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The Measurement of Aerodynamic Admittance Using Discrete Frequency Gust Generation

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SUMMARY A pair of controlled circulation aerofoils have been developed to produce discrete frequency sinusoidal gusts, which can be superimposed on varying levels of grid-generated turbulence. This facility, set up in the high speed section of the Monash University 450 kW wind tunnel, is to be used as a tool to directly measure the aerodynamic admittances of a range of two-dimensional bluff bodies. This paper describes the techniques developed to produce the discrete longitudinal and lateral gusts and the determination of the aerodynamic admittance function from measurements of the input velocity spectra and output force spectra on two-dimensional models.

Results are presented of proving tests which have been made on a NACA 0006 aerofoil section of 300 mm chord, which was used to approximate the behaviour of an ideal two-dimensional flat plate. The measured aerodynamic admittance is shown to exhibit reasonable agreement with the Sears Function (the accepted theoretical expression for the aerodynamic admittance of a flat plate). Reasonable confidence in the facility has now been gained to continue with measurements of aerodynamic admittance on bluff bodies in turbulent flows in which the wake excitation mechanism is present jointly with the incident turbulence mechanism.

1 INTRODUCTION

One of the research programmes currently being undertaken at Monash University is concerned with developing prediction techniques for the cross-wind response of bluff-body structures. Of specific interest are structures and situations where the excitation is due either exclusively or jointly to the mechanisms associated with the incident turbulence and the wake.

One of the more notable deficiencies of the current literature in this area lies with the almost total absence of reliable aerodynamic admittance data. Therefore, one of the primary objectives of the programme became the need to be able to measure the aerodynamic admittance for any given structure in any given turbulent environment. It should be noted that whereas there are fairly straightforward means of making this measurement in the case of structures that are excited exclusively by the incident turbulence, for the majority of structures where there are significant (yet unknown) contributions from both the incident turbulence and the wake, there has been, to date, no such method.

A technique capable of making these measurements has now been devised and the appropriate hardware fitted to the Monash 450 kW wind tunnel - this paper outlines the technique and presents some preliminary results made on a "flat plate" model in smooth flow.

2 BACKGROUND

2.1 Cross-Wind Excitation Mechanisms

For the cross-wind response of structures, Melbourne (1975) identifies three quite separate (although frequently superimposed) excitation mechanisms; they are associated with

a) the wake
b) the incident turbulence, and
c) the cross-wind displacement.

It is the first two mechanisms that are of interest in the current programme, and they will now be briefly described.

2.1.1 Wake excitation

Although probably first identified in the shedding, at critical wind speeds, of a Von Karman vortex street from a tall tower or chimney, the term "wake excitation" includes all wake induced excitations and not just those associated with critical velocities. Further, it is important to appreciate that the "wake" in this context is not just a base flow but originates at the shear layer shed from the leading edge of a bluff body.

The actual forcing under this mechanism comes from local pressure fluctuations in the wake which, in turn, induce fluctuating forces on the body. Consequently, wake excitation is significant for situations in which a significant wake is generated, in particular for bluff bodies with short afterbodies where flow reattachment is not possible. Some examples of structures that would typically receive significant wake excitation are tall buildings, chimney stacks and towers.

2.1.2 Incident turbulence excitation

Under the incident turbulence mechanism, the changing speed and direction of the incident turbulent wind directly induce varying lift forces and pitching moments on the structure. The ability of incident turbulence to produce a significant cross-wind response depends on its ability to generate a cross-wind (lift) force on the structure as a function of longitudinal wind velocity and angle of attack. In general, this requires either a section with a high lift curve slope (such that a change in angle of attack is effective in producing a change in lift) or a section with a non-zero lift coefficient at zero degree incidence (such that a change in speed is effective in producing a change in lift).

Hence, this mechanism may be significant for structures with a long afterbody where there is reattachment of the flow and an insignificant wake. Some examples of structures that would typically receive significant incident turbulence excitation are aerofoils, flat plates and streamlined bridge decks.

2.1.3 Wake and incident turbulence mechanisms operating jointly

For each of the above two excitation mechanisms there is a range of specific structures for which that mechanism is the sole or predominant source of excitation. At one extreme there are the structures that approach a flat plate with streamlined profiles, long afterbodies and high lift-curve slopes; such structures are almost exclusively excited by incident turbulence. At the other extreme there are the more prismatic structures with their bluff profiles, shorter afterbodies and consequently significant wakes; these structures are almost exclusively wake excited. However, there are many structures which must be considered as lying between these two extremes and are thus subjected to significant contributions from both mechanisms; a particular example is that of a not so slender box girder bridge section.

