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Dynamic Behaviour of Transmission Lines Structures under Synoptic Wind Loads

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SUMMARY

This paper reports a study conducted at The University of Western Ontario (UWO) in collaboration with The Centre for Energy Advancement through Technological Innovation (CEATI), which focusses on assessing the dynamic behaviour of transmission lines under synoptic wind loads. The collaboration between UWO and CEATI started a number of years ago, when CEATI participated in a large project, funded mainly by Manitoba Hydro, to study the effect of non-synoptic wind loads on transmission line structures. The current study represents the second phase of collaboration between UWO and CEATI. A numerical model capable of predicting the dynamic response of a multi-span transmission line system under both the mean and fluctuating components of synoptic wind loads is presented in this study. The model has been validated experimentally using results of a previous aero-elastic test of a multi-spanned transmission line system conducted at the Boundary Layer Wind Tunnel Laboratory at the University of Western Ontario. A parametric study is conducted on four different transmission line systems namely: guyed steel lattice tower, self-supported steel lattice tower, H-framed steel tower and cantilever steel pole. For each system, a full nonlinear dynamic analysis in the time domain is conducted under properly synthesized turbulent synoptic wind to evaluate time histories of the system's responses. Peak responses of each system, such as tower and conductor deflections, base shear force and conductor reactions, are determined from this analysis. Such peak responses are due to the mean, background and resonant components. A similar analysis is also repeated in the quasi-static manner to identify peak responses due to mean and background components only. Ratio between peak responses including mean, background and resonant effects to the peak responses including mean and background effects is evaluated and referred to as the Dynamic amplification factor (DAF). Such a DAF is used to identify the cases where the dynamic effect is important for the line design.

KEYWORDS

Transmission lines – Synoptic wind – Turbulent wind – Dynamic analysis – Quasi-static analysis

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1 Introduction

Previous studies on the dynamic buffeting response of transmission lines (Davenport 1962, Momomura *et al.* 1997, Loredo-Souza and Davenport 1998, Holmes 2008, Lin *et al.* 2012, Aboshosha *et al.* 2016) showed that natural frequency of a typical tower is typically higher than the frequencies corresponding to the maximum turbulence energy, which leads to a negligible resonant response. The studies also showed the resonant effect for conductors might be small due to the high aerodynamic damping associated with the conductors' motion regardless of the close natural frequency of the conductors to the frequencies of the strong turbulence. This is likely true for conductors subjected to high wind speeds. However, this assumption requires further investigations under low wind speeds when aerodynamic damping is small. As such, the following tasks are the main objectives of the current study:

1- To develop a numerical model capable of conducting dynamic analysis of multi-spanned transmission line structures.
2- To validate the numerical model using the results of an aeroelastic wind tunnel test of a multi-spanned transmission line that was recently conducted at the Boundary Layer Wind Tunnel Laboratory (BLWTL) at Western University.
3- To conduct the dynamic analyses of four examples of transmission lines under different wind speeds are conducted using the numerical code. The purpose is to identify the range of velocities at which the resonant components contribute to the response.

This paper is divided into five sections. In section 1, introduction and objectives of the study are provided. In section 2, a description of the numerical model used in the study is outlined. Section 3 provides details about the TL systems considered in the study. Dynamic responses of the considered TL systems under turbulent wind load are illustrated in section 4, while the findings and conclusions obtained from the study are presented in section 5.

2 Numerical Model

2.1 Wind Field

Wind velocities associated with synoptic winds can be decomposed into a mean and a fluctuating component. The fluctuating wind velocities was generated numerically using the technique described by Chen and Letchford (2004 a,b) and Chay *et al.* (2006). In applying this technique, the Power Spectrum Density (PSD), which describes the energy of the wind fluctuations in the frequency domain, proposed by von Karman (1948), was used to synthesize turbulent velocities. Turbulent length scale, L_u, was calculated employing the approximate relationship $L_u=L_{uv}/0.3$, where L_{uv} is the turbulent length scale of the longitudinal fluctuations, u, along the transverse direction v. The length scale, L_{uv}, was considered equal to 67 m assuming an open terrain exposure according to the ASCE 74 (2010). Correlations among the fluctuating components were introduced based on the coherency decay function proposed by Davenport (1979, 1980) using a coherency decay constant with a value of 10, which is suitable for structural design purposes. The mean velocity turbulence intensity profiles were obtained from the ESDU (2001, 2002) using an aerodynamic roughness z_0 of 0.03 m. A sample of the turbulence velocity variation with time at height 30 m is shown in Figure 1.

