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Flutter control of bridges using eccentric wings

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ABSTRACT

The eccentric-wing flutter stabilizer is a passive aerodynamic device for raising the flutter speed of a bridge. It consists of wings running parallel to the bridge deck. In contrast to similar devices proposed in the past, the wings do not move relative to the bridge deck and they are positioned outboard the bridge deck to achieve a greater lateral eccentricity. This enables the wings to produce enough aerodynamic damping to effectively raise the flutter speed. A parametric flutter analysis study is presented in which both the properties of the bridge and the configuration of the wings are varied. The bridge properties and the wing configuration are each summarized in four non-dimensional quantities. Former publications by the authors focused on wing configurations with large eccentricities. While such arrangements are particularly effective, they have encountered concerns about their aesthetic quality. Furthermore, the strong flutter speed increase achievable in this manner cannot always be fully utilized given that torsional divergence may become governing over flutter. Therefore, wing configurations with reduced eccentricity are the focus of the present study. It is found that eccentric wings continue to be an interesting way to cost-efficiently raise the flutter resistance of a bridge. Renderings of such a configuration show that a well-designed flutter stabilizer can be appealing and aesthetic concerns be unwarranted.

1. INTRODUCTION

Flutter is a criterion that governs the design of long-span bridges. Various measures have been proposed to raise the flutter resistance of bridges, that is, their critical wind speed for flutter onset (flutter speed). The twin deck concept was described by Richardson (1981) and has been implemented in a few bridges. It is a passive aerodynamic measure that takes advantage of the gap between the two (or more) bridge decks. It means additional cost due to the cross beams required to connect the individual decks. (Diana 2007) examined the effect of winglets positioned above the

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bridge deck edges without a distinct vertical or horizontal offset. Only qualitative indications were given concerning the impact of such devices on the flutter speed. (Raggett 1987) and (Liu 2006) suggested wings that are rigidly mounted at a certain vertical distance above the bridge deck edges. The authors' previous publication (Starossek 2021) shows that the impact of such a configuration on flutter is small. An active aerodynamic device for raising the flutter speed was proposed in Ostenfeld (1992). It consists of wings, installed along the sides of the bridge deck, the pitch of which is controlled by actuators. Hence the safety of the bridge would depend on energy supply and the proper functioning of control software and hardware – a condition that meets resistance due to reliability and durability concerns.

In view of these developments, it seems promising, for raising the flutter speed of a bridge, to develop passive aerodynamic devices, which nevertheless are sufficiently effective without implying substantial additional cost such as the cross beams in the twin deck concept. The eccentric-wing flutter stabilizer possibly meets these requirements. It consists of wings running parallel to the bridge deck (Fig. 1). In contrast to similar devices proposed in the past, the wings do not move relative to the bridge deck and they are positioned outboard the bridge deck to achieve a greater lateral eccentricity with regard to the bridge axis. This is accomplished by connecting the wings to the bridge deck by means of lateral cantilever support structures longitudinally spaced at a certain distance.