2.2 Prediction of Response due to Incident Turbulence Excitation and the Role of the Aerodynamic Admittance

Currently, the most widely accepted method of predicting the cross-wind response of a structure to incident turbulence excitation is through the use of Davenport's (1962) spectral approach. The main equations involved in the technique can be listed as follows (simplified by assuming only one mode of structural response):-

Mean square of cross-wind (z direction) response,

$$\sigma_z^2 = \int_0^\infty S_z(n) \,.\, dn \qquad \text{— 1}$$

Spectrum of cross-wind displacement,

$$S_z(n) = \frac{S_{F(n)}}{(2\pi n_o)^4 M^2} \,.\, \chi_m^2(n) \qquad \text{— 2}$$

where n_o = natural structural frequency in the cross-wind mode

$\chi_m^2(n)$ = mechanical admittance of the cross-wind mode

M = generalized mass in the cross-wind mode

$= \int_{-b/2}^{b/2} m(y) \,.\, z^2(y) \,.\, dy$

b = spanwise length of structure

$m(y)$ = mass per unit length

$z(y)$ = mode shape (normalised to equal 1 at the centre of the deck)

Spectrum of cross-wind aerodynamic force

$$S_F(n) = \rho^2 \bar{u}^2 c^2 \left[C_{F_{z_o}}^2 \, S_u(n) + \tfrac{1}{4}\left(\frac{dC_{F_z}}{d\alpha}\right)^2 S_w(n) \right] . C . \chi_{aero}^2(n) \qquad \text{— 3}$$

where $\bar{u},\rho$ = mean longtidudinal velocity and density of wind

c = chord length of structure

$C_{F_{z_o}}$ = lift coefficient at 0° angle of attack

$\frac{dC_{F_z}}{d\alpha}$ = lift curve slope

$S_u(n)$ = spectrum of longitudinal velocity

$S_w(n)$ = spectrum of velocity in the cross-wind direction

C = spanwise velocity cross-correlation function

$\chi_{aero}^2(n)$ = aerodynamic admittance function

It can be seen that the technique uses as a starting point the SPECTRA OF LONGITUDINAL (S_u) and LATERAL (S_w) TURBULENCE in the oncoming wind. These are related to the AERODYNAMIC FORCE SPECTRUM (S_F) via various constants, steady flow aerodynamic coefficients, a spanwise velocity cross-correlation and the AERODYNAMIC ADMITTANCE (χ_{aero}^2). This aerodynamic admittance is simply a transfer function relating velocity fluctuations in a turbulent wind to the cross-wind force experienced by a certain structure subjected to that wind. In an ideal (quasi-steady) situation, turbulent velocity fluctuations of all frequencies are instantaneously reflected in a changing aerodynamic force pattern. In a real situation, however, higher frequency (smaller scale) velocity fluctuations are increasingly less effective in producing changes in aerodynamic force. It is the role of the aerodynamic admittance to account for this deviation between ideal and real behaviour.

The FORCE SPECTRUM, then, describes the actual aerodynamic forces exerted on the structure. The structure's response, however, depends on its resonant characteristics which must be accounted for via the MECHANICAL ADMITTANCE FUNCTION (χ_m^2). The final result of the technique is the SPECTRUM OF DISPLACEMENT (S_z), the area under which is equal to the mean square response (σ_z^2).

Apart from some non-linear characteristics, the technique's main limitation arises from an acute lack of knowledge of the behaviour of the aerodynamic admittance under varying conditions of body geometry and turbulence. The aerodynamic admittance for a two-dimensional flat plate is well established on theoretical grounds, and is given by the Sears Function. Liepmann's approximation to the Sears Function is:-

$$\chi_{aero}^2(n) = \frac{1}{1+2\pi^2(\frac{nc}{\bar{u}})} \qquad \text{— 4}$$

It has also been suggested that the Sears Function could be equally well applied to structures such as streamlined bridge decks whose sections approached that of a flat plate. With the recent growth of expertise in boundary layer wind tunnel measurements, some researchers have expressed disenchantment with the use of the Sears Function even for streamlined deck sections. Once the geometry of the structure varies significantly from that of a flat plate, and hence cannot be regarded as being excited exclusively by the incident turbulence, considerable uncertainty begins to surround the choice of a suitable aerodynamic admittance function. What was plainly needed in order to proceed beyond this bottleneck was an experimental means of directly measuring the aerodynamic admittance of a given structure even when,

a) the geometry of that structure meant that it received significant contributions from both excitation mechanisms, and

b) the structure was subjected to a variety of turbulent environments.

