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Research paper

Dynamic Response of Self-Supported Power Transmission Tower Subjected to Wind Action

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Abstract

A power transmission tower carries electrical transmission conductor at adequate distance from the ground. It must withstand all nature's forces besides its self-weight. In structural analysis, natural frequency, mode shape and damping ratio are used to define the structural dynamic properties which relate to the basic structural features. This paper described the dynamic analysis including the modal and the time history analysis on each segment of the self-supported transmission tower to understand its dynamic responses subjected to wind action. The factors such as different height above ground, a different value of wind speed and different wind angle of attack were included in this study to see the influence of those factors towards dynamic response of the structure. The contribution of the wind towards the displacement of the structure is determined in this study by comparing the result obtained in a linear static analysis which considered the load combination without and with the presence of wind action. It was found that displacement using dynamic analysis is bigger than static linear analysis. The result illustrates that the studied factors gave a significant effect on the dynamic response of the structure and the findings indicate that dynamic analysis is vital in structural design.

Keywords: *dynamic response; natural frequency; self-supported transmission tower; wind action; wind time series.*

1. Introduction

Transmission lines that carry the task of power networking system need to be designed at a safe state in order to avoid any possible failure as the tower needs to withstand all other forces besides their self-weight such as strong wind, earthquake as well as snow loads. Thus, the structural and electrical requirements need to be considered for a safe and economical design [1]. Loads imposed to the transmission tower structure have been classified by Lu et al. in [2] and wind load is considered as a dynamic load. However, in academic research field it is measured as real-time load whereas, in the practical design field, United States and Australia design standard simplify the wind load as a static load which considered terrain and topography condition and exposure condition of wind direction to compute the wind speed and change the speed to wind pressure on the tower structure [3-6]. Static load consists of the dead load including the structures self-weight and all the attachments. An unstable load such as broken wire as well needs to be considered in the design as an accidental load. These loads need to be combined by considering the loading factors for the strength and stability in order to determine the most crucial load combination. As for that, static load and dynamic load are considered in lattice transmission tower, (LTT) design. The LTT is one of the most critical structures affected by wind due to its slenderness and wind load is very vital for the structural design of a transmission tower [7]. Thus, the parameters and measurements used in calculating design wind load for transmission tower are important [8].
In structural engineering, dynamic properties are determined as natural frequency, mode shape and damping ratio in structural engineering. These properties are related to basic structural properties such as structure type, geometry, mass distribution, structural stiffness and construction joint. Dynamic action such as various types of wind loads are imposed to each LTT, reinforced transmission tower and line systems. Compared to other engineering structures, LTTs have several unique characteristics including tall structure but with low mass, truss-frame structural type, material and geometric nonlinearity and sway components. Lu et al. as in [2], theoretical method, practical method and experimental method may be applied to determine the dynamic properties of the transmission tower structure including structural frequencies, vibration modes and damping ratios. A theoretical method is developed based on the equation of motion. Practical methods usually used are Rayleigh's Method and Dunkerley's Method by calculating manually the natural frequency of the tower structure. The widely used experimental methods are free vibration test, forced vibration test and ambient vibration test.
Many studies have been conducted to investigate the dynamic responses of the transmission tower structure due to dynamic action especially wind action. It is essential in order to improve the safety and security of power line system and to avoid any possible failure [9]. A 3D non-linear analysis including the large displacements was carried out by Dua et al. as in [10] to study the dynamic response of transmission tower-line systems under fluctuating wind loads, caused by conductors. Effects of parameters like coherence along element length and integration time step were considered. EN-50341 defines wind pressure including 2-second gusts with peak wind velocities, for conductors, insulators and towers. In the real design practice, static load are applied individually on towers and conductors and the coupling effect are considered separately ignored.

