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Buffet loading, dynamic response and aerodynamic control of a suspension bridge in a turbulent wind

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ABSTRACT

This paper describes experiments relating to the buffet response and control of a section of a long-span suspension bridge deck elastically mounted as part of a wind tunnel experiment. The bridge section is subject to grid generated flow turbulence. Two grids are used — one is a standard biplanar grid, while the second is a new design that provides larger turbulence length scales. The buffet response results are compared with admittances calculated using unsteady, three-dimensional, lifting-surface theory that extends standard two-dimensional Sears' theory. The bridge deck heave and pitch responses are predicted with comparisons made with wind tunnel measurements. In order to suppress buffeting, and increase the deck's critical flutter speed, the deck model is fitted with controllable leading- and trailing-edge flaps. Two sets of passive controllers, which use the flap angles as the control inputs, are demonstrated and evaluated for their capability to suppress the buffet response of the deck and increase its critical flutter speed. The first set of controllers sense the deck's position (pitch angle and heave, or pitch angle alone), whilst the second set (which are mechanical controllers) sense the vertical velocity of the flap hinge points. The control system design problem is solved as a mixed H_2/H_∞ optimisation problem. The wind tunnel experiments show that these control systems can reduce considerably the deck's buffet response, whilst simultaneously increasing its critical flutter speed.

1. Introduction

Long-span bridges, which may be suspension bridges or cable-stayed bridges, are known to be sensitive to wind-induced influences. The iconic Tacoma Narrows incident (Billah and Scanlan, 1991) is the best known case of a wind-induced disaster. However, a significant number of other bridges have also experienced detrimental wind-induced effects in which the bridge response was of sufficiently large amplitude to cause concern. An important wind induced phenomenon is aerodynamic instability that is often, but not always, a classical two-degree of freedom heave-pitch flutter. Another wind-induced phenomenon is aerodynamic buffet, which is produced by turbulence in the incident air stream. These phenomena are given careful consideration in the design of any new bridge.

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Buffet loading occurs on all bridges, but usually only generates significantly adverse effects on long span bridges in high winds. Turbulence in the incident wind induces a random unsteady aerodynamic load (buffet), which is dominated by the bridge deck's response to the vertical component of the gust velocity. Buffet loading also results from flow separation occurring around a non-streamlined deck. The resulting aerodynamic forces are inherently unsteady due to vortex shedding, but may also interact strongly with the incident turbulence in the wind. This self-buffeting will not be considered explicitly in this paper except within the context of the aerodynamic control of the wind tunnel model.

Aeroelastic analysis of wind sensitive bridge decks is now standard and is usually carried out by employing a strip theory analysis (for the aerodynamics), since the wavelengths of the relevant spanwise structural modes of the deck are large compared with the aerodynamic chord (bridge deck width). However, the theory is less accurate when predicting buffet loads when the spanwise length scale of the incident turbulence is small. This is especially true for wind tunnel simulations where it is often difficult to generate representative large turbulence length scales.

Many bridge decks are composed of closed, near trapezoidal sections, presenting a streamlined thin structure approximating a negatively cambered flat plate. Unsteady thin aerofoil theory has been shown to be quite accurate in determining the aerodynamic derivatives of these bridge sections. Similarly, Sears' theory (Sears, 1941) for convected two-dimensional gusts is often used to predict buffet forces on thin bridge sections due to incident turbulence. The strip theory method and the implications of three-dimensionality are discussed fully in Larose and Mann (1998) for example. Previous work (Graham, 1970) has extended Sears' theory to three-dimensional flows by considering oblique sinusoidal gusts. Following this work Jackson et al. (1973) showed that aerodynamic derivatives calculated in this way for the individual Fourier components of homogeneous turbulence could predict quite accurately the admittance for induced lift on a thin aerofoil or plate section in a turbulent flow where two dimensional theories, including strip theory, over-predicted the forces.

