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Wind-Resistant Design of the New Type Communication Steel Tower based on Wind Tunnel Experiment

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Abstract

In Japan, most of the communication steel towers are mainly designed as typical truss structures. Recently, a new type of communication steel tower is developed which improves structural appearance and maintainability. This tower is about 90 meters high and has four large steel tubes that serve as the main vertical supports. It has an uncommon structural configuration that even the local standard or the AIJ Recommendations for Loads on Buildings has no pertinent wind load provisions for its kind. Moreover, it has a large aspect ratio that could probably cause resonance during severe vortex- induced vibration. In order to determine the structure's resistance against wind loading, wind tunnel experiment is performed.
There are two kinds of wind tunnel experiments that were used in this study: (1) the dynamic force balance test, and (2) the aerodynamic vibration test. The dynamic force balance test was carried out to investigate the structure's susceptibility to wind load. The resonance occurrence at wind speed of 500-year return period is further confirmed by aerodynamic vibration test. In this study, the authors introduce an example of wind-resistant design of the new type communication steel tower by using these wind tunnel experiments.

Keywords: communication steel tower, wind tunnel experiment, vortex- induced vibration, resonance

1. Introduction

In Japan, most of the communication steel towers are mainly designed as typical truss structures. A new type of communication steel tower was developed that has more improved which improves structural appearance and maintainability. The tower is 89.15 meters high and has four large vertical steel tubes with 1.9 meters diameter. There are two platforms located at the upper most levels of the tower where the parabolic shape antennas are installed. The tower is located at 1000m to the southwest side of Yokohama City in Kanto Region where the surface characteristic is nearly flat and the nearby structures are low to middle rise buildings. The following pictures show the actual communication steel tower in the site.

Figure 1: Overview of the new type of communication steel tower (daytime & nighttime)

Unlike other typical truss towers that are made of latticed elements, the tower has simple but uncommon structural configuration that is formed by four large tubular columns diagonally erected at its supports and smoothly intersected at the mid height, where the four columns are jointly combined. Due to its shape, it is difficult to determine the corresponding design wind load if the approach will be based on the local standard or the AIJ Recommendations for Loads on Buildings. It is also necessary to consider the influence of vortex-induced vibration and aerodynamic unstable vibration. In order to determine the resistance and response of the structure against probable severe wind load, wind tunnel experiments were performed.

There are two kinds of wind tunnel experiments that were used in this study: one is the dynamic force balance test, and the other is the aerodynamic vibration test. The dynamic force balance test was carried out to investigate the structure’s susceptibility to wind load. The resonance occurrence at wind speed of 500-year return period is further confirmed by means of aerodynamic vibration test.

2. Dynamic force balance test

2.1 Experiment model

The dynamic force balance test was carried out to investigate the structure’s susceptibility to wind load. There are two scaled miniature models that were used in the dynamic force balance test, as shown in Figure 2. The first one represents the actual four-tube tower constructed in the site that has diameter and total height of 1.9 meter and 89.15 meters, respectively. The other model was configured to represent experimentally a three-tube tower with diameter and height of 20 meters and 89.15 meters, respectively. All models were miniaturized forms of the actual tower structures in 1/300 geometrical scale, which was determined in consideration that the experiment wind speed required to acquire the fluctuating wind speed data in the frequency range exceeding the non-dimensional natural frequency of the steel tower does not become too small.

