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Shaking table test result of the developed Long Stroke Tuned Mass Damper

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Abstract

Tuned Mass Dampers (TMD) against long period and long duration earthquake for upgrading existing high-rise buildings were developed and have already applied to some high-rise buildings in the wake of the large response of high-rise buildings induced by the Great Tohoku earthquake in 2011. The structural control performance of TMD attribute to its stroke and mass. The authors developed TMD with long stroke to realize its performance because a large amount of reinforcement is required to existing high-rise buildings by adopting the large weight. To realize the TMD with long stroke, the multi-stage pendulum is adopted and developed oil dampers with long stroke are installed in line between the weight and the floor to accommodate the large displacement of weight. The shaking table test of 1/3 reduced model was conducted to verify the inter-stage displacements are the same, the rotational angles of the weight and supporting frames are small when the transverse amplitude is large, vertical response of TMD affect little to the transverse motion, and the accuracy of analytical model considering the geometrical nonlinearity. We clarified the smooth transverse motion of developed TMD despite the large amplitude and the vertical input, and the accuracy of simulation model.

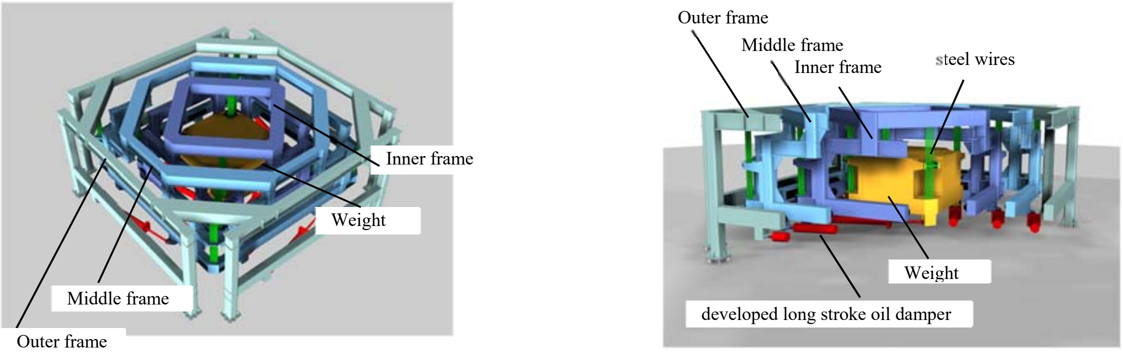
Keywords: TMD, long stroke, shaking table test, torsional motion, rolling motion, vertical motion

1. Introduction

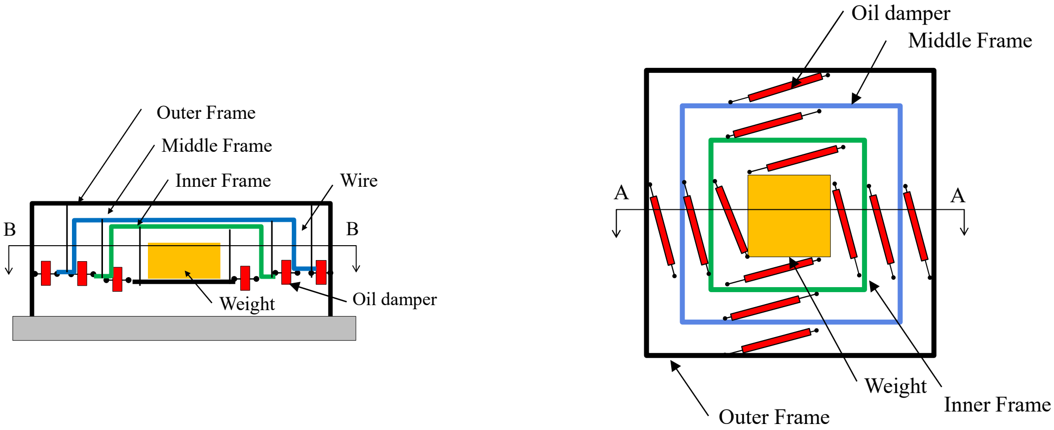
In 2011, the great Tohoku earthquake occurred, and large amplitude response of high-rise buildings located far from the epicenter, for example Tokyo and Osaka, were observed driven by the long period component contained in the earthquake[1]. Some non-structural members like ceilings and inner walls were damaged, and some furniture was overturned by the responses of high-rise buildings. The stronger and longer duration earthquakes, for example the megathrust earthquakes in subduction zone, are expected soon, it is necessary to reinforce the existing high-rise buildings. To add damping is an effective counter major against long period and long duration earthquake as the earthquake is like a stational sinusoidal wave. Tuned mass damper (TMD) installation to existing high-rise building is one of the effective countermeasures and the other effective measures are hysteresis and viscous damper installation to some stories of existing high-rise buildings, but the latter needs reinforcements in each story, so tenants are forced to stop their operation during the reinforcement work. On the other hand, the TMD installation needs reinforcement only around the top of the high-rise building and affect little to most of the tenant operation, therefore the TMD for the existing high-rise buildings is developed and have already applied to some high-rise buildings[2][3]. The authors developed long stroke TMD. To minimize the load to the existing frame, small weight is adopted and to maximize the performance of TMD, multi-stage pendulum which has the longest stroke, around 4.0m stroke, is adopted by utilizing the gravity potential for restoring force. To realize this long stroke TMD, long stroke oil dampers are developed[4], and the load-deformation relationship of steel wires suspending the weight were verified[5]. In this paper, the shaking table test results of 1/3 reduced model are reported. The research objectives are the verification of the period and damping ratio, the small rotational angle of weight, smoothness of transverse motion with vertical response, and the accuracy of simulation model.