The following sections describe such a technique.

3 MEASURING THE AERODYNAMIC ADMITTANCE

3.1 Basis of the Technique

The technique developed for the direct measurement of the aerodynamic admittance function is based on the use of a two-dimensional model of a section mounted on a force measuring balance in a wind tunnel. The two-dimensional model is then subjected to discrete frequency velocity fluctuations ("gusts") superimposed on top of a background turbulent flow field. The model then experiences an increased fluctuating aerodynamic force dependent on the value of the aerodynamic admittance at that particular gust generation frequency. Thus, by varying this frequency and measuring the resulting changes in aerodynamic force, the form of the aerodynamic admittance can be determined.

3.2 Generation of the Discrete Frequency Gusts

Discrete frequency gust generation was achieved using harmonic circulation control about a pair of twin parallel aerofoils placed upstream of the model. This technique of gust generation was successfully used by Ham, Bauer & Lawrence (1974), in smooth flow only, to test the gust response of a helicopter rotor.

3.2.1 Basic principle behind a controlled circulation aerofoil (CCA)

Control of the circulation around the aerofoil is achieved by injecting fluid tangentially through a slot in the upper surface of the aerofoil, near to the blunt trailing edge. This jet re-energises the upper surface boundary layer, delaying separation and hence causing the flow about the aerofoil to be asymmetric. Circulation is therefore introduced around the aerofoil, the strength of which depends upon the strength of the issuing jet. Harmonic circulation control is achieved via controlled blowing with a sinusoidal variation from slots in the upper and lower surfaces, as shown in the inset in Figure 1.

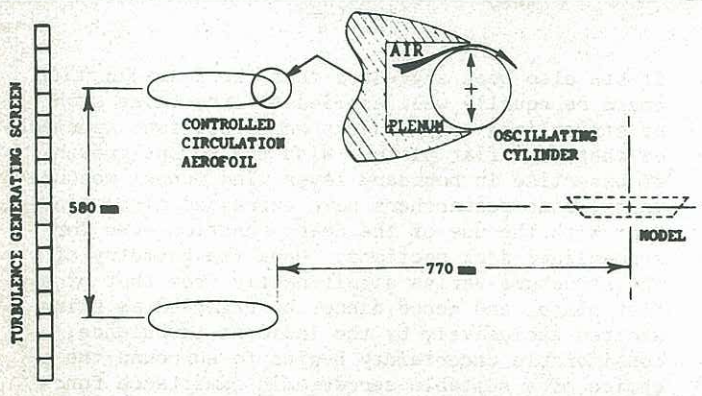

Figure 1 Experimental layout of model and harmonic controlled circulation aerofoils

3.2.2 The combined effect of a pair of harmonic controlled circulation aerofoils

Consider for a moment a pair of harmonic circulation controlled aerofoils positioned as shown in Figure 1, and operating in phase. As the circulation around each aerofoil varies, incremental longitudinal and cross-wind velocities are induced over the surrounding region. By vector addition it can be seen that the longitudinal velocities from the two aerofoils cancel along the centreline between them. The cross-wind velocities are, however, additive; thus, as the circulation around the CCA's varies harmonically, sinusoidal cross-wind "gusts" are generated along the centreline between them. Similarly, operating the aerofoils 180° out of phase leads to the generation of sinusoidal longitudinal gusts.

The circulation control is regulated such that at no stage does the wake from either aerofoil impinge directly on the model and the effect is to preserve the characteristics of the existing turbulent flow and to superimpose the generated gusts on top of it.

3.2.3 Design of the harmonic controlled circulation aerofoil

The harmonic CCA designed by Ham et al consisted basically of an elliptical section aerofoil modified by the addition of a rotatable eccentrically mounted cylinder recessed into the trailing edge.

Although the Monash design operates under exactly the same principle as that above, it features a number of design innovations. The most significant difference between the two designs is that in the case of the Monash design the trailing edge cylinder oscillates rather than rotates. This was accomplished by allowing the cylinder to be displaced by an internally rotating camshaft. This technique reduced the machining and balancing tolerances required in manufacture and avoided the aerodynamic assymetry caused by the wall stress on a cylinder rotating in the one direction at the trailing edge.

