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Numerical study of the wind loads on a cooling tower by a stationary tornado-like vortex through LES

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ABSTRACT

A tornado simulator is built and large eddy simulations are carried out to model the swirling flow fields in a tornado-like vortex and the tornado-induced wind loads on a cooling tower. When the cooling tower is close to the tornado core, the mean and fluctuating loads exerted by the tornado tend to be much larger than those applied by a straight-line wind. However, when the cooling tower is sufficiently far from the center of the tornado, $r > 3.0r_c$, the aerodynamic force coefficients show almost the same value as those induced by the straight-line wind. In the tornado core, the forces show the maximum fluctuations. To explain these large force fluctuations, spectrum analyses are carried out and two peaks are identified. These two peaks are found to be the result of two factors, i.e., the sub-vortices in the tornado and the vortex shedding in the wake of the cooling tower. This is the most important finding in this study, and it clarifies the dynamic response of a cooling tower exposed to a tornado.

1. Introduction

In power plants, the cooling towers are very important structures, which are sensitive to wind forces owing to their significant height and relatively thin wall. The damage to cooling towers caused by straight-line winds has been studied by many researchers. However, only a few studies have focused on tornado-induced damage to cooling towers. Although the reports about tornado-induced damages to cooling towers are limited, serious consequences can arise if a cooling tower cannot resist the tornado-induced forces. In China, many nuclear power plants are being planned, and thus, much more attention should be paid to tornado-induced damages to cooling towers.

Owing to the limited research about tornado-induced wind loads on cooling towers, the features of the aerodynamic forces on other types of structures caused by tornadoes are introduced beforehand in order to provide a general idea about the tornado-induced wind loads. With the aid of tornado-like vortex simulators, i.e., the Ward type (Church et al., 1977, 1979; Diamond and Wilkins, 1984; Mishra et al., 2008; Matsui and Tamura, 2009), ISU type (Haan et al., 2008; Tari et al., 2010; Kikitsu et al., 2011; Cao et al., 2015; Wang et al., 2016, 2017), and WindEEE (Hangan, 2014; Refan and Hangan, 2016), there have been several attempts to physically investigate the wind loads on structures subjected to tornado-like vortices. Jischke and Light (1983) applied a Ward-type simulator to study the tornado induced aerodynamics forces on structures. They proposed that an addition of swirl to the flow provided a significant change in the forces on the model. Mishra et al. (2008) also adopted the Ward-type simulator to generate a tornado-like vortex and examined the forces on a cubical structure. The results show the pressure distribution and have different characteristics compared to those in a straight-line

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Nomenclature

A_i	projected areas of the cooling tower
C_{F_i,V_H}	aerodynamic force coefficients in i (x, y, z) directions
$C_{F_i,V_H,RMS}$	fluctuation of the aerodynamic force coefficients
C_{pe,V_H}	external pressure coefficient
C_s	Smagorinsky constant
d	distance from cell center to the closest wall
D	diameter of the updraft hole
f_i	instantaneous aerodynamic forces
F_i	time averaged aerodynamic forces
H	height of cooling tower
h_{vmax}	height of the globally largest tangential velocity
h_1	height of convergent chamber
l	height of convective chamber
L_s	mixing length for subgrid scales
r	radial distance
P	mean pressure on the ground
P_e	mean pressures acting on external cooling tower surfaces
P_{min}	minimum mean pressure on the ground
P_r	reference pressure
$\tilde{p}$	filtered pressure
Q	flow rate
Re_c	Reynolds number for the cooling tower
Re_t	Reynolds number of the tornado
r_0	radius of updraft hole
r_c	radius at which V_c occurs
r_{Hmax}	radius at which V_{Hmax} occurs
r_L	length ratio
r_s	radius of convergent chamber
r_{vmax}	radial location of the globally largest tangential velocity
r_w	radius of convective chamber
S	swirl ratio
$\tilde{S}_{ij}$	rate-of-strain tensor for the resolved scale
u, v, w	rms of fluctuating streamwise, spanwise, and vertical velocities
$\tilde{u}_i$	filtered velocities
u_τ	friction velocity
U_H	radial velocity at the height of the cooling tower
V_c	maximum tangential velocity in the cyclostrophic balance region
V_H	tangential velocity at the height of the cooling tower
V_{Hmax}	maximum tangential velocity at the height of the cooling tower
w_0	updraft wind velocity at the outlet
x, y, z	Cartesian coordinates

Greek symbols

λ_L	length scale
μ	air viscosity
ω_i	vorticity component of the flow along x_i
Ω	surface of the cooling tower
θ	wind angle at the height of cooling tower
σ	standard deviation of the fluctuating force

wind tunnel. Applying the tornado simulator in Iowa State University, Haan et al. (2009) studied the instantaneous wind load on a gable-roof building with the laboratory-simulated tornado. The results show that the lateral force caused by tornado is 50% higher than that specified by engineering standards (American Society of Civil Engineers 2006, hereafter "ASCE 7-05", Kumar, 2010), and the lift force caused by the tornado is two or three times as large as ASCE 7-05. Rajasekharan et al. (2013a, b) used a tornado simulator at Tokyo Polytechnic University to study the forces caused by a tornado on structures. As in Yang et al. (2010, 2011), significant differences between the forces caused by the tornado and those caused by a straight-line wind