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EXPERIMENTAL DETERMINATION OF THE AERODYNAMIC ADMITTANCE OF A BRIDGE DECK SEGMENT

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The gust loading on bridge decks is described by the dynamic forces on a chord-wise strip and by the spatial distribution of these forces across the span. An experimental method to evaluate the aerodynamic admittance of a segment of a bridge deck that includes a combination of the cross-sectional admittance and the spatial distribution of the forces is presented in this paper. The method is based on wind tunnel tests in turbulent flow on a motionless section model of the deck. The approach has been validated experimentally on a closed-box girder bridge deck but can be applied to bridge decks of any cross-section.

1. INTRODUCTION

THE SPECTRUM OF THE MODAL LIFT FORCES due to the buffeting action of the wind on a bridge deck has been expressed (Davenport 1962) by

$$S_{F_z}(f_j^*) = (\tfrac{1}{2}\rho \bar{V} B)^2 [4C_z^2 S_u(f^*) + C_z'^2 S_w(f^*)]\, |A_z(f^*)|^2\, |J_z(f_j^*)|^2, \tag{1}$$

where f_j^* is a reduced frequency $= f_j B/\bar{V}$ associated with the jth vibration mode; $|A_z(f^*)|^2$ is a lift cross-sectional admittance linked to the longitudinal, u, and vertical, w, components of the turbulence; $|J_z(f_j^*)|$ is the joint acceptance function of mode j; ρ, B, $\bar{V}$, C_z and C_z' are, respectively, the air density, the deck width, the mean wind velocity at deck level, the lift coefficient and the variations of the lift coefficient with angle of wind incidence; and S_{u,w,F_z} denotes power spectral density of the wind components u or w or of the lift force F_z. Equation (1) can be written for the lateral and torsional degrees of freedom by replacing subscript z by x and m, respectively.

The cross-sectional aerodynamic admittance can either be approximated as in Liepmann (1952), Davenport (1962), Irwin (1977), using for example analytical expressions derived for a thin airfoil (Fung 1969), or measured as in Lamson (1957), Holmes (1975), Walshe & Wyatt (1983), Jancauskas (1983), Jancauskas & Melbourne (1986), Kawatani & Kim (1992), Sankaran & Jancauskas (1992), Larose (1992), Sato *et al.* (1994) and Bogunovic Jacobsen (1995), or evaluated indirectly (Grillaud *et al.* 1991). Liepmann's approximation to Sears' function is the most commonly used form of the lift aerodynamic admittance of a thin airfoil in fully correlated gusts with sinusoidal fluctuations (Liepmann 1952):

$$|\phi_z(f^*)|^2 = \frac{1}{1 + 2\pi^2 f^*}. \tag{2}$$

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The joint acceptance function is of the form

$$|J_z(f_j^*)|^2 = \int_0^l \int_0^l \frac{S_{L_1L_2}(\Delta y, f^*)}{S_L(f^*)}\, \mu_j(y_1)\, \mu_j(y_2)\, \mathrm{d}y_1\, \mathrm{d}y_2, \tag{3}$$

where μ_j is the jth mode shape and $S_{L_1L_2}/S_\mathrm{L}$ is the normalized cross-spectrum of the lift force between strips 1 and 2 separated by a span-wise distance Δy.

It has been shown (Larose 1992; Bogunovic Jacobsen 1995; Larose & Mann 1998) that the evaluation of the joint acceptance function is problematic, given the difficulty in defining the spatial distribution of the aerodynamic forces that appeared to be better correlated than the wind fluctuations of the incident flow. In Larose & Mann (1998) an analytical model of the span-wise lift force coherence has been proposed and compared to direct measurements of the gust loading (Larose *et al.* 1997) for a family of streamlined bridge decks. The applicability of this analytical model and of an *ad hoc* empirical model is limited until now to deck cross-sections that have a relatively long, fully re-attached flow region, i.e., bridge decks with aerodynamic characteristics approaching the characteristics of a thin airfoil.

This paper presents an experimental method to evaluate, for bridge decks of any cross-section, an aerodynamic admittance that includes a combination of the cross-sectional admittance and the span-wise distribution of the forces. This quantity will be referred to as segmental admittance of a motionless bridge deck. Even though it is obtained from an intrinsically two-dimensional approach (a 2-D section model), it has a three-dimensional (3-D) character when compared to the cross-sectional admittance of a strip that is purely two dimensional (2-D). The main advantage of the proposed approach is that it eliminates the difficult task of measuring the span-wise coherence of the aerodynamic forces to obtain a clear picture of the spatial distribution of the gust loading.

By itself, the proposed technique to measure the aerodynamic admittance is not new. It has been used by several researchers, e.g. Walshe & Wyatt (1983), Sato *et al.* (1994), and Bogunovic Jacobsen (1995). However, the definition of what one really measures is original and has been verified experimentally. The verification was made possible with the help of the analytical and empirical models presented in Larose & Mann (1998).

