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The Effect of Incident Flow on Aerodynamic Admittance of a Truss Girder

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Abstract

An approach to identify 1-wavenumber, 2-wavenumber and complete 2-dimensional admittance for truss girder is proposed in this paper. The assumption of successive truss girder is put forward to obtain inner correlation and coherence of equivalent truss cross-section. The effect of incident angle and turbulence intensity of oncoming flow as well as railing porosity on aerodynamic admittance of truss girder is discussed.

Introduction

The traditional 1-wavenumber aerodynamic admittance obtained by direct buffeting force measurement normally contains 3-dimensional (3D) spatial distribution information, influenced by both turbulence filed and structure itself. Unfortunately, lateral distribution of buffeting force is not explicitly shown by this form, which would lead to imprecise calculation of buffeting response. 2-wavenumber admittance is proposed to separate span-wise correlation information, and its validity is proved in a series of previous studies. 2-dimensional (2D) admittance, either directly obtained by pressure measurement for a single cross-section, or assuming lateral turbulence integral length scale equals to 0 in force measurement, is conforming to the 'strip assumption', and is commonly considered neglecting the spatial re-distribution of buffeting force. However, a recent study of Massaro [5] proved that, when aspect ratio comes to higher than 20, the difference between buffeting response using 2-wavenumber admittance and 2D admittance is quite small, which largely enhance the availability of 2D admittance for long-span bridges or super high-rise buildings.

Nevertheless, when the study extends to truss girder cross-section, both the separation of lateral correlation (for 2-wavenumber admittance) and the lateral full correlation assumption (for 2D admittance) becomes not quite feasible, limited by its unclosed and discontinuous configuration. Buffeting force measurement is only available for truss girder segment with certain span-wise length. By introducing force coherence model, the direct measured 1-wavenumber admittance is converted to 2-wavenumber admittance. Yet the 2-wavenumber admittance is still related to the segment span-wise length. For the calculation of buffeting response, the 2-wavenumber admittance for equivalent truss cross-section is put forward by assuming truss girder cross-section continuous. The spatial correlation of equivalent cross-sections as well as the equivalent 2D admittance could be achieved subsequently on this premise.

Furthermore, one of the crucial steps in truss girder admittance identification is fitting of buffeting force coherence. Some existing coherence models are commonly used (e.g. Jakobsen [1], Larose [2], *et al.*). Most of these models are constructed referring to the turbulence coherence model. As correlation of buffeting force is proved higher than of corresponding turbulence component, there still leaves room for coherence model improvement. Li *et al*. [3] proposed an exact theoretical solution for aerofoil lift coherence, consisting of double exponential items, which embodies explicit physical meaning of turbulence and unsteady aerodynamic force. By adopting this model, the fitting of buffeting force might be more precise.

Based on mentioned background, using the double exponential coherence model, this paper briefly introduces the approach to recognize different forms of admittance for truss girder segment and equivalent cross-section, as well as the inner correlation of equivalent cross-section. The effects of incident flow on admittance, including incidence and turbulence intensity, are discussed thereafter. Railing porosity effect is studied as well.

Aerodynamic Admittance Identification Approach

Generally, the contribution of along-wind turbulence component to buffeting force on bluff bodies is not negligible, especially with attack angles. Take buffeting lift force as an example, the conventional 1-wavenumber lift admittance for a whole truss segment is normally written as:

$$\left|\chi_{L,gross}\left(k_1\right)\right|^2=\frac{S_{L,gross}\left(k_1\right)}{\left(\rho Ub\right)^2\cdot\left[4C_L^2S_u\left(k_1\right)+\left(C_L^{'}+C_D\right)^2S_w\left(k_1\right)\right]} \quad (1)$$

Here the difference between longitudinal and vertical component admittance is ignored. This 1-wavenumber admittance actually contains composite 3D spatial information. To reveal the lateral distribution of buffeting force, the admittance could be modified to a 2-wavenumber form:

$$\left|\chi_{L,gross}\left(k_1,k_2\right)\right|^2=\left|\chi_{L,gross}\left(k_1\right)\right|^2\cdot 2\int_0^{+\infty} coh_{L,gross}(k_1,\Delta y)\exp(-2\pi ik_2\Delta y)d\Delta y \quad (2)$$