2. Concept of TMD system

The concept of developed TMD is to minimize the load to the existing high-rise building. The performance of TMD is determined by the mass and the stroke. The TMD with small weight and long stroke are adopted to minimize the load to the existing building and to maximize the performance of TMD. The authors proposed multistage pendulum shown in fig1(a). to realize the restoring spring with long stroke and to suppress the height of TMD. The three-stage pendulum consisting of middle frame, inner frame and weight is illustrated in fig1(a). Wires and oil dampers are installed in line between supporting frames and weight. The performance of wires and oil dampers are verified by other experiments[4][5]. The inter-stage displacements between the frames and weight are nearly the same and their strokes are around 1.5m and total stroke is around 4.5m. The movement of proposed TMD is illustrated in fig1(d) and the schematic figure is also shown in the fig1(b)(c).

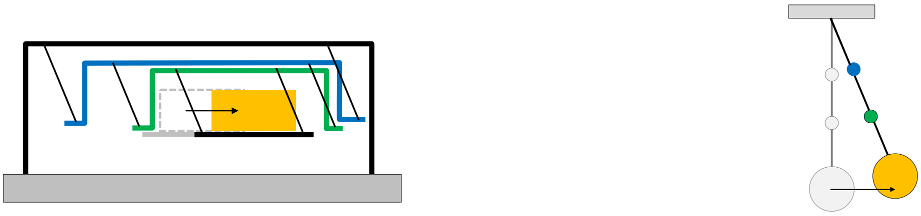


(a) image of the developed TMD



(b) A-A Section

(c)B-B Oil damper arrangement



(d)motion of multistage pendulum

Fig. 1 Overview of the developed multi-stage TMD

3. Shaking Table Test

3.1 Overview

The shaking table tests of 1/3 reduced specimen shown in fig.2 was carried out to verify (1)vibration character is the same as the designed value, (2)the inter-story displacements are same, (3)rotational angles of weight and frames are small, (4)vertical response of weight doesn't affect the transverse motion of TMD, and (5)the accuracy of analytical model. The designed parameters are shown in table 1 and the natural period and the damping factor are 3.14s and 6.4%. The similarity rules are determined to coincide the acceleration of test specimen with that of the full scale TMD and they are shown in table 2 the length is reduced to 1/3 and the time is reduced to $1/\sqrt{3}$. The width is 4.64m and the height is 2.0m.

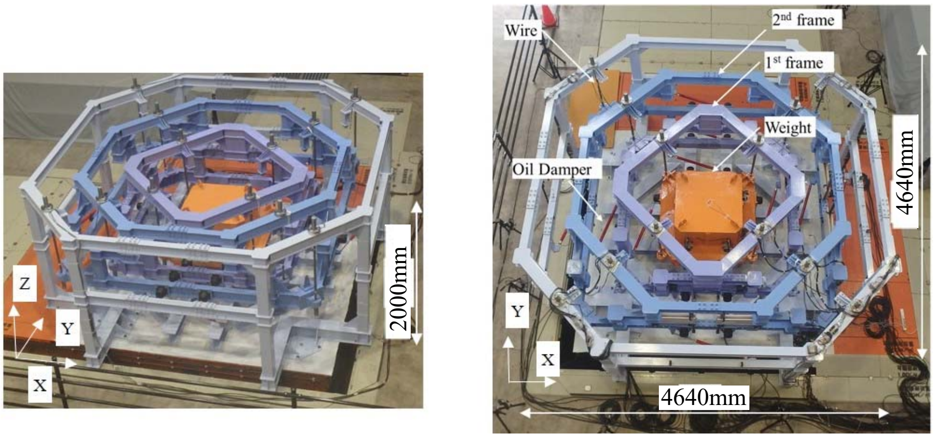


Fig.2 Shaking table test specimen

Table 1 Parameter of test specimen

weight	Weight	5.6 [ton]	
	inner frame	1.2 [ton]	
	middle frame	1.6 [ton]	
inertia	weight	X	2.37 [ton m]
		Y	2.37 [ton m]
		Z	1.48 [ton m]
	inner frame	X	1.14 [ton m]
		Y	1.14 [ton m]
		Z	1.53 [ton m]
	middle frame	X	2.71 [ton m]
		Y	2.71 [ton m]
		Z	4.47 [ton m]
Damping coefficient of oil damper		2.4 [kNs/m]	
Wire construction		IWRC6xFi(21) G/O	
Wire diameter		φ31.5	
Wire length		0.89 [m]	

