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AEROELASTIC RESPONSE OF LONG-SPAN BRIDGES TO DOWNBURST WIND FIELDS: A NONLINEAR TIME-DOMAIN INVESTIGATION

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Abstract. *In recent years, extreme atmospheric events such as downbursts have been increasing in both strength and frequency. Considering their interaction with long-span bridges, these phenomena are characterized by significant spatial and temporal variations of the angle of attack along the bridge deck, which can strongly affect the aeroelastic response of the structure. The objective of this study is to investigate the aeroelastic response of long-span suspension bridges to the passage of a downburst. The three-dimensional mean wind field is generated by superimposing a simplified analytical stationary downburst model onto an environmental turbulent wind field. The resulting wind field can therefore be represented as the sum of a low-frequency component and high-frequency fluctuations characterized by time-varying statistical properties. The structural response is evaluated using a nonlinear time-domain approach, in which the effects of the low-frequency wind field are modeled through quasi-steady theory, while the influence of high-frequency turbulence is considered using a time-varying linearized approach around the quasi-steady solution. This methodology enables the capture of nonlinear effects associated with low-frequency variations in the angle of attack caused by the downburst and allows comparison with approaches assuming stationary and ergodic wind fields. Different wind scenarios are generated to analyze the influence of downburst size, position relative to the bridge, and translation speed. Furthermore, several long-span bridges with varying structural and aerodynamic characteristics are examined to assess the sensitivity of these properties to downburst-induced loads.*

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1 INTRODUCTION

In recent years, the frequency and intensity of extreme atmospheric events, such as downbursts and typhoons, have increased due to changes in wind climate. Significant aeroelastic responses of long-span suspension bridges have been observed during extreme events, highlighting the need for a deeper understanding of their impact on these structures [1]. Downbursts are among the most dangerous events, exhibiting a highly correlated three-dimensional flow field in which the environmental wind is superimposed on a vertical jet flow. This results in significant variations in both wind magnitude and direction, leading to severe low-frequency changes in the angle of attack [2]. This aspect makes it essential to consider aerodynamic nonlinearities in the computation of the bridge response [3].

The objective of this study is to investigate the aeroelastic response of long-span suspension bridges to the passage of a downburst. In the following, the downburst wind scenario is compared to a stationary wind field. Preliminary simulations were run considering only a section of the bridge deck and modelling the aerodynamic forces with the quasi-steady theory [4].

In the final version of the work, a more detailed analysis will be conducted considering a full-bridge numerical model and the complete wind time-space distribution in which turbulence will be generated with time-varying statistical algorithms to account for variations in the mean wind speed during the downburst event. The structural response will be evaluated using a nonlinear time-domain approach in which the effects of the low-frequency wind field are modeled through quasi-steady theory, while the influence of high-frequency turbulence is considered using a time-varying linearized approach around the quasi-steady solution [3]. A sensitivity analysis will be performed by varying the downburst radial dimension, the environmental wind speed and the impact location along the bridge longitudinal axis.