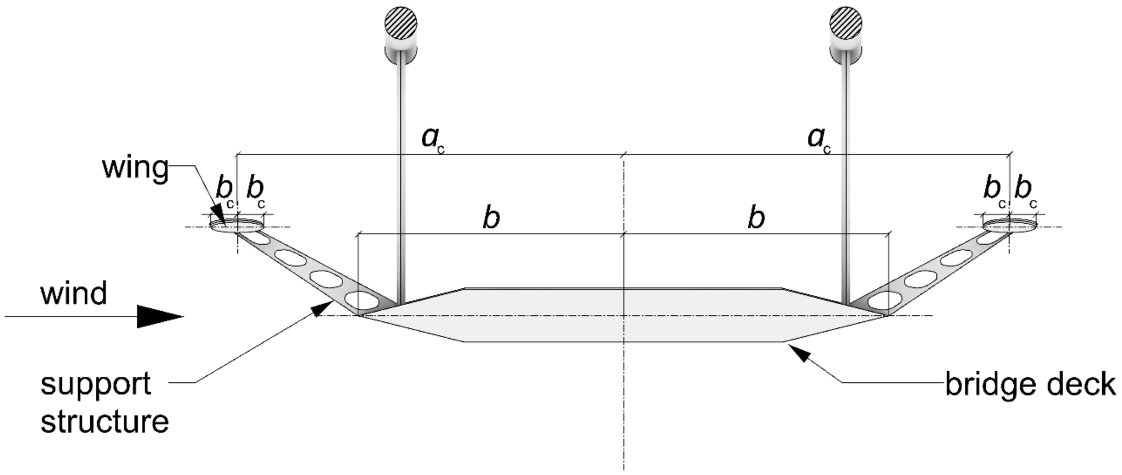

Fig. 1 Bridge deck with eccentric-wing flutter stabilizer – cross section

Both the leeward wing and the windward wing produce aerodynamic damping of the bridge deck motion, particularly of the rotational motion component, which raises the flutter speed. It can be shown that the wing-produced aerodynamic damping of the bridge deck's rotational motion increases quadratically with the eccentricity of the wings. Consequently, the flutter-suppression effectiveness of the wings is the greater the larger their eccentricity. This was confirmed by wind tunnel tests, which also validated analytical approaches for determining the flutter speed of bridge-wing assemblies. The cost was investigated on the basis of design studies for the wings and their support structures and was found to be competitive (Starossek 2018).

A parametric flutter analysis study is presented in which both the properties of the bridge and the configuration of the wings are varied. The bridge girder always consists of a single streamlined deck. Former publications by the authors focused on wing configurations with large eccentricities (Starossek 2021a, 2021b). While such arrangements are particularly effective, they have encountered concerns about their aesthetic quality. Moreover, the strong flutter speed increase achievable with large-eccentricity wings cannot always be fully utilized given that torsional divergence, which is unaffected by the wings, may become governing over flutter. Therefore, results for wing configurations with reduced eccentricity are presented here along with considerations on torsional divergence and renderings of a bridge equipped with wings.

2. ANALYSIS APPROACH

The study is based on classical bridge flutter theory. Steady-state harmonic vibration is assumed and studied in the frequency domain. The oncoming wind is assumed to be non-turbulent. [It has been found that the response of the bridge to buffeting and vortex shedding is reduced when wings are added (Meyer 2018), which is ascribed to the aerodynamic damping produced by the wings.] The motion-induced lift forces and aerodynamic moments are linearly related to vertical displacements and rotations, and the respective velocities and accelerations, by analytical non-stationary aerodynamic coefficient functions (Theodorsen 1934), assuming aerodynamic streamlined contours of bridge deck and wings. Aerodynamic interference between the windward and leeward wings and the bridge deck is neglected so that the theory can be applied separately to each of these three elements. In practice, interference can be prevented by positioning the wings above or below the bridge deck with sufficient vertical offset to the bridge deck and between them.

For greater generality, the input data and results are presented as non-dimensional quantities. As far as the structural properties of the bridge are concerned, the non-dimensional flutter speed depends on four non-dimensional parameters. The parameter space within which these quantities are varied is chosen on the basis of existing or planned long-span bridges. The configuration of the wings can likewise be summarized in four non-dimensional parameters, provided the study is limited to configurations with identical wings on both sides of the bridge deck, as it is done here.

The analyses are performed on a simple generic system, that is, a simply supported girder, without or with wings, with torsionally fixed ends, to which actual bridge and bridge-wing systems can be mapped, using generalization, by the non-dimensional input parameters defined here. The various girder and girder-wing systems are modelled with a specially developed finite aeroelastic beam element capable of simultaneously modelling the girder and the wings. The wing length, which can be smaller then the bridge length, can thus properly be taken into account. Multi-degree-of-freedom flutter analyses are performed. The results are presented as the flutter speed increase ratio, that is, the relative flutter speed increase due to the wings. Reference is made to (Starossek 2021b) for further details on the analysis approach.

3. INPUT AND OUTPUT DATA FORMAT

Flutter theory was originally based on a generalization of the actual structural system to a system with two degrees of freedom, heave and rotation. In such a two-degree-of-freedom flutter analysis, the structural properties of a bridge can be summarized in four non-dimensional and two dimensional quantities (Starossek 1992). The non-dimensional quantities are 1) the *frequency ratio*, ε, defined as

$$\varepsilon \stackrel{\text{def}}{=} \frac{\omega_\alpha}{\omega_h} \tag{1}$$

where ω_α = natural circular frequency of torsional vibration, and ω_h = natural circular frequency of vertical vibration, of an undamped bridge system without wings in a vacuum (without motion-induced wind forces), both associated with the lowest symmetric or lowest antisymmetric modes of vibration, whichever governs flutter, 2) the (structure-to-air) *mass ratio*, μ, defined as

$$\mu \stackrel{\text{def}}{=} \frac{m}{\pi \rho b^2} \tag{2}$$

where m = mass per unit length, ρ = air density, b = half chord of aerodynamic contour of bridge deck, 3) the *reduced mass radius of gyration*, r, defined as