2. DESCRIPTION OF THE APPROACH

The experimental technique consists of measuring the vertical, torsional and lateral forces at the extremities of a section model of a bridge deck, in turbulent flow, the model being restrained from any wind-induced motion. For the experiments to be valid, four main criteria have to be respected:

(i) the section model has to be as rigid and as light as possible, so that its lowest eigenfrequency corresponds to a region of the wind spectrum where only a fraction of the wind energy of the largest gusts is present (above 20 Hz);

(ii) the length-to-width ratio of the model should be larger than 6 : 1 to ensure an adequate representation of the gust loading;

(iii) the geometric scale of the model should be selected in relation to the length scale of the incident turbulent flow field, and the span-wise coherence of the flow field should be representative of full-scale conditions; for lift and pitching moment it is essential to respect in model scale the ratio of the length scales of the vertical component of the turbulence to the deck width, while a definite mismatch between the full-scale and model-scale length scales of the longitudinal component would be acceptable; for drag, a mismatch of 2–3 in *u*-component length scales is acceptable since the characteristic dimension, the deck depth (typically 3 to 4 m), is often much smaller than the u-component length scales (typically 150 to 200 m); and

(iv) the model should not undergo any visible motions during the wind tunnel tests (high-frequency vibrations with amplitude less than 0·3 mm).

These four criteria can generally be met in today's wind tunnel operations. However, since it is difficult to alter the span-wise coherence of the incident flow field in the wind tunnel to match the flow conditions of the natural wind at a given site, this aspect of criterion (iii) can be limited to a documentation of the span-wise coherence of the flow. Generally, the root coherence in the wind tunnel should approach the root coherence of the natural wind, and, if anything, it would be slightly larger in model scale. The influence of the variations of the root coherence of the flow on the spatial distribution of the wind loading in model scale is a field of research that awaits development.

Also related to criterion (iii), a series of experiments conducted by the author and reported in Larose (1992) and Larose & Mann (1998) have shown that the lift and pitching moment cross-sectional aerodynamic admittances were directly proportional to the ratio of the w-component length scales to the deck width, $\mathscr{L}_w/B$. These experiments were conducted for closed-box girder bridge decks. It was observed however that the lift and pitching moment admittances were insensitive to the u-component length scales. It is believed that the generation of lift and pitching moment on a bridge deck is only slightly influenced by the energy distribution of the u-component spectrum. This influence is mostly associated with the energy content of the small-scale turbulence, which wind tunnels have generally no problem producing.

The measured time-histories of the aerodynamic forces are converted to power spectral densities of the body-force coefficients, $S_{C_{z,x,m}}(f)$. The spectra of the force coefficients will in most cases show a resonant peak at the eigenfrequency of the force balance and model ensemble. If the model meets criterion (i), the resonant peak can be filtered out by fitting a single degree-of-freedom mechanical admittance function to the peak and subsequently removing its contribution without affecting the lower frequency part of the spectra that contains the information required.

The resulting lift force spectrum corresponds in all points to the spectrum defined by equation (1) but in a dimensionless form,

$$S_{C_z}(f_j^*) = \frac{S_{F_z}(f_j^*)}{(\frac{1}{2}\rho \bar{V}^2 B)^2}. \tag{4}$$

Rearranging (1), the lift aerodynamic admittance can be obtained by a quotient of a combination of spectral functions:

$$|A_z(f^*)|^2 = \frac{\bar{V}^2 S_{C_z}(f^*)}{[4C_z^2 S_u(f^*) + C_z'^2 S_w(f^*)]|J_z(f^*)|^2}. \tag{5}$$

The subscript j has vanished from equation (5) since no motion of the model should be present [criterion (iv)].

Similarly, the aerodynamic admittance of the pitching moment can be expressed by

$$|A_m(f^*)|^2 = \frac{\bar{V}^2 S_{C_m}(f^*)}{[4C_m^2 S_u(f^*) + C_m'^2 S_w(f^*)]|J_m(f^*)|^2}, \tag{6}$$

where

$$S_{C_m}(f_j^*) = \frac{S_M(f_j^*)}{(\frac{1}{2}\rho\bar{V}^2B)^2}, \tag{7}$$

and M is the pitching moment about the bridge longitudinal axis.

All quantities of the right-hand side of equations (5) and (6) can be determined experimentally, with the exception of the joint acceptance function. The one-point spectrum and the span-wise coherence of the wind have to be determined without the model in place and the static coefficients and their linearized slope have to be obtained from tests in turbulent flow for wind conditions (wind speed and turbulence intensity) identical to the test conditions that prevailed during the force measurements.

Equations (5) and (6) can define two quantities depending on how the joint acceptance function is evaluated. If $|J_{z,m}(f^*)|^2$ is evaluated using the span-wise co-coherence of the aerodynamic forces obtained from experiments or from the empirical model of Larose & Mann (1998), if applicable, equations (5) and (6) would define a cross-sectional admittance, $|A_{z,m}(f^*)|_{2-\mathrm{D}}$, roughly comparable to Sears' function.[†]

If $|J_{z,m}(f^*)|^2$ is evaluated on the basis of the strip assumption using the span-wise co-coherence of the incindent w fluctuations, equations (5) and (6) would define a segmental admittance, $|A_{z,m}(f^*)|_{\mathrm{seg}}$, that includes in its definition the three dimensionality of the wind loading, implying a larger span-wise co-coherence of the aerodynamic forces.

