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Buffeting forces acting on a rectangular 5:1 cylinder in various turbulent flows

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SUMMARY
The paper experimentally investigates characteristics of buffeting lift forces on a rectangular 5:1 cylinder in various turbulent flows, and their corresponding three-dimensional aerodynamic admittances (3D-AAFs) as well as two-dimensional aerodynamic admittances (2D-AAFs) are respectively identified. The 3D-AAF is obtained by using the traditional approach, which is directly determined by the ratio of one-dimensional lift spectrum and one-dimensional turbulent spectrum, while the 2D-AAF is obtained by using a combined theoretical and experimental method. Consistent with most of previous studies, the values of 3D-AAF of each model change with the flow field, and even in the same flow field (the same turbulence intensity), the 3D-AAFs are still different when the ratio of turbulent integral scale to model width (the dimensionless turbulent integral scale) is different. Compared to the 3D-AAF, the 2D-AAF eliminates the discrepancies caused by the dimensionless integral scale. For different dimensionless integral scales but constant turbulence intensity, the 2D-AAFs are almost consistent. However, the results also indicate that the turbulence intensity still have certain influence on the 2D-AAF of a 5:1 rectangular cylinder. For different turbulence intensities, the values of 2D-AAF have some differences, which are closer to the quasi-steady value when the turbulence intensity is lower.

Keywords: buffeting; aerodynamic admittance; 5:1 rectangular cylinder; wind tunnel test

1. INTRODUCTION

The buffeting of a structure induced by the turbulent flow is always one of interesting issues in the field of structural wind engineering. A key quantity of this issue is the so-called aerodynamic admittance (AAF), which is a frequency-dependent function describing the aerodynamic transfer relationship between turbulent velocity and buffeting force. The aerodynamic admittance directly measured in the turbulent flow based on the traditional method is usually called as the 3D-AAF. It has been found by many previous studies (e.g., Larose and Mann, 1998; Yan et al., 2017; Ma et al., 2019) that the 3D-AAF is usually much less than the Sears function at low frequencies, what's more, the 3D-AAF is also found to be not fixed but changes with the ratio of turbulent integral scale to structural characteristic dimension.

Based on the consideration of three dimensionality of turbulent flow, several previous studies (Massaro and Graham, 2015; Li et al., 2015) confirmed that the buffeting force of a structure in the turbulent flow contains the so-called three-dimensional effect (3D-effect). Just due to the influence of 3D-effect, the 3D-AAF is less than the Sears function and depends on the ratio of integral scale to structural characteristic dimension. The work of Yang et al. (2019) proposed an improved method to quantify the 3D-effect, and the 2D-AAF can be obtained by separating out the 3D-effect from the 3D-AAF. With this method, Li et al. (2022) showed the 2D-AAFs of an airfoil obtained in different turbulent flow fields have good consistency, which confirmed that the 2D-AAF of an airfoil is related to the cross-sectional shape itself. Nevertheless, considering the significant difference between an airfoil and a bluff body, a further investigation on the 2D-AAF of a bluff body in different turbulent flow fields is necessary. Hence, in the present work, the 2D-AAFs of two 5:1 rectangular cylinders with different geometric scales in three turbulent flow fields are investigated, which might be helpful to better understand this issue.

2. METHODOLOGY

The 3D-AAFs can be expressed as the ratio of the one-dimensional lift spectrum to the one-dimensional fluctuating velocity spectrum:

$$|A(k_1^*)|^2 = \frac{S_L(k_1)}{(\rho UB/2)^2\left[4C_L^2 S_u(k_1)+(C_L'+C_D)^2 S_w(k_1)\right]} \tag{1}$$

Where ρ is the air density, U is the mean flow velocity, C_D and C_L is the drag and lift coefficients separately, C'_L is the slope of lift coefficient, $S_L(k_1)$ is the one-dimensional lift spectrum; $S_u(k_1)$ and $S_w(k_1)$ are the one-dimensional longitudinal (u) and vertical (w) turbulence spectra separately. To acquire 2D-AAFs, the 3D influence factor needed to be calculated, it can be written as:

$$g_{3D} = \frac{\int_{-\infty}^{+\infty} \mu(k_1^*,k_2^*)\left[4C_L^2 S_u(k_1)+(C_L'+C_D)^2 S_w(k_1)\right]dk_2}{4C_L^2 S_u(k_1)+(C_L'+C_D)^2 S_w(k_1)} \tag{2}$$

Where $\mu(k_1^*, k_2^*)$ is the spanwise influence term, it can be obtained by fitting empirical model of coherence function. Thereby, the relationship between 2D-AAFs and 3D-AAFs can be expressed as follows:

$$|\chi(k_1^*)|^2 = \frac{|A(k_1^*)|^2}{g_{3D}(k_1^*)} \tag{3}$$

3. EXPERIMENTAL SET-UP

The experiments were conducted in a low-speed wind tunnel (XNJD-1) at Southwest Jiaotong University. The tunnel has a test section of 2.4 m (width)×2 m (height) with a 0.5% background turbulence intensity. Three grids with different mesh sizes (160, 330, and 450 mm) and different bar widths (25, 70, and 85 mm) were used in the experiments. The mean flow velocity was set to U=10 m/s and the flow velocities were measured by the TFI Cobra Probe. The depths of tested 5:1 rectangular cylinder model A and model B were D = 50 and 100 mm respectively, while the corresponding chord lengths were B = 250 and 500 mm, and the spanwise length of all the models was L = 1500 mm. The surface wind pressures of the model were measured by the Scanivalve ZOC33 miniature pressure scanner. The sampling frequency of the flow velocity and the pressure measurements were 512 Hz, and the sampling time was 90 s.