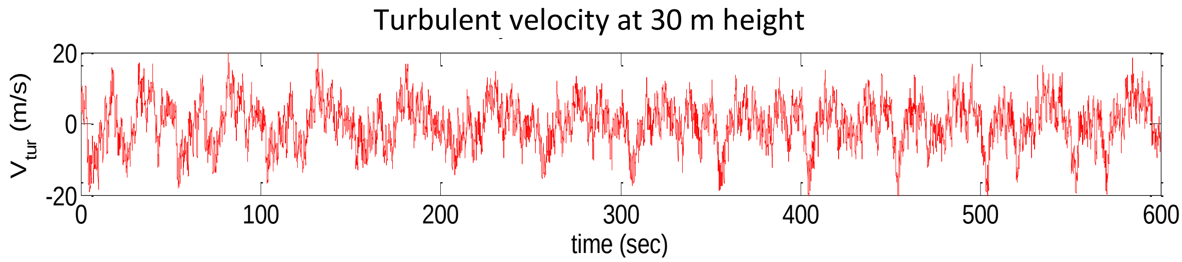

Figure 1 generated turbulent velocity for open terrain exposure

2.2 Finite Element Analysis

The response of TLs under synoptic wind is non-linear. This is mainly because of the behavior of the conductors and the supporting guys (if exist). Dynamic behavior of TLs subjected to fluctuating synoptic wind can be evaluated using fully non-linear dynamic analysis under the total instantaneous wind load including both the mean and fluctuating components. This method is not practical and very time consuming. According to Sparling and Wegner (2007), a significant saving in computational time without compromising the accuracy of the solution can be achieved by analyzing the system in two steps. The first step involves conducting a non-linear analysis under the mean component of the wind load to obtain the structure mean response, M. The second step involves analyzing the system linearly under the fluctuating load to obtain the fluctuating response, F. The use of linear analysis here can be justified because of the small ratio between the fluctuating and the mean components. A third step can be conducted in order to identify the background component, B, by analyzing the system quasi-statically under the fluctuating loads. By subtracting the background, B, component from the fluctuating response F, the resonant component of the response, R, can be obtained. A summary of the steps followed to analyze the system and to obtain various response components is presented in Figure 2.

The steps summarized in Figure 2 were followed by Aboshosha and El Damatty (2015) in analyzing various transmission line conductors subjected to synoptic and non-synoptic wind.

