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Defining the vortex loading period and application to assess dynamic amplification of tornado-like wind loading

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A B S T R A C T

Tornados are transient loading events, and several studies in the literature have shown their capability to produce dynamically amplified structure response. The present study utilizes the dynamic load factor (DLF) concept to develop the first generalized methodology to assess the possible dynamic amplification of structure having specified fundamental period T_n to tornadic wind loads. The two-dimensional impact of a rigid, circular cylinder by an impinging vortex is directly simulated; the resulting loading time history is then used to excite a single degree of freedom (SDOF) response model. The vortex load application period T_v is defined as the value of T_n for which the structure's response experiences greatest dynamic amplification. An expression for T_v is defined as a function of three vortex properties: critical radius, translational velocity, and tangential velocity profile, so that T_v can be computed using documented tornado-vortex properties. The range of possible tornado-vortex tangential velocity profiles is identified, and DLF curves are defined for the forcing produced by each vortex profile. A review is conducted of the range of documented tornado parameters and fundamental periods of real-world structures. Finally, the documented tornado parameters, expression for T_v, and DLF curves for the vortex profiles are used to define the possible dynamic response amplification of a structure as a function of T_n.

1. Introduction

Tornados are transient wind loading events that produce the highest documented wind speeds on Earth. Each year, more than 1200 tornados occur in the United States (US) and its territories (Edwards and Brooks, 2010) causing 110 deaths (NWS, 2014) and approximately $500 million US in property damage (NWS, 2012). Despite the substantial annual cost of tornados, building design codes such as ASCE 7-05 fail to make provision for tornadic wind loading.

Tornadic wind loading of a structure, illustrated in the schematic Fig. 1, has been investigated using both physical experiment and computer simulation.

Jischke and Light (1983) measure forces produced on a rectangular structure by a stationary vortex and report that vortex loading is greater than loading produced by equivalent-velocity straight-line wind. Selvam and Millet (2005) simulate 3D loading of a cube by a Rankine Combined Vortex (RCVM) and report that cross-stream (Y-direction) and vertical (Z-direction) vortex loading is 1.5 and 2.0 times (respectively) greater than loading produced by simulated straight-line wind.

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Nomenclature

A	Projected area
C	Damping coefficient
Cd	Drag force coefficient $(2 \cdot F_d/\rho \cdot U_{ref}^2 \cdot A)$
Cl	Lift force coefficient $(2 \cdot F_l/\rho \cdot U_{ref}^2 \cdot A)$
C_M	Mean force coefficient (Analogous to mean Cd for free stream)
C_H	Harmonic force coefficient (Analogous to Cl amplitude for free stream)
D	Diameter of the cylinder
DLF	Dynamic amplification of structure′s response to applied forcing (DLF= x_m/x_{st})
F_d	Drag force
F_l	Lift force
F_o	Amplitude of dynamic forcing
f_{Cl}	Frequency of vortex shedding
fn	fundamental structure frequency $(f_n=1/T_n)$
f_v	Vortex loading frequency $(f_v=1/T_v)$
n	Exponent for Vatistas′ vortex model
K	Structure stiffness
M	Structure mass
P_∞	Ambient/Reference Pressure
P^*	Dimensionless pressure $(P/\rho \cdot U_\infty^2)$
Re	Reynolds number $(D \cdot U_\infty / \nu)$
r	Radial ordinate of the vortex
r_c	Critical radius for the vortex
r_p’	Radial distance between the vortex center and the boundary node
St	Strouhal number, dimensionless vortex shedding frequency $(f_{Cl} \cdot D/U_\infty)$
T_{lag}	Time required for the vortex and cylinder centers to align (X_o / U_∞)
T_d	Dynamic load application period
T_n	Fundamental structure period
T_v	Period of vortex load
T_v^*	Dimensionless vortex loading period
t	Time
t^*	Dimensionless time $(t \cdot U_\infty/D)$
U	Horizontal velocity
U_{ref}	Reference velocity
U_∞	Bulk velocity of the fluid stream
U^*	Dimensionless horizontal velocity (U / U_∞)
V	Vertical velocity
V_R	Resultant velocity
V_θ	Tangential velocity of the vortex
V^*	Dimensionless vertical velocity (V /U_∞)
X	Horizontal coordinate
X_o	Starting location of the vortex
X^*	Dimensionless horizontal coordinate (X/D)
X’	Horizontal ordinate of translating reference frame attached to vortex
x_m	Maximum structure response to applied forcing
x_p	Horizontal coordinate of boundary node with respect to cylinder center
x_p’	Horizontal coordinate of boundary node with respect to vortex center
x_{st}	Structure response to static amplification of maximum forcing value $(x_{st}=F_o/K)$
Y	Vertical ordinate
Y^*	Dimensionless vertical coordinate (Y/D)
Y’	Vertical ordinate of translating reference frame attached to vortex
y_p	Vertical coordinate of boundary node with respect to cylinder center
y_p’	Vertical coordinate of boundary node with respect to vortex center
α	Angular velocity of the vortex
θ	Resultant velocity direction
δt^*	Solution time step
Δr	Radial node spacing
ζ	Damping ratio
ω_n	Fundamental angular structure frequency
ρ	Density of the fluid
ν	Kinematic viscosity of the fluid
DLF	Dynamic load factor
L–O	Lamb-Oseen
RC	Reinforced Concrete
RCVM	Rankine Combined Vortex Model
SDOF	Single Degree of Freedom
S–K	Scully-Kaufmann

Sengupta et al. (2008) and Haan et al. (2010) use Iowa State University’s translating vortex simulator to measure loading of cube and gabled-roof structures respectively by translating, tornado-like vortices. Sengupta et al. (2008) reported that vortex loading on the cube is up to 1.5 times greater than straight-line wind loads computed via ASCE 7-05. Haan et al. (2010) report that the cross-stream and vertical loading of the gabled structure by the vortex is up to 1.5 and 3.2 times greater than straight-line wind loads computed via ASCE 7-05. Briefly summarized, tornadic winds produce cross-stream and vertical loads that are respectively 1.5 and 2.0–3.2 times greater than loads produced by wind having a uniform velocity distribution.

The dynamic nature of tornadic wind loading creates potential for dangerous dynamic amplification of structural response, which is commonly quantified by an integer multiple known as the dynamic load factor (DLF). Several studies evaluate the dynamic amplification of structures’ responses to tornadic wind loads. All studies define the time history of the wind velocity incident on the building and then use empirical equations, which are defined as functions of the incident wind velocity, to define the forcing time history. Wen (1975) studies the response of a multi-story building to a simplified Kuo (1971) vortex and reports that the maximum structure response is amplified by DLF=4.0. Two similar studies evaluate multi-story structures′ responses to a modified RCVM vortex and report maximum response amplification of DLF=2.0 (Tan, 1975; Seniwongse 1977). Dutta et al. (2002) analyze the responses of single- and multi-story structures to a tornadic wind