As mentioned above, the evaluation of $|A_z(f^*)|_{\mathrm{seg}}$ has a major advantage over the evaluation of the cross-sectional admittance since it does not require an evaluation of the span-wise coherence of the forces. It can thus be used for any cross-sectional shape that could be modelled by a 2-D section model. Its disadvantage is that it cannot really be compared to any other benchmark quantity unless an evaluation of the spatial distribution of the forces is made (or is available) for the cross-section studied.

3. EXPERIMENTAL VERIFICATION

The technique described in the foregoing was used to determine the cross-section admittance and the segmental admittance of a closed-box girder bridge deck. The results were compared with the cross-sectional admittance measured directly on a chord-wise strip of a section model, as described in Larose *et al.* (1997), for a similar ratio of the turbulence length scale to the deck width and similar turbulence intensity.

3.1. FORCE MEASUREMENTS

A section model of the Höga Kusten Bridge in its construction stage configuration (60% porous railings, no median divider) was mounted rigidly on the force balance rig of the Danish Maritime Institute (DMI) 2·6 m wide, 1·8 m high and 21 m long Boundary Layer Wind Tunnel 2. The model length was $l = 2{\cdot}55$ m and was built at a geometric scale of 1 : 60 (deck width $B = 0{\cdot}367$ m). A sketch of the deck cross-section is given in Figure 1. The deck width to deck depth ratio for this bridge is $B/D = 5{\cdot}5$.

The wind tunnel tests were conducted at a mean wind speed of 8·0 m/s in turbulent flow. Large spires, mounted at the inlet of the wind tunnel 15 m upstream of the model, were used to generate the turbulent flow field. The vertical turbulence intensity at deck level, I_w, was

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[†] Note that Sears' function represents the lift admittance of a thin airfoil in a fully correlated sinusoidal gusts while $|A_z(f^*)|_{2-\mathrm{D}}$ is the lift admittance of a bluff body in turbulent flow with random fluctuations in u, v and w.

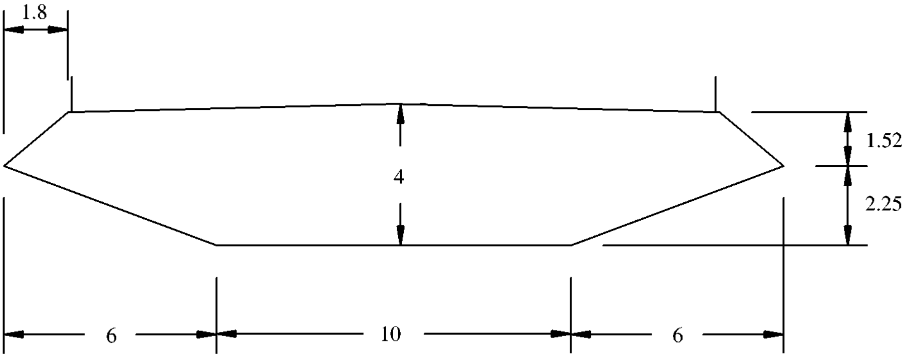

Figure 1. Sketch of the deck cross-section of the Höga Kusten Bridge (dimensions in meters).

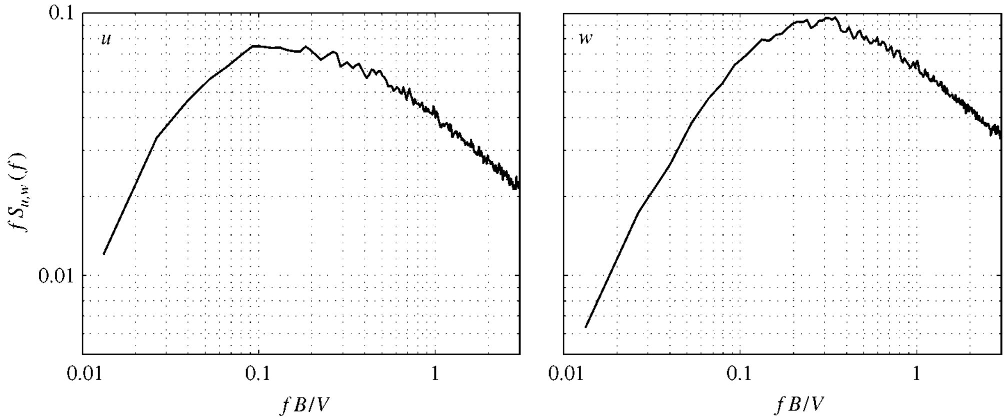

Figure 2. Spectra of the u and w components of the incident turbulent flow as a function of reduced frequency.