Investigation on the response of transmission tower regards to tornado loads has been carried out by Ahmad and Ansari as in [11]. The time history of velocities (u,v and w) and force (*Qx* and *Qy*) were generated at the different level of the tower. Central difference method (CDM) was implemented by Srikanth et al. as in [12] in the dynamic analysis by considering 0.02 seconds time step interval. The analysis was conducted on each assigned segment to see the force resulting from wind action and earthquake action on the tower and it was found that wind is the predominant load acting on the tower. Dynamic characteristic of steel frame tower has been measured by Glanville and Kwok as in [13] to define the vibration frequencies, mode shapes, and damping values. Referring to the lumped mass assumption, STRAND6 is used to calculate the natural frequency and vibration modes. For the response of the tower in term of acceleration due to wind action, power spectral density was figured as part of the natural frequency. Brewer [14] stated that it is crucial to understand the shape that the structure will naturally displace when deal with the dynamic properties of a structure. This is called free vibration and it occurred without the presence or influence of any other dynamic excitation, external forces, support motion or damping. PLS-Tower and SAP2000 is used in the study of tower modelling and analysis. In order to know the natural frequency, modal analysis is conducted using the eigenvector method. Zang et al. [15] did a study on dynamic analysis of the heliostats regards to the wind by evaluating the vibration modes, strain and displacement for the purpose of improving the structural models that able to expect the motions or deformations of the heliostat due to gravitational and dynamic wind loading. Study on the dynamic response of a tower structure in term of natural frequency has been conducted by Li et al. [16]. Different structural parameters including Young's Modulus, the density of the material, the cross area of the member, torsional stiffness and bending moment inertia have been studied to determine the most favourable factor that affects the natural frequency of the structure. Differential sensitivity analysis was implemented and it was found that Young's Modulus, the density of material and cross area of the member are the most important parameters that affecting the dynamic properties of the structure.

Dynamic actions are simplified by static analysis and represented by equivalent static loads [17]. Due to the properties of the transmission tower such as lightweight, slender and subject to dynamic nature action, static analysis is insufficient for the design purpose. Therefore, dynamic analysis is crucial to obtain a more accurate result for stresses on the bars and nodal displacement. Study of modelling structural dynamic response of transmission tower by Mcclure and Lapointe in [18] stated that static analysis is the basic calculation in the structural design of overhead power line, and environmental loads were assumed as static or quasi-static. However, dynamic analysis is important to be conducted in order to predict the response of the transmission line due to shock loads which normally occurred by sudden failure or sudden ice-shedding on conductor. The response of the tower towards wind action is as well affected by the wind angle of attack. It is necessary to investigate the effect of wind angle of attack towards the response of the tower because of the wind angle variation in the natural environment [19]. Mara and Hong as in [20] investigated the dynamic response of self-supported transmission tower subject to traditional atmospheric boundary layer wind (ABL) and downburst wind, and for wind loading at different directions relative to the tower. It was found that the largest resultant wind load of self- supported tower occur at a 50^o angle of attack. Study of the progressive collapse of transmission tower under different angles of attack by Tian et al. in [21] found that the stress under 45^o angle of attack was bigger than the stress under 0^o and 90^o angle of attack. The need of dynamic analysis nowadays is crucial not only to study the dynamic properties of the transmission tower structure due to dynamic action, but as well as to predict the response of the structure due to sudden actions. Wind action is one of the main contributions that may cause the structure deformation. Therefore, it is necessary to conduct a study on wind loading and wind-induced dynamic performance of transmission tower. Although this type of study is well established for transmission line system, the factors that might affect the response of the structure have not been extensively studied.

This paper described the dynamic analysis of a self-supported lattice steel power transmission tower to determine the dynamic response of the tower structure specifically due to wind action. A few factors such as the effect of different heights above ground, the effect of different values of wind speed and the effect of wind angles of attack towards the dynamic response of the structure are investigated. The analysis was conducted under basic design wind speed of 33.5 m/s and maximum wind speed of 48.58 m/s, considering the data obtained from Malaysia Meteorological Department as recorded for Kuala Lumpur and Selangor area.

