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Keynote Paper

Development of Code Provisions for Transmission Lines under Downbursts Using Numerical Modeling and WindEEE Testing

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ABSTRACT

Failure incidents of transmission lines during localized wind events, in the form of downbursts and tornadoes, have been observed frequently in various locations around the globe. A research program focusing on this problem started more than a decade ago at the University of Western Ontario, Canada. The current paper presents a summary of this research program through the Davenport's Chain for Wind Engineering where an additional link is added to the chain to account for the special features of the downburst and tornado events. A summary and the main findings of the research related to each link of the chain are presented in this paper. The current paper focuses mainly on downbursts. The research involved development of computational fluid dynamics models to simulate and characterize the downburst and tornado wind fields. Those were incorporated into an in-house developed nonlinear finite element model forming a unique package that can predict the behaviour and the failure modes of a transmission line structure under both downbursts and tornadoes. The numerical analysis is conducted by varying the localized wind events in space in order to predict the locations leading to peak internal forces in various members of a transmission tower. A novel experiment was conducted in this research program at the recently established WindEEE dome facility. The experiment involved testing a 1:50 multi-span aero-elastic model under a simulated downburst. The experiments served to validate the numerically predicted wind field and to estimate the turbulence characteristics of downbursts. The tested aero-elastic model was also used to validate the finite element model. A major outcome of this research program was the development of a set of load cases that simulate the critical effects of downbursts and tornadoes on a generic transmission line structures. Those load cases, which were recently presented to the ASCE-74 committee, will be discussed in this paper.

1 Introduction

Failure of transmission line structures during downburst and tornado events is one of the major

problems facing the electrical utility industry worldwide. Those type of events, which are spatially localized, are referred to as High Intensity Winds (HIW). For example, in Canada, two of the major utility companies in that country, Manitoba Hydro, and Hydro One Ontario, suffered from an extensive amount of failures for their transmission line systems due to those type of localized wind events. Since 1999, at least 21 transmission line structures failure incidents have been reported by those two companies either due to downbursts or tornadoes (McCarthy and Melsness, 1996, Hydro One failure report, 2006). The situation is not better in other countries such as China, Russia, South Africa, and Australia where similar failures have been reported (Hawes and Dempsey, 1993, Dempsey and White, 1996, Zhang, 2006, Kanak et al., 2007). The social and economic drawbacks resulting from such failures are tremendous. Recently in 2013, The White House in Washington estimated that more than 600 power outages occurred due to severe weather causing an annual average of economy loss ranging between $18 billion to $33 billion (The White House, 2013).
Responding to this problem, an extensive research program that started more than a decade ago at the University of Western Ontario, and was funded through a number of phases by both Manitoba Hydro and Hydro One, Ontario, investigated various aspects related to this problem. The research benefited from the advancement of numerical simulations using Computational Fluid Dynamics (CFD) models. It also benefited from the recent establishment of the first three-dimensional wind testing chamber where downbursts and tornadoes can be simulated together with structural models on a relatively large scale. The research program followed in a general sense the wind loading chain that was established by Alan G. Davenport for synoptic winds (Isyumov, 2012). This study will highlight how each link of the Davenport's chain was applied for this localized HIW application and particularly to the transmission line problem. One extra link was added to the Davenport's chain as a result of the conditions imposed by the localized nature of HIW event. Research gaps existing in each link of the HIW chain are discussed as well. The research in the HIW chain, pertaining to transmission line structures, reached the stage of development of equivalent load cases, which were proposed to ASCE-74 committee in charge of updating the loading criteria for transmission line structures. Although, the research was conducted in parallel for downbursts and tornadoes, the current paper focuses on downbursts.

2 Davenport Chain

A schematic of the Davenport's chain is provided in Figure 1 below. This chain starts with an identification of the local wind conditions described in the statistical terms. This is followed by including the effect of local wind exposure influenced by terrain roughness and topography. The aerodynamic characteristics of the structure are then used to determine the aerodynamic forces acting on the structure. The dynamic effects associated with wind-induced resonant vibrations are then included. The final link involves development of set of equivalent static forces and setting-up performance criteria based on the structural response.