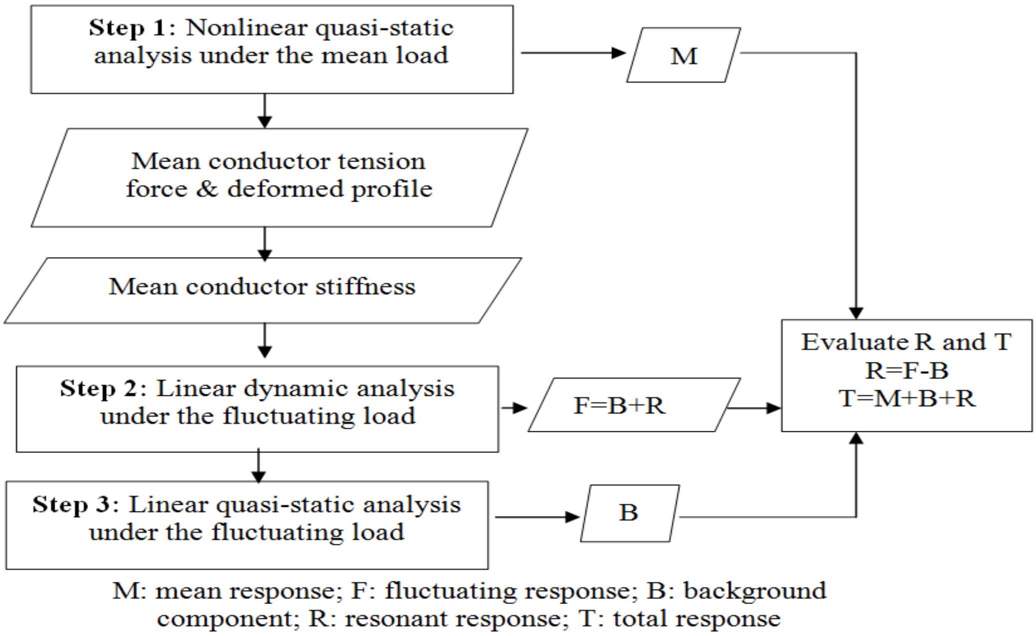

Figure 2 Steps of analyzing the TL systems

2.3 Validation of the Numerical Model

A 1:50 scale multi-span guyed TL aero-elastic wind tunnel test was recently conducted at the BLWTL at Western University by Hamada (2014). The aero-elastic behaviour of the TL was investigated under synoptic wind corresponding to an open terrain exposure. In the test, the effects of the conductors, and the angle of attack were investigated. More details about this test are provided Hamada (2014).

The case of the zero angle of attack with and without the presence of conductors is chosen for validating the developed Numerical code. This case is shown in Figure 3. The validation is conducted on two stages. First, a validation of the model prediction of the mean TL responses is carried out. The measured responses of the mean guys' tension and the tower mid-height bending moment are compared with the numerical model prediction. Table 1 summarizes the comparison results for the "no conductor" case and Table 2 summarizes the results for the "with conductor" case. As shown in the tables, the model prediction of the mean response is in a very good agreement with the aeroelastic test measurements with less than 5 % difference for the "no conductor case" and about 10 % for the "with conductor" case. The second stage of validation is conducted by comparing the responses corresponding to the fluctuating wind loads. This fluctuating bending moment results from the conductor longitudinal forces transferred to the tower. By comparing the rms of the bending moment, it is found that the values estimated by the aero-elastic test and the numerical model are within 8% difference which gives confidence in the numerical model.

