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ASSESSMENT OF DYNAMIC EFFECT OF TRANSMISSION LINE CONDUCTOR LONGITUDINAL REACTION DUE TO DOWNBURST LOADING

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Abstract: With electricity being a cornerstone of our modern world's growth and sustainability, the maintenance of a functional electricity transmission network against devastating powers of nature is essential. Studies reported that High Intensity Winds (HIW), which refers to intense wind loading phenomena like tornadoes and downbursts, have been the major cause of transmission line failures across the world. The current study focuses on the effect of downburst loading on the computed longitudinal reactions of electricity conductors on transmission towers. To accurately assess the longitudinal reactions due to downburst loading, the current study utilizes a dynamic analysis model that accounts for the non-linearity of conductor cables, along with the associated local and non-stationary nature of loading. The study also highlights the complexity of the analysis introduced by the aerodynamic damping of the conductor cables, which is affected by the non-stationarity of the loading phenomenon leading to a time varying damping value. Consequently, the study proposes an engineered assumption related to the computation of the aerodynamic damping that can greatly simplify the analysis. The assumption that is based on the characteristics of the loading wind field is then validated using experimental data of a wind tunnel scale test of a downburst simulation conducted at the WindEEE dome. The comparison between the numerical and the experimental results show the adequacy of the proposed assumption as an alternative that can reduce the complexity of the analysis by using a single value of aerodynamic damping that is time independent rather than a varying damping value.

1 INTRODUCTION

Acknowledging the significant role electricity plays in socio-economical development of our communities, it is of clear relevance that the maintenance of a functioning electricity transmission network is a key component in sustaining uninterrupted power vitally needed in our everyday lives. Out of the transmission line failures reported worldwide, Li (2000) reported that 90% of weather-related failures of transmission line systems are associated with thunderstorms. Out of the different phenomena occurring in thunderstorms, tornadoes and downbursts are the most severe due to the high intensity wind speeds that can exceed the design speeds at which the structure systems were designed to withstand. Focusing on downbursts, that were defined by Fujita (1985) as a downdraft of air that causes damaging wind close to the ground, several studies have reported failures of transmission line systems due to downburst events (Kanak et al. (2007) McCarthy and Melsness (1996) Zhang (2006)). The damage associated with downburst events is not just because of high intensity speeds; the special nature of the loading phenomenon introduces new modes of failures in comparison to conventional straight wind. While conventional wind is expected to cause uniform loading on consecutive spans of the transmission line system, the locality of the downburst phenomenon causes differential loading between spans of conductor systems, which in turn result in excessive longitudinal reactions that the cross-arm members were not designed to withhold. The illustration in Figure 1 shows how the positioning of the downburst centre affects the loading applied on each span. The areas annotated A1 and A2 represent the total forces applied on the spans across sides of the considered transmission tower. The resulting loading case, named the oblique load case, arises due to the inclination angle θ measuring the deviation of the downburst center from the line normal to the transmission line system.