Table 2 Reduction ratio

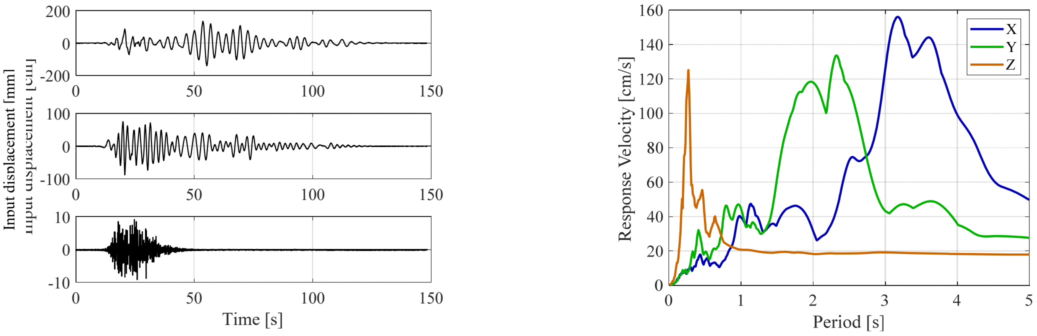
Physical quantity	Unit	Reduction ratio
Displacement	[m]	1/3
Velocity	[m/s]	$1/\sqrt{3}$
Acceleration	[m/s^2]	1
Force	[kgm/s^2]	1/80
Time	[s]	$1/\sqrt{3}$
Size	[m]	1/3

3.2 Excitation conditions

Some excitation conditions are listed in the table 3 and the waves and the response spectrums of the high-rise building response of the Great Kanto earthquake are illustrated in the fig.3. The transverse sweep wave excitation and vertical white noise excitation are conducted to verify the vibration characteristics of test specimen with middle amplitude. Three sinusoidal excitations are conducted, unidirectional input, 2-directional input with the same phase, and 2-directional input with 90 degree phase delay to verify the equal inter-stage displacement and the rotational angles are small for every case. A band limited white noise excitation in the vertical direction is added in the latter 2 cycles of the transverse sinusoidal excitation to verify the vertical response doesn't affect the transverse motion. The response displacement of 50 story high-rise building of the simulated Great Kanto earthquake excitation is conducted to verify the smooth actuation of the TMD. The natural period of the high-rise building is 5.14s and 5.28s in the transverse X, Y direction and they are reduced to 2.97s and 3.04s, the direction is the same as the direction of shaking table test, and 0.43s in the vertical direction and reduced to 0.24s.

Table 3 Excitation waves to shaking table

Input wave	Dir.	Dur. [s]	objective
white noise	Z	120	identify vertical vibration characters (3.3.1)
sweep wave (Period 2s～4s)	X	60	identify transverse vibration characters (3.3.1)
	Y	60	
unidirectional sinusoidal wave (10 cycle Period 3.14s)	X	70	verify equality of inter-stage displacement (3.3.2) and rotational angles are small (3.3.4)
	Y	70	
2-directional sinusoidal wave (phase delay 0° 10cycle Period 3.14s)	XY	70	verify rotational angles are small (3.3.4)
2-directional sinusoidal wave (phase delay 90° 10cycle Period 3.14s)	XY	70	verify rotational angles are small (3.3.4)
unidirectional sinusoidal wave(transverse) (10cycle Period 3.14s) + band limited white noise (vertical) (latter 2cycle 5Hz～20Hz)	XZ	70	verify the vertical response affect little to the transverse response (3.3.3)
the Great Kanto wave response (50F)	XYZ	144.3	verify the simulation model (4.1, 4.2)



(a) Reduced displacement waveform of top floor (b) Resoponse velocity spectrum (h=5%)

Fig.3 Reduced top floor responses of the high-rise building (input the Great Kanto earthquake)

3.3 Shaking table test result

3.3.1 Vibration character

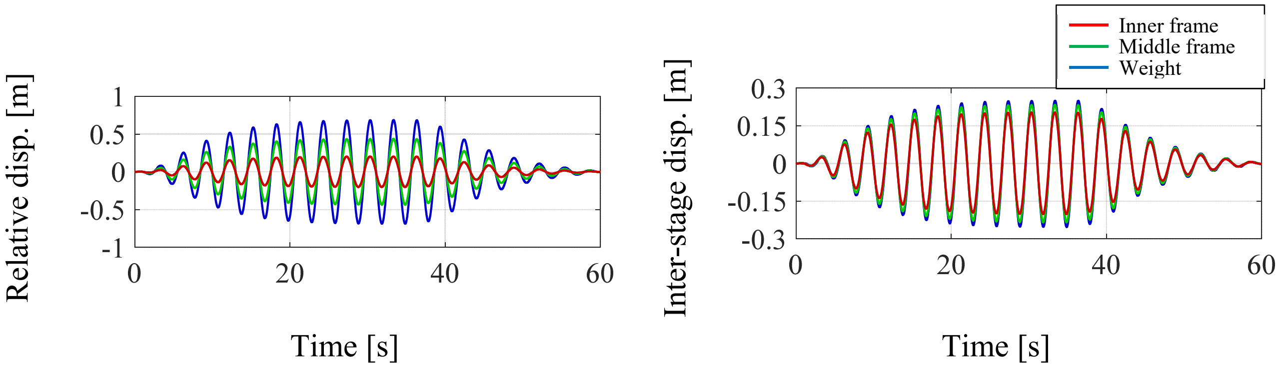
The SIMO ARX model, whose model order is 2, is applied for the identification of the TMD's dynamic character. The input data is measured acceleration at shaking table, and the output data are the measured accelerations at middle frame, inner frame, and weight. The ARX's parameters are calculated by the least-mean-square error method. The calculated vibration characters are listed in table 4. The values are almost the same as the designed value.