2. Method

This section presents the tower model description used in this study as well as the method used, including modal analysis and time history analysis.

2.1. Model Description

A structural model of a 275 kV self-supported transmission tower with 51.2 m height was prepared. Section properties such as member sizes and materials were assigned to each member of the tower structure. The sizes vary from SAE 45x45x5 to SAE 130x130x10. Table 1 shows the element section properties of the tower model. Among other parameters, wind pressure varies at different height. Thus, the tower was divided into fifteen segments to accurately define the effect of different height over the tower. The reference height of each segment is at the top of it and is shown with dashes in Fig. 1. 33.5 m/s wind speed represents mean wind speed and 48.58 m/s wind speed represents maximum wind speed of Kuala Lumpur and Selangor area were used in the simulation to evaluate the responses of the tower structure towards different wind speeds.

Table 1: Element section properties

Type	Material	
	S275	S355
SAE 45x45x5	200	352
SAE 50x50x5	10	32
SAE 60x60x5	42	40
SAE 65x65x6	15	4
SAE 70x70x5	4	42
SAE 70x70x6	12	16
SAE 75x75x6	221	N/A
SAE 80x80x6	8	16
SAE 90x90x6	2	88
SAE 90x90x8	N/A	48
SAE 110x110x10	N/A	12
SAE 130x130x12	N/A	112

Autodesk Robot Structural Analysis software was used to conduct static and dynamic analysis in this study. Static linear analysis including wind simulation in 0^o, 45^o and 90^o angle of attack as in Fig. 2 was considered and the forces obtained were used to conduct the dynamic analysis. Dynamic analyses conducted in this study were modal analysis and time history analysis.

2.2. Modal Analysis

The modal analysis defines the characteristics of vibration such as natural frequencies and corresponding mode shapes [22]. Modal analysis was carried out using the eigenvector method. The analysis was conducted on the whole tower structure and 100 modes were considered in order to capture 80% to 90% of mass participation ratio. The mass participation ratio indicates the percentage of how much of the structural mass of the model is participating for a given direction and mode [8]. In tower analysis, it is useful to determine the mode shape and natural frequencies which depend on the mass and stiffness distributions as it allows knowing if the frequency of any applied periodic loading will match with a modal response and hence cause resonance, which leads to large oscillations [17]. The value of the damping ratio 0.02 is possible to be used in this study [22, 23]. Modal analysis was done for 33.5 m/s and 48.58 m/s wind speed as mentioned in the method section.

