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Aeroelastic model Test for a Tall Building using Tuned Liquid Column Damper

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ABSTRACT

To *investigate the effectiveness of a tuned liquid column dampers(TLCD) in suppressing wind-induced excitation motion of a tall building, aeroelastic wind tunnel tests were conduceted. A 1: 200 scaled model of an aeroelastic tall building was built, and TLCD models of mass ratio of 1.5%, 3% and 4.5%, respectively, were designed and tested with the building model. As such, in this study, after installing TLCD of various types (horizontal length, mass ratio) on the top most floor of aeroelastic model that is similar to the actual structure, centered* around the interval where the vortex-induced vibration of low wind speed occurs, by conducting aeroelastic model experiment in suburban areas(α=0.15) and attain wind-induced vibrations response (displacement), we studied the effects of wind vibration control.

1. INTRODUCTION

As the design and construction technologies have dramatically improved in accordance with the recent development of materialistic characteristics of structural materials and the development of structural analysis, in order to acquire larger living spaces than small structures with limited land areas, in countries abroad and in Korea, the increases in super-tall building structures that are more flexible as compared to smaller structures have been accelerating. On the other hand, even in cases where there are hardly any earthquakes since the damages resulting from the increases in the frequency and severity of hurricanes can bring about huge losses, the safety and serviceability problems that are attributable to wind-induced vibration for tall building structures are being raised; as such, both within Korea and also in overseas countries, a number of studies on wind-induced vibration control via various methods are being pursued. Representing this, with the goal of improving the reduction capability of

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vibration response for tall buildings and the safety of the residents, such as dizziness, nausea, migraine and anxiety, or, with improving the usability as a goal, the examples of installing vibration control device of passive type that uses TMD, TLD and TLCD which operate without a power plant is on the rise. Particularly, in the case of TLCD, many studies are being pursued on account that the constraining effect of location is better as compared to TLD; however, for most of the tests on TLCD, either the numerical methods or the proposal of the equations of motion of pendulum type with simplified TLCD-structural type and simple performance tests are being conducted. And, by installing in the middle of TLCD an orifice with different porosity, experimental equation, etc. for predicting head loss coefficient for 1 type of excitation amplitude has been proposed. In addition, in regard to the wind-induced vibration response supported by the wind load as well, studies have been conducted through Xu, Kwok, etc. since the late part of the 1990s; however, the reduction effects of wind-induced vibration response due to the wind load have been conducted only for aeroelastic model tests with TLD installed above the highest floor in the aeroelastic model that is similar to the actual model, and, since it is not easy for the aeroelastic model tests with TLCD installed to simulate the aeroelastic model and natural frequency of the scale model of TLCD, evaluations of wind vibration control performance are hardly being pursued. As such, in this study, after installing TLCD of various types (horizontal length, mass ratio) on the top most floor of aeroelastic model that is similar to the actual structure, centered around the interval where the vortex-induced vibration of low wind speed occurs, by conducting aeroelastic model tests in suburban areas(α =0.15) and attain wind-induced vibrations response (displacement), we studied the effects of wind vibration control.

2. WIND-TUNNEL EXPERIMENT

A wind-tunnel experiment using an aeroelastic model was conducted in a boundary layer wind-tunnel located at the Department of Architecture Engineering, Chon-buk National University, Jeonju, Republic of Korea. It is an open-type wind-tunnel characterized by a test section of 2.1m width, 1.7m height and 18m length. Photo. 1 shows the appearance of wind-tunnel. The boundary layer flow condition representing natural wind flow over suburban terrain indicated that the power law exponent of the mean longitudinal wind velocity profile was 0.15 and that the longitudinal turbulence intensity was about 10% at the top of the building model. The vertical distribution of the mean longitudinal wind velocities and the longitudinal turbulence intensities are shown in Fig. 1. The power spectrum of lateral component of turbulence at height of 40cm in suburban area(α =0.15)is also indicated in Fig. 2. The direction of the wind normal to the front face of the aeroelastic model has a zero angle of attack as shown in Fig. 3.

