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Article

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A note of wind engineering: Describing tower pre-assembly work at quayside for offshore wind turbine

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Abstract

A tower of an offshore wind turbine usually has several sections. The sections need to be assembled to form a full tower and be ready for nacelle installation. The assembly work can be performed at a designated sea site but it can be exposed in many risks. Instead, towers can be pre-assembled at quayside prior shipping to the sea site to reduce risks. In the present paper, the author shares the experience on tower pre-assembly work at quayside, in the wind engineering aspect. The wind engineering in this work includes wind data collection, wind data analysis, aeroelastic phenomenon of the towers, and eventually the aerodynamic loads on the towers. In the beginning, wind detector LiDAR is introduced to collect the wind data, and then the Method of Independent Storms is demonstrated for wind data analysis. For aeroelasticity, the present work showed that the vortex shedding frequency resonates with the natural frequency and the flutter frequency. Finally, through the gust factor and drag coefficient, aerodynamic load to the tower is determined, to be the result of the present work. The purpose of this work is to provide a complete approach to calculate the aerodynamic load on the tower, from the very beginning of wind data collection. All data and inputs in this paper are random, to avoid infringing intellectual properties and patents.

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Keywords: Offshore wind turbine; Tower pre-assembly; Wind engineering; Risk

1. Introduction

Offshore wind project is a commencing technology in Taiwan. Different than onshore one, offshore environment is a lot harsh and requires advanced techniques such as wind conditions observation/prediction, structural stable to severe wind and ocean wave/current, seabed condition surveyors for the foundation, and sea cable capability to the grid to onshore substations. Before the wind turbine towers are shipped to the sea sites, normally a key step, called pre-assembly harbor, the tower sections are assembled at quayside, to reduce risks of assembly work on the sea. To perform this task, quayside foundation structures, including caissons, prudent designs and calculations to the bearing capacity for towers are needed to avoid collapse during the loads and overturning moment by coast wind.

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Nomenclature

a	A parameter related to standard deviation of Gumbel distribution
a_s	Slope of the extrapolating of the Gumbel regression
A	Tower surface area
b_i	The intersect value to the Gumbel reduced variate
B	Tower width in cross wind direction ($B = D$ in the present paper)
C_d	Drag coefficient of [a single tower: 1.07] and of [a tower in the group of tower: 1.2 (the largest value)]
C_p	Pressure coefficient
D	Tower diameter: 5 m
E	Youngs Modulus of tower $23 \times 10^9 \text{ N/m}^2$
f	Tower natural frequency
f_{damped}	Tower flutter frequency
f_{free}	Tower flutter frequency
F	Force
g_Q	Peak factor for background response: 3.4
g_R	Peak factor for resonance response
g_V	Wind speed peak factor: 3.4
G	Gumbel reduced variate
G_f	Gust factor
h	Tower height: 71 m
I	Area moment of inertia
$I_{\bar{z}}$	Turbulence intensity: 0.09
L	Tower width in along wind direction ($L = D$ in the present paper)
$L_{\bar{z}}$	Integral scales for turbulence: 0.15 m
M	Tower mass: 500 tons
N_1	Resonance factor parameters for integral scales for turbulence, aerodynamic admittance function
Q	Background response factor
r	Return period
R	Resonant response factor
R_B	Resonant factor for across wind direction, aerodynamic admittance function
R_e	Reynolds number
R_h	Resonant factor for height direction, aerodynamic admittance function
R_L	Resonant factor for along wind direction, aerodynamic admittance function
R_n	Resonant factor for integral scales for turbulence, aerodynamic admittance function
u	A parameter related to mean value of Gumbel distribution
S_t	Strouhal number
ΔT	Temperature change
v_0	10 min average wind speed from the right hand side
v_1	10 min average wind speed from the left hand side
V_{ref}	Extreme wind speed
v_x	Wind speed in the radical component
v_y	Wind speed in the tangential component
$\bar{V}_{\bar{z}}$	Hourly averaged wind speed m/s at height z
α	The angle that LiDAR can detect incoming wind
β	Structural damping ratio

η_B	Resonance factor parameters for across wind direction, aerodynamic admittance function
η_h	Resonance factor parameters for height direction, aerodynamic admittance function
η_L	Resonance factor parameters for along wind direction, aerodynamic admittance function
μ	Air viscosity: 1.82×10^{-5} kg/m s at 27 °C
ρ	Atmosphere density