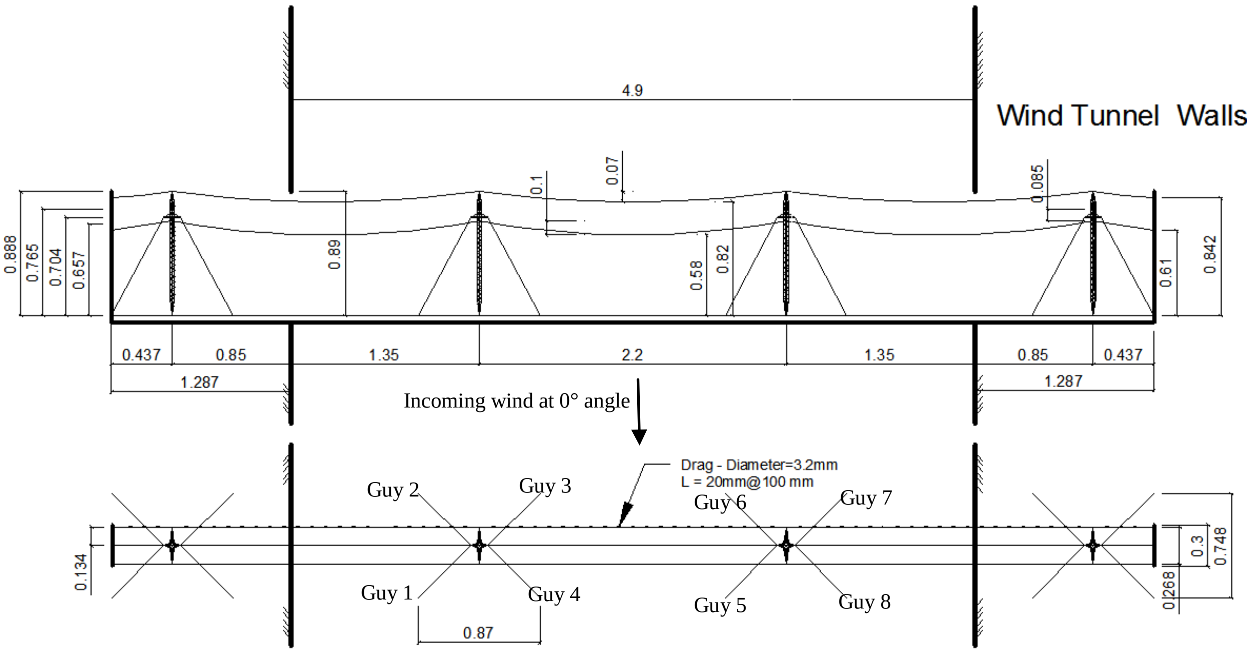

Figure 3 Considered case for validating the numerical model (dimensions in m)

Table 1 Responses obtained from the aeroelastic test and the numerical model (no conductor case)

	Supporting Guys Far Tower Guy 2 (kN)	Supporting Guys Far Tower Guy 3 (kN)	Supporting Guys Near Tower Guy 6 (kN)	Supporting Guys Near Tower Guy 7 (kN)	Bending Moment Mid. Height Far Tower (kN.m)	Bending Moment Mid. Height Near Tower (kN.m)	Conductor Longitudinal Reaction Far Tower (N)
Aeroelastic Model	53	56	52	59	106	86	425
In-house Finite Element Model	60	63	60	63	97	97	370

Table 2 Responses obtained from the aeroelastic test and the Numerical model (with conductor case)

	Supporting Guys Far Tower Guy 2 (kN)	Supporting Guys Far Tower Guy 3 (kN)	Supporting Guys Near Tower Guy 6 (kN)	Supporting Guys Near Tower Guy 7 (kN)	Bending Moment Mid. Height Far Tower (kN.m)	Bending Moment Mid. Height Near Tower (kN.m)	Conductor Longitudinal Reaction Far Tower (N)
Aeroelastic Model	53	56	52	59	106	86	425
In-house Finite Element Model	60	63	60	63	97	97	370

3 Considered TL Systems

Four TL systems covering various types of supporting towers are considered in this study. The considered towers are: (1) Guyed lattice tower, (2) Self-supported lattice tower, (3) H-frame steel pole and (4) Steel cantilever pole. Table 3 the overall dimensions of the towers, the conductor types, and other important properties.

Table 3 Properties of the considered TL systems

No	System	Tower properties: H (m)	W* (m)	E (Gpa)	Freq** (Hz)	Conductor properties: L (m)	S (m)	w (N/m)	v (m)	A_p (m^2)	Freq** (Hz)
1	Guyed lattice	48	13	200	2.30	460	16	17.9	4.2	0.044	0.15
2	Self-supported lattice	52	13	200	2.36	299	8.5	11.6	3.2	0.042	0.19
3	H-frame steel pole	33	16	200	1.48	290	8.5	6.3	3.1	0.040	0.19
4	Steel cantilever pole	41	2	200	0.68**2	124	3.7	6.3	2.1	0.040	0.45**1

Where H is the tower height, W is the tower width, E is the elasticity modulus, L is the span length, S is the sag length, w is the conductor weight, v is the insulator length, Ap is the projected area of the conductor

* the width reported is the width at the cross arms; for guyed lattice tower, w at the base is 9.00 m and 8.5m in transverse and longitudinal directions, respectively; for the guyed tower, distance between the guys is 43m and in the transverse and longitudinal directions, respectively; for the H frame tower, w at the base is 8.2 m; for the steel pole, tip diameter is 0.8 m with increasing tapering slope of 0.0196 m/m'.

** Frequencies are evaluated at v_{wind}=25 m/s

**1 Coupled conductor-tower mode

**2 Tower mode only

4 Results of dynamic analysis of the considered TL systems under turbulent wind

The technique described and validated above is employed to analyze the four TL systems. Results obtained from the technique are provided in this section.

Figure 4 shows a sample of a conductor reaction at the insulator location predicted by the numerical model. This specific conductor belongs to the guyed TL system with conductor span of 500 m. The results shown in the figure includes the mean (M), background (BG) and resonant responses (R) corresponding to a wind speed of 25 m/s. By summing those components, the total response including the dynamic effect, is evaluated. Summation of the mean and background components leads to an estimation of the quasi-static response of the TL, which is shown in Figure 4.