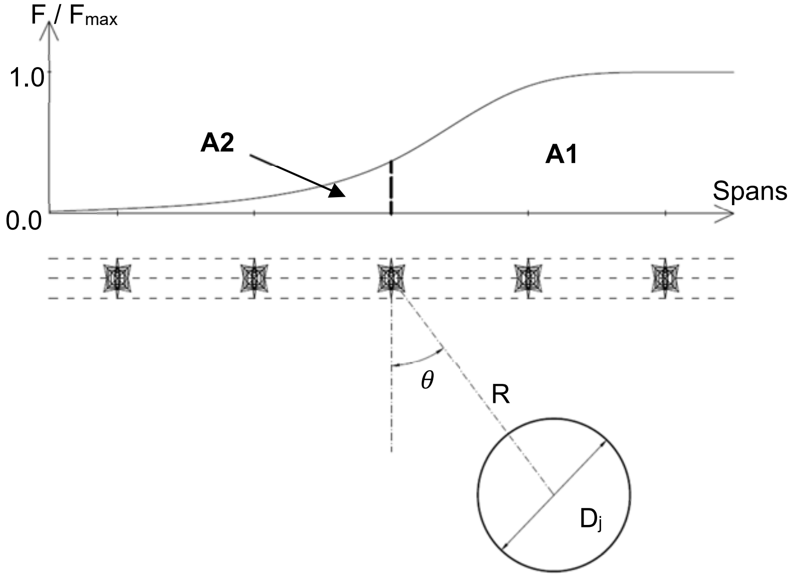

Figure 1: Oblique load case illustration

Moreover, adding to the complexity of the loading case, the downburst loading is known for being nonstationary, a term which indicates that the statistical properties of the loading time history are not constant, but instead varying with time. This can be shown in Figure 2**Error! Reference source not found.** where the mean velocity of the flow varies with time as opposed to a constant mean anticipated in the case of conventional straight winds. It is usually challenging to perform structural analysis on conductor systems considering the non-stationarity of the downburst loading. Yet, several efforts have been trying to evaluate the response of transmission line systems due to downburst loading cases. Of those, the work done by Aboshosha et al. (2016), Lin et al. (2012), Shehata et al. (2005) and Shehata and El Damatty (2008) considered the combined transmission line system (i.e. tower and conductors). Other researchers like Mara et al. (2010), Mara and Hong (2013) and Savory et al. (2001) only studied the tower structure, as opposed to researches like Darwish et al. (2010), Aboshosha and El Damatty (2014) and Elawady and El Damatty (2016) who only studied the conductor systems. The latter study focused in particular on the implications of the oblique load case on the longitudinal reactions that would be transferred from the conductors to the supporting tower structure. Solving for the longitudinal reactions using the technique developed by Aboshosha and El Damatty (2015), the study developed a set of charts that can be used by practitioners to compute the longitudinal reactions reflecting the variation of parameters like the conductor properties and the wind loading conditions. Nevertheless, the study considered a quasi-static approach to compute the longitudinal reactions due to downburst loading. This was essentially based on the assumption that the aerodynamic damping, known to be of relatively large values, should suffice in neutralizing the dynamic effect. Yet, dynamic analysis has to be performed before reaching such conclusion.

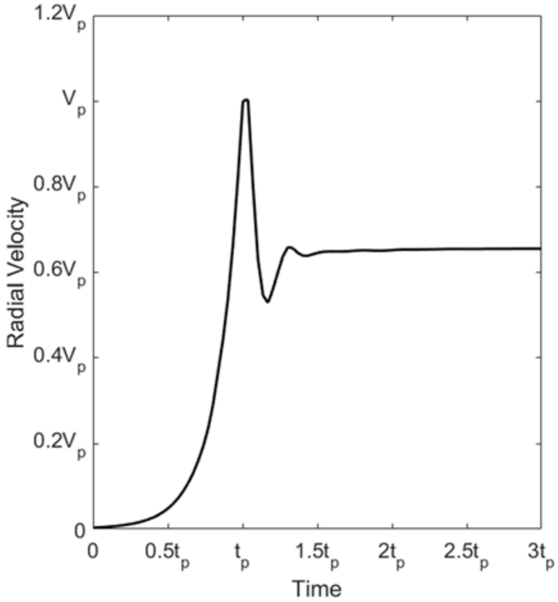

Figure 2: Mean radial velocity vs Time for downburst wind field at a probe point

Accordingly, the aim of this study is to develop a numerical tool that is capable of capturing the dynamic responses of conductor systems due to downburst loading, specifically focusing on the longitudinal reactions. The following sections will cover the basic assumptions of the model, as well as the experiment used to validate the outcome of the numerical model.

2 NUMERICAL MODEL

The analysis of conductor systems is usually a complex procedure due to the nonlinearity of the cable structures. The complexity increases with the introduction of the characteristics of the loading conditions associated with downbursts, where the loading properties vary with time. The variation of the loading properties (mean wind speed) complicates the evaluation of important analysis parameters such as the aerodynamic damping. For the case of conventional wind, the expression developed by Davenport (1962) and shown in equation [1] computes the aerodynamic damping coefficient ζ_a for each mode i as a function of the air density ρ, the drag coefficient C_D, the cable diameter D, the mass per unit length m, the frequency of the considered mode f and finally the mean velocity V. It is more convenient to apply this expression for the case of straight winds which have a constant mean velocity. Yet, for the case of downbursts, where the mean velocity varies with time, it is more complex since the damping is in this case varying with time.