7·3% and the vertical turbulence macroscale, $\mathscr{L}_w$ (inverse of the wave number corresponding to the peak of the wind spectrum in its $fS_w(f)$ representation [§]) was 0·22 m. The ratio $\mathscr{L}_w/B$ was 0·60. In itself, the ratio of 0·60 does not meet criterion (iii) for this bridge deck. A ratio of $\mathscr{L}_w/B$ between 1 and 1·5 would be a better modelling of the full-scale conditions. However, the purpose of this experimental verification was to compare the present method with a more involved method where direct measurements of the spatial distribution of the wind loading have been made for many $\mathscr{L}_w/B$ ratios, including 0·60, 0·75 and 1·5 for bridge decks of cross-section similar to the deck studied here (Larose & Mann 1998). In the latter study, the cross-sectional admittance was found to be proportional to $\mathscr{L}_w/B$ to the $\frac{7}{6}$ power.

The auto-spectra of the u and w components of the wind are given in Figure 2. The mean force coefficients and their variations with angle of wind incidence were measured for the same exposure and are reported in Table 1.

Time-histories of the drag and lift forces and the pitching moment were measured at the extremities of the model and were recorded at a sampling frequency of 200 Hz, for 180 s. Figures 3 and 4 show the power spectral densities (1024-point fast Fourier transforms) of the lift and torsional aerodynamic coefficients. Also shown on the graphs is a fit of

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[§] For the von Kármán spectrum, $\mathscr{L}_{u,w}$ is related to the integral length scales $L^x_{u,w}$ through the following: $L^x_u \approx 0{\cdot}92\mathscr{L}_u$ and $L^x_w \approx 0{\cdot}67\mathscr{L}_w$.

TABLE 1

Static coefficients for the Höga Kusten Bridge (construction stage) in turbulent flow. The coefficients are normalized by the deck width B

$C_z(0°)$	$C'_z(0°)$	$C_m(0°)$	$C'_m(0°)$
$-0{\cdot}36$	$4{\cdot}2$	$0{\cdot}013$	$1{\cdot}07$

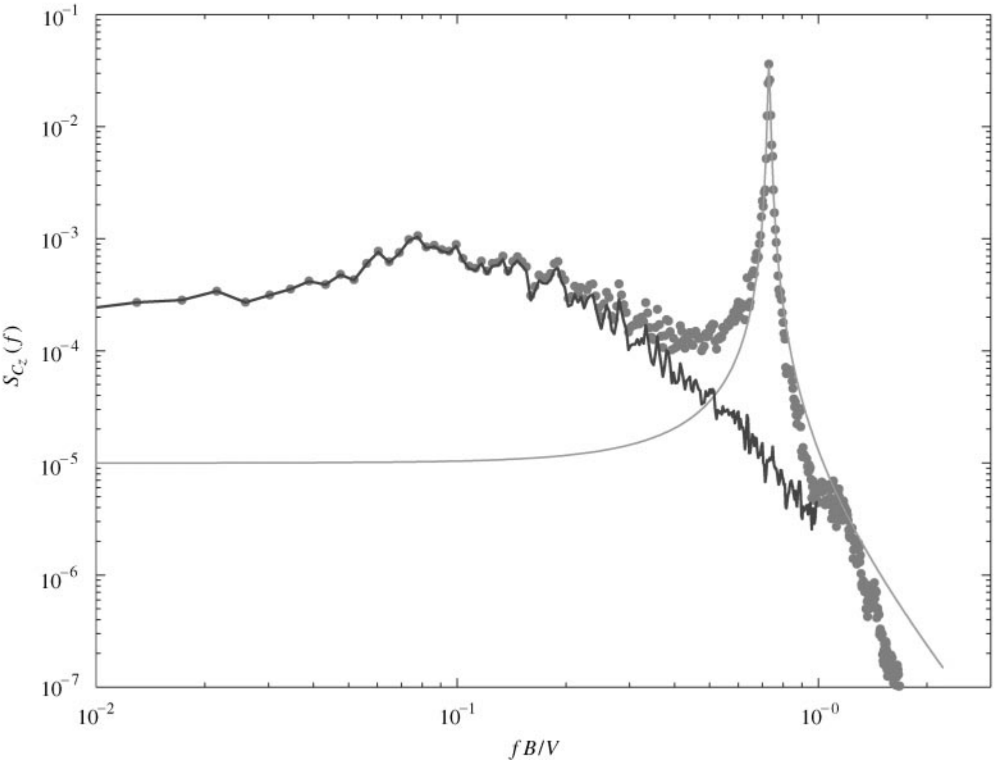

Figure 3. Spectra of the lift coefficient as a function of reduced frequency: •, measured spectral estimates; light solid line: fit of a mechanical admittance function; —: filtered spectra.

a single-degree-of-freedom mechanical admittance function of the measured spectral estimates and the resulting filtered spectra where the resonant peak has been removed.

3.2. EVALUATION OF THE JOINT ACCEPTANCE FUNCTION

Since the section model was motionless during the force measurements, i.e., $\mu(y) = 1{\cdot}0$ in equation (3), the joint acceptance function can be simplified to a double integration across the model span of the co-coherence of the aerodynamic forces or of the wind fluctuations.