Table 4 Identified vibration characters by SIMO ARX model

Direction	Natural period	Damping ratio	Maximum amplitude of weight	Participation vector		
				Middle frame	Inner frame	Weight
[-]	[s]	[%]	[m]			
X	3.18	6.71	0.38	0.35	0.72	1.16
Y	3.20	6.43	0.39	0.33	0.72	1.15
Z	0.13	3.19	0.02	0.25	0.63	0.94

3.3.2 Equality of inter-stage displacement

The measured response relative displacements and inter-stage displacements against unidirectional sinusoidal input are shown in fig.4. As shown in the fig.4, the weight and frames move equally. The inter-stage displacement between weight and inner frame is larger than the others because the transverse stiffness between the weight and inner frame is the lowest when the lengths of steel wires between frames and weight are the same.

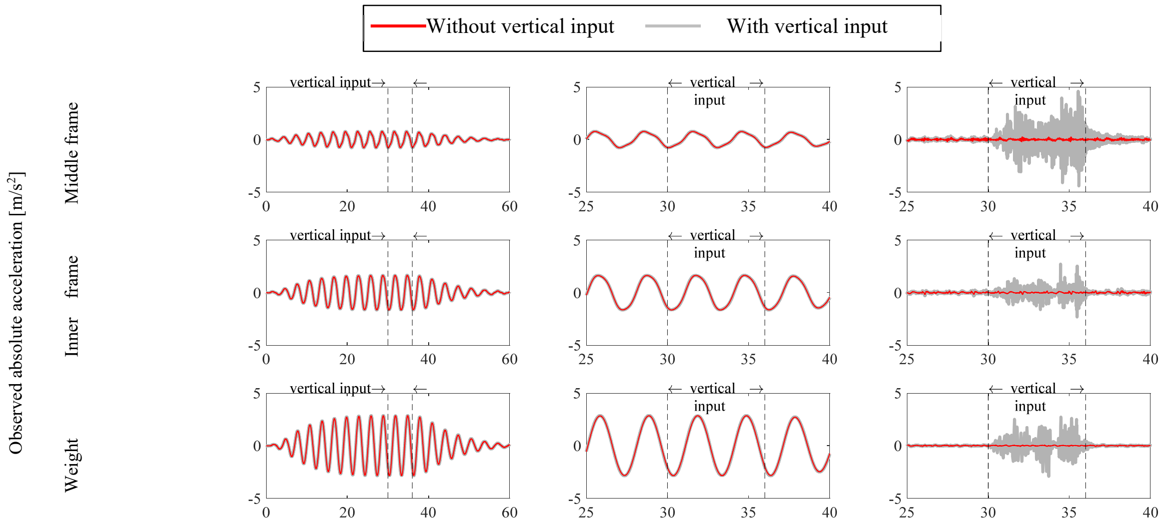


(a) Relative displacement (b) Inter-stage displacement

Fig.4 Relative displacement and inter-stage displacement of TMD

3.3.3 Effect of vertical input to transverse response of weight

The lateral acceleration responses to the unidirectional sinusoidal wave input are illustrated by the presence or absence of the vertical input in fig.5. The low pass filtered responses and the high pass filtered responses are also drawn in the section around the latter two cycles of lateral response. The low pass filtered responses correspond well and confirmed that the vertical response affects little to the transverse response, on the other hand, the high pass filtered response is clearly different. The high pass filtered responses with vertical input has the frequency components of vertical responses. Therefore, the lateral inertia force with vertical input is larger than that without vertical input.

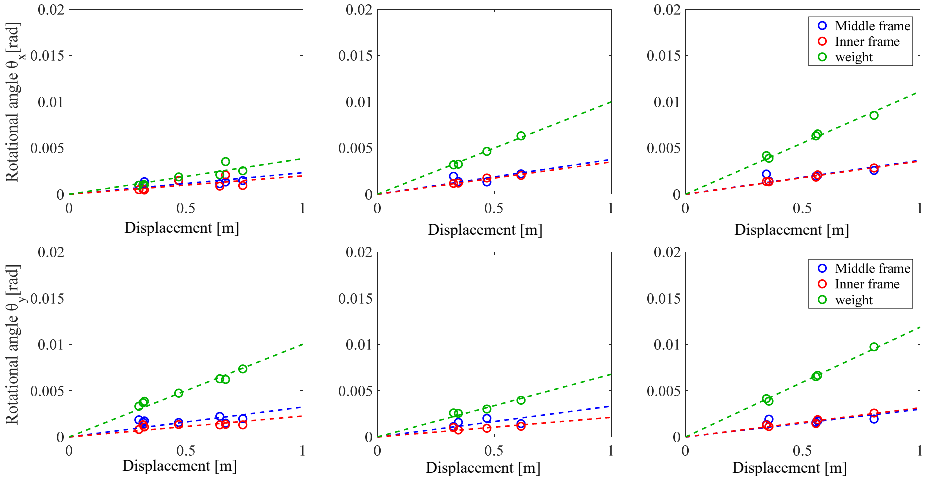


Low frequency component less than 1Hz Low frequency component less than 1Hz High frequency component higher than 1Hz

