Eccentric-wing Flutter Stabilizer for Bridges

Uwe STAROSSEK
Professor, Dr.-Ing., PE
Hamburg Univ. of Techn.
Hamburg, Germany
starossek@tuhh.de

Uwe Starossek, born 1956, received his civil engineering degree from RWTH Aachen, Germany in 1982 and his doctoral degree from Stuttgart University, Germany in 1991. He has practiced for many years, mainly in the design of large bridges worldwide. He is now a consultant and professor of structural engineering at Hamburg University of Technology, Germany.

Summary

A device is presented that aims at preventing bridge flutter. It consists of wings positioned along the sides of, and fixed relative to, the bridge deck. Flutter suppression efficiency is high provided the lateral eccentricity of the wings is large. It is a passive aerodynamic device that is more economical than other passive measures or devices. Moreover, it does not contain moving parts. This is an advantage over devices with moving parts that meet resistance due to reliability concerns. Results of a numerical study are presented in which the critical wind speed for flutter onset of a bridge without wings and with wings mounted in various configurations were determined. Preliminary wind tunnel test results are reported and a cost estimate is given.

Keywords: Long-span bridge; flutter; passive aerodynamic device; fixed wing; numerical study.

1. Introduction

Flutter is a criterion governing the design of long-span bridges. Various measures have been proposed and applied to raise the flutter resistance of bridges, that is, their critical wind speed for flutter onset (flutter speed). The concept of the twin suspension bridge was described by Richardson [1] in 1981 and since implemented in a few bridges. It is a passive aerodynamic measure that takes advantage of the gap between the two (or more) bridge decks. The decks need to be connected by cross beams, which are substantial structural elements that cause significant additional costs.

An active aerodynamic device for raising the flutter speed was proposed by Ostenfeld et al. [2] in 1992. It consists of wings, installed along the sides of the bridge deck, whose pitch is controlled by actuators. A closed-loop control is envisaged in which, based on accelerometer measurements, an algorithm produces the control signals for the actuators such that the movement of the wings generate stabilizing aerodynamic forces. With such device, the safety of the bridge depends on energy supply and the proper functioning of control software and hardware – a condition that meets resistance with bridge owners and authorities. The concept has not yet been applied.

![Fig 1: Passive aerodynamic-mechanical device for flutter suppression [3]](image)

A passive aerodynamic-mechanical device was described by Starossek et al. [3] in 2008, which also includes variable-pitch wings along the sides of the bridge deck (Fig. 1). Instead of being controlled by an actuator, the pitch of a wing follows the movements of a tuned mass damper inside the bridge deck to which the wing is coupled by means of a linkage or gear. With proper tuning, the flutter suppression efficiency can be similar to that of actively controlled wings. Being a passive device, the safety of the bridge would not depend on energy supply and a control system. It still includes
moving parts though, which is unusual and raises the threshold of acceptance. The concept has not yet been applied.

2. Eccentric-wing flutter stabilizer

In view of the development described above, it seems promising, for raising the flutter speed of a bridge, to pursue passive measures that do not include moving parts, but also do not require substantial additional structural elements or structural strengthening. The eccentric-wing flutter stabilizer presented in the following meets these requirements.

The device consists of wings positioned along the sides of the bridge deck. A configuration with wings equally positioned on both sides of the deck is shown in Figs. 2 to 4. In certain cases, further discussed below, it is advantageous to provide wings on only one side of the deck or to provide wings on both sides, but to design them differently, that is, with different widths and lateral eccentricities (dimensions $2b_c$ and $a_c$ in Fig. 2). The wings are mounted on transversely orientated support structures that are laterally attached to the bridge deck. Hence they do not move relative to the bridge deck. It can be shown that the flutter suppression efficiency of the device is high provided the lateral eccentricity of the wings is large.

![Fig 2: Bridge with eccentric-wing flutter stabilizer – cross section](image)

![Fig 3: Bridge with eccentric-wing flutter stabilizer around center of main span – plan view (not to scale)](image)

Wings and support structures are envisaged as light-weight components. The wings are aerodynamically shaped such that the lift under inclined wind is large and the resistance is small. Their profile can be symmetric about a horizontal plane or doubly symmetric approaching an elliptical shape.
The lateral eccentricity of the wings is on the order of the bridge deck width \((a_c/b \approx 1.5\) to 2.5; see Fig. 2). The width of one wing in direction transverse to the bridge axis is on the order of one tenth of the bridge deck width \((h_c/b \approx 0.05\) to 0.20). The wings are preferably positioned above or below the bridge deck with sufficient vertical offset to avoid aerodynamic interference between the wings and the bridge deck including traffic.