The span-wise normalized co-spectrum of the wind fluctuations for the turbulent flow field of this investigation was described in Larose (1997) by

$$\mathrm{cocoh}_w(\gamma) = \exp\left[-c_1\gamma^{c_2}\right]\cos(c_3\gamma), \tag{8}$$

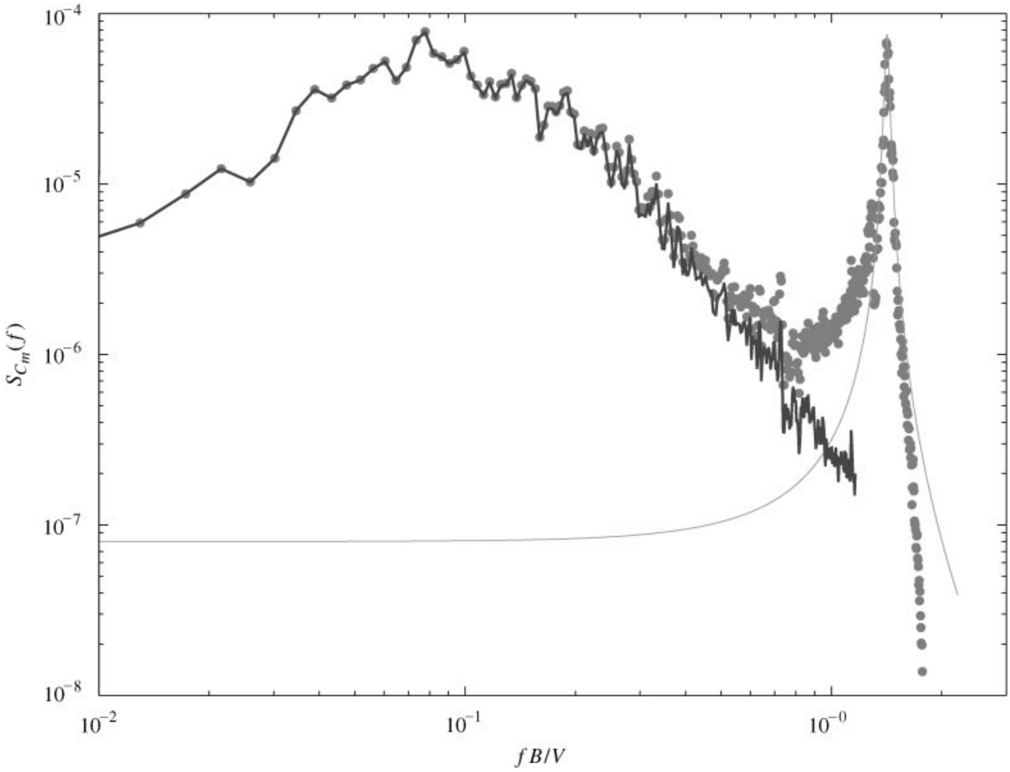

Figure 4. Spectra of the pitching moment coefficient as a function of reduced frequency: •, measured spectral estimates; light solid line: fit of a mechanical admittance function; —: filtered spectra.

where

$$\gamma = k_1 \varDelta y \sqrt{1 + \frac{1}{(k_1 L)^2}}, \tag{9}$$

with $k_1 = 2\pi f/\bar{V}$ (wave number), $L_{\mathrm{coh}} = 0{\cdot}27$ m (a length scale fitted to the experiments), $c_1 = 0{\cdot}73$, $c_2 = 1{\cdot}03$, and $c_3 = 0{\cdot}27$; γ is the von Kármán collapsing parameter.

An empirical formulation of the span-wise co-coherence of the lift and torsional forces for a family of closed-box girders similar to the deck of the Höga Kusten Bridge was given in Larose & Mann (1998) and is of the form

$$\mathrm{cocoh}_{L,M}(\eta) = \exp\left[-c_1 \eta^{c_2}\right] \cos(c_3 \eta), \tag{10}$$

where, for lift,

$$\eta = k_1^a \varDelta y \sqrt{1 + \frac{1}{(k_1^a L_F)^2}}, \tag{11}$$

$$L_F = L \frac{(p + \varDelta y/B)^2}{(q + r(\varDelta y/B))^2}, \quad p = 1{\cdot}0,\ q = 0{\cdot}46,\ r = 1{\cdot}42,\ L = 0{\cdot}39 \quad \mathrm{m} \tag{12}$$

$$a = \left(\frac{B}{D}\right)^4 \frac{(p + \varDelta y/B)^2}{(q + r(\varDelta y/B))^2}, \quad p = 0{\cdot}160,\ q = 0{\cdot}088,\ r = 0{\cdot}935 \tag{13}$$

and $c_1 = 0{\cdot}346$, $c_2 = 1{\cdot}50$, and $c_3 = 0$.