Zhong *et al.* [6] proved that, by assuming truss girder segment equivalent to segment of successive cross-section, the 2-wavenumber admittance for equivalent cross-section of a truss girder is:

$$\left|\chi_L^{eq}\left(k_1,k_2\right)\right|^2=\left|\chi_{L,gross}\left(k_1,k_2\right)\right|^2\Big/4c^2\,\mathrm{sinc}(2\pi k_2c) \quad (3)$$

The 1-wavenumber equivalent cross-section admittance is correspondingly obtained:

$$\left|\chi_L^{eq}\left(k_1\right)\right|^2=\int_{-\infty}^{+\infty}\left|\chi_L^{eq}\left(k_1,k_2\right)\right|^2dk_2 \quad (4)$$

The inner correlation function of these equivalent cross-sections is therefore deducted:

$$R(\Delta y)=\frac{\iint_{-\infty}^{+\infty}\left|\chi_L^{eq}\left(k_1,k_2\right)\right|^2[4C_L^2S_u\left(k_1\right)+\left(C_L^{'}+C_D\right)^2S_w\left(k_1\right)]\exp(ik_2\Delta y)dk_1dk_2}{\int_{-\infty}^{+\infty}\left|\chi_L^{eq}\left(k_1\right)\right|^2[4C_L^2S_u\left(k_1\right)+\left(C_L^{'}+C_D\right)^2S_w\left(k_1\right)]dk_1} \quad (5)$$

Hence the 1-wavenumber (3D), 2-wavenumber and complete 2D admittance for equivalent truss cross-section, as well as the 1-wavenumber (3D) and 2-wavenumber admittance for truss segment are all obtained, provided the truss segment lift and turbulence component time history be measured in wind tunnel tests, coherence model for segment lift be fitted for the convenience of Fourier transform.

The above procedure is also valid for drag and moment admittance, only by changing the aerodynamic coefficients and corresponding buffeting force component:

$$(\rho Ub)^2 \cdot \left[4C_L^2 S_u(k_1) + \left(C_L' + C_D\right)^2 S_w(k_1)\right] \rightarrow (\rho Ub)^2 \cdot \left[4C_D^2 S_u(k_1) + C_D'^2 S_w(k_1)\right] \quad (6)$$

$$(\rho Ub)^2 \cdot \left[4C_L^2 S_u(k_1) + \left(C_L' + C_D\right)^2 S_w(k_1)\right] \rightarrow (2\rho Ub)^2 \cdot \left[4C_M^2 S_u(k_1) + C_M'^2 S_w(k_1)\right] \quad (7)$$

Li *et al.* (2016) proposed a buffeting force coherence model for bluff bodies as:

$$Coh_{i,gross}(k_1, \Delta y) = \frac{\lambda_i^2 \exp(-2\pi A_i \Delta y) - \lambda_i A_i \exp(-2\pi \lambda_i \Delta y)}{\lambda_i^2 - A_i^2} \quad (8)$$

This coherence model states fluid-structure interaction to some extent. A_i represents turbulence and its variation, λ_i is the Layer correction factor of admittance, both need to be fitted.

Experimental description

The experiments were carried out in a closed circuit type, high speed wind tunnel (XNJD-1), of which the working section owns a width of 2.4m, a height of 2m and a length of 16m. The turbulence was generated by two grids: one with meshes of 0.33m╳0.33m and bars of 0.07m wide (Grid-1), the other one with meshes of 0.21m╳0.21m and bars of 0.04m wide (Grid-2). Turbulence characteristics, including its correlation, were measured by 2 Cobra Probes of different lateral distances in the same plane with motionless model. The sampling frequency was set as 256Hz, and the sampling time was 120s.

A large-span truss girder suspension bridge was adopted as prototype of the motionless model, which consisted of 10 separate identical rigid truss segments. The bottom beams and bracings of segments were made of glass fibre, other parts made of plastic to ensure its slight mass yet enough stiffness. Each segment owned a size of 0.35m (width) ╳0.09m (height) ╳ 0.198m (length). The original railings were reduced in the same scale ratio with the segments, with redesigned porosities. The segments are mounted in a line and connected with a base steel beam by 10 steel stings of NACA0015 cross-section. To minimize the disturbance generated by support components, each sting was designed height same as the segments and chord length of 0.05m, with the two edges of base steel beam all rounded. Incidence was variable by rotating base steel beam with segments jointed on it.

