests the TMD device will be assigned to tune to two frequencies f_a and f_b. f_a is the designed fundamental frequency of the TMD device when the structure is built on rigid site, while f_b is designed corresponding to the first modal frequency of the SSI system f_s. The designed frequencies of TMD devices for A1 and A2 frames on group-pile foundation are listed in Table 4. In the table, f_0 is the first modal frequency of the frame without considering the effect of soil-pile-structure interaction. λ_a And λ_b are frequency rates of f_a and f_b to f_s, respectively.

Tab.4 Fundamental frequencies of the controlled system and TMD

Frame	f_0	f_s	f_a	f_b	λ_a	λ_b
A1	5.86	4.88	5.76	4.80	1.18	0.98
A2	6.64	5.86	6.60	5.76	1.13	0.98

For both the A1 and A2 frames including group-pile foundation, two group tests are investigated, respectively. In one group test the fundamental natural frequency f_a of TMD device is determined according to the modal characteristics of the frame on rigid site. In the other group test the fundamental frequency f_b of TMD is tuned by characteristics of the soil-pile-structure interactive system.

The maximum seismic acceleration responses at the top of the steel frame and the corresponding vibration control effectiveness of TMD for the group-pile foundation-frame interactive system from each test case are listed in Tabs.5 and 6. The excitations of the shaking table are same as mentioned in the previous section. As for the seismic strain responses, the results are shown in Tabs.7 and 8. The vibration control effectiveness of TMD is calculated by Eq. (1). Some typical time histories of seismic responses of the frame with TMD frequency f_b are shown in Fig.8-11. From the data listed in Tab.2-3, Tab.5-8 and time histories, the following conclusions can be drawn.

The performance of TMD device is dependent on its designed fundamental frequency. Control effectiveness of TMD device with fundamental frequency f_a is lower than that of TMD device with frequency f_b. In some cases, TMD with frequency f_b can reduce the seismic responses of the frame, however, it is hard for TMD device with frequency f_a under the same conditions.

The vibration control effectiveness α of TMD device for the frame built on group-pile foundation is far below than that of TMD for frame on rigid site, simultaneously TMD on group-pile foundation performances instability. In most tests, as shown in Tabs.5-8, the values of α are small comparing with those in Tabs.2 and 3, even less than zero for both TMD with frequency f_b and TMD with frequency f_a. Comparing Fig.6 and 7 with Fig.8-11, the TMD device for structures built on group-pile foundation performances worse, though the SSI effects has been taken into account in its frequency design.

It can be concluded that SSI have considerable effects on the performance of TMD device installed on the top of the frame. When design the TMD device for structure built on soft soil, the SSI effects must take into account in order to determined the optimal frequency of TMD. However, the control effectiveness of TMD device with optimal frequency is still much lower than that of the TMD device designed for the structure built on rigid site.

Tab.5 Maximal acceleration response and effectiveness of corresponding TMD

Earthquake Motion		A1N4	A1T4b		A1T4a	
		Peak value (g)	Peak value (g)	α (%)	Peak value (g)	α (%)
El Centro wave	0.1g	0.172	0.167	2.9	0.169	1.7
	0.2g	0.400	0.342	14.5	0.381	4.8
Shanghai wave	0.1g	0.183	0.199	-8.7	0.205	-12.0
	0.2g	0.418	0.427	-2.2	0.556	-33.0
Artificial wave	0.1g	0.206	0.200	2.9	0.193	6.2
	0.2g	0.381	0.376	1.3	0.413	-8.4

Tab.6 Maximal acceleration response and effectiveness of corresponding TMD

Earthquake motion		A2N4	A2T4b		A2T4a	
		Peak value (g)	Peak value (g)	α (%)	Peak value (g)	α (%)
El Centro wave	0.2g	0.470	0.405	13.8	0.438	6.8
Shanghai wave	0.2g	0.464	0.419	9.7	0.438	5.6
Artificial wave	0.1g	0.233	0.192	17.6	0.193	17.2
	0.2g	0.474	0.456	3.8	0.432	8.9

Tab.7 Maximal strain response and effectiveness of corresponding TMD

Earthquake Motion		A1N4	A1T4b		A1T4a	
		Peak value (g)	Peak value (g)	α (%)	Peak value (g)	α (%)
El Centro Wave	0.1g	15.9	18.6	-17.0	17.4	-9.4
	0.2g	33.5	30.4	9.3	36.2	-8.1
Shanghai Wave	0.1g	17.7	20.3	-14.7	22.0	-24.3
	0.2g	38.4	46.7	-21.6	51.7	-34.6
Artificial wave	0.1g	18.9	20.3	7.4	19.3	-2.1
	0.2g	36.9	37.3	-1.1	42.0	-13.8

Tab.8 Maximal strain response and effectiveness of corresponding TMD

Earthquake motion		A2N4	A2T4b		A2T4a	
		Peak value (g)	Peak value (g)	α (%)	Peak value (g)	α (%)
El Centro wave	0.2g	32.9	33.7	-2.4	34.7	-5.5
Shanghai wave	0.2g	36.4	35.0	3.8	34.6	4.9
Artificial wave	0.1g	19.3	16.1	16.6	16.2	16.1
	0.2g	37.3	37.2	0.0	37.7	-1.0