Each aerofoil has a chord of 400 mm and a span of 1 m. The trailing edge cylinder has a diameter of 32 mm and operates with a total gap (upper blowing slot plus lower blowing slot) of 0·50 mm and an eccentricity of 0·25 mm. The system can generate gusts over the frequency range 0-20 Hz, and can comfortably produce incremental gust velocities in excess of 20% of mean tunnel speed.

3.2.4 Experimental arrangement

All measurements were made in the 2 x 1 metre working section of the Monash University 450 kW wind tunnel. This insertable section was specially developed for the current programme to enable force and displacement measurements to be made on a range of models under conditions as close to two-dimensional as possible.

The installation consists of three major sections:-

1. Turbulence Generating Screens - A series of wooden slat screens, situated upstream of the test section, are used to generate various levels of background turbulence in the range 0% - 15%.

2. Gust Generators - The two CCA's are installed horizontally in the section, 580 mm apart and 770 mm upstream of the model centreline. These are activated either in phase to produce lateral gusts, or 180° out of phase to produce longitudinal gusts.

3. Model Support and Measurement Balance - The model is supported horizontally across the section on a strain-gauge balance capable of measuring the force or displacement response of the model in each of its three modes, lift, moment and drag.

3.2.5 Instrumentation

Velocity measurements were made using a TSI constant temperature hot-wire anemometer and a x-configuration probe. Spectral measurements were made using a Schlumberger Real Time Analyzer. A wide range of peripheral instruments ranging from photo-probe rev. counters to vernier scale manometers was also used.