Photo. 1 The appearance of Wind-Tunnel

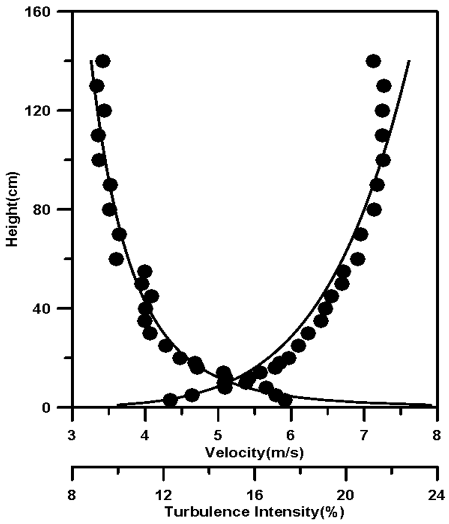


Fig. 1 Vertical distribution of the wind velocity and turbulence intensity

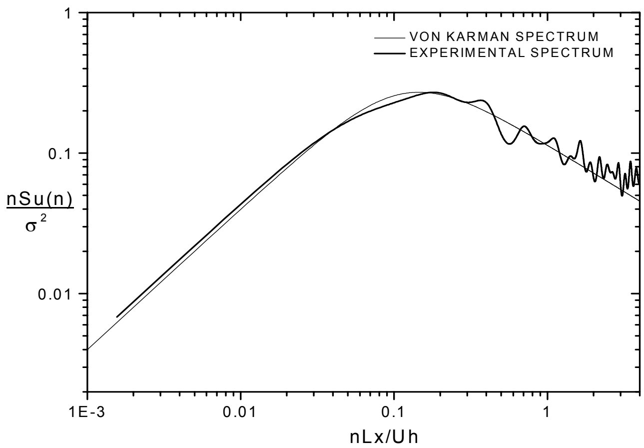


Fig. 2 The power spectrum of lateral component of turbulence

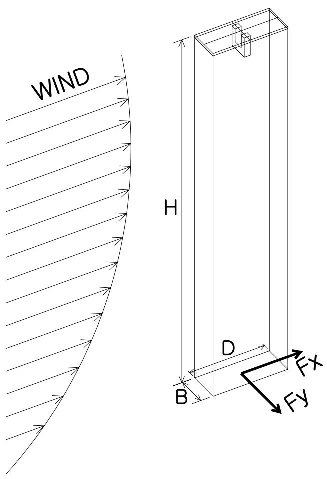


Fig. 3 The direction of the wind normal to the front face of the aeroelastic model

3. AEROELASTIC WIND TUNNEL TESTS

3.1. Gimbal divice

In aeroelastic model test, gimbal that maintains X direction and Y direction degree of freedom of vibration model was used which is composed of spring that assigns rigidity, damping device that assigns damping, detection device of response and support device that supports these. In particular, frame that supports gimbal should have heavy weight because it should not vibrate within measured frequency range even if model vibrates. In order to have mass(m), damping coefficient(c) and rigidity(k) the dynamic characteristics of actual building expressed in gimbal by law of similarity as they are, mass(m) was taken from model mass, damping coefficient(c) from damping device that used silicon oil with different viscosity to adjust damping ratio and rigidity(k) from device like spring etc. At this time, as for spring that adjusts rigidity, totally 4 coil springs with the same modulus of elasticity were used with two in X direction and two in Y direction. Damping device is composed of circular damping plate and installed at the bottom of gimbal, and to change the damping ratio of structure, silicon oil was used below circular damping plate in this device. Methods of measuring model vibration include two methods, the method of installing strain gauge at the copper plate of X direction and Y direction linked to coil spring, and the method of using non-contact type optic laser displacement meter, but for more precise measurement, optic laser displacement meter(LK-2101) was used in the measurement. Therefore, from the gimbal below, free vibration test was done at top layer of model, and after natural frequency and damping ratio of the model were obtained, aeroelastic wind tunnel test was done on wind tunnel. Photo 2 shows the appearance of gimbal, and photo 3 thru 5 the detailed appearance of gimbal by parts. Photo 6 shows the appearance of gimbal installed within wind tunnel.