Two high-frequency dynamic balances were used to measure unsteady buffeting force. The balances were mounted below bottom bracings at corresponding segments' geometric centres. The sampling frequency was 1000Hz and the sampling time was 60s.

The truss girder segments were tested for cases below:

(1) Incident flow of five incidences: -5°, -3°, 0°, 3°, 5°.

(2) Incident flow of two turbulence intensities: generated by Grid-1 (I_u=8.1%, I_w=8.8%,), Grid-2 (I_u=4.1%, I_w=4.9%,).

(3) Railing of four porosities: 36%, 55%, 73%, 100%.

Influence of Incidence

Lift coherence as well as correlation of truss segment present no obvious trend along with incidence at the range of -5°~+5°. Inner correlation function of equivalent cross-section shows very slight difference, as shown in figure 1.

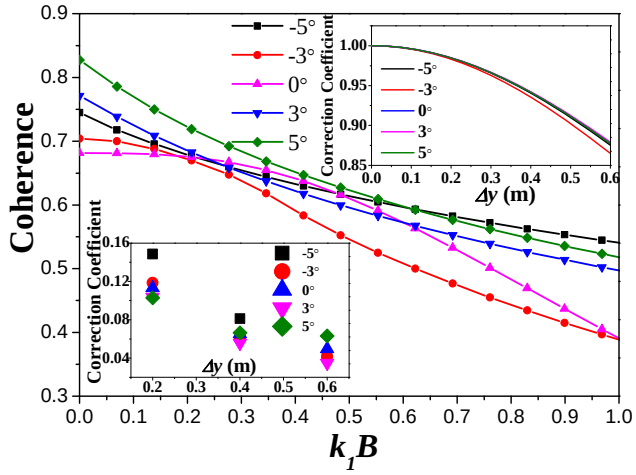

Figure 1. Fitted lift coherence functions of truss segment under different incidences. The lower-left inset graph is the correlation coefficients of lift on truss segment under different incidences; the higher-right inset graph is the correlation coefficients of lift on equivalent truss cross-section under different incidences.

3D lift admittance of equivalent truss cross-section at -5° and +5° is apparent larger than other conditions at higher wavenumber band. 2D lift admittance becomes smaller when incidence getting larger at low wavenumber end (except for -3°), yet this trend rapidly attenuates as frequency increases, shown in figure 2.

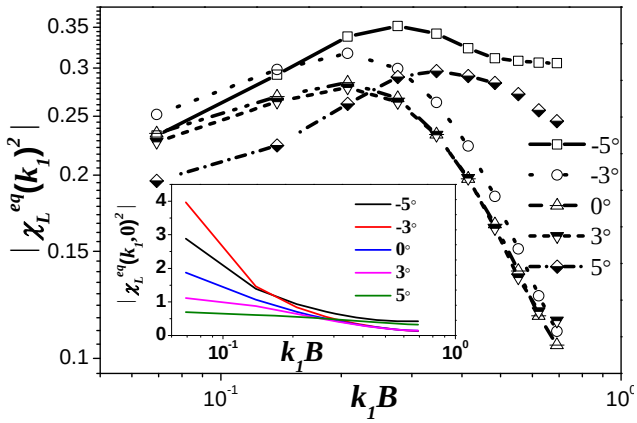

Figure 2. 3D lift admittance of equivalent truss cross-section under different incidences. The inset graph is the complete 2D lift admittance equivalent truss cross-section under different incidences.

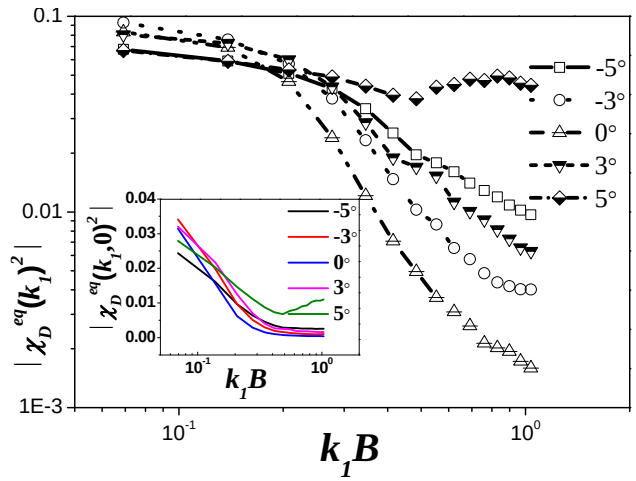

Figure 3. 3D drag admittance of equivalent truss cross-section under different incidences. The inset graph is the complete 2D drag admittance equivalent truss cross-section under different incidences.