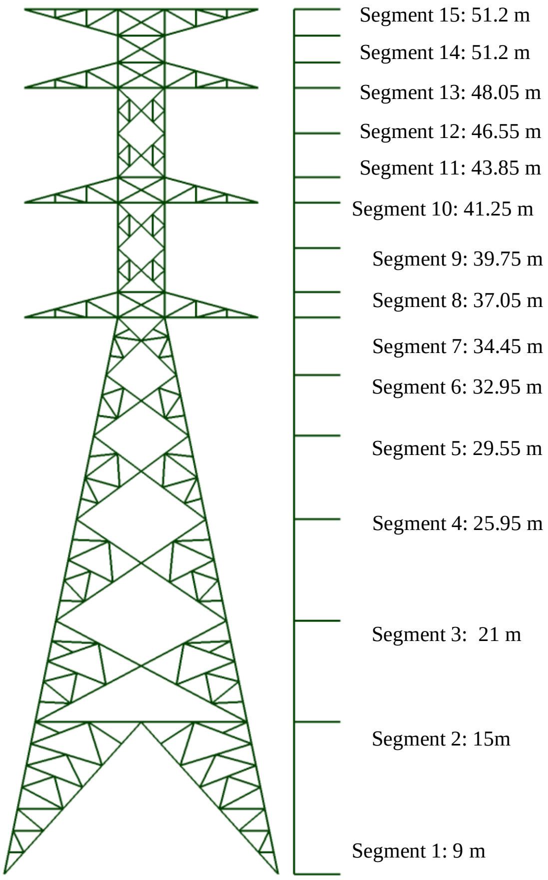


Fig. 1: Segments of tower model

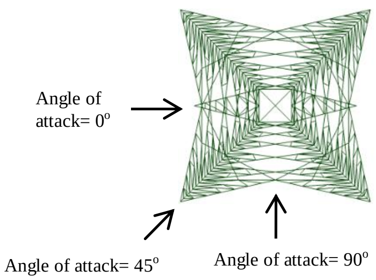


Fig. 2: Wind angle of attack

2.3. Time History Analysis

Wind time series is the basis in determining the dynamic response of structure subject to wind. Time history analysis is an approach to obtain the response of a structure over time, during and after the application of load. The analysis was then conducted on each segment of the tower as per shown in Fig. 1 by applying Newmark Method. 600 seconds of simulated time Sine wave with 0.05 time step was considered in the analysis. Although 0.01 was the right time step according to Dua et al. as in [10], due to constraints of memory usage, a time step of 0.05 seconds was used. The different angles of attack of 0°, 45° and 90° were considered to see the effect of the angles towards the response of the tower on the same wind speed used. The time history analysis was conducted for 33.5 m/s and 48.58 m/s wind speed as mentioned in previous section.

3. Result and Discussion

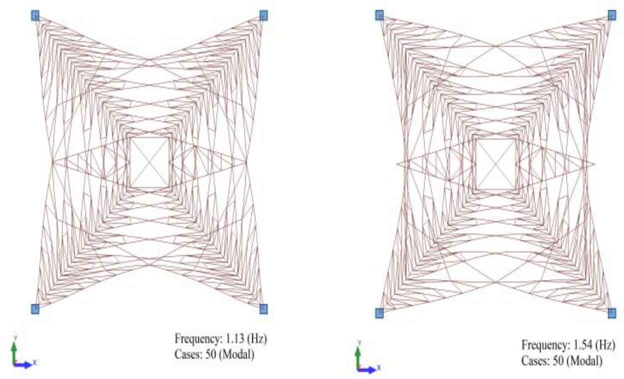
This section presents the natural frequency of the tower structure and the response of the structure in term of displacement under a few conditions which mentioned in the previous section. Discussion on the obtained finding is presented in this section.

3.1. Natural Frequency and Mode Shape

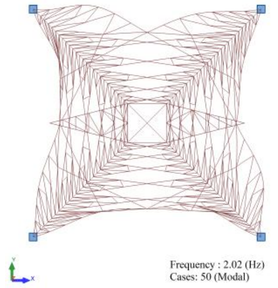
Every structure has the tendency to vibrate at certain frequencies, called natural or resonant frequencies. Each natural frequency is identified with a certain shape, called mode shape, which the model tends to displace when vibrating at that frequency. This is typically done by including enough modes in the analysis to capture 80% to 90% of mass participation [14]. In this study, 100 modes shape was considered to capture 89.3% for longitudinal direction. It is necessary to ensure that the results are comprehensive of an acceptable level of structure mass when performing modal analysis. The mass participation ratio specifies the percentage of how much the structural mass of the model is participating for a given direction and mode. Table 2 shows the natural frequency for particular mode as well as the mass participation ratio in every direction. Fig. 3 shows the top view of the first three modes of the transmission tower. It can be observed that most of the significant deformation was contributed by the bottom part of the transmission tower for the first three modes. The structure began to show significant deformation on the upper part of the structure when it reached the tenth mode onwards. Fig. 4 shows the top view of the tenth mode of the structure.

Table 2: Modal mass participation ratios.