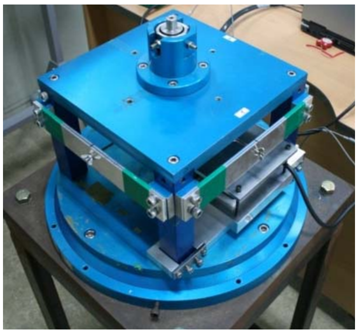


Photo. 2 The appearance of gimbal

Photo. 3 X-axi and Y-axi of gimbal

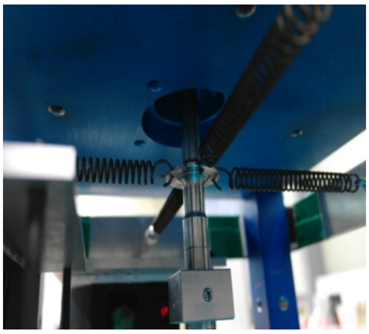


Photo. 4 Spring of X-axi and Y-axi

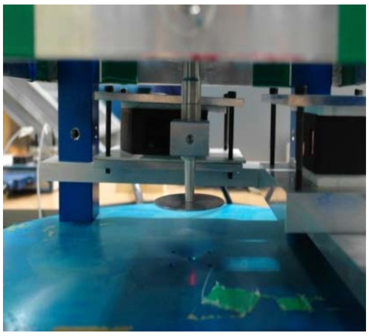


Photo. 5 Circular damping plate of gimbal

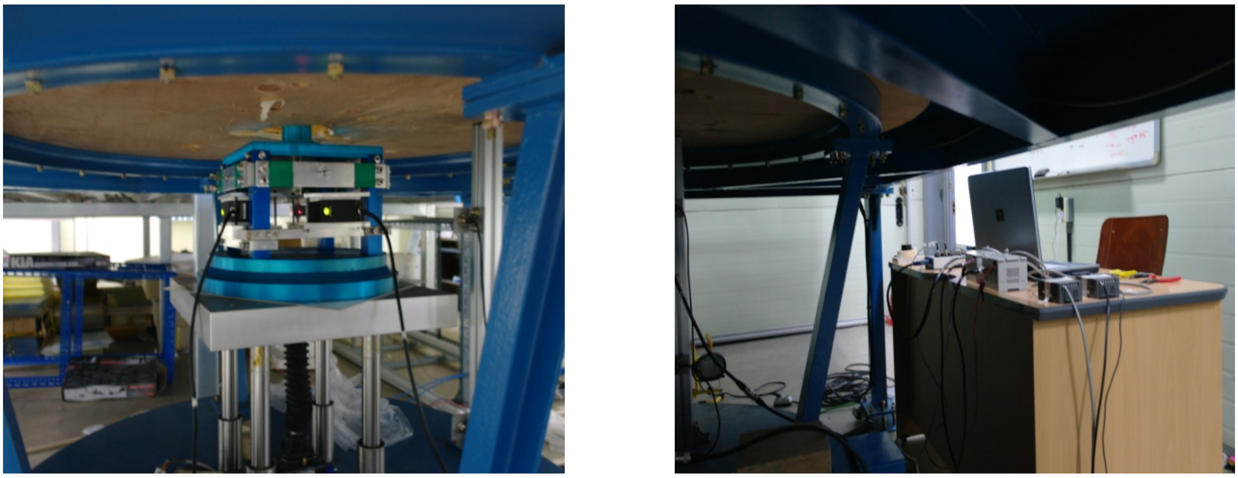


Photo. 6 The appearance of gimbal installed within wind tunnel.

3.2. Similarity Condition and Aeroelastic model

In order to find out the characteristics of vibration response the experiment objective, model was produced so TLCD may be installed at top layer by applying 1/200 scale with the ratio of long side to short side(Depth/Breadth) 3 where vortices occur frequently at low wind speed. In case of such aeroelastic model, the vibration characteristics of building can be obtained accurately only if similarity requirement is met. As such, the similarity requirement to be considered in modeling building vibration characteristics is to match 3 parameters like non-dimensional frequency, mass ratio and damping ratio etc to actual object. Such similarity requirement is applied by changing expression according to the method of modeling experiment model. Specifically, mass ratio indicates that if fluid density is the same in experiment and actual object, generalized mass is one third of length scale cube, and the similarity parameter on building elasticity, a parameter that combines structure elasticity and wind speed, is expressed as non-dimensional frequency in general, and represents the relationship of wind speed, model scale and natural frequency scale. The correlation of such three parameters are shown in expressions Eq. (1) thru Eq. (3).

$$\textbf{Mass :}\ \left(\frac{m_j}{\rho b^2 h}\right)_M = \left(\frac{M_j}{\rho B^2 H}\right)_P \tag{1}$$

$$\textbf{Natural frequency :}\ \left(\frac{n_j \cdot b}{v}\right)_M = \left(\frac{n_j \cdot B}{vV}\right)_P \tag{2}$$

$$\textbf{Damping rato :}\ (\xi_j)_M = (\xi_j)_P \tag{3}$$

Where

v,V = representative wind speeds
ρ = air density

v,V = jth modal masses of the model and the prototype structure, respectively
b,B = widths of the model and the prototype structure, respectively
h,H = heights of the model and the prototype structure, respectively
ξ_j = jth modal damping ratio; and the subscripts M and P denote the model and the prototype structures, respectively

The law of similarity of actual object and model of structure the subject of this study is shown in Table 1 since when determining the scale of model, the wind direction appearance area of model should be less than 5% of wind tunnel cross-section area, measure was taken so this aeroelastic model of 3.89% shall fall within less than 5% blockage factor. The natural frequency of aeroelastic model was set to 3Hz so TLCD water tank can be installed. Table 2 shows the dimension and mass of aeroelastic model with the ratio of long side to short side (Depth/Breadth) 3. There are totally 9 types of TLCD models to be installed at top layer of aeroelastic model, and experiment was done so the natural frequency of TLCD model is set to the same value as the natural frequency(3Hz) of aeroelastic model, so it may become 1 time, 2 times and 3 times generalized mass of aeroelastic model. Table 3 shows the specification of TLCD model installed in aeroelastic model. Photo 7 shows the appearance of TLCD model and aeroelastic model installed within wind tunnel.

Table. 1 Similarity law of the scaled model

	Prototype	Model	Scale
Height (m)	160	0.8	1/200
Cross sectional area ($\mathbf{m^2}$)	430.7 (11.6m *34.8m)	0.01	-
Volumn ($\mathbf{m^3}$)	64592	0.008	-
Natural frequency (Hz)	0.3	3	10
Density ($\mathbf{kg/m^3}$)	120	120	1

Table. 2 Dimension and mass of aeroelastic model

Aspect ratio	Breadth(cm)	Depth(cm)	Height(cm)	Mass(g)
3	5.8	17.4	80	1000

Table. 3 Specification of TLCD model installed in aeroelastic model

Horizontal Length	B (mm)	D (mm)	H (mm)	Water mass	Mass Ratio (%)	Model freq. (mm)	TLCD Freq. (mm)	TLCD Model Name
25mm	35	10	50	5.6	1.5	2.91	2.9	25HM1
	35	20	50	11.2	3	2.91	2.9	25HM2
	35	30	50	16.8	4.5	2.91	2.9	25HM3
30mm	40	10	45	5.6	1.5	2.91	2.9	30HM1
	40	20	45	11.2	3	2.91	2.9	30HM2
	40	30	45	16.8	4.5	2.91	2.9	30HM3
35mm	50	10	45	5.6	1.5	2.91	2.9	35HM1
	50	20	45	11.2	3	2.91	2.9	35HM2
	50	30	45	16.8	4.5	2.91	2.9	35HM3