For HIW, one extra link was added to the chain, as shown in Figure 2, reflecting the effect of the localized nature of HIW events. As mentioned earlier, the state-of-the-art knowledge in the modified Davenport's chain, as pertains to the response of transmission line structures to downbursts, is described in this paper.

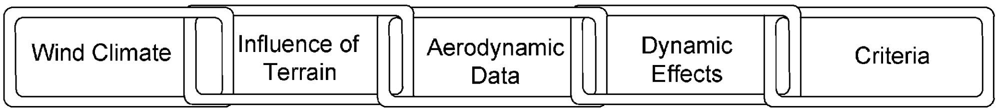

Figure 1 Davenport's chain for normal wind cases

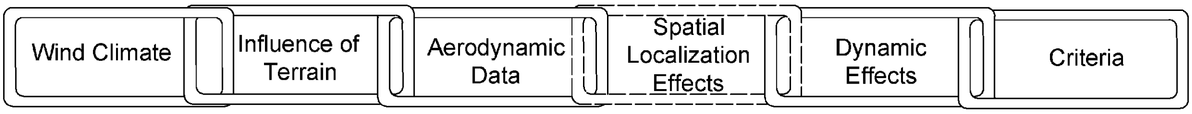

Figure 2 Modified Davenport's chain for HIW cases

2.1 Link 1: downburst wind climate

Because of the localization nature of downbursts both in time and space, field measurements of such events are quite challenging. Several downburst field measurements attempts were found in the literature. Wolfson et al. (1985) reported the field measurements of FAA/Lincoln Laboratory Operational Weather Studies (FLOWS) where different wind intensities and durations were observed. Fujita (1985) characterized the downburst wind field using the field measurements of Northern Illinois Meteorological Research (NIMROD) and the Joint Air-port Weather Studies (JAWS). Hjelmfelt (1988) classified the measured microbursts in Colorado based on their number per each event; i.e., individual and line microbursts. Holmes et al. (2008) reported the downburst event measured near Lubbock, Texas in 2002 where an approach for the decomposition of the measured wind speed time histories in addition to a comparative study with synoptic events were reported. Recently, Solari et al. (2015 a and b) reported statistical analyses of more than 90 downburst measurements collected through the on-going "Winds and Ports" project.

With the limited field data, numerical modeling becomes the alternative. Numerical modeling of downbursts reported in the literature can be conducted using one of the following techniques: (i) Ring Vortex Model (Zhu and Etkin, 1985), (ii) Impinging Jet (Impulsive Jet) Model (Kim and Hangan, 2007, Aboshosha et al., 2015), and (iii) Cooling Source (Buoyancy-Driven) Model (Vermeire et al., 2011, Zhang et al., 2013). Many structural studies adopted the Impinging Jet model in order to simulate the downburst loads where the downburst intensity and size are characterized by the jet diameter, D_J, and jet velocity, V_J.

Using the impinging jet approach, the downburst wind field has the following characteristics:

1. The downburst velocity at a certain point in space depends on the jet diameter, D_J, and the distance between the point and the center of the downburst represented by the distance ratio, R/D_J, (see Figure 3).
2. Two components of wind speeds exist in the downburst wind field, a radial and vertical components. The vertical component is quite small compared to the radial component at the first 100 m above the ground, i.e. within the height of typical transmission towers (see

Figure 4 and 5).

3. The mean of the radial velocity speed varies with time and as such it is called a running mean. A typical variation for the radial velocity time history of a downburst having a diameter of 500 m and measured at R/D_J of 1.3 (where maximum values are shown to be located) is shown in Figure 6. The typical frequency of the mean component of the radial wind velocity of downbursts ranges between 0.01-0.05 Hz.