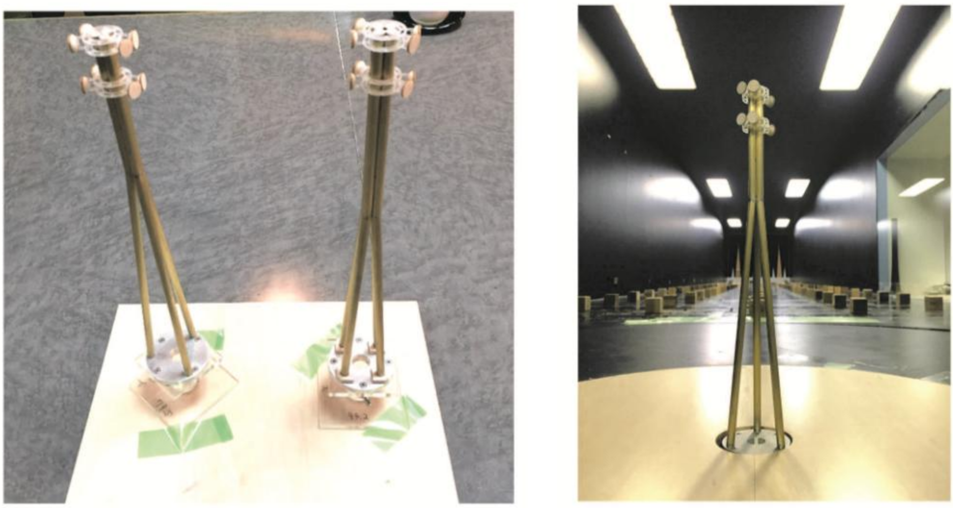


Figure 2: The experiment model used in the dynamic force balance test

2.2 Wind Tunnel

The dynamic force balance test was carried out in a turbulent boundary layer wind tunnel at Tokyo Polytechnic University. It has dimension of 2.2 meter width, 1.8 meters height and 19 meters length. The same tunnel was also used for aerodynamic vibration test.

2.3 Experimental Case

The two scaled models were used as two different experimental cases, as shown in Table 1.

Table 1: Experimental case

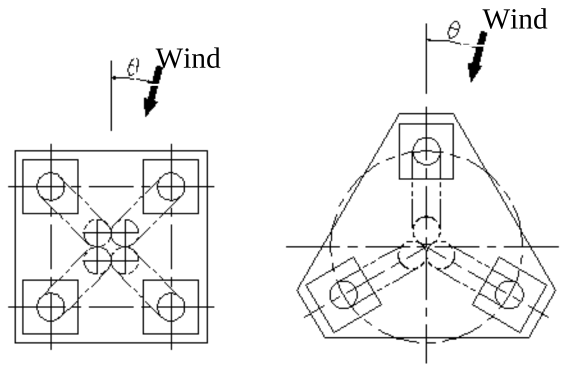
	Tower shape	*Experiment wind direction*
Case 1	*Four-tube tower*	*0° to 350° (every 10°)*
Case 2	*Three-tube tower*	

2.4 Wind Speed

The experiment wind speed was set to about 8.3 m / s at the top height of the steel tower to satisfy the ensuring the accuracy of the wind tunnel experiment and similarity law. It is aimed to obtain fluctuating wind force data in the frequency range exceeding the natural frequency of the experiment model against the design wind speed.

2.5 Wind Direction

The wind was set to 36 directions with clockwise rotation from 0 ° to 350 ° at 10 ° interval, as shown in figure 3.



(a)Case1 (Four-tube tower) (b)Case2 (Three-tube tower)

Figure 3: Definition of experiment wind direction

2.6 Wind profile

To ensure that the surface terrain roughness category III of AIJ Recommendations for Loads on Buildings be attained for the experiment, the roughness blocks, spires, and other barriers were positioned in the windward area of the wind tunnel floor.

2.7 Similarity law

The geometric scale used in the wind tunnel experiment was 1/300. The scale of the wind speed and time was arbitrarily determined according to the similarity law. However, taking into consideration the accuracy and the response of the structure, the velocity scale and the time scale were set as1/5 and 1/60, respectively.

2.8 Definition of wind force coefficient

The wind force coefficients such as (average wind force coefficient C_{Fx}, C_{Fy}, C_F, average overturning moment coefficient C_{Mx}, C_{My}, C_M) are defined as follows,

$$C_{Fx} = \frac{\overline{F}_x}{q_H BH}, C_{Fy} = \frac{\overline{F}_y}{q_H BH}, C_F = \sqrt{C_{Fx}^2 + C_{Fy}^2}$$

$$C_{Mx} = \frac{\overline{M}_x}{q_H BH^2}, C_{Fy} = \frac{\overline{M}_y}{q_H BH^2}, C_M = \sqrt{C_{Fx}^2 + C_{Fy}^2}$$

where $\overline{F}_x, \overline{F}_y$ is average wind force, $\overline{M}_x, \overline{M}_y$ is average overturning moment, q_H is average velocity pressure, B is representative width of the steel tower (four-tube tower is 3.8m) and H is total height of the steel tower (= 89.15 m). The experiment was evaluated by getting the average of the five values obtained from the time history data of each sample corresponding to real time 10 minutes for each coefficient.