To decide the overturning moment, the wind data should be collected first. LiDAR system is one of the new technology to obtain the wind information to carry out such works. After data collection, an analysis in Method of Independent Storm to determine a wind velocity, a reference velocity V_{ref} at the certain height, will be applied. This V_{ref} will then be the input for aeroelastic analysis to the tower and pressure distribution calculation on the tower surface. Aeroelasticity helps to prevent tower oscillation from resonance (lock in) with the wind flow, and the pressure distribution assists to calculate the aerodynamic load acting on the tower. The purpose of the present work is to obtain one information: the aerodynamic load to the tower, so as to enable the quayside foundation work in terms of design and construction to resist the overturning moment from the coast wind.

The present work used random information of tower weight, dimensions, and relevant facility inputs. Wind data inputs are generated and programming by MATLAB software commands, based on author's work experience to obtain the final result of aerodynamic load on tower surface. Detail analysis is in the following Section 2.

2. Work procedure

The analysis and calculations are arranged in MATLAB programming software. The wind engineering in this work includes four parts: wind data collection, wind data analysis, aeroelastic phenomenon to the towers, and eventually the aerodynamic loads on the towers.

2.1. Wind data collection

The data should be collected from a met mast at the desire location, for at least 7 years, the longer the better. The met mast should stand out from the sea level a certain height, in order to install the wind data collector at usually 10 m above the sea level. The measured data should include wind speed, wind direction, the wind speed deviation (turbulence), and the air density. The hourly data from the Center Weather Bureau of Taiwan may be a reference (see Fig. 1).

There are several type of instruments which can be used to measure wind speed and direction. Two of them are the most popular ones:

- (1) Cup anemometers. They are currently regarded as the industry standard for wind resource assessment practice.
- (2) Light detection and ranging (LiDAR). The measurement standard of LiDAR should be referred to IEC 61400-12-1. The measurement method is described as following [1]: LiDAR will shoot two laser beams of 1.4 Hz up to a certain distance in the front with an angle of 2α ($\alpha = 15^\circ$), then $\langle v_x \rangle = \frac{\langle v_0 \rangle + \langle v_1 \rangle}{2 \cos \alpha}$ is defined as wind speed in the radical direction, and $\langle v_y \rangle = \frac{\langle v_0 \rangle - \langle v_1 \rangle}{2 \sin \alpha}$ is defined as tangential direction. Also, v_0 is the 10 min average wind speed from the right hand side, and v_1 is the 10 min average wind speed from the left hand side. Therefore, the mean square root of radical and tangential wind speed is the actual wind speed $\langle v \rangle = \sqrt{\langle v_x \rangle^2 + \langle v_y \rangle^2}$, and the direction is $\tan^{-1} \frac{v_y}{v_x}$.

2.2. Wind data analysis

The most important for the wind data analysis is to obtain the extreme wind speed V_{ref} , which is defined in the present work as the maximum wind speed of 50 year return period, as an input value for aeroelastic analysis and aerodynamic load calculation later. The way to calculate V_{ref} is dependent on the collected data. The Method of Independent Storms (MIS) is one of the approach to calculate the V_{ref} from data. The method is to select storm