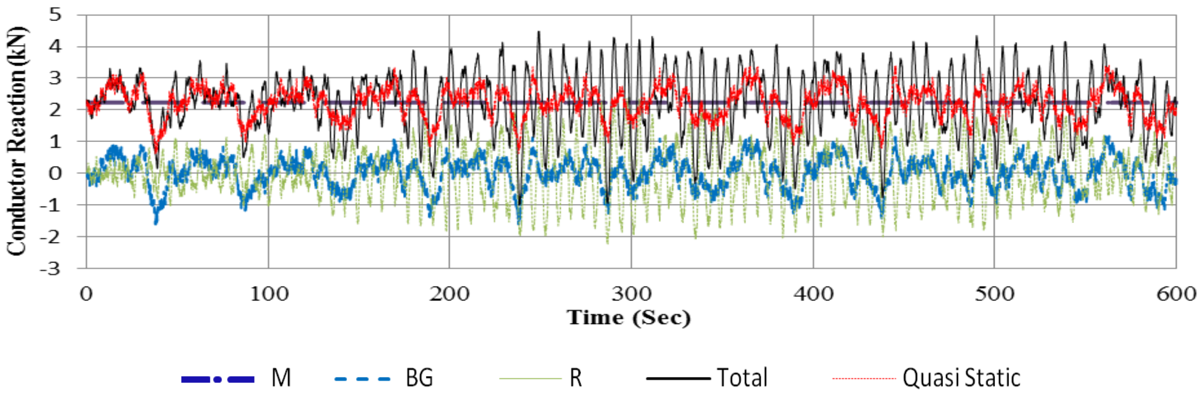

Figure 4 Conductor reaction R_y

The dynamic effect is characterized as the ratio between peak total response and the peak quasi-static response. This ratio is called the Dynamic Amplification Factor, *DAF*, as defined in Equation 1.

$$DAF = \frac{\hat{R}_T}{\hat{R}_{QS}} \qquad \text{Equation 1}$$

Where: $\hat{R}_T$ is the peak total response and $\hat{R}_{QS}$ is the peak quasi-static response. Figures 5-8 cover a range of 10 m/s to 40 m/s applied at the top cross arm level. For each TL system, five responses are selected for the comparison purpose, which are (i) tower base shear, (ii) conductor windward reaction, (iii) tower top deflection, (iv) conductor mid-span displacement, (v) tower base moment.