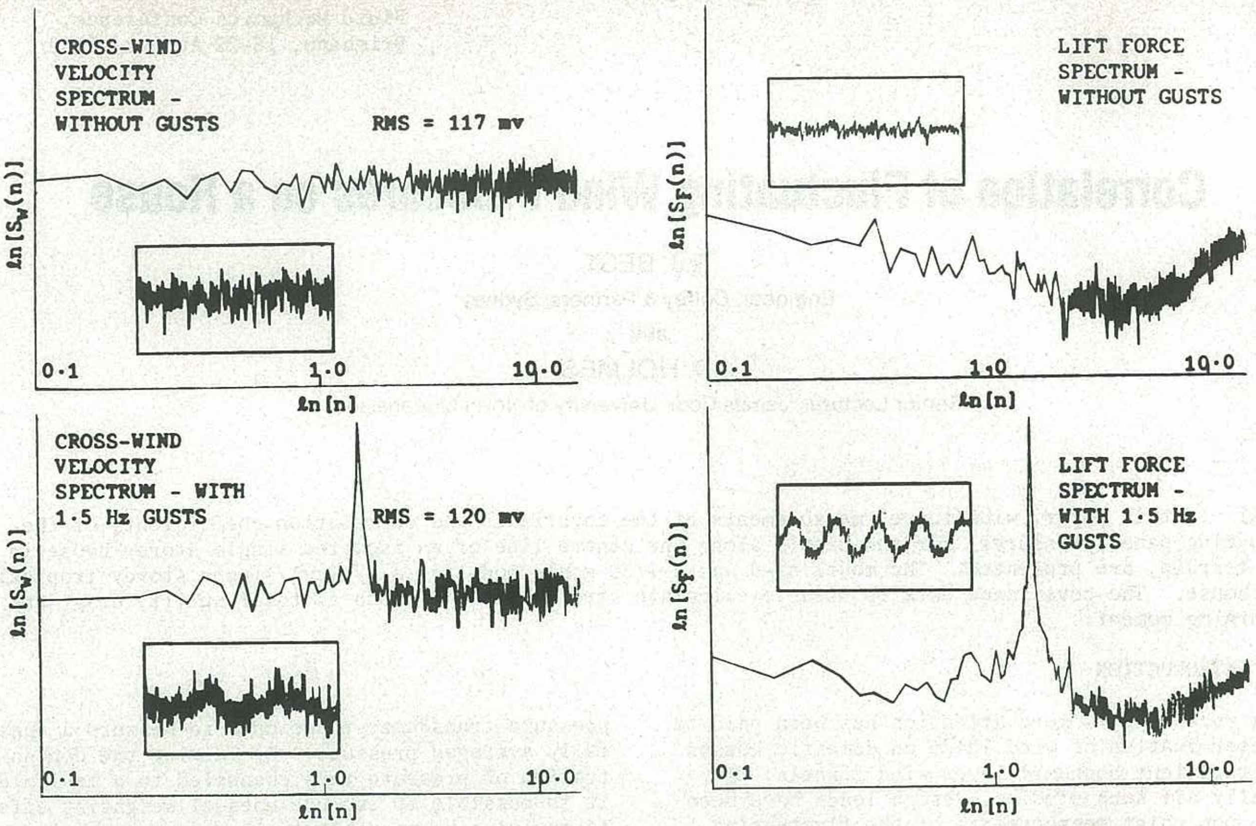

Figure 2 Sample force and velocity spectra and traces for NACA 0006 aerofoil in 5% background turbulence level with and without discrete lateral gust generation

3.3 Computing the Aerodynamic Admittance

The changes in velocity and aerodynamic force, introduced as a result of gust generation, are quantified spectrally. The effect of gust generation on the velocity spectrum is to produce a superimposed spike at a frequency corresponding to that of gust generation; the remainder of the spectrum is left unchanged. Similarly, a corresponding spike appears on the force spectrum which is dependent on the value of the aerodynamic admittance at that particular frequency. Figure 2 shows a set of force and velocity spectra before and after the generation of 1·5 Hz lateral gusts, measured for a background turbulence level of 5%.

On the basis of these spectral spikes, an estimate of the value of the aerodynamic admittance at a frequency equal to that of gust generation can therefore be made. Using equation 3, and bearing in mind that the spanwise velocity correlation at the gust generation frequency is equal to one, the aerodynamic admittance for a symmetrical structure (i.e. $C_{F_{Z0}} = 0$) can be evaluated from,

$$\chi^2_{aero}(n_{gust}) = \frac{4}{\rho^2 \bar{u}^2 c^2 (dC_{F_Z}/dx)^2}$$

$$= \frac{\text{Aero of force at } n_{gust}}{\text{Area of cross-wind velocity spike at } n_{gust}}$$

where n_{gust} = the gust generation frequency —— 5

Figure 3 shows a comparison between Liepmann's Approximation to the Sears Function and experimentally determined values of the aerodynamic admittance of a NACA 0006 aerofoil model. The aerofoil section was used to approximate the behaviour of an ideal two-dimensional flat plate. The model tested had a chord of 100 mm, span of 800 mm and thickness of 18 mm; the results shown are for smooth flow (background turbulence level = 0·6%).

4 CONCLUSIONS AND FUTURE DEVELOPMENTS

The outlined technique for the measurement of aerodynamic admittance via discrete frequency gust generation has produced reasonable agreement with the well established theoretical expression for a flat plate. As such, it is viewed as a technique that may make possible the accurate prediction of cross-wind response in situations where both the wake and incident turbulence contribute significantly to the excitation. Following development of the above technique for measuring aerodynamic admittances, the "flat plate" model will be tested under a variety of background turbulence conditions.

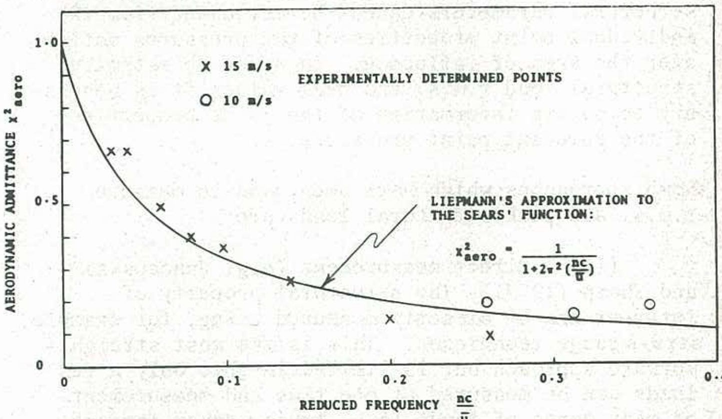

Figure 3 Aerodynamic admittance as a function of reduced frequency for NACA 0006 aerofoil in 0·6% background turbulence level

It is in the next stage that the full potential of the technique will be realised. The technique will be used to measure the aerodynamic admittance of a range of bluff sectioned structures. It is anticipated, that as the gust generation affects only a narrow band leaving the remainder of the spectrum unchanged, it will be possible to measure the relative contributions of both mechanisms.

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