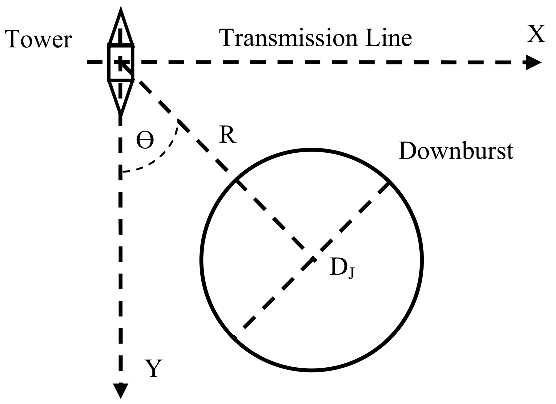

Figure 3 Downburst characteristic parameters

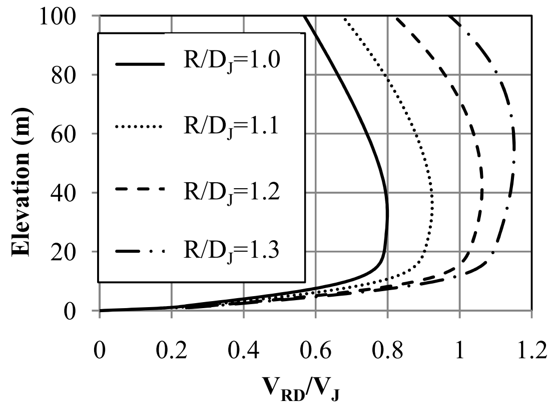

Figure 4 Radial velocity profile along the height, Shehata et al. (2005)

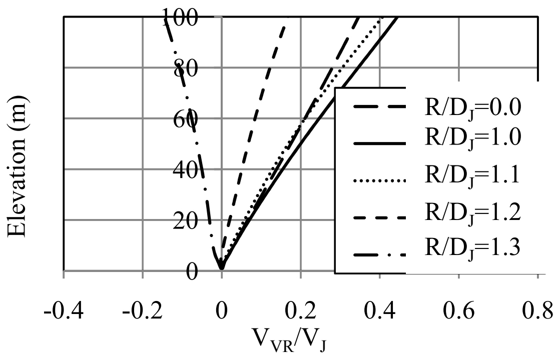

Figure 5 Vertical velocity profile along the height, Shehata et al. (2005)

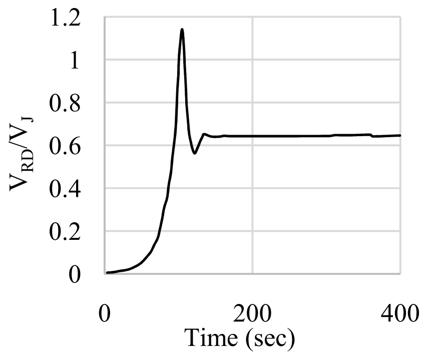

Figure 6 Time history of the radial velocity at a point, Shehata et al. (2005)

2.2 Link 2: influence of terrain

The Reynolds Averaged Navier-Stockes (RANS) equations produces only the mean components of the downbursts wind field. The Large Eddy Simulations (LES) is the alternative to account for the fluctuating component of wind (Chay et al. 2006, Gant 2009, Mason et al. 2009, Aboshosha et al. 2015). Recently, an experimental simulation of downburst winds was conducted at the WindEEE dome testing chamber to assess the dynamic response of lattice transmission tower subjected to downburst winds. A schematic view of the testing chamber is provided in Figure 7 where D_J of