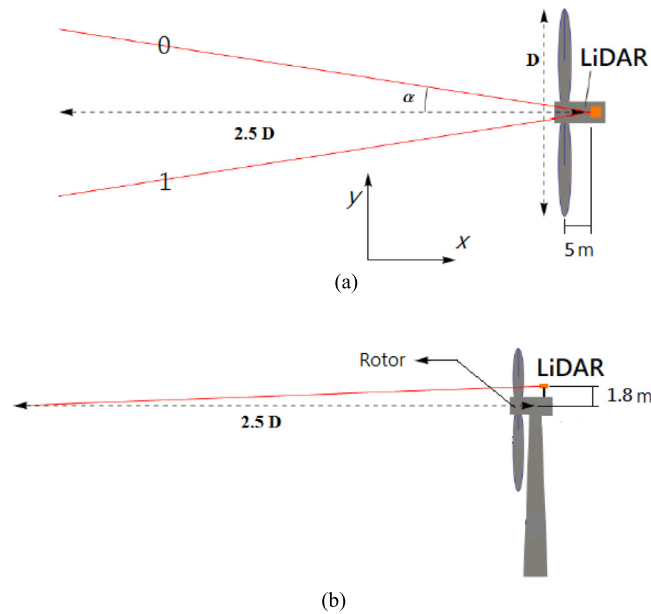


Fig. 1. Showing LiDAR set up and the way it measures the wind speed and direction on a wind turbine. It is believed to have similar set up on a met mast: (a) top view and (b) side view. The orange square represents LiDAR, and it is placed 5 m behind the blades swept plane, 1.8 m higher than the hub center line at the nacelle. The orange lines 0 and 1 are the laser beams, and gray is the wind turbine.

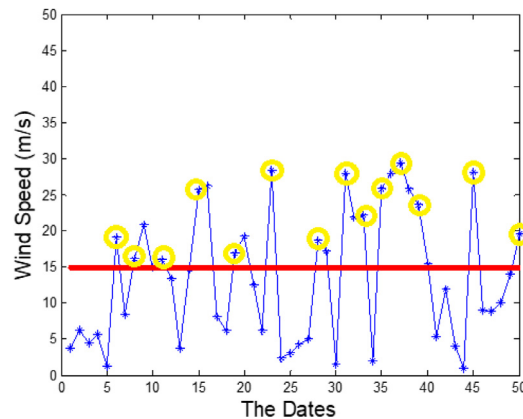


Fig. 2. The collected wind data is shown. First step is to set up a speed filter. This filter value is very much dependent on experience and previous studies. Above the speed, every storm event selected should be at least 48 h apart, appeared inside the yellow circles.

events above a set up speed filter, and arrange events of velocities in ascending order for linear regression to check if these input velocities fit Gumbel distribution. It is recommended by Cook and Gusella the duration between two storm events should be at least 48 h apart. Fig. 2 explained the situation.

We should now prepare Gumbel regression plot in extreme wind speed at Y axis and in Gumbel reduced variate: $G = \ln(-\ln(P_v))$ at X axis. Firstly, to calculate probability of an empirical value $P_y = \frac{(m-0.44)}{(N+0.12)}$, where m is rank of the wind speeds from lowest to highest. N is the total number of annual maximum observations. Secondly, apply Gringorten Estimation, a negative of the natural logarithm of P_y , that is $-\ln(P_v)$. In the end, plot extreme wind speed against the Gumbel reduced variate in Fig. 3, and it turns out all points in this graph behaved approximately linear. If the graph is not approximately linear, it indicates that the Gumbel distribution in Eq. (1) is not an appropriate distributional model for the data. In the present case, we calculate the correlation coefficient R of the linear regression is equal to 0.9988, to prove the maximum velocity data are perfectly match the Gumbel

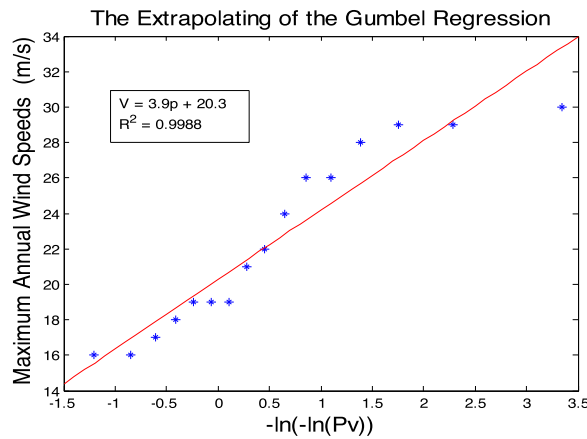


Fig. 3. Every storm event selected by MIS should be plotted in Gumbel regression plot with velocity at Y axis and Gumbel reduced variate at X axis.

distribution.

