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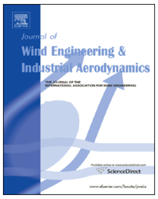

Modeling the mean wind loads on cylindrical roofs with consideration of the Reynolds number effect in uniform flow with low turbulence

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ABSTRACT

The influence of Reynolds number on the mean wind loads acting on cylindrical roofs with different aspect ratios (rise to span ratio, R/D) has been investigated experimentally. The spans D of the cylindrical roof models were 0.2 and 0.6 m, and the Reynolds numbers, based on D, ranged from 6.90×10^4 to 8.28×10^5. Three aspect ratios were studied; $R/D = 1/2$, 1/3 and 1/6. The surface pressure distributions and force coefficients were determined using wind tunnel measurements in uniform flow with low turbulence. The effects of the different aspect ratios and Reynolds numbers were briefly discussed. The aim of this investigation was to find a simplified approach to parameterize estimation of the pressure coefficients C_p, which considers the influences of the aspect ratio of the roof model together with the Reynolds number. It was found that a modified pressure model, in terms of a re-normalized formation, represented the experimental data accurately for the cylindrical roof model with a variety of aspect ratios. This approach was also found to be reliable for evaluating wind pressure distributions on cylindrical and spherical roofs.

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1. Introduction

Curved roof structures, typically involving cylindrical or spherical forms, are increasingly used for modern buildings due to their attractive architectural shapes and large unsupported interior spaces. Since the roofs are often light and flexible, wind loads represent a significant design problem, particularly for roofs with very little dead weight. Some codes (i.e. EN1991-1-4 and ASCE7-95) give recommended values for surface pressure coefficients on curved roofs; however, there is some concern regarding the reliability of this data. Blackmore and Tsokri (2006) pointed out that there is little information available on the wind loads on cylindrical roofs within a limited range of aspect ratios in low-turbulence conditions. Further, a potential Reynolds number sensitivity for curved roofs may introduce design difficulties. The wind loads should be evaluated by considering the parameters influencing the wind pressure distributions on these structures. The parameters included in the present investigation are the aspect ratio of the cylindrical roofs together with the Reynolds number.

As is well known, for structures with curved surfaces, the separation point is not generally fixed and some Reynolds number sensitivity may still be found. Johnson et al. (1985) compared the circumferential pressure distributions on a semi-cylindrical roof in the Reynolds number (Re) range 1.0×10^4–4.75×10^5. The experimental results showed a strong Re dependence with peak suctions steadily increasing up to 1.5×10^5 and then decreasing somewhat. Regarding the wind pressures on cylindrical roofs with low aspect ratios (less than 0.5), wind tunnel measurements on roof models with $R/D = 1/3$ and 1/5 have been carried out by Li et al. (2006) at $\mathrm{Re} = 1.33 \times 10^5$ and by Ding and Tamura (2013) at $\mathrm{Re} = 1.6 \times 10^5$. A comparison of the previous results revealed that the regions where windward pressures occurred were remarkably reduced with decreasing aspect ratio, and consequently the Reynolds number sensitivity may be influenced by a change in aspect ratio. However, to the author's knowledge, there is little research regarding the effects of Reynolds number on the pressure distributions of cylindrical roofs with low aspect ratios. Hence, it is considered worthy of accumulating more detailed experimental data on this issue.

It is well known that the potential flow theory is an accurate theory based on the assumption that the flow is irrotational and inviscid. However, it fails to evaluate the actual pressure distribution around a circular cylinder or sphere because of the effects of viscosity that leads the flow separation. Thus, Niemann (1980) and

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Nomenclature

B	length of the cylindrical roof
C_d	drag coefficient
C_l	lift coefficient
C_p	pressure coefficient, $(p-p_0)/0.5\rho U^2$
C_p^*	re-normalized pressure coefficient, $(C_p-C_{p,\min})/(C_{p,\max}-C_{p,\min})$
$C_{p,\max}$	maximum value of C_p
$C_{p,\min}$	minimum value of C_p
C_{ps}	C_p at separation point
D	span of the cylindrical roof
h	wall height of the cylindrical roof
Iu	turbulence intensity of boundary layer
O	center of the circular cylinder
p, p_0	pressure, static pressure
R	rise height of the cylindrical roof
Re	Reynolds number, UD/ν
U, u	free-stream velocity, velocity
X, Y, Z	direction
δ	boundary layer thickness
θ	radial angle between the normal to the surface and the free-stream wind direction
θ^*	normalized radial angle, $-(\theta-\theta_{\min})/(\theta_{\max}-\theta_{\min})$
$\theta_{\max}$	radial angle for maximum pressure
$\theta_{\min}$	radial angle for minimum pressure
θ_s	radial angle for the separation
κ	geometric parameter as function of aspect ratio
λ	parameter introduced to re-normalize C_p^*
μ, ν	dynamic, kinematic viscosity
ρ	density of the fluid