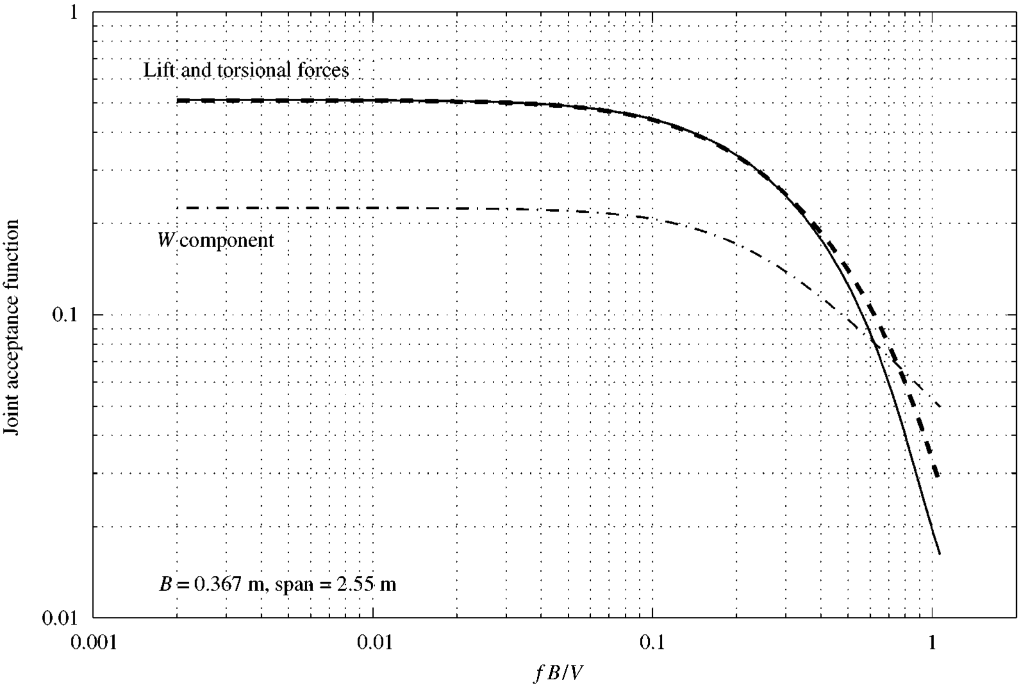

Figure 5. Variations of the joint acceptance function with reduced velocity for a 2·55 m long section model, with uniform mode shape, $B = 0{\cdot}367$ m and $B/D = 5{\cdot}5$.

For the pitching moment

$$a = \left(\frac{B}{D}\right)^{1/0{\cdot}15} \frac{(p + \Delta y/B)^2}{(q + r(\Delta y/B))^2}, \quad p = 0{\cdot}098,\ q = 0{\cdot}059,\ r = 0{\cdot}970 \tag{14}$$

and $c_1 = 0{\cdot}341$, $c_2 = 1{\cdot}33$, and $c_3 = 0{\cdot}22$.

The joint acceptance function was calculated for the three cases given above and the results are shown in Figure 5. The difference between the curves for the forces and the curve for the wind is due to the three dimensionality of the wind loading, the span-wise co-coherence of the forces being larger than the co-coherence of the incident flow.

3.3. THE AERODYNAMIC ADMITTANCES

The cross-sectional admittance and the segmental admittance were calculated using equations (5) and (6) for both lift and pitching moment and the results are shown in Figures 6 and 7. The cross-sectional admittance obtained with this technique agreed very well with the cross-sectional admittance measured directly on a chord-wise strip (dotted line on the graphs) for $\mathscr{L}_w/B = 0{\cdot}58$ on a similar cross-section. The segmental admittance showed larger values than the cross-sectional admittance since it included the contribution of the secondary cross-flow over the 2·55 m span that increased the force co-coherence.

Also shown in Figures 6 and 7 is a comparison of the cross-sectional admittance obtained from the technique described here, compared to the Liepmann's approximation to Sears' function and to the empirical model of the 2-D aerodynamic admittance given in Larose