$$r \stackrel{\text{def}}{=} \frac{1}{b}\sqrt{\frac{I}{m}} \tag{3}$$

where I = mass moment of inertia per unit length, and 4) a parameter that quantifies the inherent structural damping. For the latter, the *damping parameter* g is chosen: the damping forces are assumed to be g times the elastic restoring forces acting with a phase shift of 90° so that they are in counter-phase to velocity (Försching 1974). For the analyses performed here, the equivalent viscous modal damping ratio-to-critical, ξ, is approximately

$$\xi \approx g/2 \tag{4}$$

Properties m and I refer to the bridge deck plus, if present, the suspension cables. More generally, they are generalized properties related to the distributed mass of the system by the respective mode of vibration. They do not include the mass of the wings, which is part of the wing parameters and specified separately. The dimensional structural quantities used to compute the flutter speed are b and ω_h. These quantities are not varied in this study given that the non-dimensional flutter speed and the flutter speed increase ratio, which are of interest here, are independent of them. The flutter speed also depends on the aerodynamic contour of the bridge deck, which here is assumed to be streamlined.

The properties of the wings can likewise be summarized in four non-dimensional quantities, that is (see Fig. 1), 1) the *relative wing eccentricity*, $\tilde{a}_{\mathrm{c}}$, defined as

$$\tilde{a}_{\mathrm{c}} \stackrel{\text{def}}{=} \frac{a_{\mathrm{c}}}{b} \tag{5}$$

2) the *relative wing width*, $\tilde{b}_{\mathrm{c}}$, defined as

$$\tilde{b}_{\mathrm{c}} \stackrel{\text{def}}{=} \frac{b_{\mathrm{c}}}{b} \tag{6}$$

3) the *relative wing length*, $\tilde{L}_{\mathrm{c}}$, defined as

$$\tilde{L}_{\mathrm{c}} \stackrel{\text{def}}{=} \frac{L_{\mathrm{c}}}{L} \tag{7}$$

where L_c = total length of wings on one side of bridge deck, L = total length of bridge, and 4) the *relative wing mass*, $\tilde{m}_{\mathrm{c}}$, defined as

$$\tilde{m}_{\mathrm{c}} \stackrel{\text{def}}{=} \frac{m_{\mathrm{c}}}{m} \tag{8}$$

where m_c = mass per unit length of wings on one side of bridge deck (including a contribution of the support structures). The quantities a_{c}, b_{c}, m_{c} and hence their non-dimensional equivalents are assumed to be constant along the length of the wings. The aerodynamic contour of the wings is assumed to be streamlined.

The definition of the *non-dimensional flutter speed*, ζ, given for completeness, is

$$\zeta \stackrel{\text{def}}{=} \frac{u}{\omega_h b} \tag{9}$$

where u is the flutter speed. In this paper, flutter analysis results are presented only in terms of the *flutter speed increase ratio*, R, defined as the flutter speed of the bridge with wings to the flutter speed of the same bridge without wings, that is,

$$R \stackrel{\text{def}}{=} \frac{u_{\text{with wings}}}{u_{\text{without wings}}} = \frac{\zeta_{with\ wings}}{\zeta_{without\ wings}} \tag{10}$$

4. TORSIONAL DIVERGENCE

When the same aerodynamic assumptions are adopted as for the non-stationary aerodynamic coefficient functions used for computing the flutter speed, the critical wind speed for torsional divergence (divergence speed) of a bridge without wings, u_{div}, is

$$u_{\text{div}} = \omega_\alpha b\sqrt{\mu r^2} \tag{11}$$

(Starossek 1992). When identical wings are added on both sides of the bridge deck along the entire length of the bridge, it can be shown that the divergence speed decreases by a fraction of $\tilde{b}_c^2$, which is neglected here.

5. PREVIOUS RESULTS

Fig. 2 is adopted from the author's previous study (Starossek 2021a). The four solid lines show the flutter speed increase ratio, R, plotted against the frequency ratio, ε, for four different values of mass ratio, μ, the other input parameters being fixed to values as shown in the figure caption. Note that $\tilde{a}_c = 2$, which corresponds to a large wing eccentricity, and $\tilde{L}_c = 1$, which indicates that the wings extend over the entire length of the bridge. The four dashed lines represent the divergence speed, u_{div}, also referred, for sake of comparison, to $u_{without\ wings}$, that is, the flutter speed of the same bridge without wings. The divergence curves (dashed lines) are independent of the existence or parameters of the wings. For $\mu = 15$, it is seen that divergence becomes governing over flutter for all values of ε considered here. For $\mu = 25$, it is governing