$$F = e^{e^{-a(x-u)}} \tag{1}$$

Once one has ascertained that the Gumbel distribution provides an adequate distributional model and has confirmed the location parameter (the intercept) and the scale parameter (the slope), the percentile with 10 min interval for 50 years return period should be calculated

$$p = 1 - \frac{1}{r \times n} \tag{2}$$

where r is 50 years and n is 16 for the sixteen of storm events selected in Figs. 2 and 3. The result of percentile p is then substituted into Gumbel percent point function (or inverse cumulative distribution):

$$G = -\ln [-\ln (p)] \tag{3}$$

With all the necessary inputs, the Gumbel percent point function $G = 6.684$, the scale parameter $a_s = 3.9$, and the location parameter $b_i = 20.3$, finally the 50 years return period of the extreme wind speeds v_{ref} at 10 m is determined to be 46.4 m/s in the following Eq. (4).

$$V_{ref} = b_i - a_s \ln [-\ln (p)] \tag{4}$$

2.3. Aeroelastic to the towers

When the tower exposes around the coming wind, the analysis is commonly simplified into the along-wind direction part and the cross-wind direction part. The first part will be discussed later in Section 2.4. This Section 2.3 the focus will be on the second part, the aeroelastic phenomenon.

Aeroelasticity is very complex. Therefore, only two aeroelastic mechanisms will be discussed in the present work. The first mechanism is vortex shedding interacting with the vibrating tower. Vortex shedding occurs when the Reynolds number of the flow reaches a certain value. The flow swings left and right itself at the leeward side of the tower creating lateral forces and generates vortices downstream of the tower. The vortices grow into the so called Von Kármán vortex street with a certain frequency. The frequency of the generated vortex can be determined by Strouhal number. The alternating force of vortex shedding from left and right keep pushing the tower so the tower begins to vibrate in the lateral direction with its own frequency, the natural frequency, swaying in a periodic motion. This alternating force does not vary as the tower vibration amplitude or frequency changing, it varies only depending on Reynolds number. What needs to be very careful in the design aspect, is to avoid the lock in effect. Lock in happens when the frequency of the vortex shedding aligned with the natural frequency of the tower. The alignment of these two causes the flow efficiently energize the tower body motion and resonate and enlarge tower

oscillating amplitude. It results in a damage to the tower. Therefore, the most important is to calculate these two frequencies and check if they are resonant. The frequency of the vortex shedding can be found by Strouhal number

$$St = \frac{fD}{v_{ref}} \quad (5)$$

To calculate the frequency, firstly to decide the Strouhal number. Usually, Strouhal number is a function of Reynolds number. Also, in the present work, a long circular cylinder scenario is considered to be the tower shape. With wind speed $v_{ref} = 46.4$ m/s, the Reynolds number is found to be 1.53×10^7 . In the situation the Strouhal number is 0.3 [2]. Refer to Eq. (5), the vortex shedding frequency is 2.78 Hz. In the following the tower natural frequency (first eigen mode only) is calculated. For a simple model, the tower is regarded as a mass on the one end of a cantilever beam with negligible mass and a point attached to the wall [3]. The first natural frequency of cantilever beam reads:

$$f = \frac{1}{2\pi} \sqrt{\frac{3EI}{ML^3}} \quad (6)$$

Substituting the tower mass, height, area moment of inertia, and young's modulus, the frequency is calculated to be 0.93 Hz. By comparing to the vortex shedding frequency in Fig. 4, there is no obvious resonance occurred in the beginning, however, the resonance takes place around the 43th–53th second.

Furthermore, the gust factor, which will be used in Section 2.4 to calculate the aerodynamic load, should use natural frequency to obtain. Besides natural frequency, to determine gust factor, aerodynamic admittance function is also necessary. It includes resonance factor and resonance factor parameters η . The Equation set (1) lists all the aerodynamic admittance functions needed for calculating the gust factor G_f . It is noted that per Chapter 6 of ASCE 7 “slender buildings or other structures are flexible if their natural frequency is less than 1 Hz” [4]. More of the gust energy goes into the structure, once they become more flexible [5]. Therefore, it is inferred that the dynamic response is significant for this kind of building/structure.