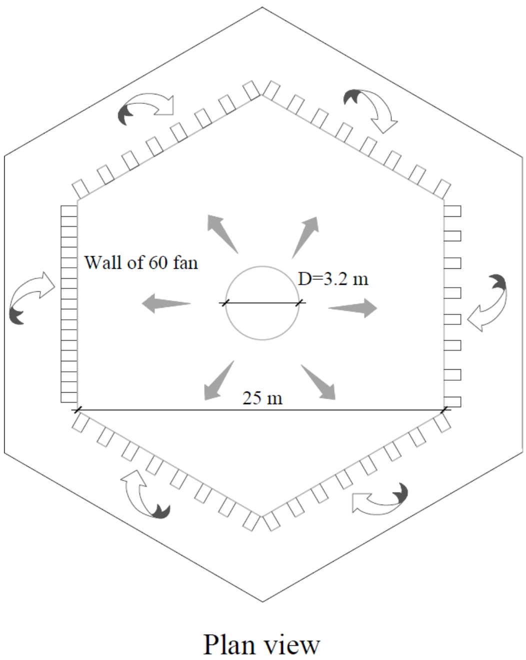

Figure 7 Schematic plan view of testing chamber and downburst simulation at the WindEEE.

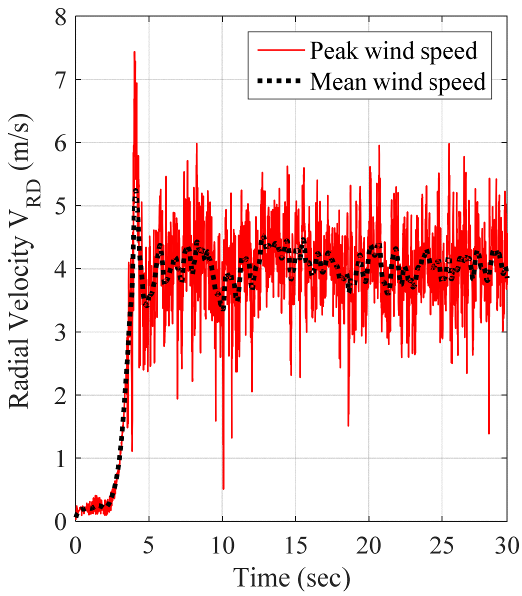

Figure 8 Mean wind component decomposition

Figure 9 Downburst formation snapshot at WindEEE

3.2 m is used in the model scale. The downburst wind field (including turbulence) was measured by cobra probe devices distributed radially between R = $0.7D_J \sim 3.0D_J$ and vertically along 1 m height for an open terrain exposure. Figure 8 shows a sample of the measured downburst radial velocity. The figure shows the decomposed running mean component which was extracted so that the cutting-off frequency of the running mean component was greater than the shedding frequency of the main vortices by an order of magnitude. Based on the decomposition criteria, the turbulence intensity of the wind field was calculated and found to be in order of 0.1~0.14 near the location of the maximum radial velocity component. This agreed well with the findings reported by Solari et al. (2015-a) for a real downburst events.

Figure 9 shows a snapshot of the transmission line model constructed at the WindEEE dome during the formation of the downburst vortices.

2.3 Link 3: aerodynamic data

Design codes provide procedures for estimating the aerodynamic forces acting on the towers and the conductors resulting from synoptic wind loads. A number of questions arises about the applicability of those procedures for the transient, time varying downburst wind fields. The forces actin on the tower angles depend on the drag and the shielding coefficients which depend on the section solidity ratio. Shehata et al. (2005) utilized the mean wind speed time histories provided by the CFD model developed by Hangan et al. (2003) and proposed a scaling-up procedure in order to estimate the spatial and the time variations of the wind velocities associated with full-scale downbursts. In their model, Shehata et al. (2005) considered the shielding and the drag coefficients given by the National Building Code of Canada (NBCC 90) in order to estimate the horizontal forces of downburst winds acting on both the conductors and the tower. They also developed a procedure for the calculation of the forces associated with the vertical component of the wind field

Available design codes do not consider the effect of different wind pitch angles on the estimated aerodynamic forces. Given that the mean component of the downburst and tornado wind field has a vertical component, the effect of the yaw angle on the aerodynamic coefficients needs to be investigated. Mara et al. (2010) reported a slight increase in the drag coefficients measured in wind tunnel experiments for lattice transmission line sections under at a yaw angle of 20° compared to the drag coefficients calculated using code equations. More studies are recommended to assess the accuracy of the drag and shielding coefficients of the tower sections especially for tornadoes where the vertical component of the wind field is more significant compared to that of downburst.