Fig.5 Compare transverse response of weight with and without vertical input

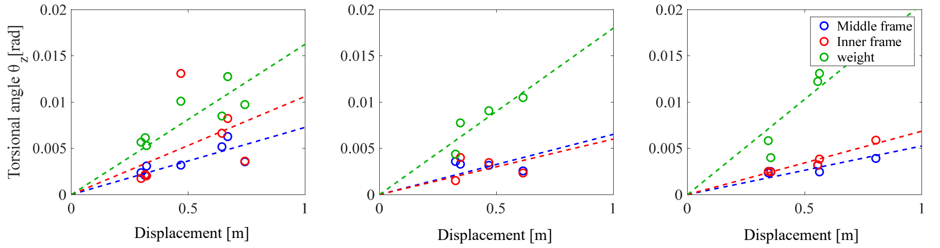
3.3.4 Rotational angle response

The maximum rotational angle responses for unidirectional sinusoidal wave, bidirectional sinusoidal wave without phase delay, and sinusoidal wave with a phase delay of 90 degrees are drawn in fig.6a,b. The maximum rotational angle $\theta_x \theta_y$ is less than 0.01 rad and the torsional angle θ_z is less than 0.02 rad, so they can be ignorable. The rotational angle differences between the weight and inner frame or middle frame are because the rotational moment or torsional moment acting on the weight is the largest. The rotational angle is proportional to the response displacement at every excitation case.



(a) Unidirectional sinusoidal wave (b) Bidirectional sinusoidal wave (ph0°) (c)Bidirectional sinusoidal wave (ph90°)

Fig.6a Rotational angle response of TMD



(a)Unidirectional sinusoidal wave

(b)Bidirectional sinusoidal wave (ph0°)

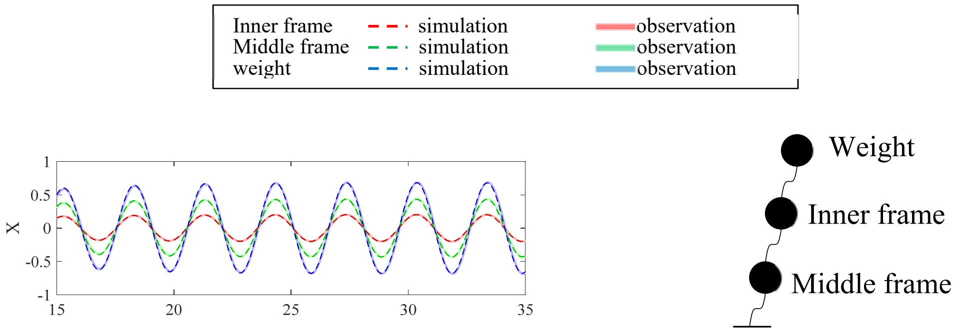
(c)Bidirectional sinusoidal wave (ph90°)

Fig.6b Torsional angle response of TMD

4. Verification of analytical model of TMD

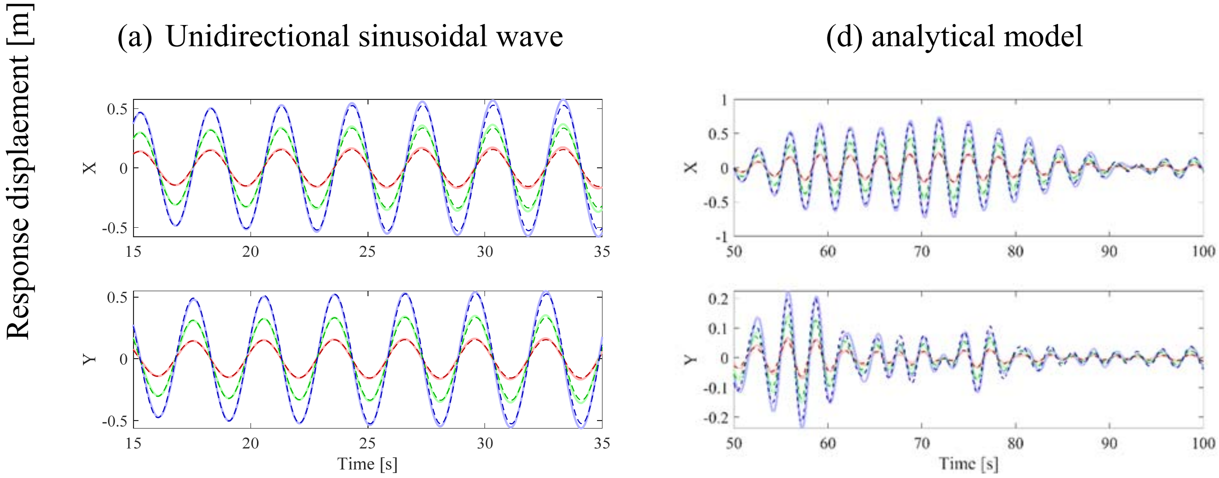
4.1 3DOF(degree of freedom) lumped mass system

The test specimen is modeled as the 3 DOF lumped mass model in the transverse direction and orthogonal direction independently. The calculated response wave forms of TMD are compared with those of observed about the cases of the unidirectional sinusoidal wave, the 2 directional sinusoidal waves (90-degree phase delay) and the Great Kanto earthquake in the fig.7. The calculated response and observed responses are close and verified the accuracy of this simple analytical model.



