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CHAPTER 92

ACTIVE CONTROL OF LONG BRIDGES USING FLAPS[1]

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ABSTRACT

The main problem in designing ultra-long span suspension bridges is flutter. A solution to this problem might be to introduce an active flap control system to increase the flutter wind velocity. The investigated flap control system consists of flaps integrated in the bridge girder so each flap is the streamlined part of the edge of the girder. Additional aerodynamic derivatives are shown for the flaps and it is shown how methods already developed can be used to estimate the flutter wind velocity for a bridge section with flaps. As an example, the flutter wind velocity is calculated for different flap configurations for a bridge section model by using aerodynamic derivatives for a flat plate. The example shows that different flap configurations can either increase or decrease the flutter wind velocity. For optimal flap configurations flutter will not occur.

1. INTRODUCTION

During the last decades the span length of suspension bridges has grown rapidly. A major limitation for the growth of span length of suspension bridges is that the inherent flexibility of the long span will cause such bridges to be very sensible to dynamic loading. To increase the span length the suspension bridge can be optimised with regard to materials, deck shapes and cables. Another possibility may be to introduce the so-called *intelligent bridge*, where active control systems are used to limit the vibrations.

The main problem in designing ultra-long span suspension bridges is flutter,

[1] Proc. Second World Conference on Structural Control, Kyoto, Japan, June 28 – July 1, 1998. Wiley 1999, pp. 851-85.

which is an aeroelastic phenomenon. The oscillations in flutter are perpendicular to the wind direction and may be torsional, vertical or a combined torsional and vertical motion. The problem with flutter becomes more important with increasing span lengths as flutter is closely related to the stiffness of the bridge, which in turn is dependent on the span length.

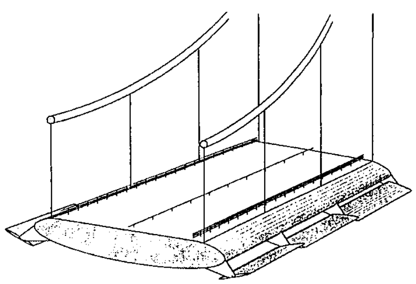
Active control systems for limitations of vibrations of civil engineering structures have primary been used to fulfill serviceability state and comfort demands. In this case a failure of the control system is not critical for the users of the structure or the structure itself. Therefore, the reliability of such systems is of less importance. Active control systems may, according to Ostenfeld and Larsen [1], be common elements in wind sensitive bridges in the future to enhance the comfort of the users.

The safety of a suspension bridge is governed by its response to infrequent and extreme loading, e.g. when it is exposed to the flutter wind velocity. As a result the active control system in an *intelligent bridge* may remain in stand-by mode for many years and perhaps decades without being activated. In this case it is very important that the control system is reliable at the very moment the dimensioning load is acting on the structure. The reliability of the control system can be improved by making several independent systems with separated power supplies and by performing regular tests, e.g. by frequent use of the active control system also to fulfill serviceability state and comfort demands.

2. ACTIVE CONTROL SYSTEM WITH FLAPS

In advanced aircrafts actively controlled surfaces are moved relatively to the main surfaces on which they exert control. The control surfaces are moved by hydraulics based on measurements from sensors attached to the main surfaces. The same principle could be applied to bridges as patented by COWIconsult [2]. Two types of actively controlled flaps are described in the patent:

1. Flaps arranged on pylons below the leading and trailing edge of the streamlined bridge girder, see figure 1a.
2. Flaps integrated in the bridge girder so each flap is the streamlined part of the edge of the girder, see figure 1b. This configuration obviates the additional flaps suspended below the bridge. This is important in terms of costs and gives the bridge an aesthetically nicer appearance. In the following this configuration is investigated.



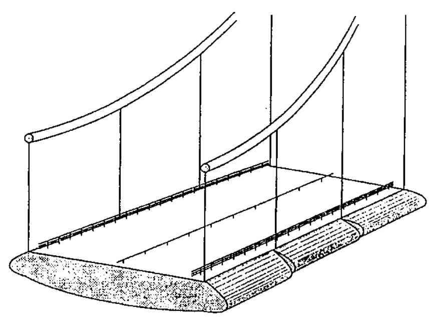


Figure 1a. Flaps on pylons below girder. Figure 1b. Flaps integrated in girder.

When the flaps are exposed to the wind they exert forces on the bridge girder. The directions and sizes of the forces can be regulated by regulating the flaps. By providing forces which counteract the motion of the girder the oscillations are damped.