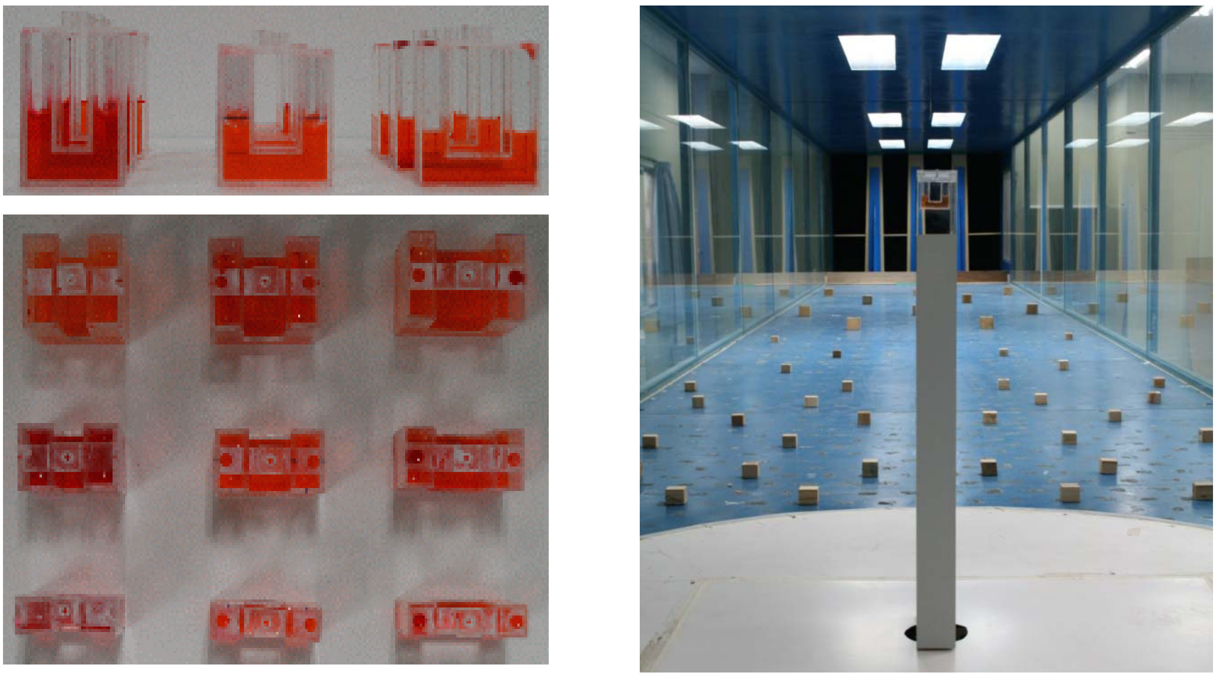


Photo. 7 Appearance of TLCD model and aeroelastic model installed within wind tunnel.

3.3. Free vibration tests

Once calibration of gimbal X axis and Y axis and adjustment of spring were completed, free vibration tests were executed to check to see if the natural frequency of experiment subject for each axis remains at target value. Furthermore, through multiple repeated tests, particularly through measurement of the natural frequency at vibration level, it was checked that the change by amplitude of natural frequency stays at minimal level. Damping constant was checked with the use of free vibration test that analyzes waveform obtained through free vibration of model in place where no vibration occurs, and after all the value was adjusted to remain in specified range through adjustment of damping device. The natural frequency and damping ratio of aeroelastic model were obtained respectively with the use of expressions Eq. (4) and Eq. (5) both of which involve logarithmic decrement by free vibration.

$$\boldsymbol{\xi} = \frac{1}{2m\pi} \ln \frac{a_l}{a_{l+m}} \quad (4)$$

$$\mathbf{f} = \frac{m}{T_{l+m} - T_l} \quad (5)$$

where

m = the number of oscillations

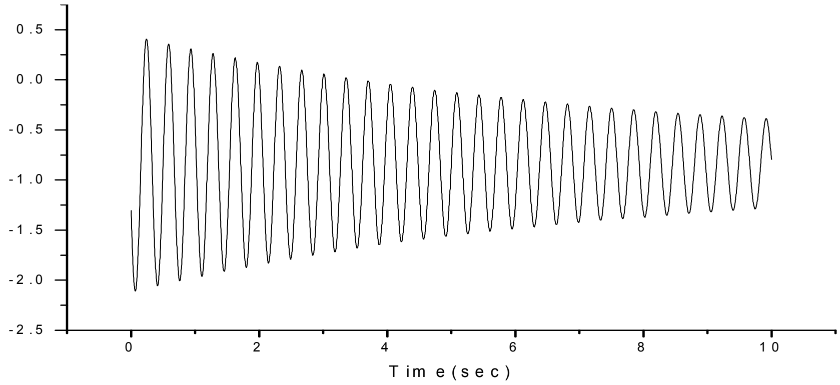
T_l = the time at the peak amplitude of the lth vibration