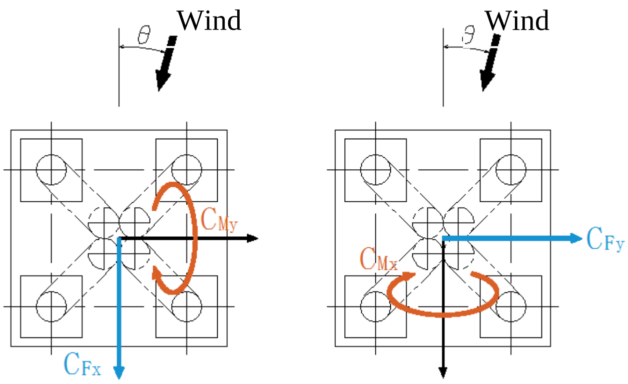


Figure 4: Definition of wind force coefficients

2.9 Results and remarks of dynamic force balance test

Figures 5 to 7 show the values of the wind force coefficient of each model.

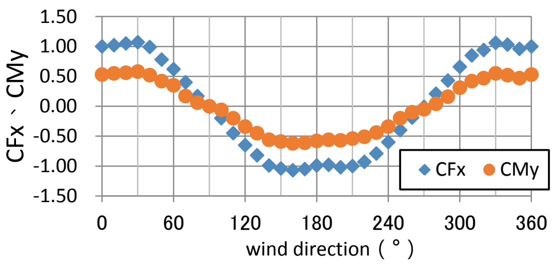


Figure 5a: Four-tube tower

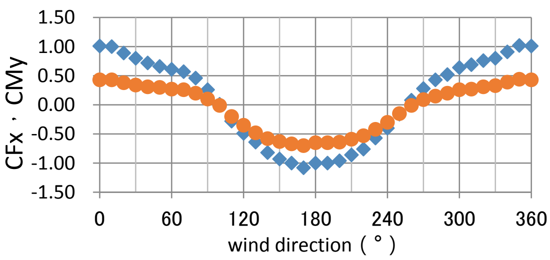


Figure 5b: Three-tube tower

Figure 5: The values of C_{Fx} *and* C_{My}

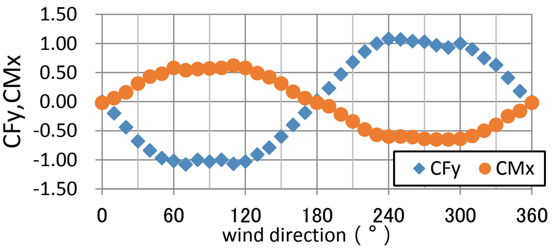


Figure 6a: four-tube tower

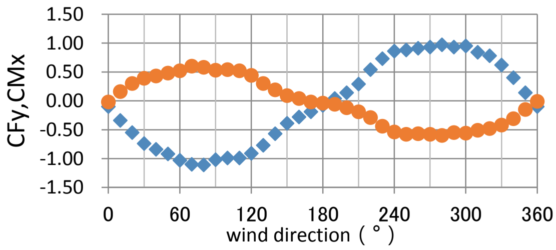


Figure 6b: three-tube tower

Figure 6: The values of C_{Fy} *and* C_{Mx}

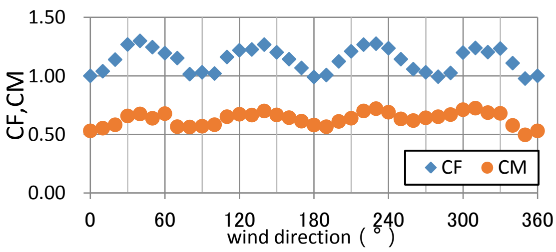


Figure 7a: Four-tube tower

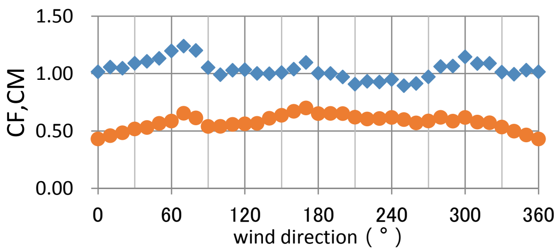


Figure 7b: Three-tube tower

Figure 7: The values of C_F *and* C_M

According to the result of four-tube tower as shown in Figure 7a, the average wind force coefficient C_F and the average overturning moment coefficient C_M show peaks at four wind directions: 40 °, 140 °, 230 ° and 310 °. Whereas, the result of three-tube tower as shown in Figure 7b indicates that the C_F and C_M have peaks at three points: 70 °, 170 ° and 300 °. The results confirm that the peak appears not in the front but in the direction affected by the wind at orthogonal direction. The maximum values of C_F are 1.30 and 1.24, and the maximum values of C_M are 0.70 and 0.72, for four-tube tower and three-tube tower, respectively.