A number of sensors are placed inside the bridge girder to measure the position or motion of the girder. The measurements are transmitted to the control unit, e.g. a computer. The flaps are regulated based on a control algorithm that uses the measurements. In this way the flaps can be regulated continuously to counteract the motion of the girder. The flaps are divided into sections in the longitudinal direction of the bridge. Each of these sections can be regulated independently. The overall safety of the active control system is increased by increasing the number of independent sections. The flaps are mounted on the bridge girder where they have the greatest effect, i.e. where the girder has the largest deflections.

3. DYNAMICS OF LONG SUSPENSION BRIDGES WITH FLAPS

For ultra-long span suspension bridges the main aeroelastic effect of concern is flutter. The total wind load on a bridge is composed by three components: the mean wind load, wind load from turbulence and the motion-induced wind load. In flutter the motion-induced wind load is the dominating part. Flutter occurs at a critical wind velocity at which the energy input from the motion-induced wind load is equal to the energy dissipated by structural damping.

The flutter phenomenon was first investigated in aerospace engineering and the relevant terms were carried over to wind engineering. Flutter of bridge sections is e.g. described by Simiu & Scanlan [3] and Larsen & Walther [4]:

- Single-degree flutter in torsion (also called stall flutter) is a pure torsional motion of the bridge section. The amplitude of the torsional oscillation grows with increasing wind velocity.
- Binary flutter (also called classical flutter) is a coupled vertical and torsional motion of the bridge section. Once the wind velocity exceeds the flutter wind velocity the oscillations grow to catastrophic amplitudes.

Based on principles of potential flow theory Theodorsen [5] has shown that for thin airfoils in incompressible flow the motion-induced vertical load and the motion-induced moment on the airfoil are linear in the vertical displacement, the torsional angle and their first and second derivatives. Assuming harmonic vibrations at the frequency ω the motion-induced forces due to movement of the bridge deck have been formulated by Scanlan

$$F_{ad}^{P} = \frac{1}{2}\rho U^2 B\left[KH_1^*(K)\frac{\dot{z}}{U} + KH_2^*(K)\frac{B\dot{\alpha}}{U} + K^2H_3^*(K)\alpha + K^2H_4^*(K)\frac{z}{B}\right]$$

$$F_{ad}^{M} = \frac{1}{2}\rho U^2 B^2\left[KA_1^*(K)\frac{\dot{z}}{U} + KA_2^*(K)\frac{B\dot{\alpha}}{U} + K^2A_3^*(K)\alpha + K^2A_4^*(K)\frac{z}{B}\right]$$

where F_{ad}^{P} and F_{ad}^{M} are the motion-induced vertical wind load (positive downwards) and the motion-induced moment (positive clockwise) due to movement of the bridge deck. The two degrees of freedom for the bridge section are described by the vertical displacement z (positive downwards) and the torsional angle α (positive clockwise). Further, ρ is the mass density of air, U is the mean wind velocity, B is the width of the bridge section, $K = B\omega/U$ is the reduced frequency and $H_1^*,\dots,H_4^*$ and $A_1^*,\dots,A_4^*$ are aerodynamic derivatives.

As for the airfoil, Theodorsen has shown that the loads due to movement of a trailing flap on a thin airfoil in incompressible flow are linear in the angle of the trailing flap and the first and second derivatives. By assuming that the angle of a leading flap has no effect on the circulation it can be shown that the loads due to movement of a leading flap on a thin airfoil are also linear in the angle of the leading flap and the first and second derivatives. The motion-induced wind loads due to movement of the flaps can therefore be described by additional derivatives.

$$F_{af}^{P} = \frac{1}{2}\rho U^2 B\left[KH_5^*(K)\frac{B\dot{\alpha}_t}{U} + K^2 H_6^*(K)\alpha_t + KH_7^*(K)\frac{B\dot{\alpha}_l}{U} + K^2 H_8^*(K)\alpha_l\right]$$

$$F_{af}^{M} = \frac{1}{2}\rho U^2 B^2\left[KA_5^*(K)\frac{B\dot{\alpha}_t}{U} + K^2 A_6^*(K)\alpha_t + KA_7^*(K)\frac{B\dot{\alpha}_l}{U} + K^2 A_8^*(K)\alpha_l\right]$$

where α_t and α_l are the angles of the trailing and leading flap, respectively, and $H_5^*,\ldots,H_8^*$ and $A_5^*,\ldots,A_8^*$ are additional aerodynamic derivatives.