Mode	Frequency (Hz)	Period (sec)	Relative mass (%)		
			UX	UY	UZ
1	1.13	0.88	0	0	0
2	1.54	0.65	0	0	0
3	2.02	0.5	0.35	2.88	0
4	2.02	0.5	3.22	3.23	0
5	2.13	0.47	6.61	3.71	0
6	2.13	0.47	7.09	7.09	0
7	2.23	0.45	7.09	7.09	0
8	2.25	0.44	7.09	7.09	0
9	2.56	0.39	7.09	7.09	0
10	2.69	0.37	44.84	7.1	0
98	11.4	0.09	86.29	87.41	1.53
99	11.51	0.09	86.29	87.41	1.73
100	11.61	0.09	86.84	87.41	1.75



a) Mode 1 b) Mode 2



c) Mode 3

Fig. 3: The first three shape modes and Eigen frequency of a), b), c)

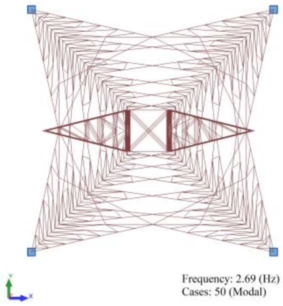


Fig. 4: The tenth shape mode and Eigen frequency

3.2. Wind Time Series

The dynamic response of the tower structure can be seen through the displacement of the structure due to wind action. The effect of displacement which regard to height is significant and can be discussed by plotting the displacement-time series for a few segments in a graph. The following time series were taken from the particular node that showed the maximum displacement at each segment. Fig. 5 and Fig. 6 show the displacement-time series of a few segments which are segment 2, segment 7, segment 11 and segment 15 for mean wind speed and maximum wind speed respectively over isolated 10 sec. It can be seen from the simulated time histories that there are a good correlation between the plots for different heights. Among the four segments for 33.5 m/s wind speed, segment 2 gave the lowest displacement value followed by segment 7, segment 9 and segment 15. While for a wind speed of 48.58 m/s, segment 2 gave the lowest displacement value followed by segment 7 and displacement of segment 11 and segment 15 do not show a constant trend.

Further discussion can be made by plotting the displacement-time series of two different wind speeds on the same segment to evaluate the effect of the response regards to the mean wind speed of 33.5 m/s and the maximum wind speed of 48.58 m/s. Fig. 7, Fig. 8, Fig. 9 and Fig. 10 show the displacement-time series of the different wind speed on the same segment of the transmission tower over isolated 10 seconds.