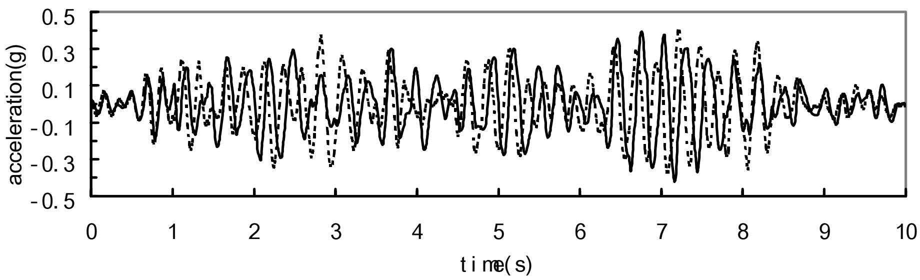

Fig.8 Acceleration time history of P4-A1 structure (Shanghai Wave, 0.2g)

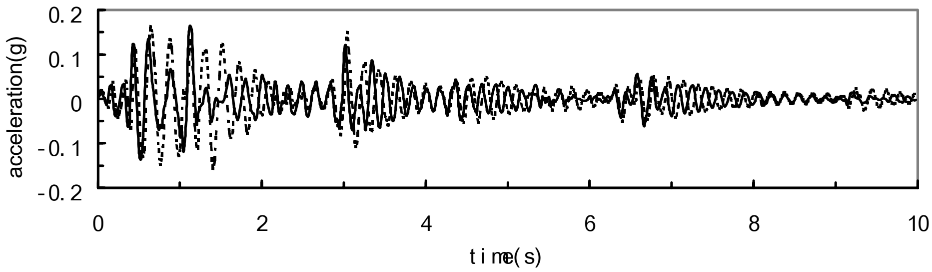

Fig.9 Acceleration time history of P4-A1 structure (El Centro Wave, 0.1g)

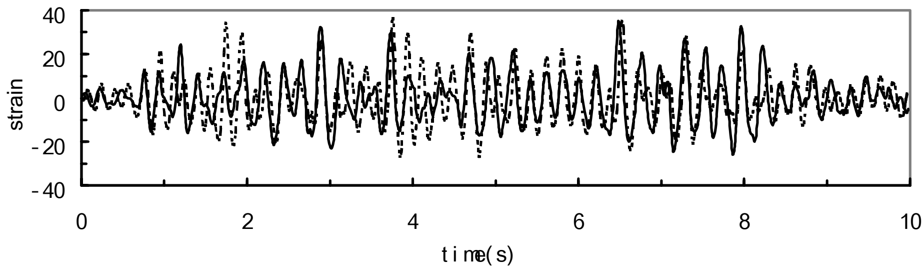

Fig.10 Strain time history of P4-A2 structure (Shanghai wave, 0.2g)

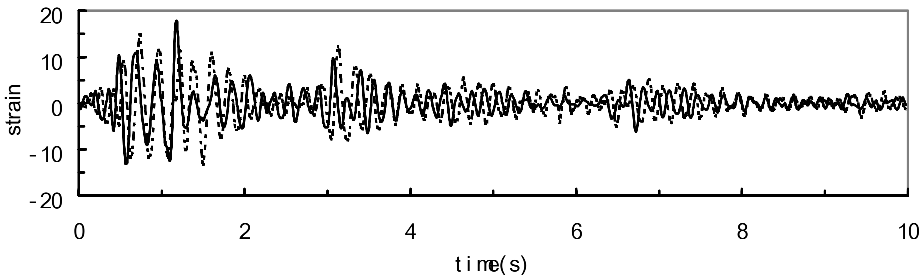

Fig.11 Strain time history of P4-A1 structure (El Centro wave 0.1g)

4 Conclusions

Soil-structure-TMD interaction problem under the excitation of earthquake is more complicated than the problem considering only the interaction between the structure and soil, for it has to investigate the performance of TMD device and determine if incorporates the effects of SSI in TMD design. In general, the structural deformation and shear force at base will be reduced due to the effects of SSI. It's often acceptable for practical reasons to assume a rigid site for a structure, because neglecting SSI effects results in the structural design more conservative. A tuned mass damper is required only when it must significantly reduce the structural responses. Understanding the actual performance of the tuned mass damper in an earthquake environment is thus pertinent for economic reasons. Many research results about the TMD's performance with the considerations of SSI effects have been achieved analytically or numerically in the past ten years. The general conclusion is that effects of soil-pile-structure interaction weaken the control effectiveness of TMD significantly. The results of shaking table model tests introduced in this paper are consistent with conclusions derived from theoretical analyses and numerical simulation.

The principle of TMD structural control is simple. However, it is necessary to analysis carefully the effects of soil-structure interaction on the seismic behaviors of the structure prior to the design of the TMD control, to determine if the control has to be applied to the structure which is built on soil site. If TMD control is required, many factors affecting its seismic performance such as its stability and reliability, etc should be taken into account due to the effects of SSI.

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References

1. Y. L. Xu and K. C. S. Kwok, Wind-induced response of soil-structure-damper system, J. Wind Engng. Ind. Aerodyn., 1992: 41: 2057-2068
2. B. Samali, K. C. S. Kwok and P. K. Geoghegan, Soil-structure-damper interaction under earthquake loading, Proc. 1st Int. Conf. on Motion and Vibration Control, Yokohama, Japan, 1992, 7-11.
3. M. Lou and J. Wu, Effect of soil-structure interaction on structural control. Dynamic Soil-Structure Interaction (Ed. By C. Zhang and J.D. Wolf), International Academic Publisher, 1997, 188-201.
4. M. Lou, J. Wu and F. Y. Cheng, Effect of soil-structure interaction on TMD control for wind and seismic response of structures. Proc. of ASCE Structure Congress, New Orleans, USA, 1999,70-74.
5. Z. Fang, H. Wu and M. Lou, Development and application of high frequency electromagnetism energy dissipation TMD devices. J. Tongji University, 2001,29(6):752-759