[1] $\zeta_{ai} = \frac{\rho C_D D V}{4\pi m f_i}$

The commercial package SAP 2000 has been used for the analyses conducted in this study. Realizing the limitations of the used software, it was essential to decide on a representative viscous damping that will be chosen as a fixed damping ratio throughout the analyzed period. This has been implemented by researchers like Dua et al. (2015) who conducted similar analyses but for conventional wind. The challenge here is to decide on a representative mean velocity that would suffice in representing the time history. Consequently, examining the time history of radial wind speed for model-scale downburst simulation shown in Figure 3, it can be shown that the downburst velocity time history generally demonstrates a constant mean beyond the peak zone. Accordingly, it is assumed that this constant value would be used in computing the values of aerodynamic damping per mode, which will then be used to compute the coefficients of viscos damping.

This will be implemented along with the usage of 2-noded cable elements to model the conductors, attached to hinged boundary conditions. This is a replication of an experimental simulation that will be discussed in the following section.

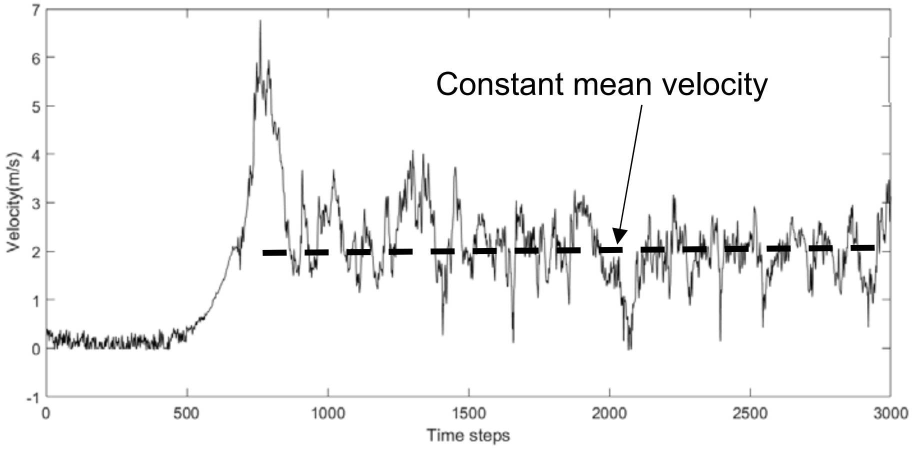

Figure 3: Time history of radial velocity

3 VALIDATION WITH EXPERIMENTAL RESULTS

To judge the applicability of the proposed assumption, where a single value of damping will be used for conducting dynamic analysis despite the varying mean velocity, the results obtained from the numerical model discussed in the previous section will be compared to experimental results in this section. The experiment considered was part of the study conducted by Elawady et al. (2017). The study tested the effect of downburst loading on model-scale transmission line systems using different configurations of structure systems, as well as loading conditions. The tests were performed in the WindEEE dome at The University of Western Ontario, being the first facility capable of simulating these types of three-dimensional flows at wind-tunnel testing scales. The case considered for validation by the current study is a case where a single span of conductors hanging between 2 rigid frames is subjected to downburst loading. The schematic shown in Figure 4 shows the conductors having a span of 2.5 meters hanging between the rigid frames, where the boundary conditions used for the numerical analysis were hinged boundary conditions.

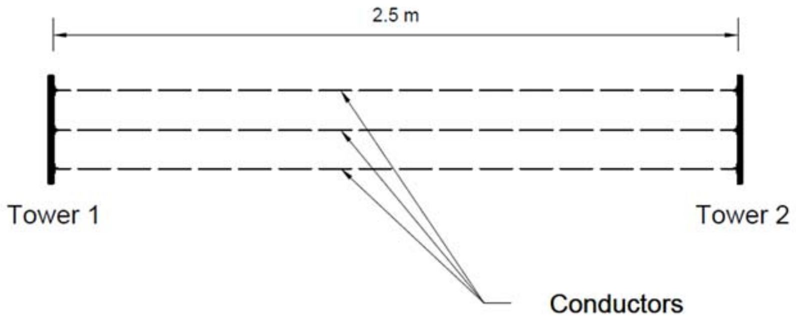

Figure 4: Layout of tested conductor system

The modelled configuration is expected to represent the actual model tested in the experiment. The illustration presented in Figure 5 shows how the cable ends are attached to leaf springs to measure the responses, and in turn transfer the straining actions from the conductors to the rigid frames.