(a) Unidirectional sinusoidal wave

(d) analytical model



(b) Bidirectional sinusoidal wave input

(c) the response wave of the Great Kanto

Fig. 7 Response displacement comparison of the 3DOF lumped mass with the observed displacement

4.2 18DOF detailed model

The detailed simulation model of multi-stage TMD was proposed. The derivation process is reported in another paper[6]. The obtained equation of motion is shown in Eq. (1) the variables are shown in the fig.8. The numerical simulation is generated based on the Runge-Kutta method with fourth order accuracy. The stiffness and damping coefficient matrix are updated step by step considering the geometrical nonlinearity of oil dampers and wires.

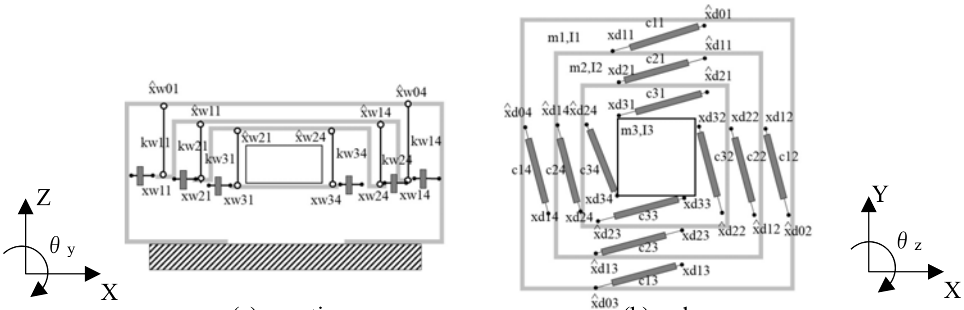
$$\begin{gathered} \mathrm{m_i}\ddot{x}_\mathrm{i} + \sum_{j=1}^{4}(\mathrm{F_{cij}} - \mathrm{F_{ci+1j}}) + \sum_{j=1}^{4}(\mathrm{F_{kij}} - \mathrm{F_{ki+1j}}) - \mathrm{m_i g}\mathbf{e}_\mathrm{z} = -\mathrm{m_i}\ddot{x}_g \\ \mathrm{I_i}\ddot{\theta}_\mathrm{i} + \sum_{j=1}^{4}\left(\frac{\partial \dot{x}_{dij}}{\partial \dot{\theta}_i}\right)^\mathrm{T}\mathrm{F_{cij}} - \left(\frac{\partial \dot{\hat{x}}_{dij}}{\partial \dot{\theta}_i}\right)^\mathrm{T}\mathrm{F_{ci+1j}} + \sum_{j=1}^{4}\left(\frac{\partial x_{wij}}{\partial \theta_i}\right)^\mathrm{T}\mathrm{F_{kij}} - \left(\frac{\partial \hat{x}_{wij}}{\partial \theta_i}\right)^\mathrm{T}\mathrm{F_{ki+1j}} = -\mathrm{I_i}\ddot{\theta}_g \end{gathered} \quad (1)$$

m_i: mass of the i_{th} frame; I_i: inertia of the i_{th} frame; x_i: position vector of the i_{th} frame's center of gravity; z_i: vertical component of the position F_{cij}: damping force of the j_{th} damper of i_{th} frame; F_{kij}: restoring force of the j_{th} wire of the i_{th} frame; e_z: unit vector in the z direction;$\ddot{x}_g$: input acceleration vector; $\ddot{\theta}_g$:input rotational acceleration vector, $x_{wij}, \hat{x}_{wij}$: position vector of the wire joint shown; $x_{dij}, \hat{x}_{dij}$: position vector of the oil damper joint.

The constant vector like all variables are the designed values except the wire stiffness. Steel wires have the load-deformation relationship which are the quadratic function in the small load section and the linear function in the large load section confirmed in another paper. Loads acting on the wires are large in the case of full scale TMD and show the linear load-deformation relationship, but the loads acting on the reduced model were small, and the load-deformation relationship were quadratic function, so the stiffness differs corresponding to the load level. In this simulation, the wire stiffness is modeled as the linear unidirectional spring whose stiffness is derived from the identified values shown in the table 1.