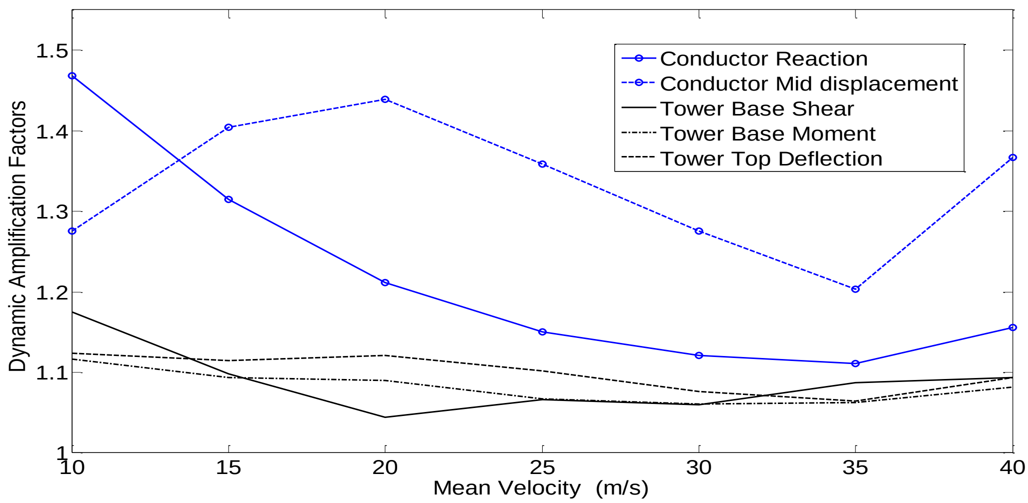

Figure 5 DAF for the guyed tower

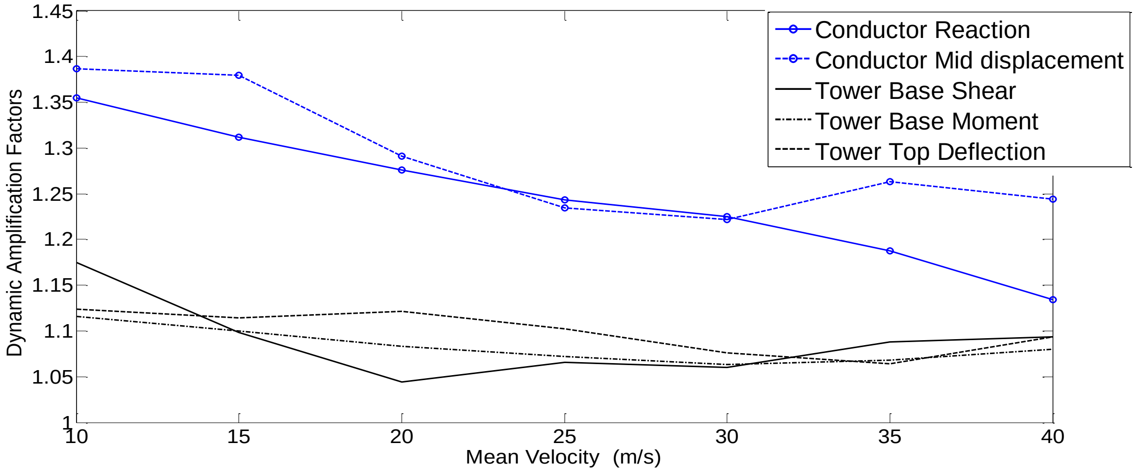

Figure 6 DAF for the self-supported tower

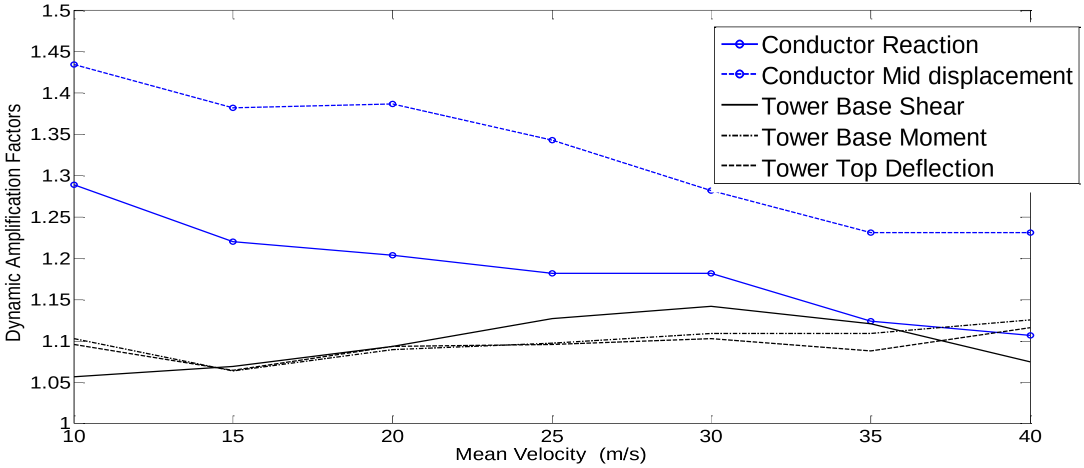

Figure 7 DAF for the H-frame steel TL

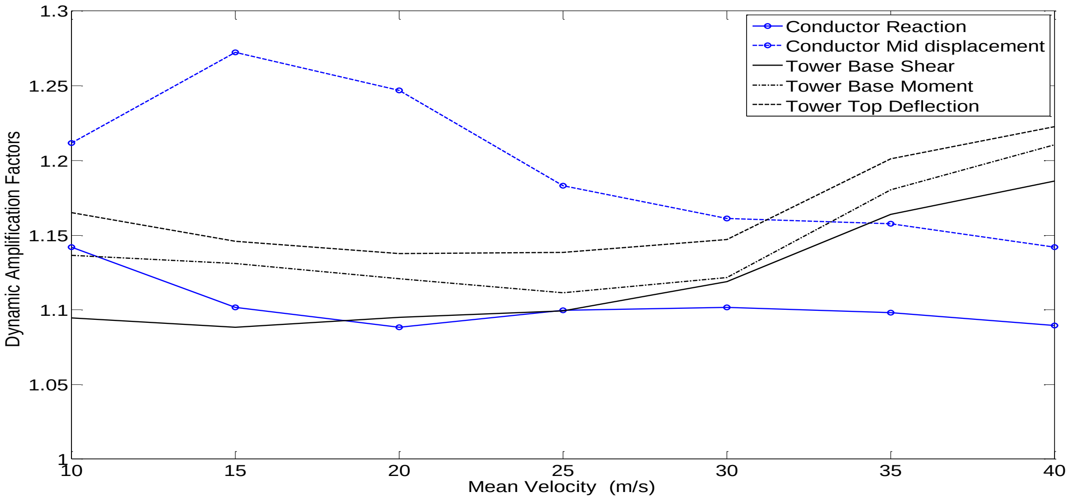

Figure 8 DAF for the TL with steel pole

The figures indicate that the conductors generally exhibit larger differences between the peak total and quasi-static responses than the towers. High value of DAF (greater than 1.10) emphasizes the importance of including the dynamic effect while evaluating the peak responses. The conductors have larger values for DAF especially at low wind speeds. In most of the cases, the DAF decreases with the increase of wind speed. This trend results from the increase of the aerodynamic damping associated with an increase in wind speed, which tends to attenuate the resonant component. Generally, the DAF increases with the increase of the conductor span. The conductors' reactions' DAF are found to vary between 1.10 and 1.47 with an average value of 1.29, while the conductors' displacements' DAF are found to vary between 1.15 and 1.63 with an average value of 1.39. For guyed, self-supported steel lattice and H-frame towers, which all have relatively high natural frequencies greater than 1 Hz, the DAF is found to vary between 1.04 and 1.17 with an average value of about 1.10. Steel cantilever pole, which have relatively low frequency of about 0.7 Hz, are found to experience some dynamic behaviour where the DAF is found to vary between 1.06 and 1.32 with an average value of 1.25. The fundamental mode of those lines includes coupling between the tower and the conductors, which can be the reason behind the significant dynamic effect experienced by the tower.

5 Conclusions