$$G_f = 1.927 \left(\frac{1 + 1.7I_{\bar{z}} \sqrt{g_Q^2 Q^2 + g_R^2 R^2}}{1 + 1.7g_V I_{\bar{z}}} \right) \quad (i)$$

$$Q = \sqrt{\frac{1}{1 + 0.63 \left(\frac{B+h}{L_{\bar{z}}} \right)^{0.63}}} \quad (ii)$$

$$R = \sqrt{\frac{1}{\beta} R_n R_h R_B (0.53 + 0.47R_L)} \quad (iii)$$

$$g_R = \sqrt{2 \ln(3600 f_n)} + \frac{0.577}{\sqrt{2 \ln(3600 f_n)}} \quad (iv)$$

$$N_1 = \frac{f_n L_{\bar{z}}}{\bar{V}_{\bar{z}}} \quad (v)$$

$$\eta_h = \frac{4.6 f_n h}{\bar{V}_{\bar{z}}} \quad (vi)$$

$$\eta_B = \frac{4.6 f_n B}{\bar{V}_{\bar{z}}} \quad (vii)$$

$$\eta_L = \frac{15.4 f_n L}{\bar{V}_{\bar{z}}} \quad (viii)$$

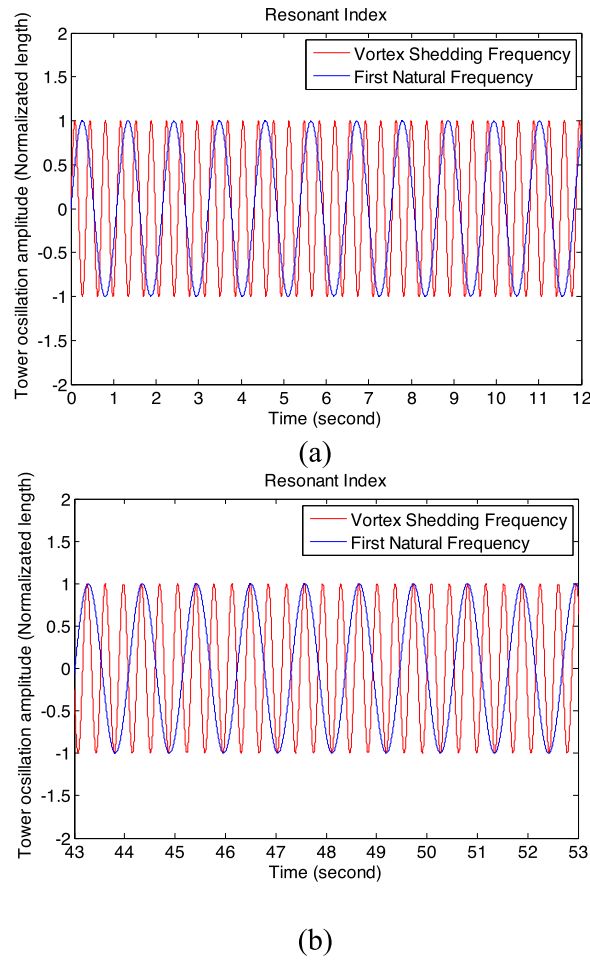


Fig. 4. The situation of vortex shedding frequency and first natural frequency: (a) no obvious resonance found, and (b) resonance is discovered from 43th second to 53th second.

$$R_n = \frac{7.47N_1}{(1 + 10.3N_1)^{\frac{5}{3}}} \tag{ix}$$

$$R_h = \frac{1}{\eta_h} - \frac{1}{2\eta_h^2} (1 - e^{-2\eta_h}) \tag{x}$$

$$R_B = \frac{1}{\eta_B} - \frac{1}{2\eta_B^2} (1 - e^{-2\eta_B}) \tag{xi}$$

$$R_L = \frac{1}{\eta_L} - \frac{1}{2\eta_L^2} (1 - e^{-2\eta_L}) \tag{xii}$$

Equation set (1). The aerodynamic admittance function for gust factor calculations.

By substituting $\bar{V}_z = 57.6$ m/s (wind speed at 71 m height of the tower, calculated from the wind shear exponent in Section 2.4), first eigen frequency of the tower $f_n = 0.93$ Hz, turbulence intensity $I_z = 0.09$, peak factor for background response $g_Q = 3.4$, wind speed peak factor $g_V = 3.4$, the integral scales for turbulence $L_z = 0.15$, the gust factor is equal to 1.54.