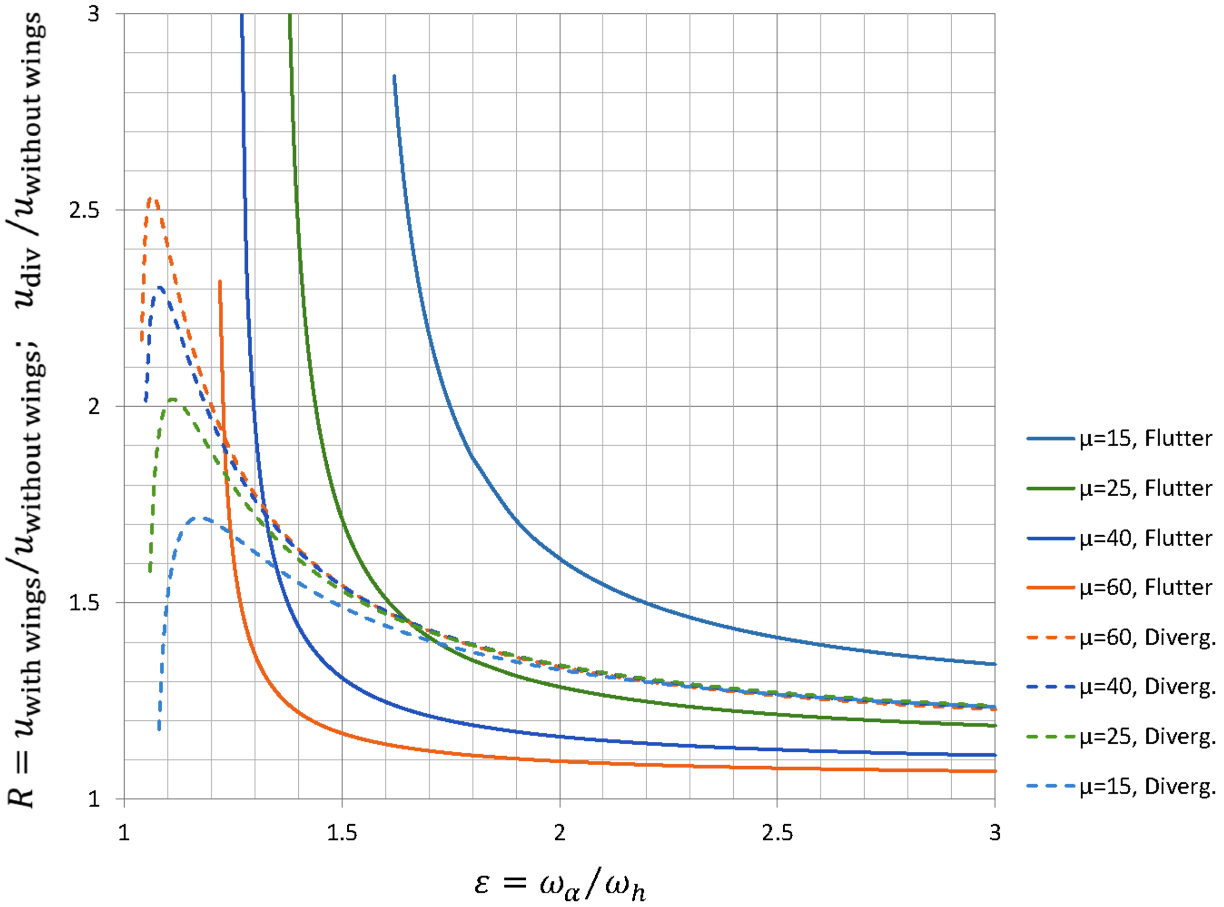

Fig. 2 Flutter speed increase ratio, R, and ratio of divergence speed to flutter speed without wings, against frequency ratio, ε ($r = 0.8$, $g = 0.01$, $\tilde{a}_c = 2.0$, $\tilde{b}_c = 0.1$, $\tilde{L}_c = 1$, $\tilde{m}_c = 0.015$).

for $\varepsilon \leq 1.66$, for $\mu = 40$, it is governing for $\varepsilon \leq 1.32$, and for $\mu = 60$, it is governing for $\varepsilon \leq 1.23$.