T_{l+m} = the time at the maximum, amplitude of the (l+m)th vibration

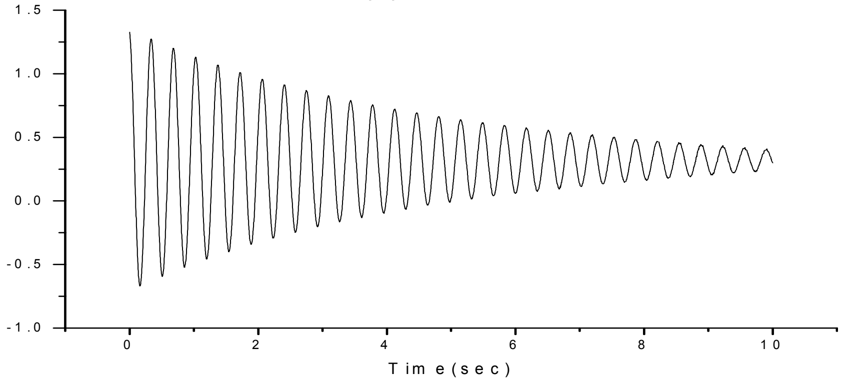
a_l = the peak amplitude of the lth oscillation

a_{l+m} = the peak amplitude of the (l+m)th oscillation

Fig. 4 shows the time history of free vibration for the two axes(X axis and Y axis) of aeroelastic vibration model, and Photo 8 the appearance of free vibration test of aeroelastic model on top of gimbal. To change damping ratio, 4 types of silicon oils, KF96-100CS, 500CS, 1000CS and 3000CS were used, and the numbers by silicon oil names represent the magnitude of viscosity. CS a unit of dynamic viscosity indicates cSt, and 1cSt becomes $1\text{mm}^2/s$. Photo 9 shows the appearance of 4 silicons installed on the damping plate of gimbal, and Table 4 the natural frequency and damping ratio for X axis and Y axis by the change of silicon oil viscosity. The more oil viscosity, the higher damping ratio, and natural frequencies were all the same except for 3,000CS. Table 5 shows the natural frequency and damping ratio of the case where mutually different 9 TLCDs are installed on top layer of aeroelastic model. Overall the more the length and mass of horizontal tube increase, the natural frequency decreases, but damping ratio increases.



(a) X-axis



(b) Y- axis

Fig. 4 Time history of the building for model(X-direction, Y-direction)

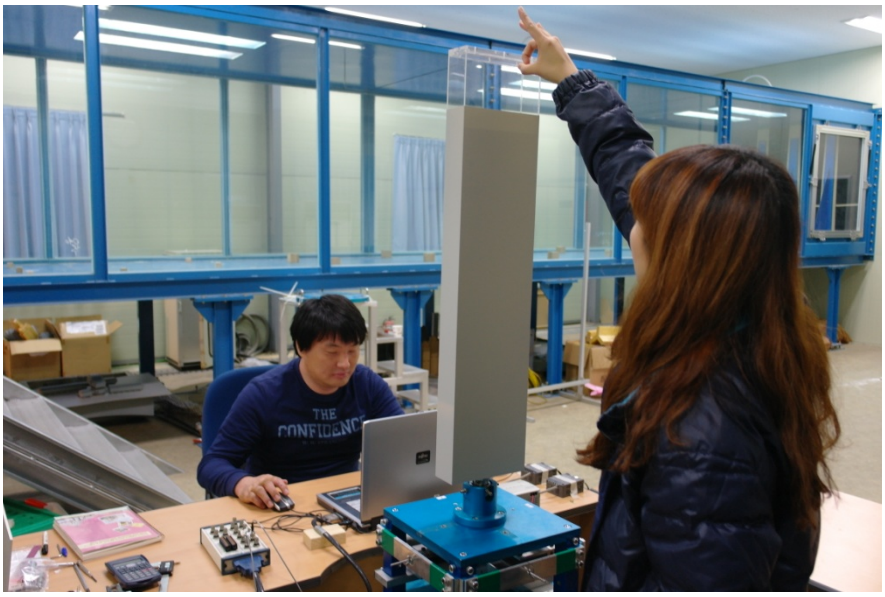
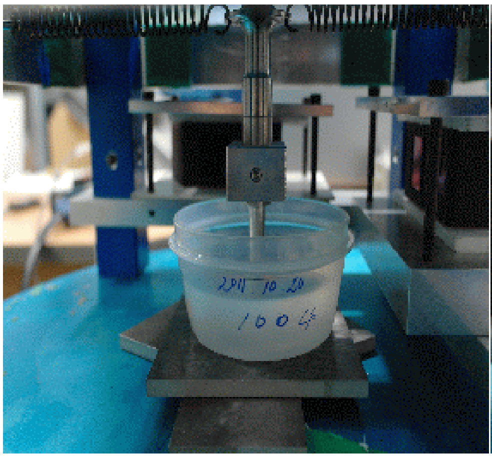
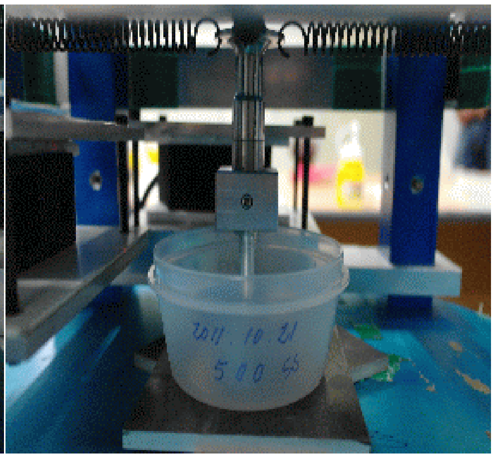
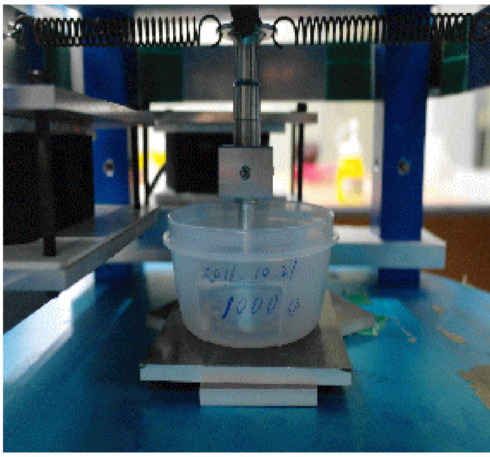
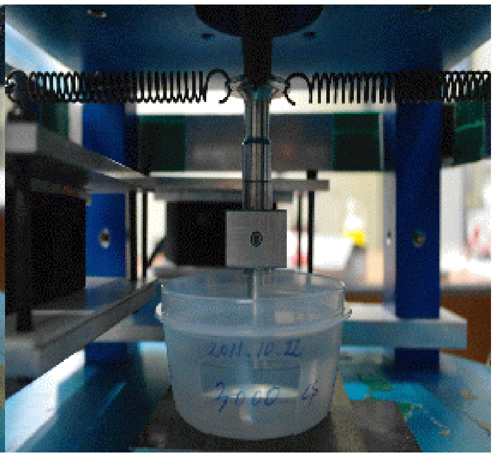