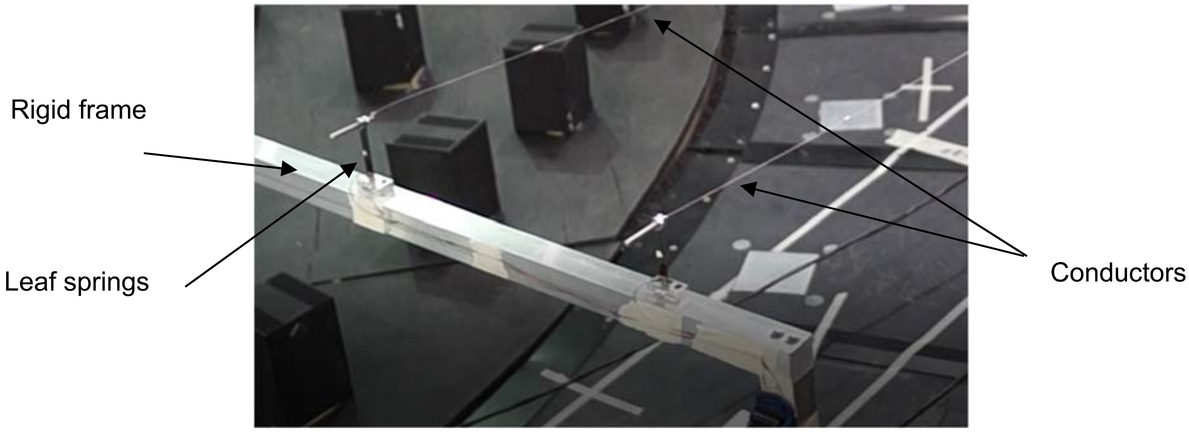

Figure 5: Leaf spring instrumentation at cable ends

Consequently, the next step would be to apply the wind loading mimicking the wind field obtained from the experiment. To do so, the wind field obtained from the CFD simulation reported by Ibrahim et al. (2017) has been used to make sure the applied wind field, which reflects the loading on the cable nodes, would correctly represent the synchronization between different points at an adequate resolution, which was not achievable using the provided experimental results. Nevertheless, the CFD results were not fully representative of the turbulent component of the flow. This is due to the limitation imposed by the mesh size used in the CFD simulation, where the frequencies captured were truncated at a maximum which reflects the size of mesh grid used. To overcome such limitation, the technique used by Darwish et al. (2010) has been utilized. The technique superimposes a turbulent component of the flow, which in the current study was taken from the measured experimental results, on the mean component of the flow, which is taken from the CFD simulation. This procedure guarantees that the used wind field fulfills the synchronization between separate points as well as includes a wider range of frequencies for the turbulent component. The limitation in this case would be the over-correlation of turbulence in the resulting wind field, since the imposed turbulent component was taken from a single point and then calibrated based on the values of peak mean component. Yet, the correlation in this case is deemed acceptable since the structure considered is a single span, where correlations are not expected to deviate much from unity. A sample of the resulting time history is shown in Figure 3.

Accordingly, the resulting wind field was used to compute loading time histories at cable nodes, where time history nonlinear analysis was performed to deduce the longitudinal reaction at the cable ends. As for the damping, the damping per mode was computed as discussed in the previous section, and the viscous damping coefficients were applied accordingly. Furthermore, to verify the validity of the chosen mean velocity, which is the non-varying segment following the peak part, a comparison has been made as shown in Figure 6. The main idea behind the comparison is to vary the damping coefficients, where the full damping value corresponds to the values computed in accordance with the previous section. The values were then reduced to one half and one quarter of that full value. Judging by the presented time histories of longitudinal reactions plotted, it appears that only the post-peak portion of the time history is sensitive to dynamic amplification since the peak zone did not demonstrate any significant difference despite the dramatic change in the damping values. Therefore, it can be assumed with reasonable confidence that using a constant mean velocity value when computing the aerodynamic damping should suffice since the peak zone, where the mean velocity varies greatly, is not sensitive to dynamic excitations.