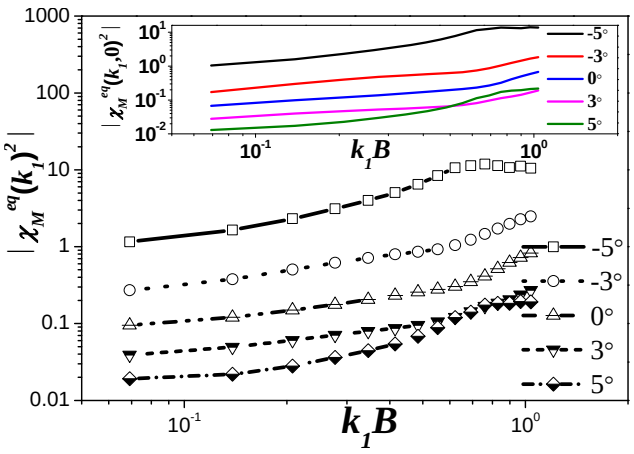

Figure 4. 3D overturning moment admittance of equivalent truss cross-section under different incidences. The inset graph is the complete 2D overturning moment admittance equivalent truss cross-section under different incidences.

Both 3D drag and overturning moment admittance of equivalent truss cross-section has exact the same tendency with their corresponding 2D admittance (figure 3~4). Drag admittance shows not much difference at low wavenumber end. However, at high wavenumber end, the larger absolute incidence is, the higher admittance becomes. Positive incidences own higher drag admittance than negative incidences. Overturning moment admittance decreases while incidence increases at all shown wavenumber scope.

Influence of Incident Turbulence Intensity

Figure 5 shows the larger turbulence intensity is, the higher lift correlation is, both for truss segment and equivalent cross-section (figure 5). 3D lift admittance has the same trend, while 2D lift admittance has a contrary trait at low wavenumber end (figure 6). Drag and overturning moment admittance present the same trend between their 2D and 3D admittance again, respectively (figure 7~8). Drag admittance increases at low wavenumber end and changes to decrease at high wavenumber end as turbulence intensity getting larger. Overturning moment admittance is in proportion to turbulence intensity.

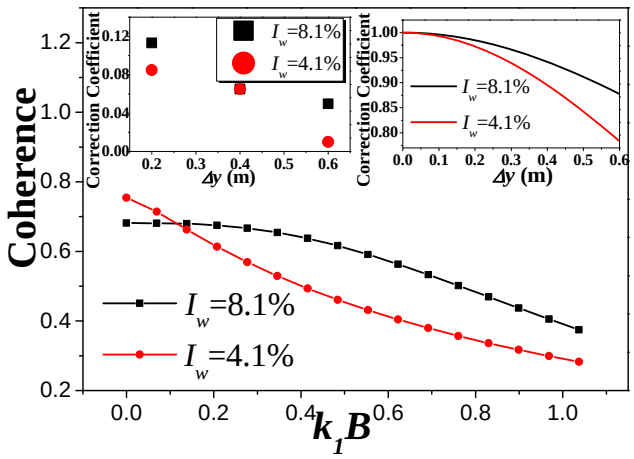

Figure 5. Fitted lift coherence functions of truss segment under different incident turbulence intensities. The lower-left inset graph is the correlation coefficients of lift on truss segment under different incident turbulence intensities; the higher-right inset graph is the correlation coefficients of lift on equivalent truss cross-section under different incident turbulence intensities.

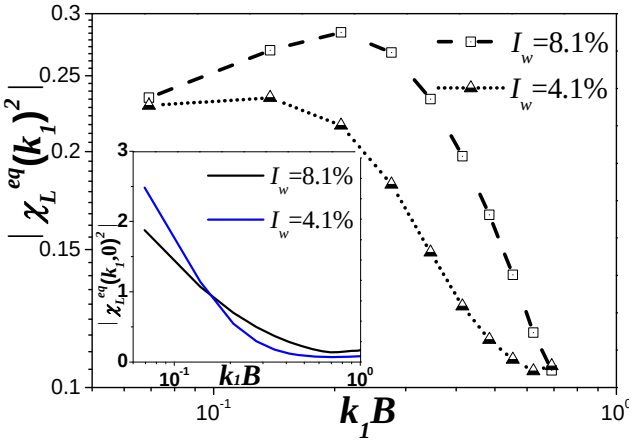

Figure 6. 3D lift admittance of equivalent truss cross-section under different incident turbulence intensities. The inset graph is the complete 2D lift admittance equivalent truss cross-section under different incident turbulence intensities.