Photo. 8 Appearance of free vibration test of aeroelastic model on top of gimbal.

a)100cs b) 500cs

c) 1000cs d) 3000cs

Photo. 9 Appearance of 4 silicons installed on the damping plate of gimbal

Table . 4 Natural frequency and damping ratio by the change of silicon oil viscosity

Viscosity	Aspect ratio (D/B)			
	Natural frequency		Damping ratio	
	X- axis	Y- axis	X- axis	Y- axis
NO silicon	2.91	2.91	0.67	1.12
100cs	2.91	2.91	0.72	1.15
500cs	2.91	2.91	0.84	1.27
1000cs	2.91	2.91	0.95	1.37
3000cs	2.92	2.92	1.58	1.95

Table . 5 Natural frequency and damping ratio of the case where mutually different 9 TLCDs are installed on top layer of aeroelastic model.

TLCD Model	Y - direction		X - direction	
	Natural frequency(Hz)	Damping ratio (%)	Natural frequency(Hz)	Damping ratio (%)
NO TLCD	2.89	0.65	2.89	0.98
LH25-M1	2.82	0.84	2.84	1.06
LH25-M2	2.78	1.07	2.79	1.05
LH25-M3	2.74	1.18	2.76	1.08
LH30-M1	2.83	0.91	2.84	1.03
LH30-M2	2.78	1.17	2.81	1.03
LH30-M3	2.74	1.55	2.76	1.05
LH35-M1	2.84	0.97	2.85	1.00
LH35-M2	2.82	1.50	2.82	1.01
LH35-M3	2.78	2.16	2.79	1.04

4. EXPERIMENT RESULTS AND ANALYSIS

In aeroelastic vibration model test using wind tunnel, totally 9 TLCD models with varying length(L_H=25mm, L_H=30mm, L_H=35mm) of horizontal tubes and 3 different mass ratios(1.5%, 3.0%, 4.5%) in the middle of top layer of aeroelastic model were installed to find out the effect of reduction of lateral direction vibration response(displacement) in mutually different TLCD test model. Experiment analysis was conducted centered around the displacement response and spectrum value at 15 locations with wind speed of 0.7m/s ~ 5.1m/s for accross wind direction(Y-axis) at 0 degree of wind direction angle at around 1.2m/s wind speed where vortex excitation occurs. As for measured data, data were measured 5 times with 4,096 values each time at sampling frequency of 500Hz.

4.1. Displacement responses

Fig. 5 thru Fig. 7 show the non-dimensional displacement responses when no TLCD exists and by the change of TLCD mass ratio(1.5%, 3.0%, 4.5%). The figures indicated that wind speed with maximum displacement response is occurring at non-dimensional wind speed 2.38 where vortex excitation occurs, and displacement response is decreasing more at non-dimensional low wind speed in case TLCD is installed at top layer than in case TLCD is not installed.

It was found that at horizontal length L_H=25mm, displacement vibration response decreased with increase in mass ratio, and specifically it decreased by maximum 35% or more at mass ratio of 4.5% and non-dimensional wind speed 2.38 where vortex excitation occurs compared with when no TLCD exists.

At horizontal length L_H=30mm, just as at horizontal length L_H=25mm, displacement response was decreasing with increase in mass ratio, and at mass ratio 4.5%, it was decreasing by maximum 40% or more. However, the case of TLCD installed worked rather negatively with increase in non-dimensional wind speed.

When horizontal length L_H=35mm, at mass ratio 1.5%, displacement response appeared similar to other horizontal tube length, however with increase in mass ratio, displacement response at non-dimensional wind speed where vortex excitation occurs decreased by maximum 40% and 48% at mass ratio of 3.0% and 4.5%. Overall, displacement response decreased with increase in horizontal tube length, and with increase in mass ratio, it appeared advantageous at low wind speed where vortex excitation occurs.