2 WIND TIME HISTORIES

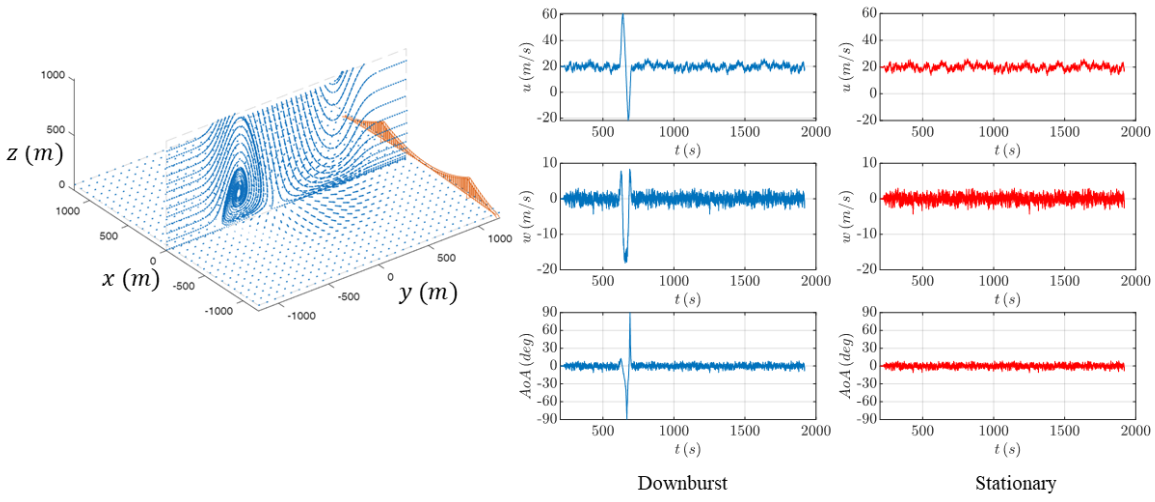

Figure 1: Horizontal and vertical wind components and AoA of the downburst (left) and stationary (right) wind time histories

In the preliminary phase of this study, two wind scenarios have been considered. In the first, the three-dimensional mean wind field is generated by superimposing a simplified analytical stationary downburst model, developed in [2], onto an environmental turbulent wind

field with a mean wind speed of U = 20 m/s. The downburst parameters required by the model and used in the simulation are reported in Table 1.

The downburst event has a duration of 120 s with horizontal wind speed ranging from – 20 m/s to 60 m/s and AoA variations within $\pm 90°$. The second scenario consists of a stationary turbulent wind field with a mean speed of U = 20 m/s. Figure 1 presents the time histories of the horizontal (u) and vertical (w) turbulent wind components at the bridge midspan section for both scenarios, each with a duration of approximately 30 minutes.

U_{max}	Maximum wind speed	45	m/s
r_{max}	U_{max} radial distance from the downburst centre	600	m
h_{max}	U_{max} height	50	m

Table 1: Downburst model parameters

3 AERODYNAMIC AND STRUCTURAL PROPERTIES

The aerodynamic and structural properties considered in this study correspond to those of the Messina Strait Bridge deck cross-section. Numerical simulations are performed using a three-degree-of-freedom (3-DOF) sectional model. The adopted structural properties are reported in Table 2, while the reference system used for aerodynamic forces, deck displacements and turbulent wind components is represented in Figure 2.

m	Mass per unit length	$6 \cdot 10^4$	kg/m
J	Moment of inertia per unit length	$4.2 \cdot 10^7$	kgm^2/m
f_y	Lateral frequency	0.0309	Hz
f_z	Vertical frequency	0.0659	Hz
f_θ	Torsional frequency	0.0806	Hz
$\zeta_{y,z,\theta}$	Damping-ratios	0.3%	-
B	Deck chord	60	m

Table 2: Deck section structural properties

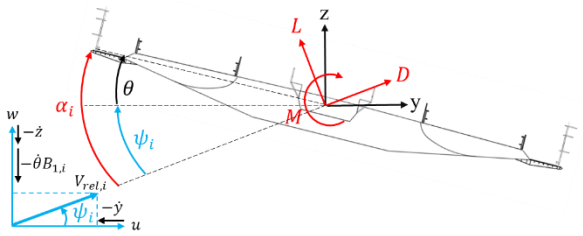

Figure 2: Deck cross-section and reference system for forces, displacements and turbulent wind components

The aerodynamic properties were measured through wind tunnel experiments performed at the Politecnico di Milano wind tunnel on a rigid sectional model of the bridge, faithfully reproducing the girder geometry. Experimental static force coefficients (SFC) were measured for AoA = $\pm 10°$, however since the AoA reached during the passage of the downburst are much higher (see Figure 1), they were extended outside this range following a procedure similar to the one proposed in [5], as shown in Figure 3.