The wind load adopted for the wind-resistant design of the four-tube tower can be set by the result obtained from dynamic force balance test. The wind load distribution is also applied by setting the coefficients C_o and β so that C_F and C_M at the base part will match with the experiment result of 1.30 and 0.70. The wind pressure w (N/m^2) is determined as follows,

$$w = C_F \cdot qH$$

$$C_F(z) = C_0 \cdot (z/H)^{\beta}$$

where C_o = 1.61 and β= 0.24. Figure 8 shows the calculated wind load.

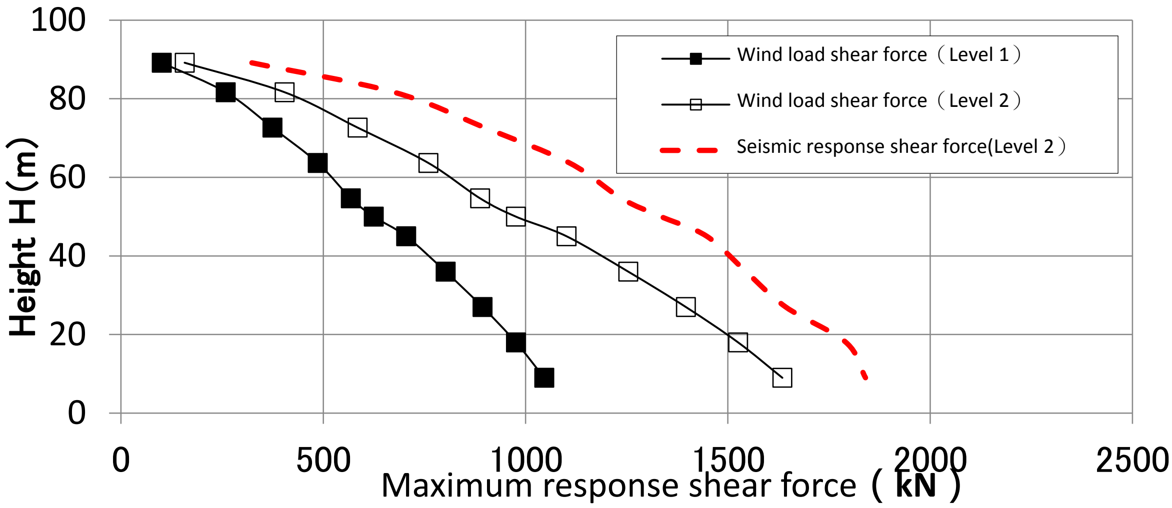


Figure 8: Calculated wind load

The two wind loads shown in the figure are for return period 50 years and 500 years events and both are smaller than the response value induced by level 2 earthquake. In the design execution, it is also confirmed that the generated stress of each part of the steel tower is less than the allowable stress of the material.

3. Aerodynamic vibration test

3.1 Experiment model

The aerodynamic vibration test was carried out to investigate the resonance occurrence at wind speed of 500-year return period. Figure 9 shows the two models used in the aerodynamic vibration test. The geometric scale used was 1/100, and both models were made up of balsa wood to adjust the mass ratio. The natural frequency and structural damping ratio of the first model (four-tube tower) were 11.2 Hz and 0.5%, respectively, while the second model (three-tube tower) has 10.9 Hz natural frequency and 0.9% damping ratio.