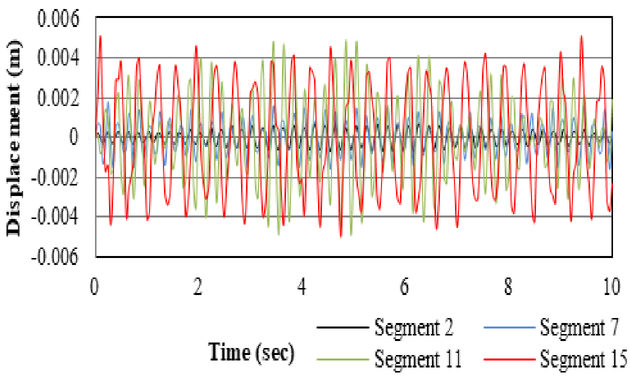


Fig. 5: Displacement-time series for 33.5 m/s wind speed

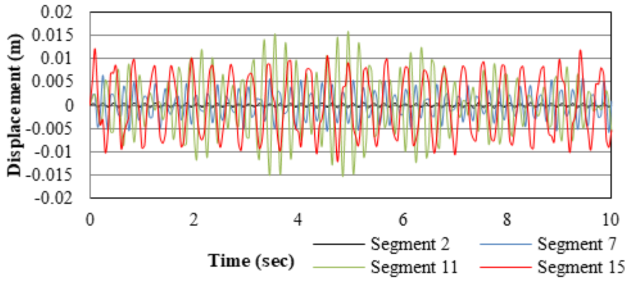


Fig. 6: Displacement-time series for 48.58 m/s wind speed

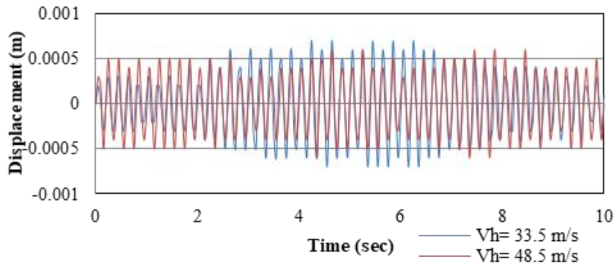


Fig. 7: Displacement-time series on segment 2

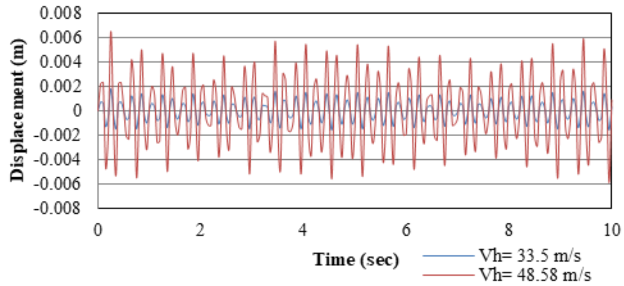


Fig. 8: Displacement-time series on segment 7

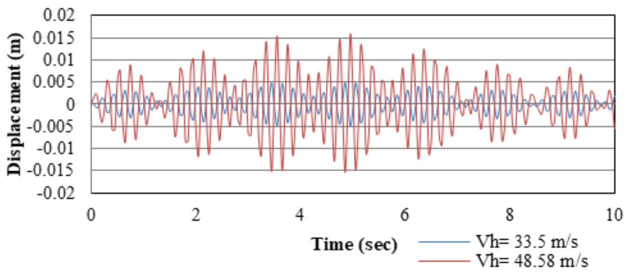


Fig. 9: Displacement-time series on segment 11

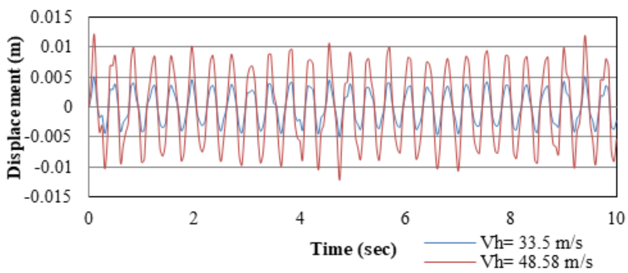


Fig. 10: Displacement-time series on segment 15

Among the plots, it can be observed that the displacement for maximum wind speed 48.85 m/s was higher than basic wind speed 33.5 m/s and there was a consistent fluctuation of time series between both wind speeds. Throughout 600 seconds, the maximum displacement for 33.5 m/s was about 0.04 m while 0.13 m for 48.58 m/s and there is a maximum difference of about 0.09 m for both wind speeds. In the static linear analysis, under the action of dead load and the normal condition without wind action, the maximum displacement was about 0.42 m, while 0.43 m displacement without wind action, at node 270. Node 270 is located on the earth wire cross arm as circled in Fig 11. Fig. 11 and Fig. 12 show the displacement of the tower structure under load combination without and with wind action from 0^o angle wind of attack, respectively.