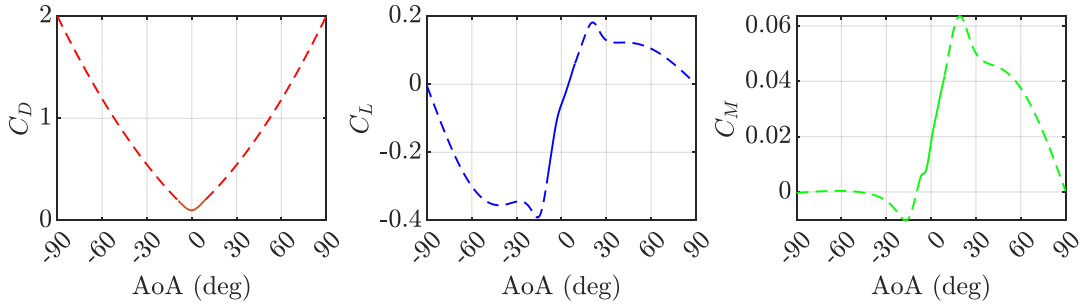

Figure 3: Static force coefficients of the Messina Strait Bridge

4 PRELIMINAR RESULTS

Figure 4 presents the computed time histories of displacements and aerodynamic forces for both stationary and downburst wind scenarios. Results highlight how the downburst induces pronounced aerodynamic forces, leading to significant peaks and an amplified aeroelastic response of the bridge.

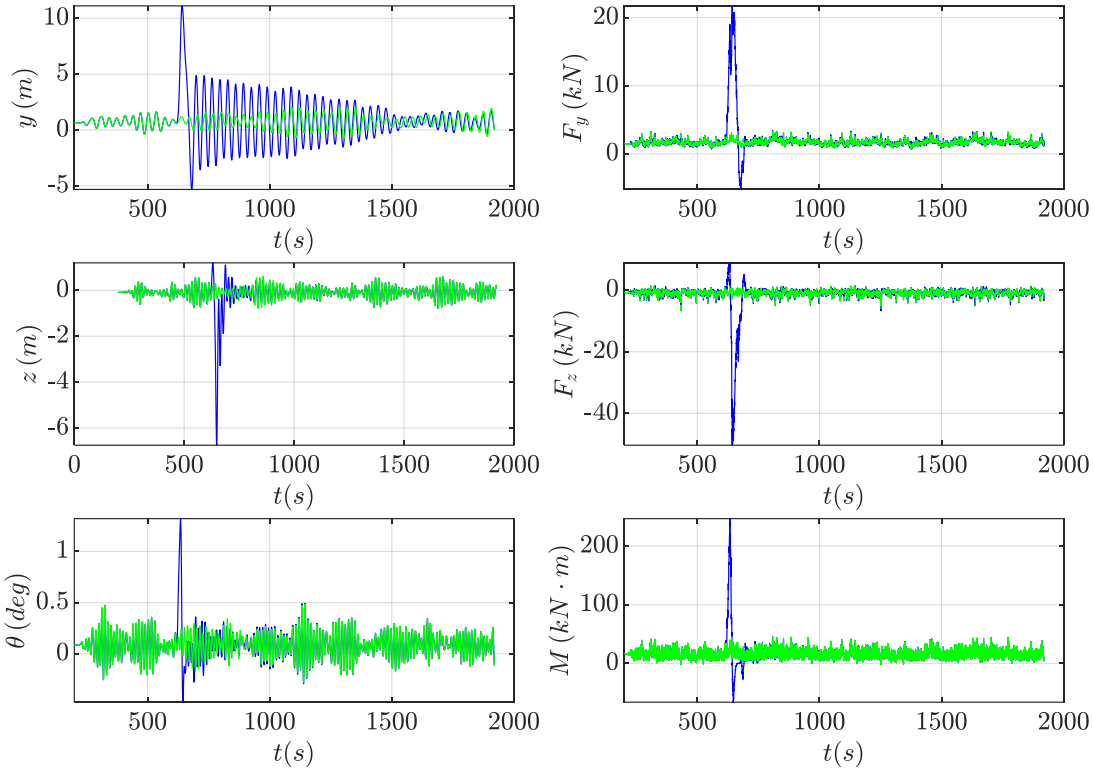

Figure 4: Time histories of displacements and aerodynamic forces for both downburst (blue) and stationary (green) case

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