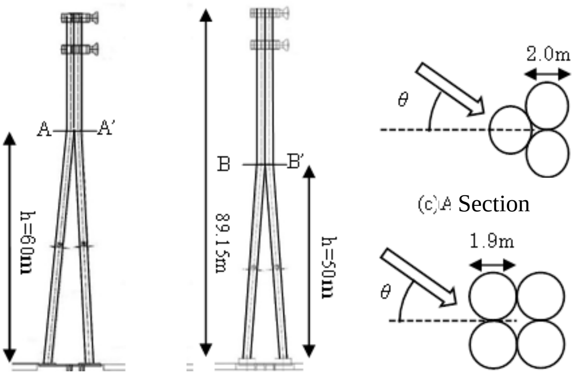


Figure 9: Illustration of the two models used in the aerodynamic vibration test

3.2 Wind Speed

The wind speed was set from 0.0 to 15.0 meters per second with 20 to 25 steps.

3.3 Wind Direction

The wind directed to four-tube tower was set in six different directions from 0 ° to 40 ° angle at 10 ° and 45° intervals, while the three-tube tower was exposed to wind with seven different directions from 0 ° to 60 ° angle at 10 ° intervals.

3.4 Wind profile

The experiment airflow was generated targeting the air flow equivalent to surface terrain roughness category II, III, and IV.

3.5 Similarity law

Based on the design wind speed expected in Yokohama City where the actual tower is located, the velocity scale and time scale were set as 1 / 5.8 and 1/17, respectively, in the experiment. For 10 minutes in real time interval, the 40000 data (sampling frequency 800 Hz) was measured five times.

The experimental result was measured in terms of deformation angle. It is determined by measuring the displacement using a laser displacement transducer and dividing it by the distance from the gimbal rotation center to the displacement gauge position.

3.6 Results and remarks of aerodynamic vibration test

Figures 10 to 11 show result of the fluctuating deformation angle due to the non-dimensional wind speed in the ground surface roughness classification II. The non-dimensional wind speed was defined as the wind speed divided by the natural frequency and the width of the model. At Figure 10a, it further indicates that fluctuation deformation angle was practically the same even when the wind angle changed in different directions. Figure 10b also shows that wind rapidly increased to 7.7 in the non-dimensional wind speed. This rapid increase was not observed at wind direction from 0 ° and 10 ° angle, however the fluctuation of the deformation angle increased at angle 20 ° wind direction or more. Moreover, as the magnitude of the non-dimensional wind speed increases, the fluctuating deformation angle also increases and further increases as the angle of wind direction decreases. It also shows that the tendency is opposite to that of the resonance phenomena. Figure 11a shows that there was no significant influence that can be attributed to wind direction for non-dimensional wind speed of 20 or less. However, it can be seen that the fluctuating deformation angle increased at angle 0 ° to 30 ° when the non-dimensional wind speed is more than 20. Figure 11b show that it increases at 7.3 in the non-dimensional wind speed.