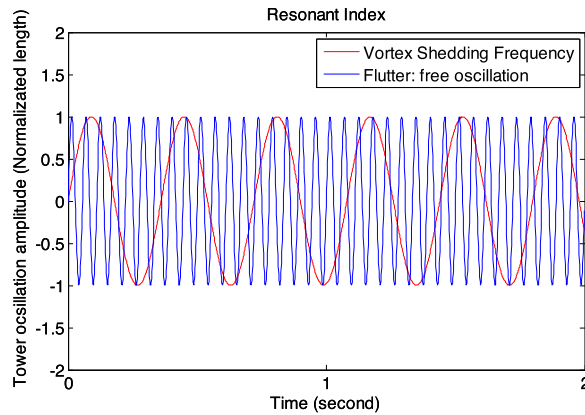


Fig. 5. The free oscillation of flutter phenomenon. The frequency is so high that the tower vibrates 18 times in one second.

The second mechanism introduced in the present paper is flutter. Flutter phenomenon is more like the material and object geometry property than an aerodynamic property. In other words, it is the object response to the input force, and the input force can be any kind of form such as wind or ocean wave. Mathematically, flutter can be described similarly as a free oscillation and damped oscillation, a self-excited vibration. For the free oscillation, the equation of motion obeys Hooke's law. Therefore, the input force is negative proportional to the vibrating amplitude, with a coefficient of stiffener. In the present work, the vibrating object is tower, and it is assumed that tower is made of concrete. Based on concrete, the tower stiffener k is related to concrete material property E (Young's modulus), tower area A , and the tower height h . For free oscillation, the frequency ω_{free} is calculated to be 18 Hz, by Eq. (7). The frequency is so high that it resonates to the vortex shedding frequency three times in one second so it dangers the tower body (see Fig. 5).

$$\omega_{free} = \frac{1}{2\pi} \sqrt{\frac{k}{M}} \quad (7)$$

On the other hand, if the air density is taking into account to the tower vibration, the vibration becomes damped oscillation. The flutter frequency can be varies based on fluid damping force change — it means the vibration of the tower is not at the same periodic time. The equation of motion for damped oscillation also obeys Hooke's law, with a damping term in the equation. The damping term depends on the air density, tower surface area, and the drag coefficient ($C_d = 1.07$ for a single tower) [6]. It is also proportional to its own vibrating speed. It means the slower the vibrated motion of the tower, the little the damping fluid force is. For the damped oscillation, the frequency is 2.87 Hz, according to Eq. (8). It is resonant to the vortex shedding frequency.

$$\omega_{damped} = \frac{1}{2\pi} \sqrt{\omega_{free}^2 - \frac{1}{\tau^2}} \quad (8)$$

Despite the resonance, the situation is not that harmful because self-excited vibrations are disturbances belong to a fundamentally different class as compared to the free or forced vibrations (not discussed in the present work). In a self-excited vibration, the excitation force that sustains the motion is created or controlled by the motion itself: when the motion stops the excitation force disappears. Therefore, even the damped oscillation resonates with vortex shedding, the tower flutter of this kind is eventually damped out and disappeared. Therefore, it causes low damage to the tower body. The situation showed in Fig. 6.

2.4. Aerodynamic loads on the towers

The aerodynamic loads refer to the static and dynamic air pressure distributed around the surface of an object when flow passes around the object. The loads can be affected by two parts: object itself and the flow part. The

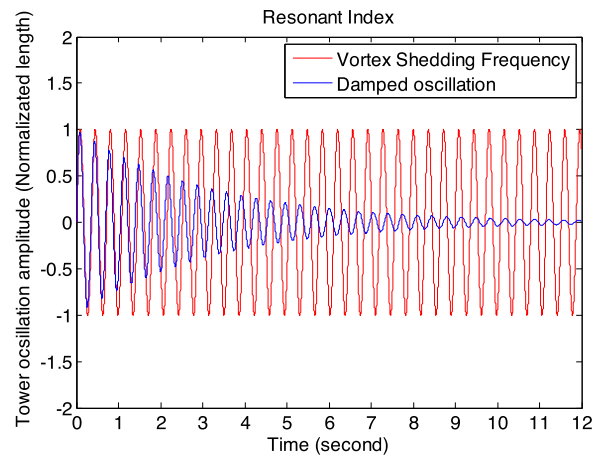


Fig. 6. The situation of vortex shedding frequency and the damped oscillation of the tower. The damped oscillation is damped out in 9 s so it causes no damage to the tower.