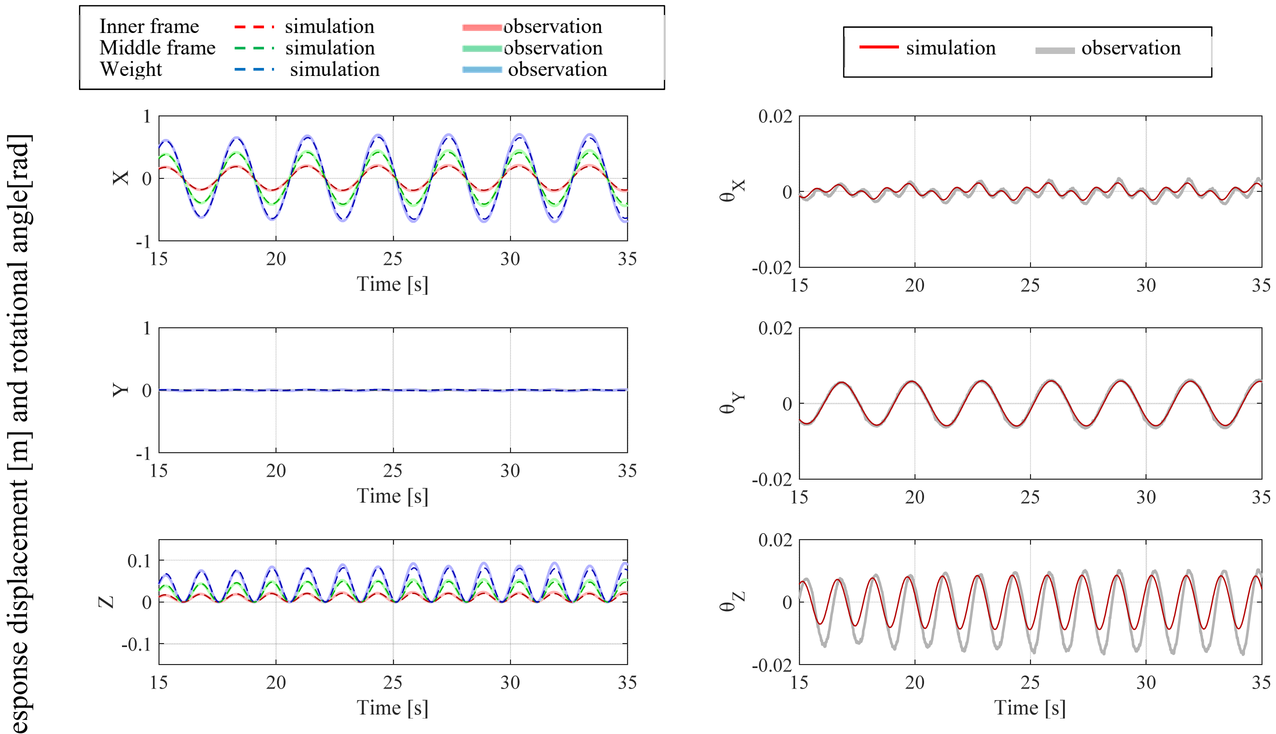
The numerical simulation results of unidirectional sinusoidal wave input are shown in fig.9(a). The transverse and vertical responses correspond well and the rotational angle θ_x, θ_y correspond well on the other hand, the torsional angle θ_z is a little different on the point of the amplitude. The torsional motion is induced by the eccentric arrangement of oil dampers, and the oil dampers are said to have the several damping coefficients and also the damping coefficient of oil damper vary depending on the stress condition, compression or tension. In this experiment, the load deformation relationship of every oil damper is not grasped but the reason of the amplitude difference is supposed to be the difference of damping coefficients and their bias. The similar tendency can be seen in the fig.9(c).

The numerical simulation results of bidirectional sinusoidal wave input is shown in fig.9(b). The trend is similar to the case of the unidirectional sinusoidal wave input, but in this case, the waveform of torsional angle and vertical response is difference in the point that the frequency component of 0.64Hz, the half of the transverse natural frequency 0.32Hz, is shown in the observed waveform. This difference derives from the inclination of weight and frames because of the stiffness' variation in the low stress area on the other hand, the full scale TMD has the wires whose stiffnesses are constant so the inclination is supposed to be small.