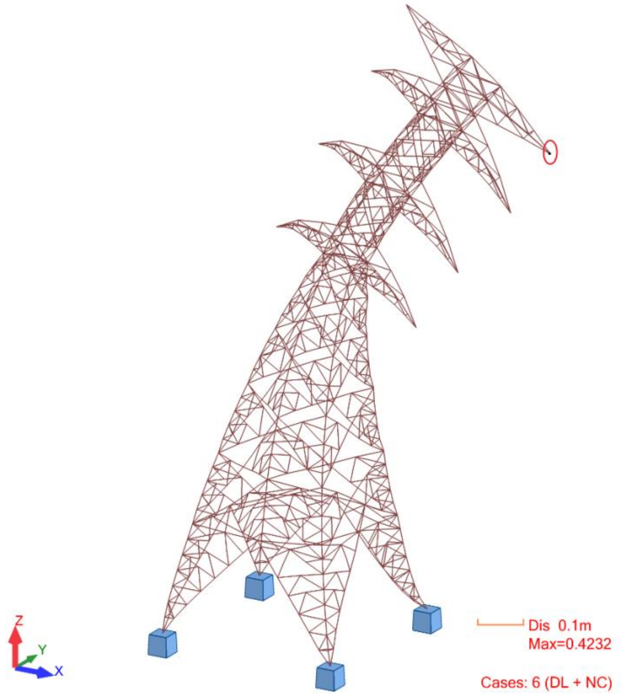


Fig. 11: Displacement of the tower without wind action

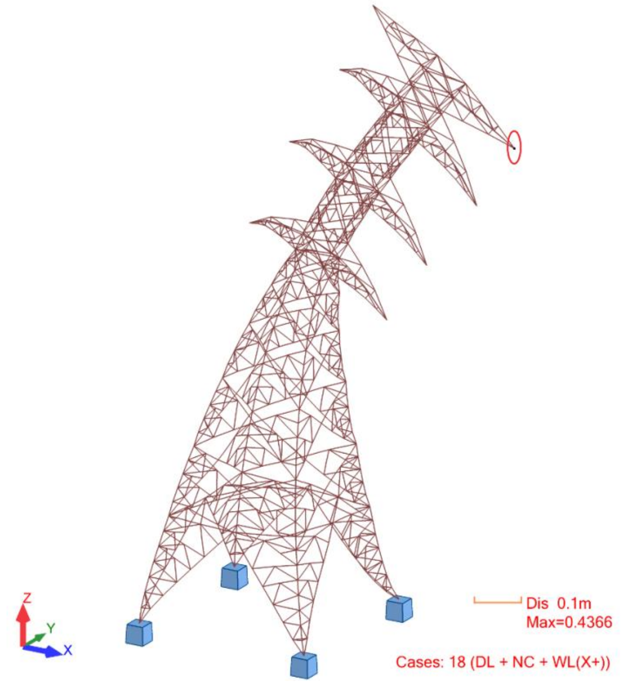


Fig. 12: Displacement of the tower with wind action

The contribution of the wind towards the structure displacement can be seen by obtaining the displacement differences between the load combination with and without wind loading acting to the structure and on the same node. Table 3 shows the displacement differences between the combination of dead load and normal condition with the combination of dead load, normal condition and wind load from various wind angles of attack using 33.5 m/s and 48.58 m/s wind speed respectively at specifically node 270 obtained from linear static analysis. The differences can be used to indicate how much the wind action affects the structure response and the differences can be compared with the result obtained from the time history analysis where no other forces considered in the analysis besides wind force. As in time history analysis for 33.5 m/s wind speed from the 0^o angle of attack, the maximum displacement was found to be 0.0210 m. By referring to the Table 3, it shows that the response of the tower which obtained from time history analysis is higher than the response obtained from the linear static analysis. There was about 0.0157 m maximum different of displacement between both analyses. In overall, the result obtained in linear static analysis without focusing on the action of wind was obviously bigger than time history analysis. This occurred might be because of the different action considered in the analysis. From the table, it can be seen as well, that at a certain angle of attacks, there was a difference of the displacement of at least 0.001 m.

Table 3: Displacement differences.

Wind angle of attack (^{o})	Displacement different (m)	
	33.5 m/s	48.58 m/s
0	0.0053	0.0134
45	-0.0085	-0.019
90	0.0006	0.0017
135	-0.0048	-0.0087
180	-0.005	-0.0133
225	-0.0049	-0.0133
270	0	0.001
315	0.0052	0.001

It shows that wind action has significant effect on the response of the tower structure. The effect of different angle of wind attack towards the response of the tower can be clearly seen at the specific time by time history analysis as in Fig. 13 for 33.5 m/s wind speed and Fig. 14 for 48.58 m/s wind speed. The simulated displacement time series are presented for isolated 10 seconds on segment 15.