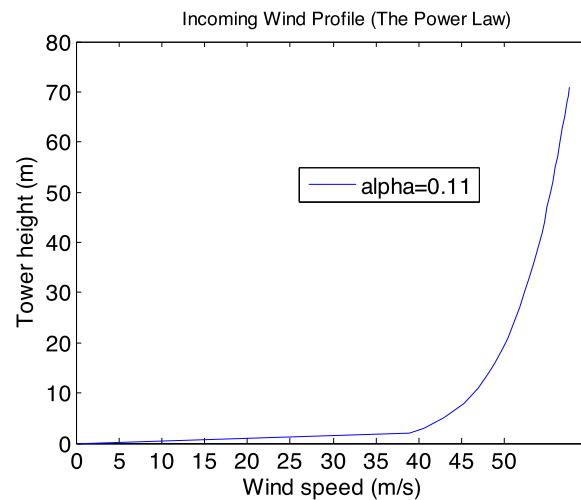


Fig. 7. The wind shear exponent of 0.11 is extrapolated from the speed 46.6 at 10 m height, to the 0 and 71 m height.

object part includes the shape, aspect ratio, angle of attack, and group effect. The flow part covers Reynolds number, exposure factor, turbulence intensity, gust factor, wind shear exponent, and wake profile. To obtain the aerodynamic load to the tower is the goal for the present work. In order to determine that, the pressure distribution on the tower surface should be obtained first. The dynamic pressure distribution depends on the velocity of the flow. In Section 2.2, the velocity v_{ref} at 10 m height has calculated so use it as an input to wind shear exponent and wake profile to obtain the wind wave front profile.

First of all, $v_{ref} = 46.4$ m/s is extrapolated with a wind shear exponent of 0.11 up to the tower top height and down to the ground level to obtain the wind front wave profile, according to the shear exponent defined in Taiwanese building code [7]. The extrapolated profile is showed in Fig. 7.

After the wind speed at different heights of the tower obtained, the values of speed are substituted into the dynamic pressure equation for calculating the pressure around the tower. On the other hand, the wake profile behind the tower is also determined, according to Subhasish Deyabc et al. [8]. The wind shear exponent wave profile and the wake profile can be referred to Fig. 8. The two wave profiles exert forces to the tower in the windward side and leeward side, together they will be the combination of the aerodynamic load.

Before continuing to calculate the aerodynamic load, there is one more parameter needed to be discussed, the drag coefficient. The drag coefficient can include the shape, aspect ratio, group effect. The physics insight of drag

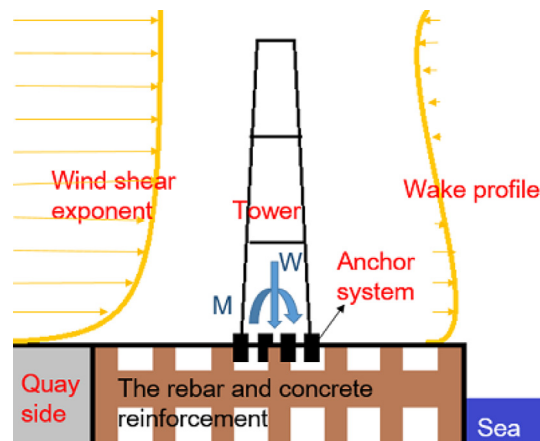
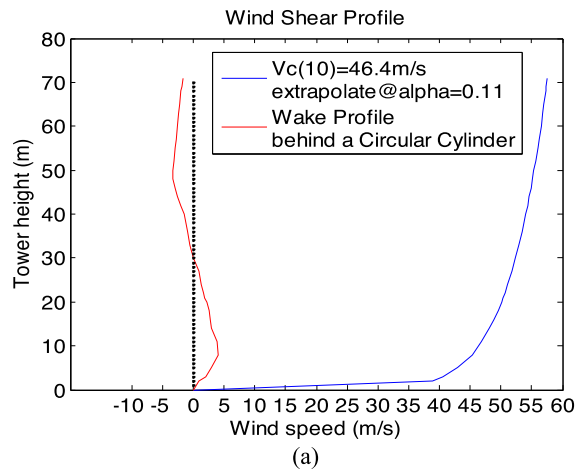


Fig. 8. The wind profile: (a) at the windward side of the tower (wind shear exponent in blue) and at the leeward side of the tower (wake profile in red). (b) The diagram showed the wind situation around the tower at quayside.