A numerical model that is capable of conducting dynamic analysis of multi-spanned transmission lines is developed. The model is validated using the responses obtained from an aeroelastic TL test previously conducted at the BLWTL at Western University. The numerical model is employed to evaluate the dynamic behavior of TL with 4 different supporting towers namely: Guyed lattice tower, Self-supported lattice, H-frame steel pole and Steel cantilever pole. Peak total responses and peak quasi-static responses are evaluated. Dynamic Amplification factor (DAF) is evaluated and the following findings are obtained.

- Peak responses of the tower and the conductor increase with the increase of the velocity.
- Conductor responses exhibit large Dynamic Amplification Factor (DAF) compared to the towers especially at the low wind speeds. This trend results from the decrease of the conductor aerodynamic damping with the decrease in the wind speed. The DAF is found to vary between 1.10 and 1.47 with an average value of 1.29 for the conductors' reactions and to vary between 1.15 and 1.63 with an average value of 1.39 for the conductors' mid-span displacements.
- The DAF steel lattice towers is ranging between 1.04 and 1.17 with an average value of about 1.10 for towers which have high natural frequencies (i.e. 1 Hz or more).
- For the steel cantilever pole which has coupled conductor-tower fundamental frequencies of about 0.7 Hz, the DAF is found to vary between 1.06 and 1.32 with an average value of 1.25. This means that the resonant component plays an important role in the overall response of pole structures under both mean and fluctuating components of the wind loading. Such an important role of the resonant component is expected to take place for poles with frequencies less than 1.0 hz.

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