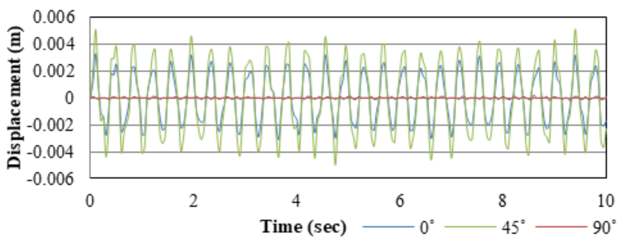


Fig. 13: Displacement-time series for different angles of attack with 33.5 m/s wind speed

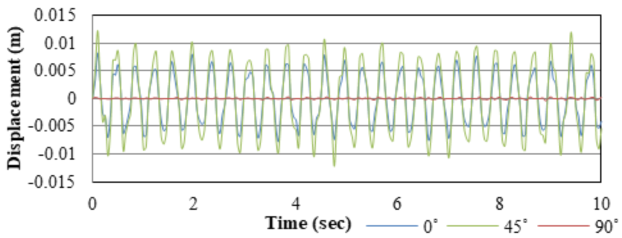


Fig. 14: Displacement-time series for different angles of attack with 48.58 m/s wind speed

Fig. 13 shows that 45^o angle of attack gave the higher response in term of displacement compared to 0^o and 90^o angle of attack. The 90^o angle of attack gave the smallest dynamic response towards wind action. Throughout 600 seconds using 33.5 m/s wind speed on segment 15, the displacement under 45^o angle of attack increases by 36.21% than that of under 0^o angle of attack and is 96.55% larger than that of under 90^o angle of attack. The results were in agreement with a study by Tian et al. in [21] that the collapse of the transmission tower easily occurs at 45^o angle of attack. Furthermore, Fig. 14 shows that there was a constant trend of the response compared to 33.5 m/s wind speed. Throughout 600 seconds on segment 15 using 48.58 m/s wind speed, the displacement under 45^{o} angle of attack increased by 32.6% than that of under 0^{o} angle of attack and it was 96.3% larger than that of under 90^{o} angle of attack. The result obtained from this dynamic analysis was different with the result obtained from linear static analysis, where 0^{o} angle of attack gave the maximum displacement of the tower structure.

4. Conclusion

In the interest of dynamic response of self-supported power transmission tower, the following main conclusions were made from this study:

1. Natural frequency and mode shape of the tower structure was obtained by conducting the modal analysis and 100 modes were considered to capture more than 80% of mass participation ratio. It is recommended that the factors affecting the natural frequency can be studied in details to determine the structural parameters and how much does the parameters control the natural frequency.
2. The effect of the displacement with regards to different height was studied by conducting the time history analysis at a different segment of the tower which has a different height above the ground. It was found that the displacement increases with the increase of height.
3. A different value of wind speed definitely leads to different displacement time series. Maximum mean wind speed caused the structure to displace more than the basic design wind speed and it shows a constant trend between both values.
4. The contribution of wind towards the response of the structure can be obtained by comparing the result from linear static analysis with and without wind action as well as compared with the response obtained from time history analysis. It can be said that there were at least 0.001 m different in displacement which caused by wind action.
5. Dynamic analysis such as time history analysis simplifies the effect of the wind towards the structure. Prevention of the structure from being fail due to sudden actions as well can be planned by concerning to the structure response in specific times.
6. The response of the structure regards to 45^{o} wind angle of attack is larger than 0^{o} and 90^{o} wind angle of attack and this is different with the result obtained from a linear static analysis by comparing the maximum displacement occur caused by the combination of wind load.

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