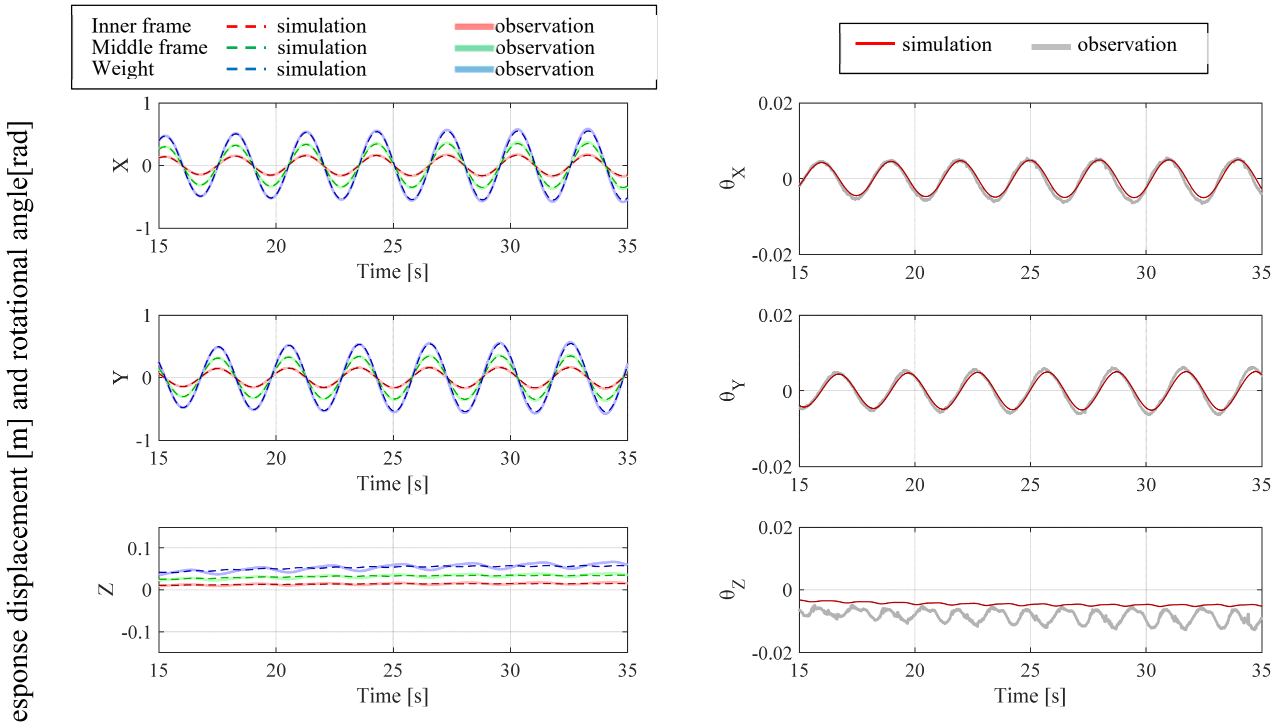
(a) section (b) plan

Fig.8 18DOF Detailed simulation model



Response displacement   Response rotational angle of weight

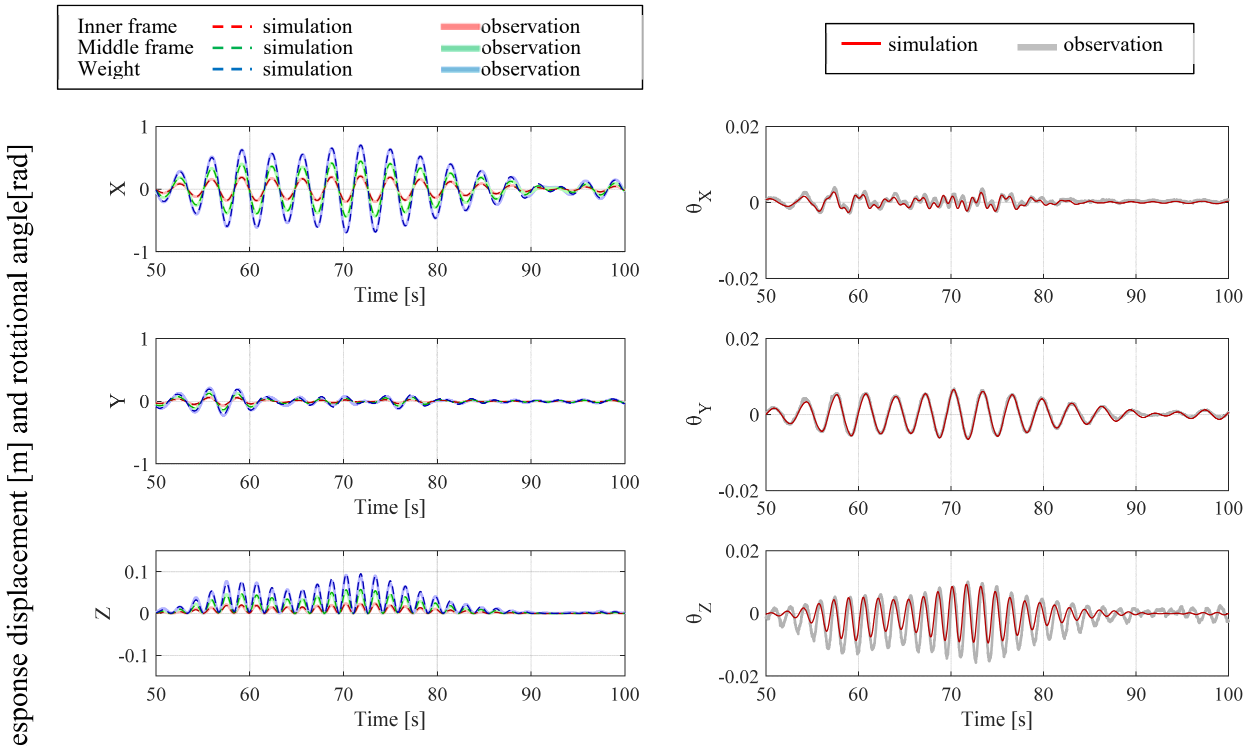
(a) Unidirectional sinusoidal wave input



Response displacement   Response rotational angle of weight

(b) Bidirectional sinusoidal wave input (ph90°)

Fig. 9 Response comparison of the detailed numerical simulation with the observed response



Response displacement

Response rotational angle of weight

(c) Response of the Great Kanto earthquake input

Fig. 9 Response comparison of the detailed numerical simulation with the observed response

5. Conclusion

The smooth action of TMD was verified when it vibrates with large amplitude by the shaking table test of 1/3 reduced model. The vertical response didn't affect the transverse response of TMD, and the rolling and torsional motions are small. A simple 3dof model could simulate the transverse motion of TMD and the detailed model could simulate not only the transverse motion but also the rotational and torsional motion except the torsional and vertical motion in the case of bidirectional sinusoidal wave input because of the inclination of the TMD, but the detailed simulation could express the trend.

6. Acknowledgement

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