It is concluded that the strong flutter speed increase achievable by the wings cannot always be fully utilized given that the divergence speed can become smaller than the flutter speed. For economy, the flutter speed should be raised, by adding wings, to not more than the divergence speed. This is achieved by reducing the otherwise sensible and possible values of parameters $\tilde{a}_{\mathrm{c}}$, $\tilde{b}_{\mathrm{c}}$, and $\tilde{L}_{\mathrm{c}}$. For $\varepsilon = 1.3$, $\mu = 15$, for instance, the referred divergence speed, $u_{\mathrm{div}}/u_{\mathrm{without\ wings}}$, is 1.63. The flutter speed increase ratio, $R = u_{with\ wings}/u_{without\ wings}$, can be lowered to this value by reducing the relative wing eccentricity from $\tilde{a}_{\mathrm{c}} = 2$ to $\tilde{a}_{\mathrm{c}} = 1.27$ or, alternatively, by reducing the relative wing length from $\tilde{L}_{\mathrm{c}} = 1$ to $\tilde{L}_{\mathrm{c}} = 0.20$. For $\varepsilon = 1.7$, $\mu = 15$, the referred divergence speed is 1.40 to which R can be lowered by reducing the wing parameters to $\tilde{a}_{\mathrm{c}} = 1.57$, or, alternatively, $\tilde{L}_{\mathrm{c}} = 0.33$. For $\varepsilon = 1.3$, $\mu = 40$, to give another example, the referred divergence speed is 1.76 to which R can be lowered by reducing the wing parameters to $\tilde{a}_{\mathrm{c}} = 1.94$, or, alternatively, $\tilde{L}_{\mathrm{c}} = 0.67$.

6. NEW RESULTS

The numerical comparisons just made show that for cost efficiency, when the flutter speed shall be lowered to the divergence speed, the wing eccentricity should better remain large because then the wing length, and thus the costs, can be greatly reduced. On the other hand, aesthetic concerns have been voiced about the large eccentricities that were the focus of the authors' previous publications (Starossek 2021a, 2021b). Therefore, the new study focuses on a reduced relative wing length of $\tilde{a}_{\mathrm{c}} = 1.5$ (instead $\tilde{a}_{\mathrm{c}} = 2$), which is believed to alleviate such concerns while still being fairly effective in reducing the flutter speed.

Fig. 3 largely corresponds to Fig. 2. The only difference is that the relative wing eccentricity is reduced to $\tilde{a}_{\mathrm{c}} = 1.5$. It is seen that the four flutter curves are lower than in Fig. 2, but the four divergence curves remain unchanged. For $\mu = 15$, divergence now is governing over flutter for $\varepsilon \leq 1.54$. For $\mu = 25$, it is governing for $\varepsilon \leq 1.25$, for $\mu = 40$, it is governing for $\varepsilon \leq 1.16$, and for $\mu = 60$, it is governing for approximately $\varepsilon \leq 1.12$. Thus, the ranges of ε in which divergence becomes governing over flutter become smaller.

In these ranges of ε, for economy, also the wing length can be reduced to bring the flutter speed down to the divergence speed. For $\varepsilon = 1.3$, $\mu = 15$ (and the other parameters as shown in the caption of Fig. 3), for instance, the referred divergence speed, $u_{\mathrm{div}}/u_{\mathrm{without\ wings}}$, is 1.63, whereas the flutter speed and the flutter speed increase ratio are infinite, that is, the (with $\tilde{a}_{\mathrm{c}} = 1.5$) remaining flutter-suppression effectiveness of the wings is still so high that no flutter occurs. Flutter only occurs when the wing length is reduced to about $\tilde{L}_{\mathrm{c}} = 0.72$; the corresponding flutter speed increase ratio is $R = 3.23$. When reducing the wing length further to $\tilde{L}_{\mathrm{c}} = 0.39$; the flutter speed increase ratio finally becomes $R = 1.63$, that is, the flutter speed then coincides with