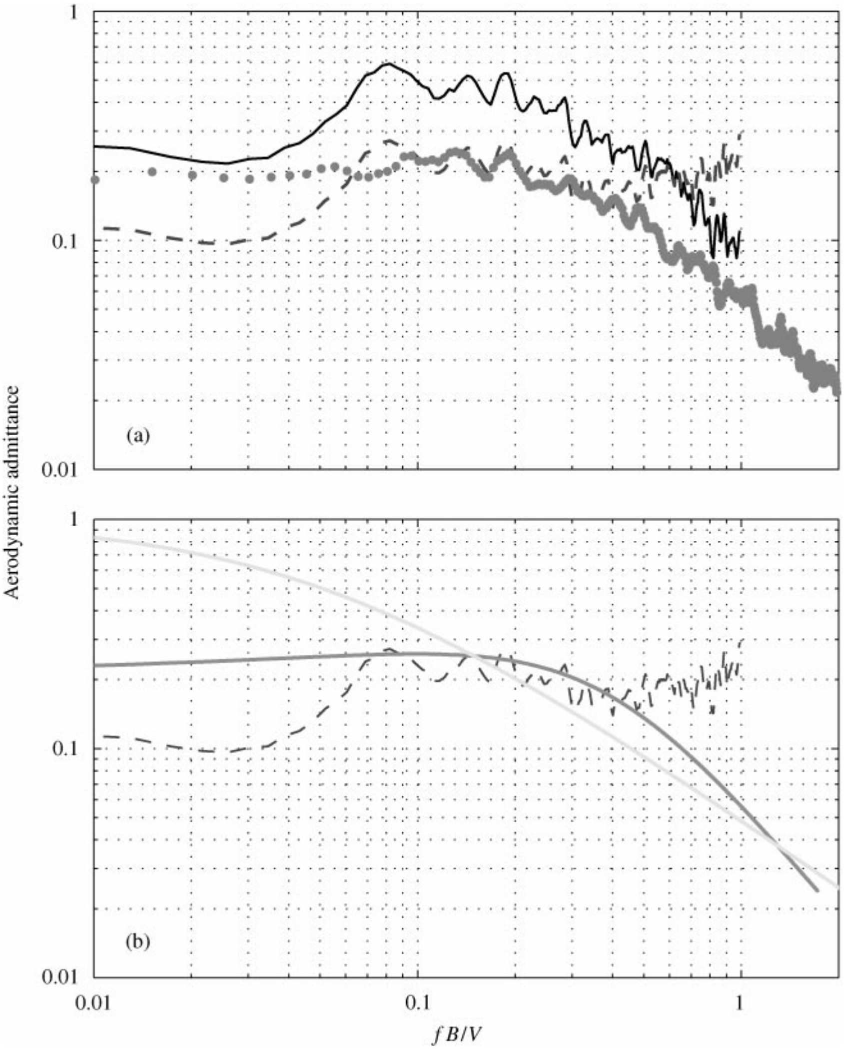

Figure 6. Variations of the lift aerodynamic admittance as a function of fB/V. In (a): •, admittance directly measured from a chord-wise strip as reported in Larose *et al.* (1997), for $\mathscr{L}_w/B = 0{\cdot}58$; —, segmental admittance; – – –, cross-sectional admittance determined with the present method. In (b), light solid line: Sears' function; dark solid line: empirical model of 2-D aerodynamic admittance of Larose & Mann (1998) for $\mathscr{L}_w/B = 0{\cdot}60$; dashed line: cross-sectional admittance determined with the present method.

& Mann (1998). The Sears' function considerably overestimated the 2-D admittance for fB/V smaller than 0·1 while the empirical model gave satisfactory results for both lift and pitching moment admittances for this $\mathscr{L}_w/B$ ratio.

4. TRUSS GIRDER BRIDGE DECKS AND OTHER BLUFF CROSS-SECTIONS

The present method can also be applied to bridge decks with more complex cross-sections, such as truss girder decks or composite decks made of a concrete slab supported by longitudinal edge beams and transverse floor beams. The main difficulty of the technique resides in building a section model with a very large flexural and torsional rigidity to reduce the influence of the resonant amplification of the aerodynamic forces. This technique has