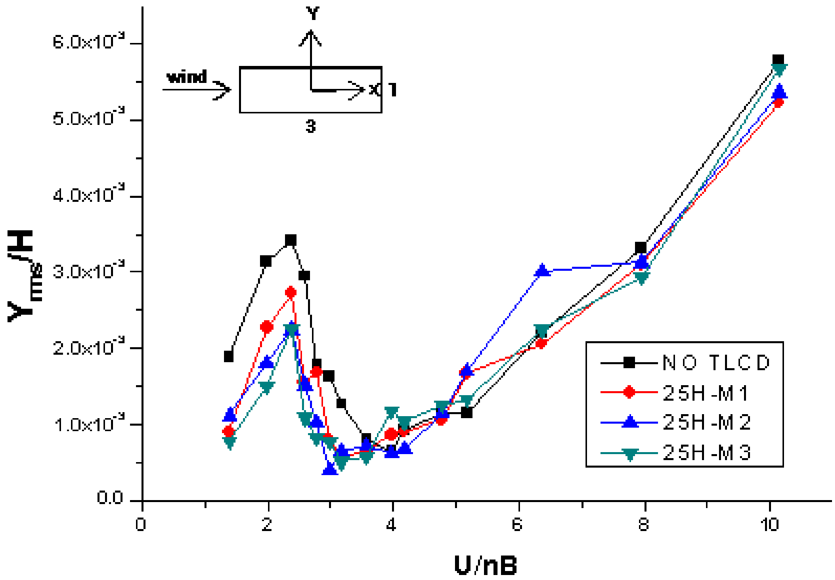


Fig. 5 Displacement response(length of horizontal tube; L_H=25mm)

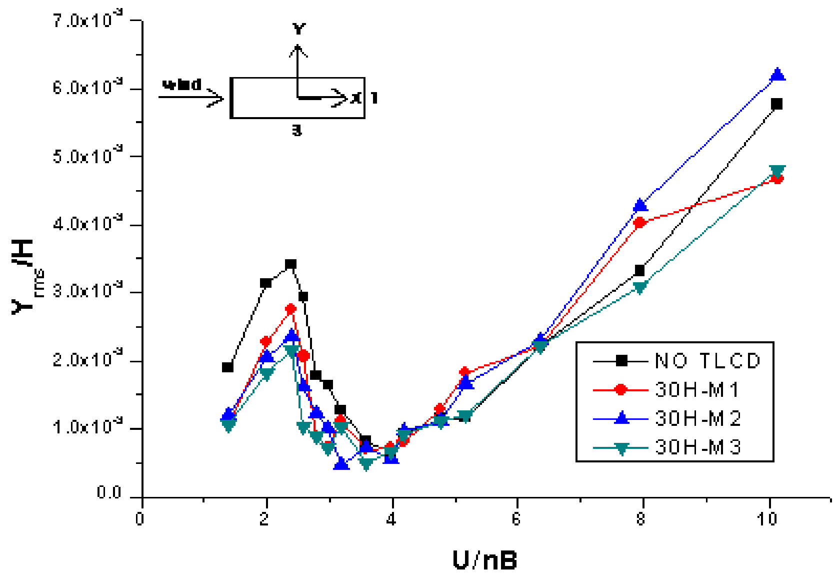


Fig. 6 Displacement response(length of horizontal tube; L_H=30mm)

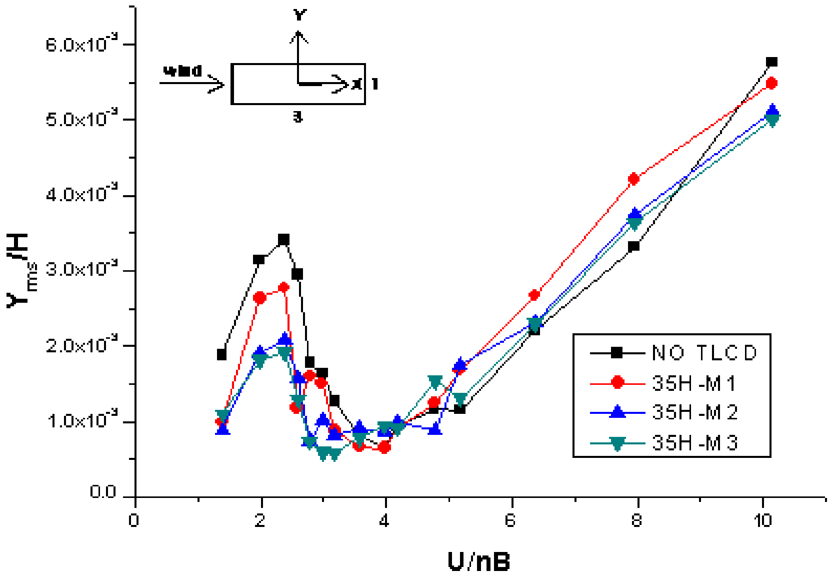


Fig. 7 Displacement response(length of horizontal tube; L_H=35mm)

4.2. Spectral analyses

Fig. 8 thru Fig. 10 show the result of displacement spectrum by change in horizontal length at wind speed 1.2m/s where maximum peak is measured. Regardless of horizontal tube length, maximum displacement spectrum appears clearly near natural frequency 2.89, and with spectrum appearing largest when no TLCD is installed, the magnitude of displacement spectrum decreases with increase in mass ratio. As for horizontal tube length, the magnitude of displacement spectrum is higher with horizontal tube length increases for all three mass ratios.