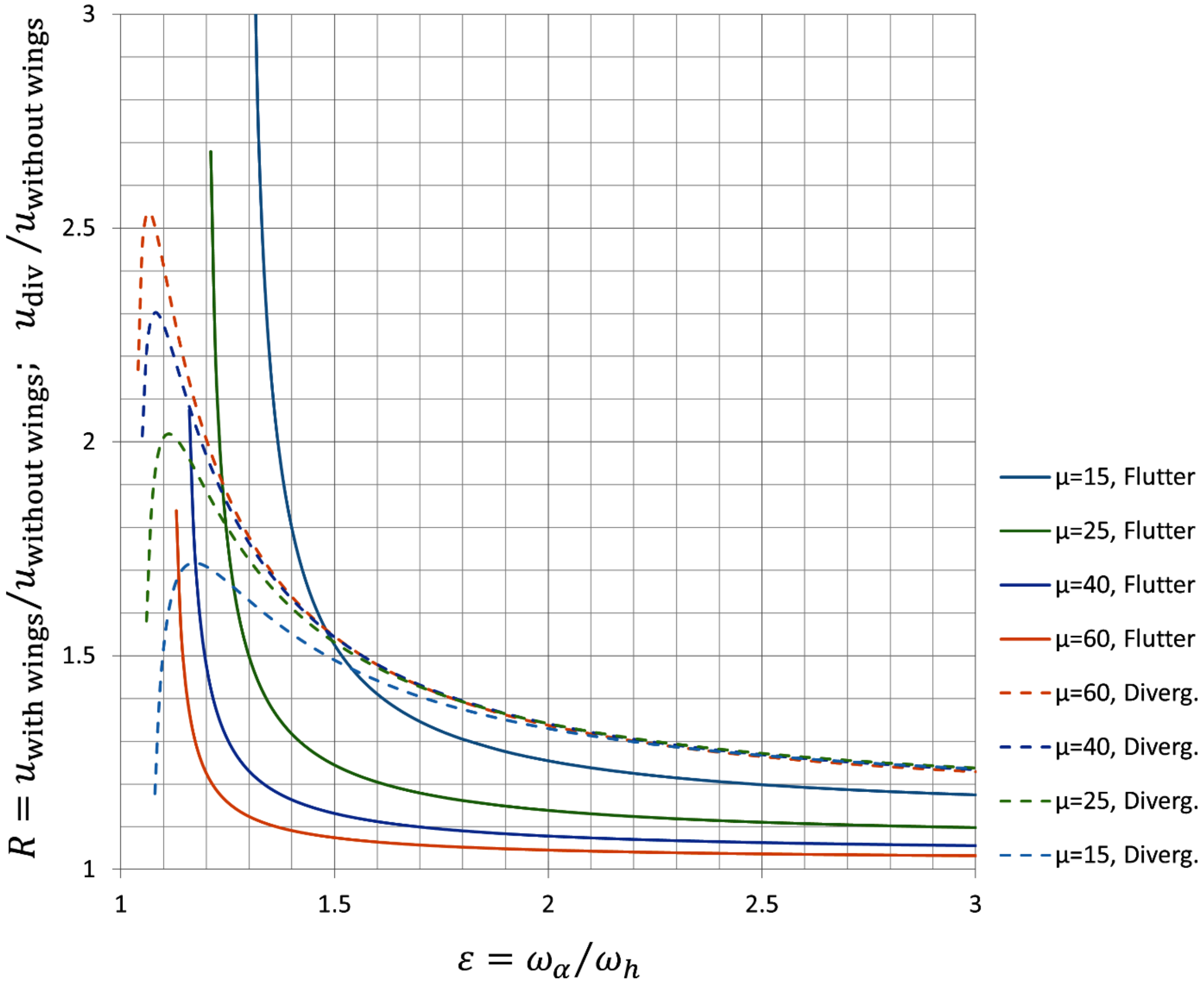

Fig. 3 Flutter speed increase ratio, R, and ratio of divergence speed to flutter speed without wings, against frequency ratio, ε ($r = 0.8,\ g = 0.01,\ \tilde{a}_c = 1.5,\ \tilde{b}_c = 0.1,\ \tilde{L}_c = 1,\ \tilde{m}_c = 0.015$).

the divergence speed. The cost of such a wing configuration ($\tilde{a}_c = 1.5,\ \tilde{b}_c = 0.1,\ \tilde{L}_c = 0.39$), including the support structures, relative to the cost of bridge deck and cables is estimated, based on (Starossek 2021a), at 2.0 %. The corresponding cost estimate for a large-eccentricity wing configuration producing the same flutter speed increase ($\tilde{a}_c = 2.0,\ \tilde{b}_c = 0.1,\ \tilde{L}_c = 0.20$) amounted to 1.3 % (Starossek 2021a).

Note the bridge parameters for which the above results are obtained, $\varepsilon = 1.3$, $\mu = 15$, $r = 0.8$, are not unrealistic for long-span bridges, when compared to the corresponding parameters, for instance, of the proposed Messina Bridge: $\varepsilon = 1.33$, $\mu = 13.8$, $r = 0.824$ (Brancaleoni 2010), (Starossek 2021a).

7. RENDERINGS

To appreciate the aesthetic impact of the eccentric-wing flutter stabilizer, renderings were prepared for a suspension bridge equipped with this device with the wing eccentricity and wing width as focused on above, that is, $\tilde{a}_{\mathrm{c}} = 1.5$ and $\tilde{b}_{\mathrm{c}} = 0.1$. The relative wing length in the following representations is larger than the optimum value of $\tilde{L}_{\mathrm{c}} = 0.39$, found above for the chosen bridge parameters, but smaller than $\tilde{L}_{\mathrm{c}} = 1$.

Fig. 4 shows an oblique bottom view of bridge and wings as it would appear from the shore or from a ship. For a more pleasant appearance, the wings do not end abruptly, but are gently curved at their ends towards the bridge deck edges. These transitions at the wing ends are in sections of the bridge where the wings have little aeroelastic effect (at least in the configuration shown here). Hence they could be designed differently or omitted.