The angles of the flaps are expressed in terms of the torsional angle of the bridge section as follows

$$\alpha_t(t) = a_t e^{-i\varphi_t}\alpha(t)$$

$$\alpha_l(t) = a_l e^{-i\varphi_l}\alpha(t)$$

where φ_t and φ_l are the phase angles between the flaps and the torsional angle and a_t and a_l are the flap amplification factors. A flap amplification factor is defined as the amplitude of the flap relative to the amplitude of the torsional motion. By expressing the angles of the flaps in terms of the torsional angle as shown above the methods described in the literature to estimate the flutter wind velocity can be used with aerodynamic derivatives H_2^*, H_3^*, A_2^* and A_3^* replaced by $H_2^*{}'$, $H_3^*{}'$, $A_2^*{}'$ and $A_3^*{}'$.

$$H_2^*{}'(K) = H_2^*(K) + H_5^*(K)a_t\cos(-\varphi_t) + H_6^*(K)a_t\sin(-\varphi_t) + H_7^*(K)a_l\cos(-\varphi_l) + H_8^*(K)a_l\sin(-\varphi_l)$$

$$H_3^*{}'(K) = H_3^*(K) - H_5^*(K)a_t\sin(-\varphi_t) + H_6^*(K)a_t\cos(-\varphi_t) - H_7^*(K)a_l\sin(-\varphi_l) + H_8^*(K)a_l\cos(-\varphi_l)$$

$$A_2^*{}'(K) = A_2^*(K) + A_5^*(K)a_t\cos(-\varphi_t) + A_6^*(K)a_t\sin(-\varphi_t) + A_7^*(K)a_l\cos(-\varphi_l) + A_8^*(K)a_l\sin(-\varphi_l)$$

$$A_3^*{}'(K) = A_3^*(K) - A_5^*(K)a_t\sin(-\varphi_t) + A_6^*(K)a_t\cos(-\varphi_t) - A_7^*(K)a_l\sin(-\varphi_l) + A_8^*(K)a_l\cos(-\varphi_l)$$

4. THEORETICAL EFFECT OF FLAPS

As an example the flutter wind velocity for binary flutter is estimated for a bridge section model with the parameters listed in table 1. The aerodynamic derivatives for the model are approximated by the values for a flat plate as summarised in appendix A.

The flutter wind velocity U_f for binary flutter is calculated for different flap amplification factors a_l and phase angles φ_l for the leading flap. The trailing flap is not moved. The results show that the flutter wind velocity is increased when the phase angle for the leading flap φ_l is in the interval $[0.6\pi/6;\ 6.6\pi/6]$, otherwise the flutter wind velocity is decreased. The phase angle for maximum increase of the flutter wind velocity is dependent on the value of the flap amplification factor a_l.

Parameter	Symbol	Value
Width of model excl. flaps	B'	0.625 m
Length of flaps	$0.25B'$	0.156 m
Width of model incl. flaps	B	0.937 m
Location of hinge	c	0.667
Mass per unit length	m	17.94 kg/m
Mass moment of inertia per unit length	I	0.589 kg m²/m
Circular frequency for bending	ω_z	5.2 rad/s
Circular frequency for torsion	ω_α	10.1 rad/s
Structural damping in bending	ζ_z	0.012
Structural damping in torsion	ζ_α	0.008
Mass density of air	ρ	1.28 kg/m³

Table 1. Parameters for bridge section model.

The flutter wind velocity U_f for binary flutter is calculated for different values of a_t and φ_t for the trailing flap. The leading flap is not moved. The results show that the interval where the flutter wind velocity is increased when the trailing flap is moved is dependent on the flap amplification factor a_t. The flutter wind velocity is generally decreased when the phase angle of the trailing flap φ_t is in the interval $[\pi/6;\ 6\pi/6]$. For phase angles outside this interval the flutter wind velocity is generally increased. Again the phase angle for maximum increase of the flutter wind velocity is dependent on the value of the flap amplification factor a_t.

The trailing flap is much more efficient than the leading flap. The potential theory used assumes that there is no separation of the flow around the flat plate. This assumption can hardly be met in practice, therefore it is expected that the effect of the trailing flap is over-estimated by the Theodorsen theory for a flat plate.