2.4 Link 4: spatial localization effects

This link represents the modification of the Davenport's chain that results from the localized effect of downbursts. The forced acting on different components of a structure depends on the location of the downburst compared to the structure. As such, in order to determine the maximum internal forces acting on an element of the structure, a complete parametric study involving varying the location and characteristics of the downburst needs to be conducted in order to determine the maximum effects. This is particularly important for long structures such as transmission lines.

Shehata et al. (2005) developed the first numerical code to account for the spatial and time variations (R, D_J, Θ, and time) of the downburst loads on the response of transmission line systems. In that numerical code, the tower members were simulated using two-node three dimensional frame elements with three rotation and translation degrees of freedom at each node. In their study, the conductors were modeled using a two-dimensional curved beam element that accounted for the cable pretension force, insulator flexibility, and geometric nonlinearity. Later, Aboshosha and El Damatty (2014) developed and validated a semi-analytical technique that takes into consideration the conductor's variables considered in Shehata et al. (2005) model with a great advantage in reducing the computational time. Shehata and El Damatty (2007) conducted a parametric study to assess the effect of a generic downburst event on the response of a guyed transmission line system. Darwish and El Damatty (2011) conducted a similar parametric study with a change in the structural system where they studied a self-supported transmission line system. Elawady and El Damatty (2016) focused on assessing the effect of a generic downburst on the longitudinal response of the conductors. The following observations were reported from those studies:

1. For self-supported tower, a downburst configuration of Θ = 0º (see Figure 3), $R/D_J = 1.3$ caused maximum transverse loads on the tower and the conductors. This caused the maximum internal forces in the tower's main shaft members.
2. For guyed tower, a downburst configuration of Θ = 90º, $R/D_J = 1.3$ caused maximum longitudinal loads on the tower and was found to be critical for the main shaft members.
3. In both systems, guyed or self-supported towers, at the cross arm zone, an oblique load case; i.e., at $0 < \Theta < 90$, was found to be critical. This was found due to the excessive forces developing in the conductors and the ground wires associated with these angles of attack.
4. For the conductors, at Θ = 30º, $R/D_J = 1.6$, a maximum longitudinal force developed in the cables (conductors and ground wires) and was transferred to the tower cross arm causing an out-of-plan bending moment. This longitudinal force is highly nonlinear and depends on the cable's properties and does not exist for the case of synpptic wind.

2.5 Link 5: dynamic effects

Lattice transmission towers are generally not susceptible to dynamic excitation of the running mean wind component due to their high frequencies (typically >1 Hz) compared to the frequency of the running mean (0.01~0.05 Hz) which contains the main energy of the wind event. On the other hand, conductors are flexible elements (natural frequency of 0.1~0.2 Hz) that are expected to be prone to dynamic excitation of downburst fluctuating component (frequency of the turbulence > 0.05 Hz in most of the cases). Previous studies such as Aboshosha et al. (2015) and Lin et al. (2012) showed that the aerodynamic damping plays an important role in attenuating the dynamic response of the cables. Loredo-Souza and Davenport (1998) reported that the resonant response, of a single spanned conductor subjected to normal wind loads, can be as important as the background response depending on the aerodynamic damping of the conductors. Darwish and El Damatty (2010) showed that the tensile force developing in the conductors due to the localized downburst configurations reduces the aerodynamic damping effect of the cables. Aboshosha and El Damatty (2015) studied the dynamic response of the conductors subjected to downburst loads and reported an increase of 6%

of the conductor forces due to the dynamic excitation. The results of the aero-elastic experiment conducted recently at the WindEEE dome showed an increase of 10~15% in the response due to the dynamic excitation for the tower and the conductors at the typical range of downburst velocities.