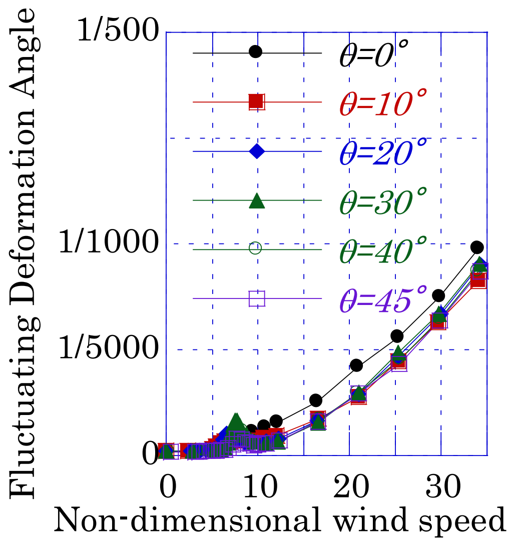


Figure 10a: Along-wind

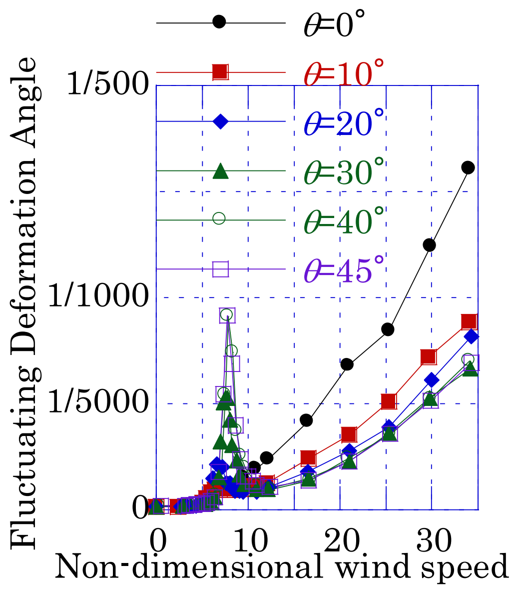


Figure 10b: Across-wind

Figure 10: Fluctuating deformation angle due to non-dimensional wind speed

(four-tube tower, the category of surface roughness II)

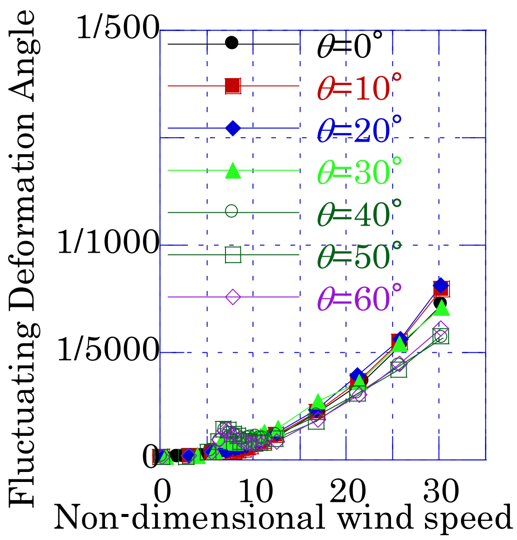


Figure 11a: Along-wind

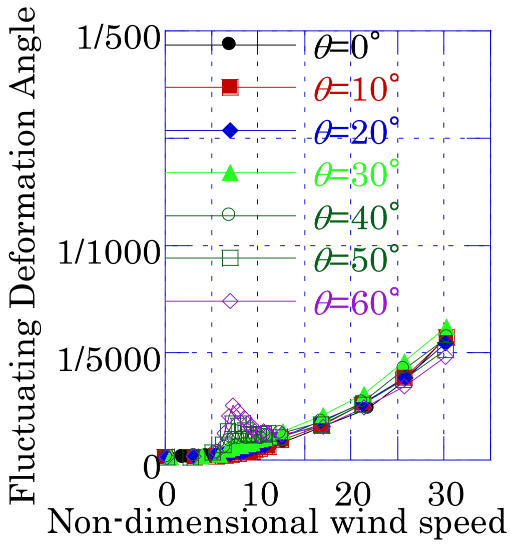


Figure 11b: Across-wind

Figure 11: Fluctuating deformation angle due to non-dimensional wind speed

(Three-tube tower, the category of surface roughness II)

In the aerodynamic vibration test of the four-tube tower, strong fluctuation occurred in the across-wind direction. PIV measurement was used to visualize the flow around the model. The PIV measurement has a smoke generating device, a laser sheet light source and a high-speed camera that can detect airflow. The device has zoom lens, adjustable aperture, and the focus that can be set with the laser sheet light. Two types of laser sheet light source were used: the “2 W” and the “1 W”. The “2 W” laser was illuminated from the leeward side, and the shadow was prevented by exposing the models to “1 W” laser. The smoke generating device was installed at 4 m from the windward side, and laser sheet light source was installed at 340 mm higher than the reference floor surface for both 2 W and 1 W. The high speed camera shot images from the top of the model in the wind tunnel and the number of frames was set to 800 fps. The measurement time was about 19 seconds, and the number of analysis frames was about 15000 sheets. The wind direction measured only 0 ° and 45 ° of the category of surface roughness II. In order to improve the accuracy of analysis, preprocessing was applied to recorded moving images.

Figures 12 shows the images of vortex formed at the back of the model. It turns out that the vortex was formed at the resonant wind speed.