For optimum cost efficiency, the wings are not placed over the entire length of the bridge but only at regions where large vibration amplitudes occur \(L_c < L\); see Figs. 3 and 4). In case flutter is governed by the first symmetric modes of vibration, these regions lie around the center of the main span (Fig. 3). In case flutter is governed by the first antisymmetric modes of vibration, these regions lie around the quarter points of the main span (Fig. 4).

In an alternative configuration, a single wing is replaced by a certain number of wings positioned above each other (Fig. 5). The flutter-suppression efficiency of such group of wings is approximately the same as for a single wing provided the sum of the widths of the wings is the same as the width of the single wing and the vertical distance between the individual wings, \(h_c\), is not too small. Advantages of such alternative configuration can be easier assembly and lower costs. It might also offer less area of attack to the vertical velocity component of turbulent wind by taking advantage of the wind shielding effect provided by the uppermost or lowermost wings.
3. Reasons of effectiveness

Because the width of a wing is comparatively small, the lift force on a wing as a function of the vertical and angular motion of the bridge deck can be thought of as quasi-stationary. An angular velocity of the deck, $\dot{\alpha}$, will result in a vertical velocity of a wing of $a_c \dot{\alpha}$. In quasi-stationary theory, this corresponds to an apparent vertical flow of the same velocity acting on the wing, which, when superimposed on the horizontal wind flow, $u$, leads to an apparent resulting quasi-stationary flow at an angle of attack of $a_c \dot{\alpha}/u$ and a lift force on the wing that is proportional to $a_c \dot{\alpha}$. This force times the eccentricity, $a_c$, produces a moment on the deck that is proportional to $a_c^2 \dot{\alpha}$ and in phase with $\dot{\alpha}$. In other words, a wing produces a wind-induced force that dampens the angular motion of the bridge deck (aerodynamic damping) and is proportional to the square of the eccentricity of the wing. This effect is independent of whether the wing is positioned on the windward side or the lee side of the deck. By raising the damping of the angular motion of the deck, the flutter speed is also raised.

Another important effect that can be explained by quasi-stationary theory is the aerodynamic stiffness produced by the wings. An angular displacement of the deck, $\alpha$, is accompanied by the same angular displacement, or pitch, of the wings. The horizontal wind flow acting on a pitched wing produces a lift force on the wing that is proportional to $\alpha$. This force times the eccentricity, $a_c$, results in a moment on the deck that is proportional to $a_c \alpha$ and in phase with $+\alpha$ or $-\alpha$, depending on whether the wing is positioned on the windward side or the lee side of the deck. In other words, a wing produces aerodynamic stiffness related to the angular displacement of the deck that is proportional to the eccentricity of the wing. This stiffness is negative for a windward wing and positive for a leeward wing. A positive aerodynamic stiffness raises the overall stiffness and hence the natural frequency of torsional vibrations and the flutter speed – a negative aerodynamic stiffness vice-versa. In a symmetrical wing layout with identical wings on both sides of the bridge deck, the aerodynamic stiffness contributions of the wings of both sides cancel and do not affect the flutter speed.

An experimental study with sectional models in a wind tunnel is underway. First results fit well with the explanations given above and confirm the effectiveness of the device. In particular, a leeward wing always raises the flutter speed. A windward wing with small eccentricity lowers the flutter speed and with large eccentricity raises it. The latter experimental result can be explained by the quadratic versus linear dependency of aerodynamic damping and stiffness on the eccentricity of a wing.

4. Determination of flutter speed

The effect of the eccentric-wing flutter stabilizer on the critical wind speed for flutter onset was studied analytically. It is assumed in this study that there is no aerodynamic interference between the bridge deck and the wings. Theodorsen’s flutter derivatives [4] are used for modelling the wind forces on the bridge deck. This is deemed sufficiently accurate for determining the relative effectiveness of the various wing configurations provided the aerodynamic contour of the deck is a streamlined closed box. The overall system and the wind forces on the wings are modelled in two different ways.