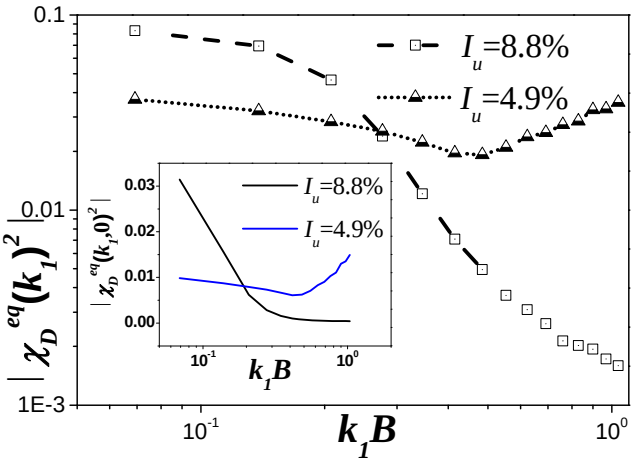

Figure 7. 3D drag admittance of equivalent truss cross-section under different incident turbulence intensities. The inset graph is the complete 2D drag admittance equivalent truss cross-section under different incident turbulence intensities.

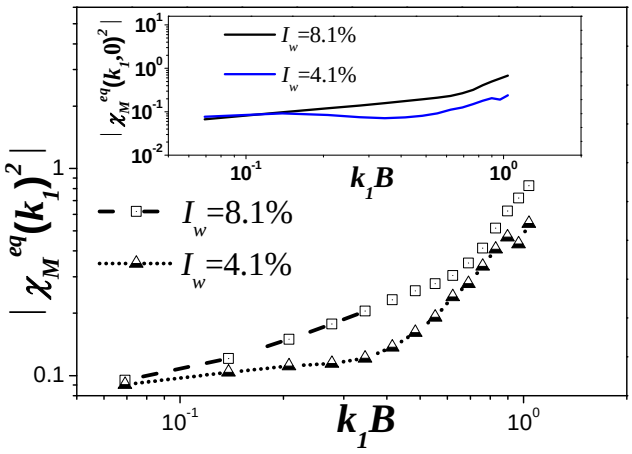

Figure 8. 3D overturning moment admittance of equivalent truss cross-section under different incident turbulence intensities. The inset graph is the complete 2D overturning moment admittance equivalent truss cross-section under different incident turbulence intensities.

Influence of Railing Porosity

Railing porosity shows no distinct influence to lift correlation of both segment and equivalent cross-section, except for the absence of railings (porosity of 100%) largely enhances the lift coherence

of segment as well as the inner correlation of equivalent cross-section, see in figure 9.

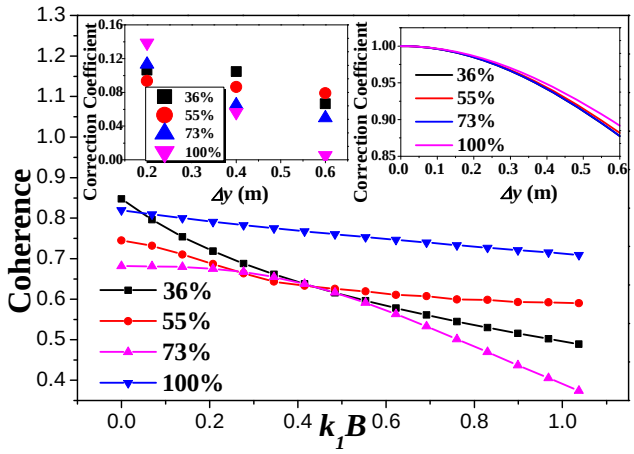

Figure 9. Fitted lift coherence functions of truss segment under different railing porosities. The lower-left inset graph is the correlation coefficients of lift on truss segment under different railing porosities; the higher-right inset graph is the correlation coefficients of lift on equivalent truss cross-section under different railing porosities.