Comparisons were then made between the numerical and the experimental results to judge the ability of the numerical model to compute the values of longitudinal reactions due to downburst loading.

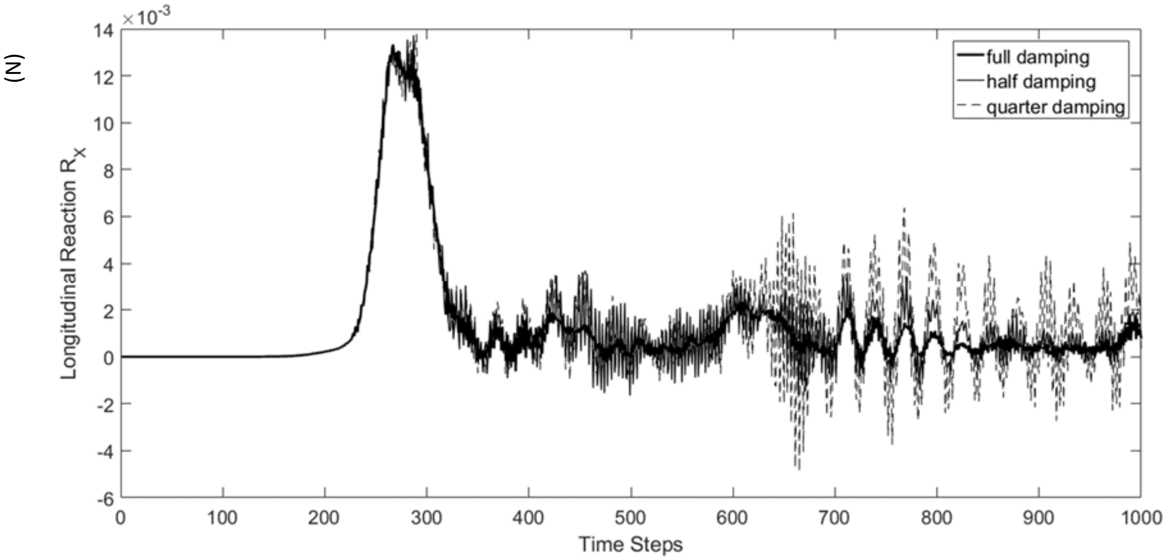

Figure 6: Comparison between time histories of longitudinal reaction corresponding to different damping

The comparison shown in Figure 7 shows a general match between the numerical and the experimental results. The agreement is relatively acceptable in terms of magnitude with an exception of the segment right after the peak zone. This is believed to be a result of the exclusion of the vertical component of the wind field as it was believed to be of minor effect on the structural response being a minor fraction of the dominating radial component of the wind velocity (Elawady and El Damatty (2016)). Yet, it appears that for the considered case the vertical velocity had a noticeable impact on the segment right after the peak zone; this is the part where the main vortex passes by the conductors, where the trailing end of it is believed to have caused this sudden secondary peak in the measured reaction. Nevertheless, judging by the generally