Harnach and Niemann (1980) proposed a simplified pressure model, modified from the potential flow theory, to determine wind loads for reinforced concrete cooling towers, and the effects of surface roughness were also taken into account. Another study, carried out by Yeung (2007), elaborated the capacity of this modified pressure model for representing pressure distributions on a circular cylinder and a sphere. This study demonstrated that there are similarities between theoretical and well-documented experimental data when re-scaled using the same parameters, and this can be used to make realistic predictions. Some alternative methods have also been developed to model the wind pressures over bluff bodies with curved shapes. Surry et al. (1991) and Montes and Fernandez (2001) used Fourier series to evaluate the distributions of wind loads on a semi-spherical structure and to study its wind-induced behavior. It was found that the pressure coefficients obtained using Fourier series formulations with twelve fitting parameters were in close agreement with experimental data. However, this method is complicated when used to evaluate wind loads under different situations and the number of parameters significantly affects the prediction accuracy.

The purpose of the investigation reported in this paper was to construct a modified pressure model for estimating the design wind loads on cylindrical and spherical roofs with various aspect ratios. This model would also be useful for describing pressure distributions considering the Reynolds number effect. A series of wind tunnel tests with simultaneous multi-pressure measurements on cylindrical roofs with three aspect ratios ($R/D=1/2$, $1/3$ and $1/6$) were conducted for a range of Reynolds numbers from 6.90×10^4 to 8.28×10^5, in uniform flow with low turbulence. The effects of the aspect ratios and Reynolds numbers on the pressure distributions are briefly described. A modified pressure model was then proposed, based on the current and well-documented experimental data from cylindrical and spherical roofs, which is suitable for various aspect ratios. For practical design purposes, an application was finally determined to predict the wind loads using experimental data from cylindrical roofs; and the Reynolds number effect was taken into account considering the statistical properties of the aerodynamic parameters used in the model.

2. Wind tunnel experiments

The experimental investigation was carried out in a closed-circuit-type wind tunnel with a working section 25 m long, 4 m wide and 3 m high, in Harbin Institute of Technology, China. The wind tunnel tests were carried out under uniform flow conditions. The objective of these tests is to investigate the effects of aspect ratio and Reynolds number on the aerodynamic loads of the cylindrical roofs in uniform flow with low turbulence, to accumulate more detailed experimental data on this issue. On the other hand, it should be noted that the experimental data obtained in the uniform flow were not intended to compare with potential flow theory, but to verify the proposed pressure model and to provide various aspect ratio evidence.

The roof geometry, coordinate system and experimental models are shown in Fig. 1. A base plate, elevated 0.5 m, was used to minimize the effect of the boundary layer over the wind tunnel floor. The base plate had a thickness of 0.02 m and a width of 2.4 m. Its 4.8 m length was long enough to ensure that the separated flow reattached to the plate surface. Additionally, the plate had a sharp edge with an attack angle of 30° to prevent the free-stream flow suddenly separating at the leading edge. The spans D of cylindrical roofs were 0.2 and 0.6 m, and these were called the small and the large models. The aspect ratios R/D ($=$ rise height/span) of the models were 1/2, 1/3 and 1/6. All the models had the same length to span ratio $B/D=1$. The free-stream flow velocity U was controlled from 6 to 20 m/s, and the corresponding Reynolds numbers, based on D, ranged from 1.66×10^5 to 8.28×10^5. In this range, the turbulent intensity of the free-stream flow velocity was measured to be within 0.5%.

A flat-plate turbulent boundary layer was generated over the base plate surface. Fig. 2 shows the variations of normalized velocity u^* and turbulence intensity I_u as a function of height Z. The maximum boundary layer thickness δ in the studied Re range was about 60 mm measured at the center position of the model. The turbulence intensity was measured to be within 0.5% when $Z>60$ mm. Thus, a wall height h ($=60$ mm) of the cylindrical model was determined to ensure an approximately uniform flow around these roofs with low turbulence intensity. The maximum blockage ratio of the cylindrical roof models was about 1.8%, with no correction to the measured data. Pressure taps were distributed uniformly over the roof surfaces with total numbers of 209 and 241 for the small and large models, respectively. On the center meridian the spacing between two neighboring taps was 9°. Instantaneous wind pressures acting on the cylindrical roof were measured using a DSM3400 pressure scanner system. A sampling frequency of 625 Hz was used and the measurement duration was 100 s.

To validate the consistency and continuity of the small and large roof models for overlapping Reynolds numbers, Fig. 3 shows the mean pressure distributions C_p derived from these two models in different aspect ratio cases with a Reynolds number of 2.48×10^5.

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