The aerodynamic stability of suspended-span bridges tends to degrade as the free span of a bridge increases. This results primarily from a reduction in the torsional stiffness of the bridge structure, but the reduced bending stiffness also reduces the critical wind speed. Extreme spans under current consideration require major design changes to preserve the safety margin between the critical flutter speed and the highest expected wind speeds (Brown, 2001). These changes include widening the deck and separating it into two roadways, but purely structural solutions usually lead to high costs.

Following the Tacoma Narrows disaster the possibility of compensating for adverse aerodynamic influences has been investigated in the context of many bridges. Initially this was in the form of controlling the airflow over the bridge deck with particular attention paid to the aerodynamic shape of the deck, the porosity of the structure and profiling the deck edges. We call this traditional passivity control, which exploits surface shaping, requires no power input, but has limited efficacy.

More recently the possibility of active control using controllable flaps has been investigated (Hansen and Thoft-Christensen, 2001; Wilde and Fujino, 1996). The concept of using flaps for control is not new; it has been used in the aeronautics industry for flutter suppression and buffet loads alleviation, where flaps respond to the wing's oscillatory motion, as seen, for example in Triplett (1972), Triplett et al. (1973), Roger et al. (1975), Karpel (1982), Borglund and Kuttenkeuler (2002), and Burnett et al. (2010). The main advantage of feedback control using controllable flaps relative to traditional structural changes is the possibility of raising significantly the critical speed for flutter along with considerable potential cost advantages. Actively controlled flaps can similarly be effective in combating buffet forces induced on a bridge deck by turbulence in the oncoming wind. Frederick et al. (2010) showed that a controlled trailing edge flap could reduce by as much as 80% the amplitude of the buffet loading on an aerofoil due to a strong turbulent flow. In this case a short (4% of chord) moving Gurney flap was used to increase the actuation bandwidth. In the case of a bridge deck the relevant response frequencies are low and bandwidth is not a major problem. However, active control requires a power supply, computers and powered actuators, and high winds are likely to disrupt these facilities.

A recent passive mechanical controller concept, which has been successfully utilised in vehicle suspension (Sharma and Limebeer, 2012) and motorcycle steering (Evangelou et al., 2007), might offer a 'best-of-both-worlds' solution. This technique does not require a power supply, but offers the benefits of actively controlled flaps. The controller is a mechanical network consisting of springs, dampers and inerters that offers good performance including such things as fast response, robustness and so on. Our recent work (Limebeer et al., 2011) has shown that controlled conventional flaps, hinged at the trailing edge of an aerofoil, or thin bridge deck section, and driven by a mechanical controller, can substantially reduce buffet loads induced by incident unsteady flow and can also be used to raise the critical flutter speed. Because the direction of the incident wind may be uncertain, controllable flaps may have to be fitted on both deck edges. This arrangement means that leading- and trailing-edge flaps will be available for control whatever the wind direction. Mechanical control systems, which are insensitive to wind direction, are proposed in Zhao et al. (2016). Controllable leading edge flaps, which are unusual in aircraft, are shown to be capable of making a significant contribution to buffet load reduction and to raising the flutter speed. This flap arrangement may, however, produce adverse effects. A conventional trailing edge flap, in order to be efficient, will usually have a 'sharp' trailing edge. When the wind direction is reversed such a flap, now on the upwind side, presents a sharp leading edge to the wind that can produce early-onset flow separation.

In Limebeer et al. (2011) and Zhao et al. (2016), the controls are the torques applied to the controllable flaps, but it is more convenient to use flap angles as the control inputs for wind tunnel experiments. The controls in Graham et al. (2011a), in which two flaps are used, are flap angles. There is no mechanical controller design in Graham et al. (2011a) or Graham et al. (2011b) and the control system is sensitive to wind direction. In Zhao et al. (2011) a simple mechanical flutter controller is designed with the flap angles as control inputs and heave velocity as the sensed feedback signal. Unfortunately, our recent wind tunnel tests show that controllers with heave velocity as the feedback cannot suppress adequately the deck's