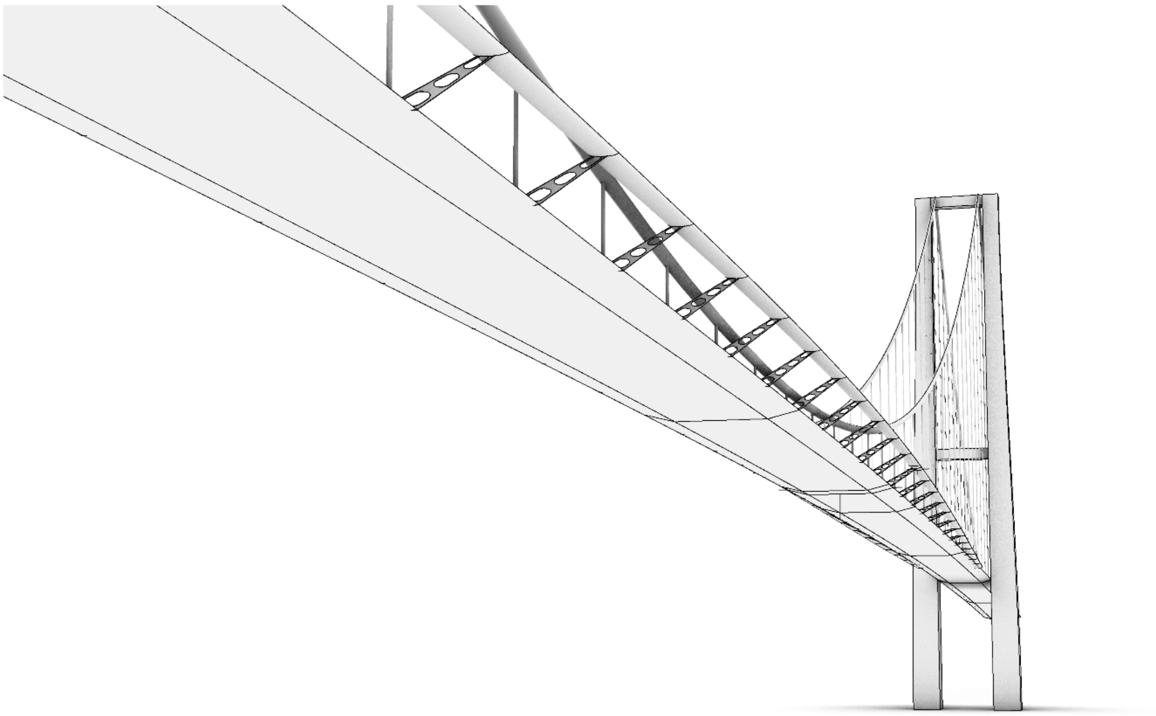

Fig. 4 Bridge with eccentric-wing flutter stabilizer – oblique bottom view

Figs. 5 and 6 show different top views of bridge and wings. Figure 6 gives an impression of how it would appear to someone crossing the bridge. The authors believe that these renderings are quite appealing and demonstrate that concerns about the aesthetic quality of the device can be effectively addressed through reduced wing eccentricity and good detail design.