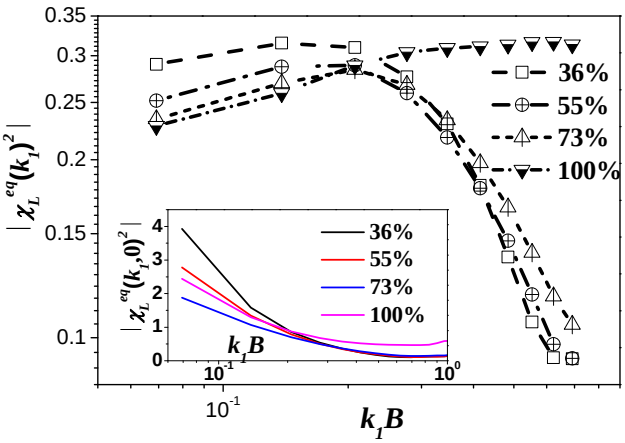

Figure 10. 3D lift admittance of equivalent truss cross-section under different railing porosities. The inset graph is the complete 2D lift admittance equivalent truss cross-section under different railing porosities.

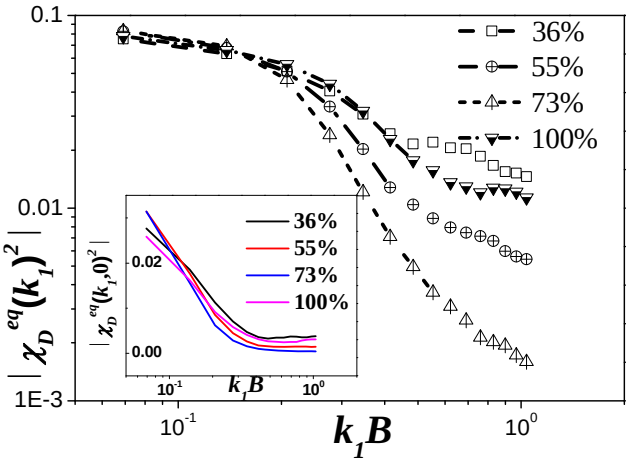

Figure 11. 3D drag admittance of equivalent truss cross-section under different railing porosities. The inset graph is the complete 2D drag admittance equivalent truss cross-section under different railing porosities.

The same tendency occurs on figure 10, in which only porosity of 100% owns larger 3D and 2D lift admittance at high wavenumber end. On the other hand, railing porosity has little effect on drag and overturning moment admittance (figure 11~12).

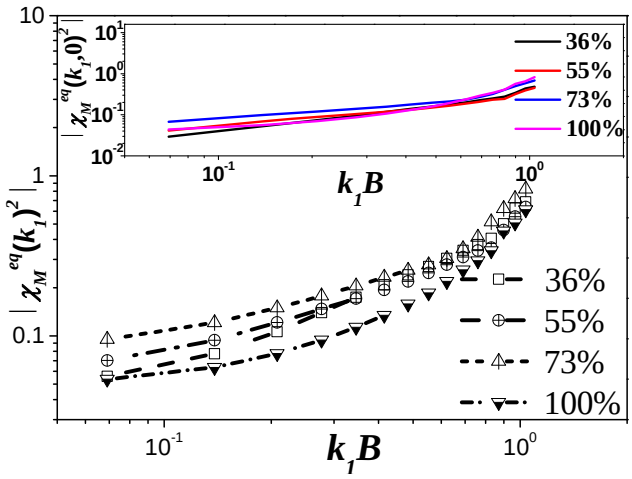

Figure 12. 3D overturning moment admittance of equivalent truss cross-section under different railing porosities. The inset graph is the complete 2D overturning moment admittance equivalent truss cross-section under different railing porosities.

Conclusions

The 2-wavenumber, 2D and 3D admittance of truss segment and equivalent cross-section is obtained in different cases of incident flow. Incidence has not much influence on correlation, but its absolute value would increase lift and drag admittance at high wavenumber end, while it is in inverse proportion to overturning moment admittance in all wavenumber range. Turbulence intensity enhances coherence of both segment and equivalent cross-section, as well as overturning moment admittance and 3D lift admittance. It enhances drag admittance at low wavenumber end yet has an opposite effect at high wavenumber end. Only at value of 100%, railing porosity has apparent influence on correlation and 3D lift admittance. At other porosity values, the influence trend on admittance is not obvious.

Acknowledgments

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