4. RESULTS AND DISCUSSIONS

The characteristic parameters of grid-generated turbulent flow fields are listed in Table 1.

Table 1. Characteristic parameters of grid-generated turbulent flow.

Turbulent flow	Mesh size(mm)	Bar width(mm)	I_w(%)	L_w(m)	L_w/B
TFI	160	25	3.0	0.024	0.24 0.48
TFII	330	70	6.6	0.034	0.67 0.34
TFIII	450	85	8.6	0.044	0.88 0.44

4.1. Measurements of 3D-AAFs and 3D-effect

Based on the experimentally-determined buffeting lift spectrum and wind velocity spectral, the 3D-AAFs of rectangular cylinder models can be obtained by Eq. (1). Fig.1 shows the experimental results of 3D-AAFs, the 3D-AAFs of rectangular cylinders are all below the Sears function due to the 3D-effect. As the turbulence intensity and turbulence integral scale increase, the 3D-AAFs are increasing. The 3D influence factor is also shown in Fig. 1. On the one hand, the larger the turbulence integral scale, the stronger the spatial correlation, and the 3D influence factor increases with the largen of dimensionless turbulent integral scale. On the other hand, an increase in turbulence intensity will reduce the average reattachment length of separated bubbles, the resulting effect is an enhancement of spanwise spatial coherence and a weakening of the 3D effect. The 3D influence factor therefore grows as the turbulence intensity increases.

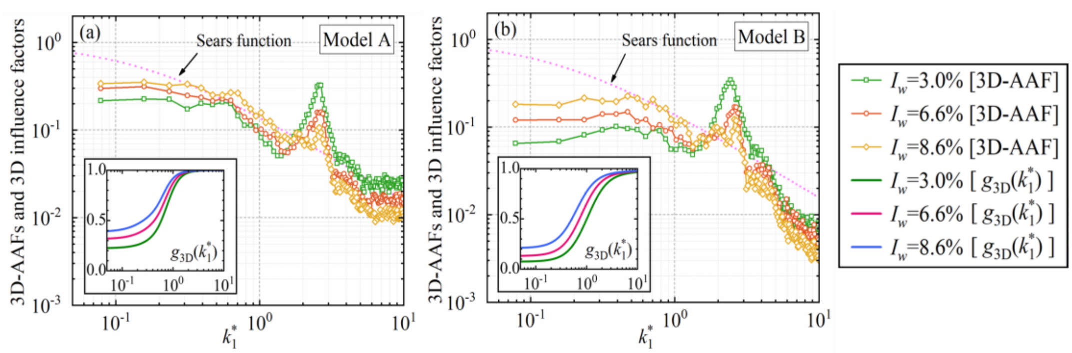

Figure 1. 3D-AAFs and 3D influence factor for different turbulent parameters.

4.2. Identification of 2D-AAFs

The 2D-AAFs is theoretically only related to the shape of the cross-section. In the same turbulent flow, the 2D-AAFs of rectangular cylinders with same aspect ratio are almost consistent, and unaffected by the varies of dimensionless turbulent integral scales. Fig. 2 demonstrates the empirical curves of 2D-AAFs in various turbulent flow, it can be observed that the 2D-AAFs are sensitive to the variation of turbulence intensity. As the turbulence intensity decreases, the 2D-AAFs get farther away from the Sears function, and closer to the quasi-steady state value of 1 in low frequencies.

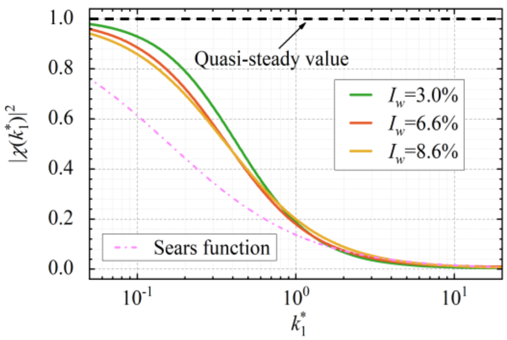

Figure 2. Empirical curves of 2D-AAFs corresponding to different turbulence intensities.

5. CONCLUSIONS

Herein, 3D-AAFs in various turbulent flows were obtained via wind tunnel tests which were all lower than the Sears function due to the influence of 3D-effect. The 3D-effect is affected by dimensionless turbulent integral scale and turbulence intensity, as they increase, the spanwise coherence improves and the 3D-effect weakens. Since the 3D influence factor calculated utilizing the empirical model, the 2D-AAFs can therefore obtain by eliminating the 3D-effect from 3D-AAFs. The results show that 2D-AAFs are almost consistent at varying dimensionless turbulent integral scales in the same turbulent flow. In addition, the 2D-AAFs move closer to the quasi-steady value as the turbulence intensity decreases.

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