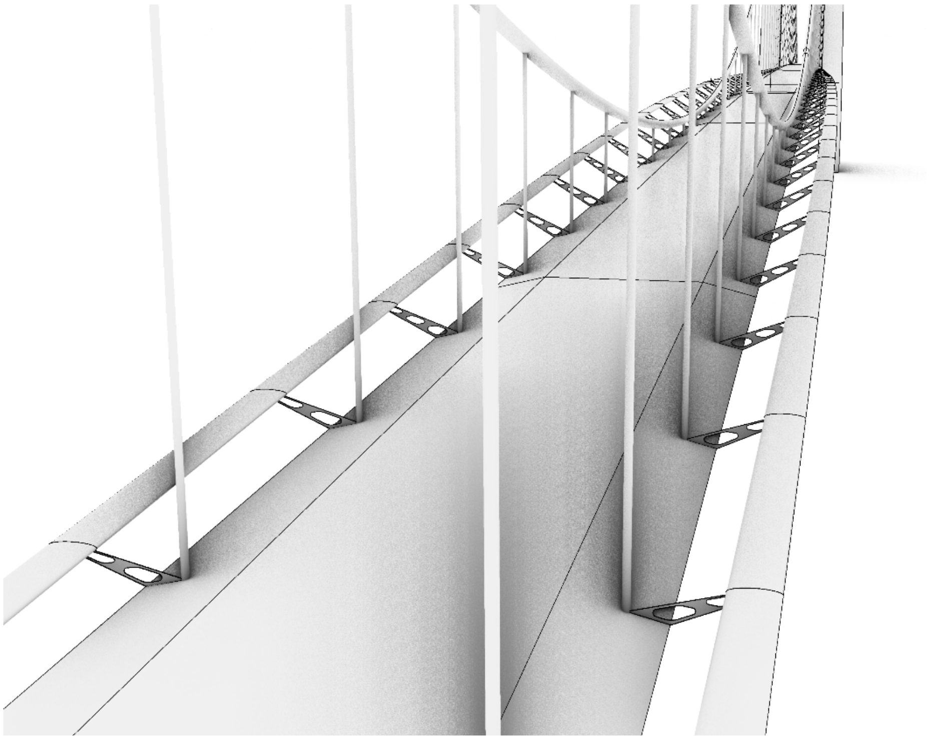

Fig. 5 Bridge with eccentric-wing flutter stabilizer – oblique top view

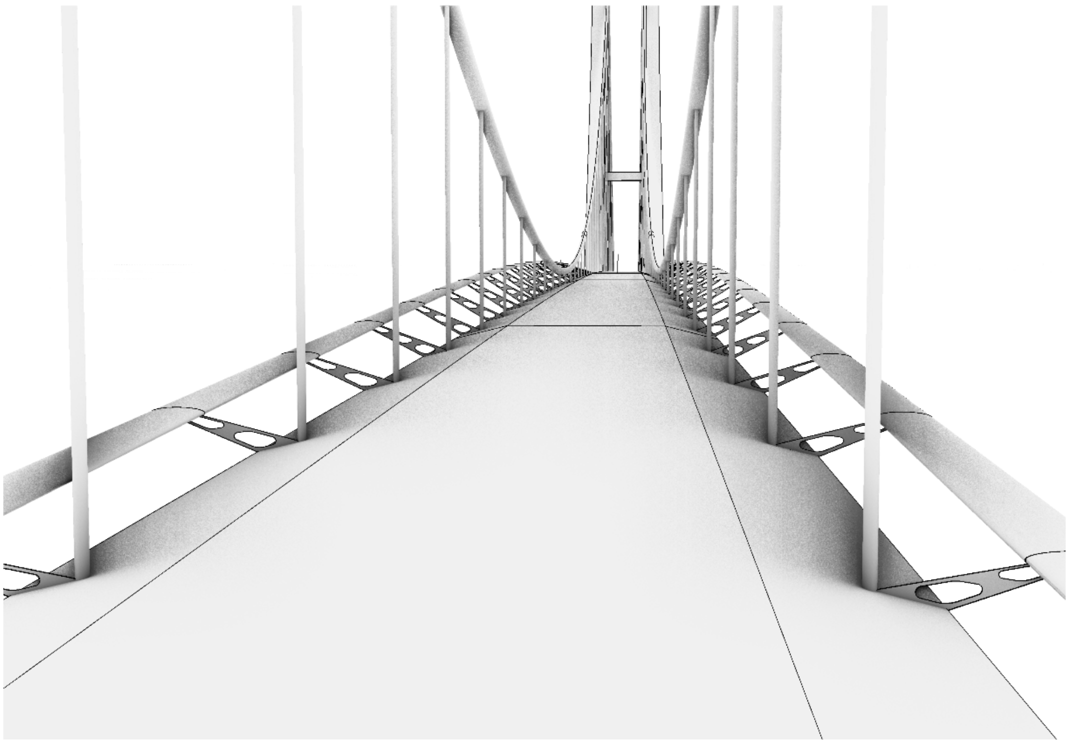

Fig. 6 Bridge with eccentric-wing flutter stabilizer – top view

8. CONCLUSIONS

The flutter speed of a bridge can significantly and cost-efficiently be raised by fixed wings that are eccentrically attached to the bridge deck. Wing configurations with large eccentricities are particularly effective but have encountered concerns about their aesthetic quality. Therefore, results for wings with a more moderate eccentricity, believed to alleviate aesthetic concerns while still being fairly effective in reducing the flutter speed, have been presented here. Another concern is that the strong flutter speed increase achieved by the wings cannot always be fully utilized given that torsional divergence may become governing over flutter. In such cases, for economy, the flutter speed increase produced by the wings should be lowered, by reducing the wing parameters, to the divergence speed. This can be achieved partly by reducing the wing eccentricity to the more moderate value suggested here, partly by additionally reducing the wing length. It is found that, for certain bridges, eccentric wings continue to be an interesting way to cost-efficiently raise the flutter resistance of a bridge. Renderings of a suspension bridge equipped with such moderate-eccentricity wings show that a pleasant appearance can result and hence concerns about the aesthetic quality of the eccentric-wing flutter stabilizer can be effectively addressed.

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