In a first approach, the bridge system is generalized to two degrees of freedom (2-DOF, heave and rotation) and it is assumed that the wind forces on the wings can be calculated by quasi-stationary theory. The rotational damping and stiffness of the two-degrees-of-freedom system is modified by adding the aerodynamic damping and stiffness contributions of the wings as described in the previous section. The conventional 2-DOF method for determining the flutter speed (see, for instance, [5]) is applicable, but has to be supplemented by a further level of iteration, given that the damping and stiffness contributions of the wings depend on the wind speed.

In a second, more sophisticated approach, the bridge deck and the wings are modelled by finite aeroelastic beam elements [5, 6]. This allows for the study of configurations where the wings are
not placed over the entire length of the bridge. Moreover, the quasi-steady flow assumption for including the wind forces on the wings is no longer required. The wind forces on both the bridge deck and the wings are modelled by using Theodorsen’s flutter derivatives.

5. Parametric study

Parametric computations were performed for a long-span suspension bridge with a main span length of \( L = 3000 \) m and a single box girder deck with a width of \( 2b = 38.0 \) m. The flutter speed of the bridge without wings was computed as 46.3 m/s. Fig. 6 shows the flutter speeds for various wing configurations relative to the flutter speed without wings, all computed by the second, more sophisticated approach described in the preceding section. The wings are assumed to be placed on the lee side only and along the entire length of the bridge deck. The relative wing width, \( b_c/b \), is varied between 0.025 and 0.170. The relative eccentricity, \( a_c/b \), is varied between 1.00 and 2.00. For a relative wing width of 0.100 and a relative eccentricity of 2.00, for instance, the flutter speed is raised by 64\% corresponding to a value of 75.8 m/s. It can also be seen in Fig. 6 that the flutter-suppression efficiency of the device increases nonlinearly with, and mainly results from, the lateral eccentricity of the wings.

![Fig 6: Critical wind speed for flutter onset as function of width and eccentricity of wings of eccentric-wing flutter stabilizer](image)

Placing wings on only one side of the bridge deck – or placing wings on both sides but designing them with different widths and lateral eccentricities – is advantageous when the expected maximum wind speeds strongly differ for both transverse directions. The wings on only one side – or, when placing wings on both sides, the wings with the larger widths and lateral eccentricities – are then placed on the lee side of the stronger wind.
When the expected maximum wind speeds are about the same for both transverse directions, identical wings should be placed on both sides of the bridge deck. This possibly reduces the overall flutter-suppression efficiency of the eccentric-wing flutter stabilizer, as it follows from the above discussion of the reasons of effectiveness. The aerodynamic stiffness contributions of the wings of both sides cancel and only their aerodynamic damping is available for raising the flutter speed. However, again assuming the parameters considered in the previous paragraph \(b_c/b = 0.100; a_c/b = 2.00\), the flutter speed would still be raised by 28% over the value without wings.

6. Cost estimate

A cost estimate based on a preliminary design was performed for the cost of support structures and wings. For the particular configuration considered in the preceding paragraph, leading to a flutter speed increase of 28%, the additional cost would amount to about 4% of the cost of the bridge. This is compared to the additional cost when the same 28% increase of flutter speed is achieved by other means, for instance, by increasing the stiffness of the bridge structure. The latter cost is expected to be in the same order as the flutter speed increase, that is, 28%.

The flutter speed can also be increased by using a twin or multiple instead of a single box girder deck. This entails cross beams for connecting the individual box girders. Such cross beams are substantial additional structural elements and the corresponding cost increase is expected to be larger than the cost increase resulting from the eccentric-wing flutter stabilizer. More accurate cost estimates of the eccentric-wing flutter stabilizer and of competing measures for increasing the flutter speed are required and currently underway.

7. Conclusions and outlook

The eccentric-wing flutter stabilizer is a promising device for raising the critical wind speed for flutter onset of long-span bridges. A substantial increase of flutter speed is reached at a comparatively small additional cost. Further study is required and underway for confirming the computed flutter speeds by wind tunnel tests with sectional bridge deck models, for improving the preliminary design of support structures and wings based on the consideration of all relevant loads including buffeting and vortex-induced loads, and for refining the cost estimate.

8. References