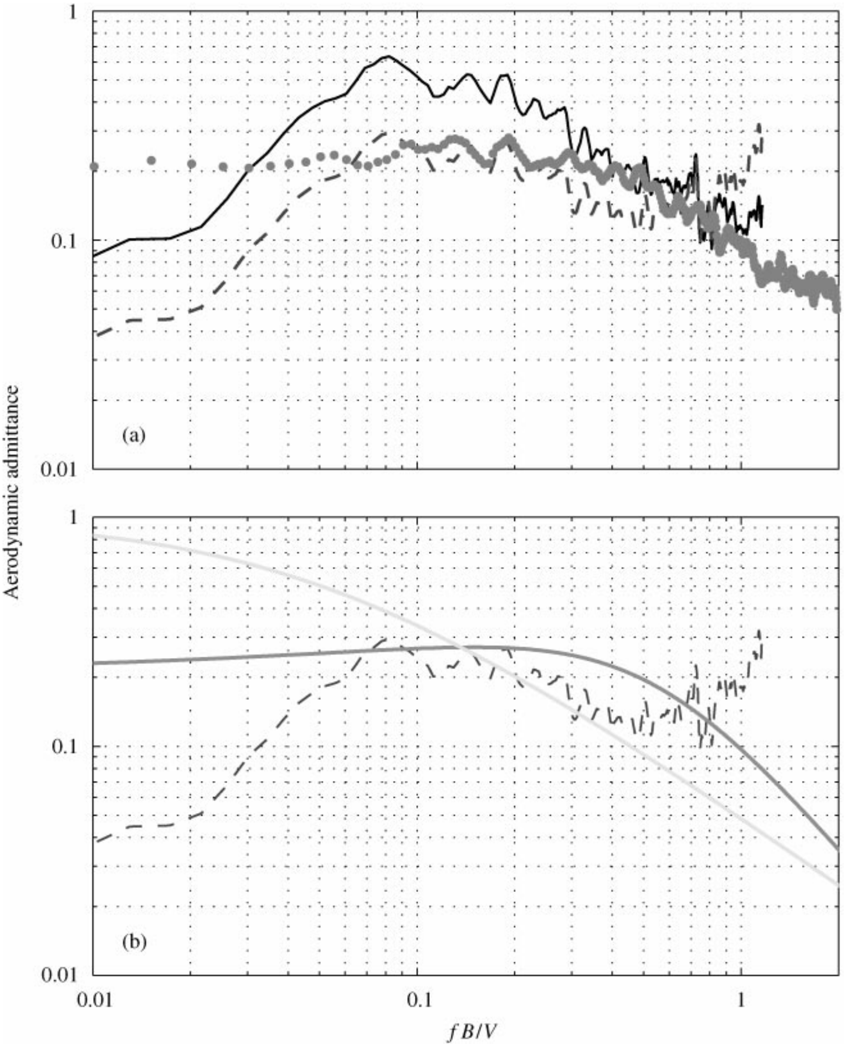

Figure 7. Variations of the pitching moment aerodynamic admittance as a function of fB/V. In (a): •, admittance directly measured from a chord-wise strip as reported in Larose *et al.* (1997), for $\mathscr{L}_w/B = 0{\cdot}58$; —, segmental admittance; – – –, cross-sectional admittance determined with the present method. In (b), light solid line: Sears' function; dark solid line: empirical model of 2-D aerodynamic admittance of Larose & Mann (1998) for $\mathscr{L}_w/B = 0{\cdot}60$; – – –, cross-sectional admittance determined with the present method.

Table 2

Static aerodynamic force coefficient for a truss girder bridge deck in turbulent flow (normalized by the deck width

$C_z(0°)$	$C'_z(0°)$	$C_m(0°)$	$C'_m(0°)$	$C_x(0°)$	$C'_x(0°)$
−0·05	3·4	0·10	0·03	0·43	−0·34

recently been applied for a truss girder bridge deck with fairly large structural members and the results are presented in Figure 8. The static aerodynamic force coefficients of the deck in question are given in Table 2 (based on the deck width).

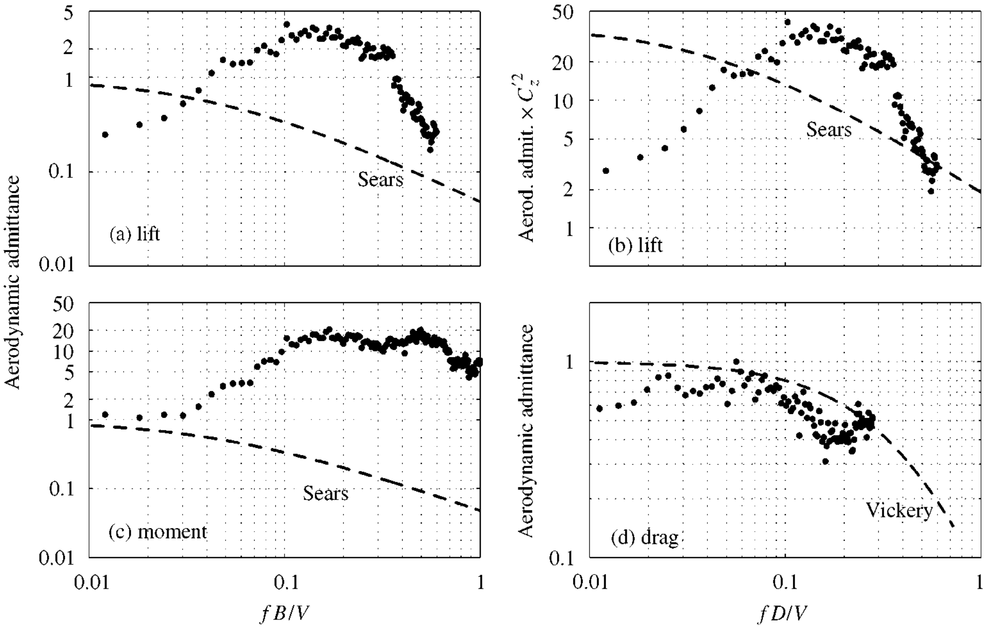

Figure 8. Segmental aerodynamic admittance for a truss girder bridge deck measured with the present technique. In (b) the ordinate has been multiplied by the lift slope squared. In (d) the dashed line refers to the drag admittance proposed by Vickery (1965): $[1/1 + (2fD/V)^{(4/3)}]^2$, where D is the deck depth.

The drag admittance was calculated by replacing subscript z by subscript x in equation (5). The results are compared in Figure 8 to the empirical expression of the drag admittance of flat plates normal to a turbulent flow as proposed by Vickery (1965).

The measured admittance of Figure 8 agreed well with similar measurements made for the truss girder of the Akashi Kaikyo Bridge reported by Sato *et al.* (1994).

5. CONCLUSION

An experimental approach to evaluate the aerodynamic admittance of a segment of a bridge deck was presented. The aerodynamic characteristic obtained with this technique has a three-dimensional character since it includes the influence of the span-wise distribution of the aerodynamic forces. The approach can be used for bridge decks of any cross-section.

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