2.6 Link 6: criteria

Based on several numerical and experimental studies conducted at The University of Western Ontario to assess the behaviour of transmission line structures subjected to downburst loads, El Damatty and Elawady (2015) proposed a set of downburst velocity profiles that are believed to cause the maximum internal forces in the tower and conductors. Those load cases are summarized as following:

1. ***Maximum transverse loads:*** this configuration represents the maximum velocity profile acting on the tower and the conductors in the direction parallel to the line direction. The critical velocity profiles along the height of the tower as well as the spans adjacent to the tower of interest are given in Figure 10 and 11, respectively.
2. ***Maximum longitudinal loads:*** this configuration represents the maximum velocity profile acting on the tower in the direction perpendicular to the line direction. The maximum velocity profile along the height of the tower is provided in Figure 12. No forces act on the conductors due to this load case (see Figure 13).
3. ***Maximum oblique loads:*** this configuration represents the maximum oblique velocity profile acting on the tower and the conductors. Figure 14 shows the radial velocity distribution along the tower height for both the transverse and the longitudinal directions associated with this load case. Figure 15 shows the radial velocity distribution of the downburst critical oblique configuration along the line spans associated with this load case. The unsymmetrical distribution of the velocity along the line spans adjacent to the tower of interest results in nonlinear longitudinal forces developing in the conductors (Shehata et al. 2005). Charts were developed by El Damatty and Elawady (2016) enabling the evaluation of those forces.

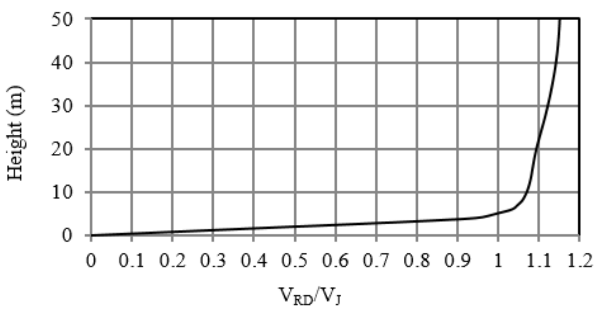

Figure 10 Radial velocity distribution along tower height at R/DJ=1.3 and ϴ=0°

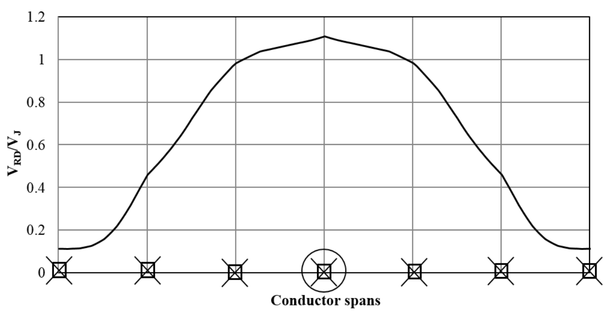

Figure 11 Radial velocity distribution over six conductor spans at R/DJ=1.3 and ϴ=0°