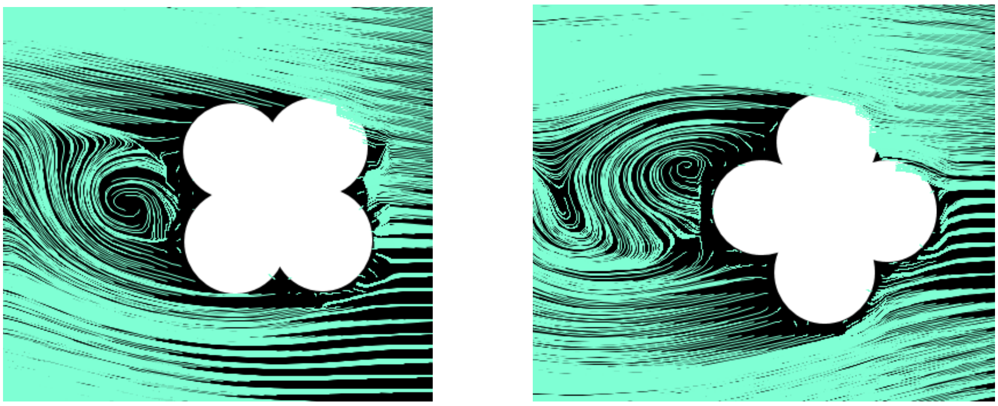


Figure 12: Stream line obtained by PIV measurement

(Right: θ = 0 °, Left: θ = 45 °, the category of surface roughness II)

Figures 13 shows the Non-dimensional power spectral density in the aerodynamic vibration test at angle 45 ° and power spectral density across wind direction of the vortex in the PIV measurement. Table 2 also shows the prevailing non-dimensional frequency in aerodynamic vibration test and PIV measurement. The non-dimensional frequency was defined as the product of the natural frequency and the width of the model divided by the wind speed. As both results were compared, it turns out that the prevailing non-dimensional frequencies were practically the same.

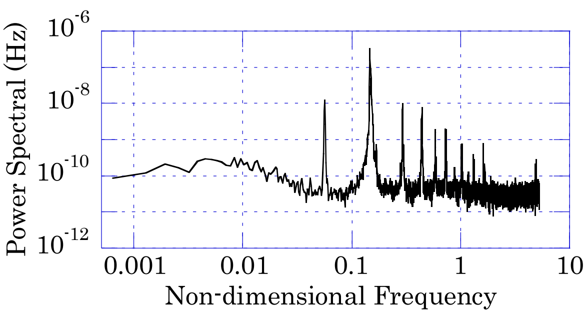


Figure 13a: Aerodynamic vibration test

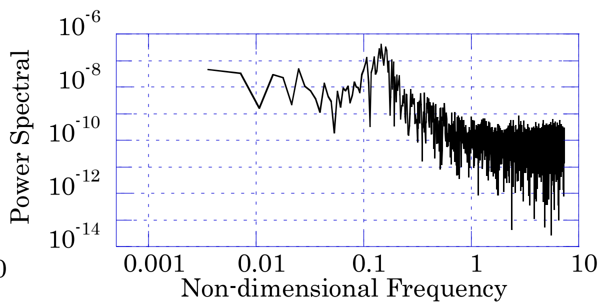


Figure 13b: PIV measurement

Figure 13: Power spectral density (θ = 45 °, the category of surface roughness II)

Table 2: Prevailing non-dimensional frequency

	Wind direction	
	$\theta = 0\ °$	$\theta = 45\ °$
Aerodynamic vibration test	*0.14*	*0.15*
PIV measurement	*0.16*	*0.14*

The aerodynamic vibration test revealed the effect of the wind direction and occurrence of unstable aerodynamics. The PIV measurement confirmed that the unstable aerodynamic vibration was influenced by the vortex formed and the frequency of the vortex at resonance was estimated.

The wind speed of return period 500 years corresponds to non-dimensional wind speed 18.8 and its fluctuating deformation angle is smaller than it of resonant wind speed. Since the resonance was confirmed in the wind speed where occurrence probability was high, series of investigation in construction site is also conducted, and fatigue safety in structural members are confirmed by a combination of stress amplitude and repeat count.

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