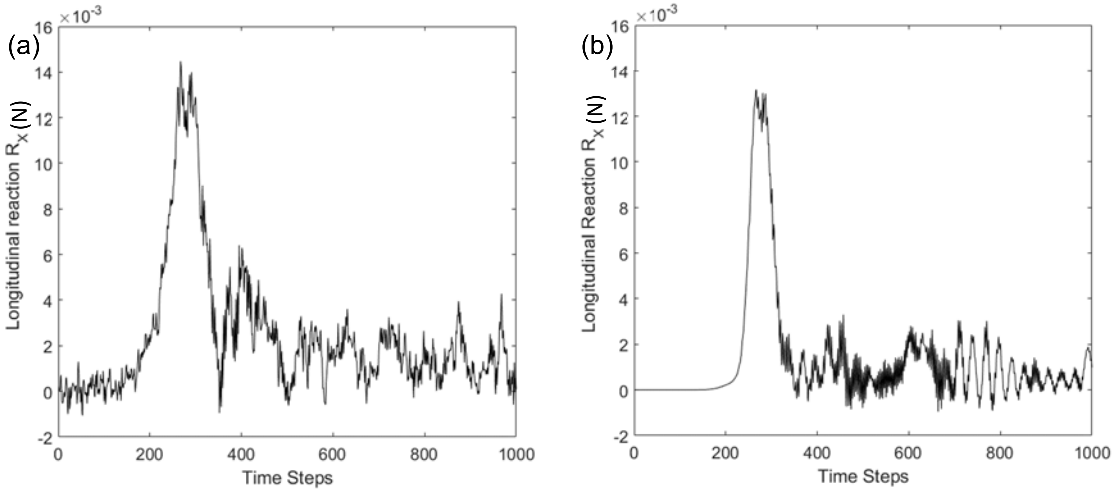

Figure 7: Comparison between longitudinal reaction for (a) experiment and (b) SAP 2000 numerical model

low frequency of the change, as well as its sudden and short effect, it can be considered to have no effect on the dynamic behaviour, which appears to need more time to build-up as shown in Figure 6.

Lastly, further comparison has been made between the turbulent component of the reactions, taken to be the residual after extracting the mean component of both the measured and the computed reactions. This was done through time filtering both time histories, and the comparison illustrated in Figure 8 shows that a difference of 4% between the peak positive and negative values within the range sensitive to dynamic amplification further justifies the validity of the used numerical model in computing the longitudinal reactions of conductor systems due to downburst loading.

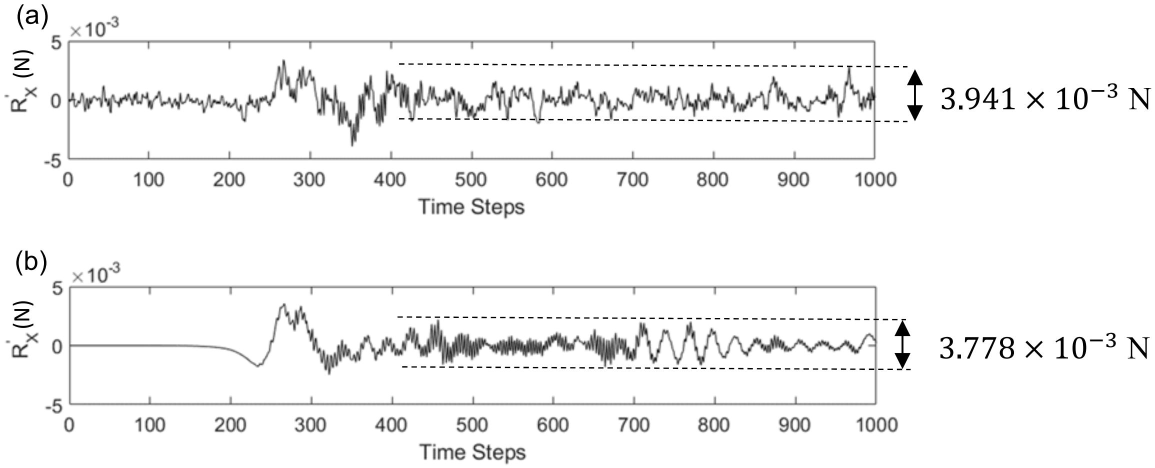

Figure 8: Comparison between fluctuating component of longitudinal reaction for (a) experimental and (b) SAP 2000 analysis

4 CONCLUSIONS

A numerical model has been developed using the commercial package SAP 2000 and was used to compute the longitudinal reactions of conductor systems subjected to downburst loading conditions. Acknowledging the limitations associated with the utilized package, an assumption has been proposed to simplify the analysis by considering one value of mean velocity, and in turn computing a single value for aerodynamic damping. To judge the validity of the proposed assumption, the results from the numerical model were compared to experimental results from a model-scale test performed at the WindEEE dome. Results show that for the post-peak zone, where the dynamic excitations are expected to develop, a relative agreement has been achieved, with turbulent components of the resulting time histories reaching a difference of 4% for the positive and negative peaks. This simplification, which has been found to yield acceptable results, can be extended to full-scale analyses, where a calibrated wind field including the turbulent component of the downburst wind field can be used to assess the dynamic effect of downburst loading on conductor systems.

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