coefficient is the ratio between the incident flow momentum (denominator) and the deflected flow momentum (numerator). Hence, drag coefficient is easily covering the shape, aspect ratio, as well as the group effect which is depended on the wind direction. The situation claimed in the present paper to the tower section pre-assembly work can be shown in Fig. 9. Three cylinder of towers are installed by the quayside and the wind is coming from three directions. Since the towers are cylinder, there is no angle of attack issue, if considering and assuming wind is blowing horizontally and parallel to the ground only. However, the shape, aspect ratio, and the group effect remained. In Fig. 9. displayed a group of tower, the drag coefficient varies from tower to tower. The middle tower will experience the largest drag coefficient, for the situation of windward in 90° direction scenario. Therefore, the largest drag coefficient is taking into account for the aerodynamic load calculations. The value for calculation in the present work is $C_d = 1.2$ [9].

Finally, the aerodynamic load on a tower can be obtained. It is regarded as the dynamic wind pressure multiplying the gust factor and drag coefficient. In fact, the load can be expressed as

$$F = \frac{1}{2} \rho v_{ref}^2 G_f C_d A \quad (9)$$

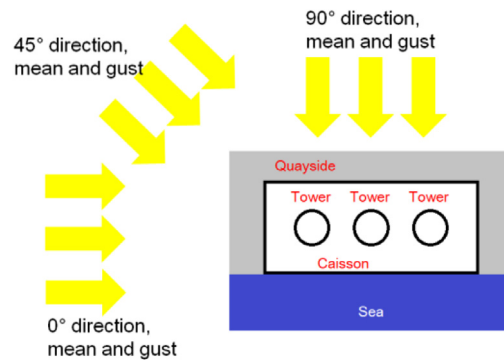


Fig. 9. The top view of the tower pre-assembly at quayside. Three towers are arranged next to each other with equal spacings in 10 m long. Windward is from three different directions, 90°, 45°, and 0° flowing toward the towers.

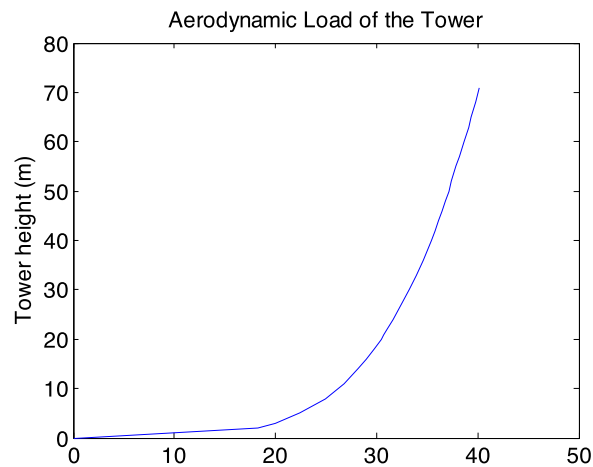


Fig. 10. Wind acts on the tower and results in the aerodynamic load on it. The figure shows the load distribution on the tower surface.

The pressure coefficient is depending on static pressure distributed around the surface of the tower, however, the dynamic pressure acting on the tower is the only consideration in the present work. Hence, pressure coefficient does not appear in Eq. (9).

3. Results and discussion

Implement of Eq. (9) in MATLAB, the aerodynamic load on different tower heights can be obtained and shown in Fig. 10.

4. Perspective and future work

The present work provides a complete method for the wind practice and research, from wind data collection, wind data analysis, aeroelastic analysis, and aerodynamic load calculation to the towers for tower sections pre-assembly work at quayside. With the complete method, one can input various data to obtain the result from different wind conditions. It is expected in the near future an algorithm can be coded, to serve as a toolbox in MATLAB or other software. Therefore, engineers can take a reference or use it for further applications, such as decide the overturning moment for the foundation and civil engineering/construction work.

The research is potentially beneficial to wind projects on Mars and other planets. Wind resource in space will be a popular research field because the electricity is essential to manned space activity and human space exploration. It is believed that wind conditions will be very different on other planets and this method may be extended and

applied to deep space. Perhaps, with strange atmospheres the method needed to be modified and new science will be discovered.

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