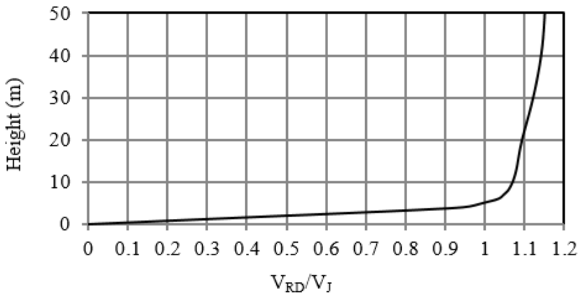

Figure 12 Radial velocity distribution along tower height at R/DJ=1.3 and ϴ=90°

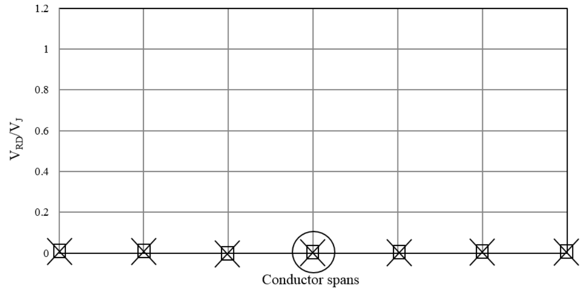

Figure 13 Radial velocity distribution over six conductor spans at R/DJ=1.3 and ϴ=90°

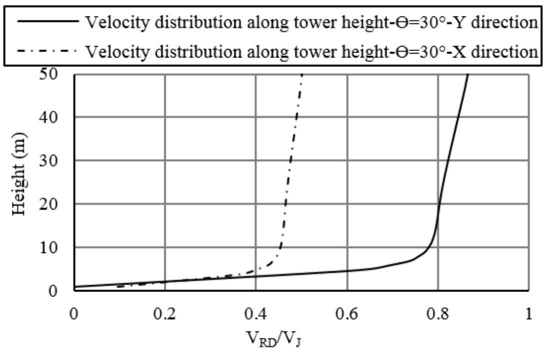

Figure 14 Radial velocity distribution along tower height at R/D_J=1.5 and ϴ=30°

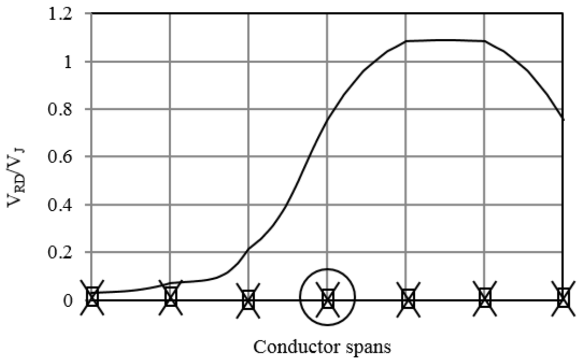

Figure 15 Radial velocity distribution over six conductor spans at R/D_J=1.5 and L/ D_J=0.5, and ϴ=30°

3 Conclusion

The current paper presented a novel contribution to the well-known Davenport's chain for wind engineering. The paper discusses the Davenport's chain for downburst studies on structures with a focus on transmission line structures. The following conclusions were made:

1. The Davenport's chain designed for synoptic wind studies requires one more link in case of localized wind events such as tornadoes and downbursts to address the localization aspects of those events in space and time.
2. Link 1: More metrological measurements are needed to fill in the gaps in the literature concerning the downburst intensities and sizes. Statistical analyses of large number of events in different places may help in building downburst velocity maps.
3. Link 2: comparative studies for the effect of different terrain exposures on structural response is needed for codification of terrain factors necessary in design guidelines.
4. Link 3: aerodynamic coefficients of tower sections subjected to downburst loads can be considered similar to those given in design manuals for synoptic wind calculations. More

studies are needed for tornado studies where a high vertical velocity component exists.

5. Link 4: Transmission tower response to downburst events varies based on the polar location of the event measured from the tower center. The numerical and experimental studies revealed that different tower members experience their peak response under different configurations of the downburst. Therefore, a parametric study considering all possible scenarios of the location of the event is needed in order to evaluate the peak internal forces in each of the tower members. Also, the tower response varies based on the structural system of the tower in addition to the conductor's properties.
6. Link 5: at the expected high downburst velocities, the dynamic response of the tower and the conductors is relatively small and is in the order of 10~15%.
7. Link 6: A set of downburst load cases has been proposed for the ASCE-74 committee in charge of updating the code manual. The proposed load cases simulate the critical loading scenarios of a downburst events acting on a generic transmission line system.

4 Acknowledgements

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