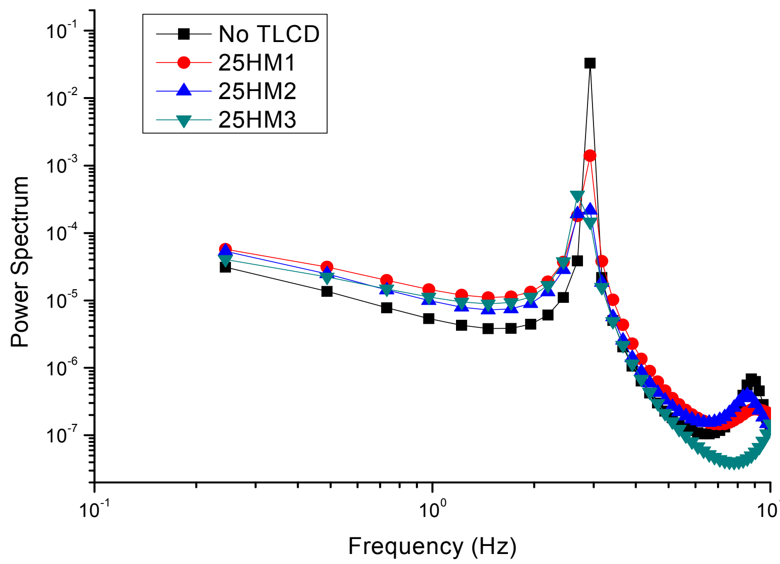


Fig. 8 Spectrum for cross-wind displacement response
(length of horizontal tube; L_H=25mm)

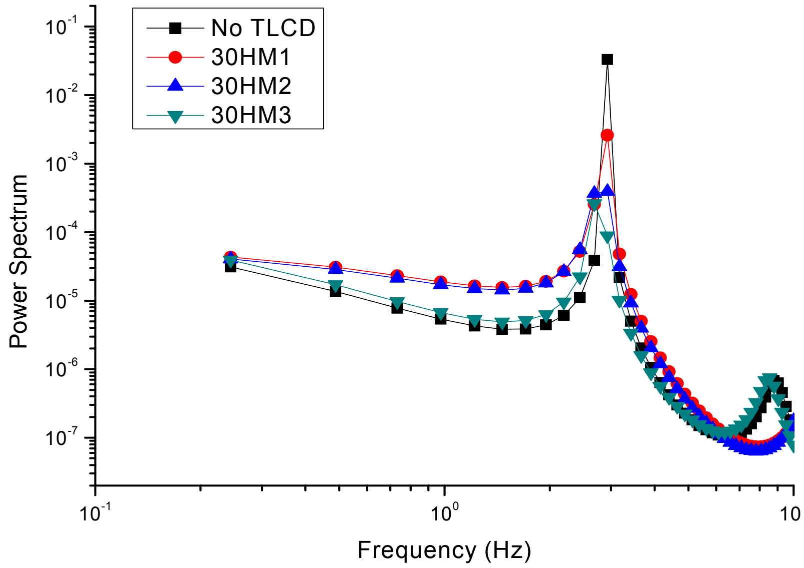


Fig. 9 Spectrum for cross-wind displacement response
(length of horizontal tube; L_H=30mm)

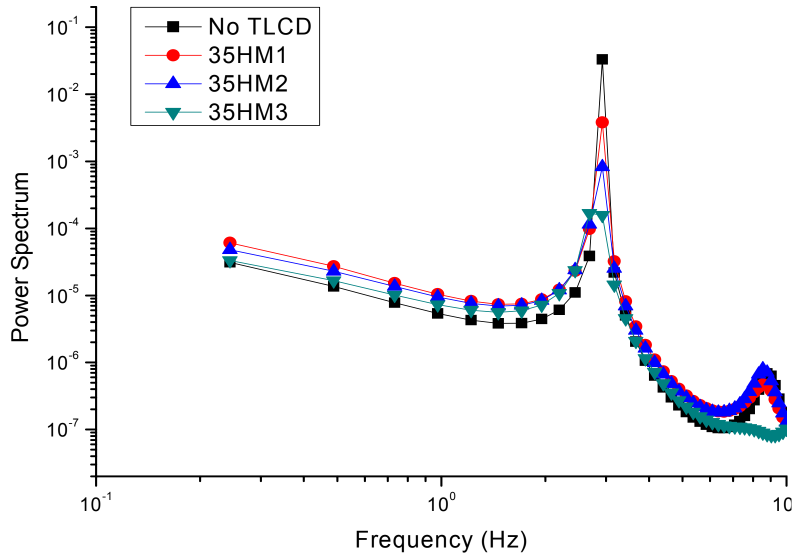


Fig. 10 Spectrum for cross-wind displacement response
(length of horizontal tube; L_H=35mm)

5. CONCLUSION

To find out the effect of reduction of vibration response in high-rise building where TLCD is installed, aeroelastic vibration test was done after installing TLCD at top layer of aeroelastic vibration model in which the ratio of long side to short side(Depth/Breadth) is 3, and the following conclusions were obtained:

1) Displacement response is decreasing more at non-dimensional low wind speed in case TLCD is installed at top layer than in case TLCD is not installed.

2) At horizontal lengths L_H=25mm, L_H=30mm, L_H=35mm all, displacement vibration response decreased with increase in mass ratio, and at mass ratio 4.5% at non-dimensional wind speed 2.38 where vortex exciation occurs, the response decreased by maximum 35%, 40% and 48% or more in comparison with no TLCD installation.

3) Regardless of horizontal tube length, maximum displacement spectrum appears clearly near natural frequency 2.89, and with spectrum appearing largest when no TLCD is installed, the magnitude of displacement spectrum decreases with increase in mass ratio.

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