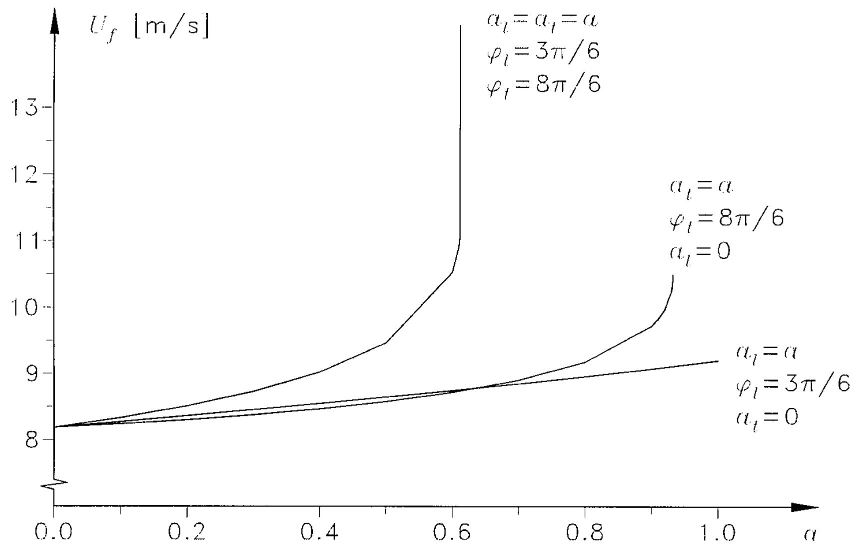


Figure 2. Movement of both flaps compared to movement of the flaps separately.

For small values of the flap amplification factors the optimal phase angles are $\varphi_l \approx 3\pi/6$ and $\varphi_t \approx 8\pi/6$. These phase angles are used in figure 2 where movement of both flaps compared to movement of the leading and trailing flap separately is shown.

As seen in figure 2 the flutter wind velocity is only slightly increased for flap amplification factors below about 0.8 when only one flap is moved. When the trailing flap is moved with a flap amplification factor a_t above 0.8 the flutter wind velocity is increased considerably, and for $a_t > 0.95$ binary flutter will not occur. By using both flaps binary flutter will not occur when both flap amplification factors are above about 0.6.

5. CONCLUSIONS

In this paper an active flap control system has been presented. The flap control system can be used to fulfil serviceability state and comfort demands or it can be used to increase the flutter wind velocity for ultra-long span suspension bridges. The system consists of sensors inside the bridge girder that measure the position of the girder. These measurements are used in a control algorithm to calculate the optimal flap positions. The flaps are then regulated continuously according to the calculated optimal positions.

The motion-induced wind loads on a bridge section are defined based on aerodynamic derivatives for the bridge deck and additional aerodynamic derivatives for movement of the flaps. By expressing the angles of the flaps in terms of the torsional angle of the bridge section the methods described in the literature can be used to estimate the flutter wind velocity for the bridge section with flaps. This is done by simply replacing some of the aerodynamic derivatives with expressions including the parameters describing the flap configuration.

The theoretical effect of the flaps is shown by an example. The flutter wind velocity is calculated for different flap configurations for a bridge section model with flaps. The aerodynamic derivatives are approximated by the aerodynamic derivatives for a flat plate. In the derivation of the additional aerodynamic derivatives for the leading flap it is assumed that movement of this flap does not affect the circulation. It can be concluded that the trailing flap is more efficient than the leading flap. But moving both flaps is again more efficient than moving only the trailing flap. The example shows that it is theoretically possible to eliminate the flutter problem for the investigated bridge section model by using the active flap control system.

In the example the potential theory is used and thereby it is assumed that there is no separation of the flow around the bridge section. This assumption can hardly be met in practice and therefore, it is expected that the effect of the trailing flap is overestimated in the example. Wind tunnel experiments performed with the described bridge section model show that the active flap control system is very efficient. But more tests are needed to compare the efficiency of the flaps on a bridge section model with the efficiency of the flaps on a flat plate.

ACKNOWLEDGEMENTS

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APPENDIX A. AERODYNAMIC DERIVATIVES FOR A FLAT PLATE

In this appendix aerodynamic derivatives for a flat plate with flaps are summarised.

$$H_1^*(K) = -\frac{\pi F(k)}{k} \qquad A_1^*(K) = \frac{\pi F(k)}{4k}$$

$$H_2^*(K) = -\frac{\pi}{4k}\left[1 + F(k) + \frac{2G(k)}{k}\right] \qquad A_2^*(K) = -\frac{\pi}{16k}\left[1 - F(k) - \frac{2G(k)}{k}\right]$$

$$H_3^*(K) = -\frac{\pi}{2k^2}\left[F(k) - \frac{kG(k)}{2}\right] \qquad A_3^*(K) = \frac{\pi}{8k^2}\left[\frac{k^2}{8} + F(k) - \frac{kG(k)}{2}\right]$$

$$H_4^*(K) = \frac{\pi}{2}\left[1 + \frac{2G(k)}{k}\right] \qquad A_4^*(K) = -\frac{\pi}{4}\frac{G(k)}{k}$$

Additional aerodynamic derivatives for a trailing flap.

$$H_5^*(K) = \frac{1}{4k}\left[T_4 - F(k)T_{11} - \frac{2G(k)T_{10}}{k}\right]$$

$$H_6^*(K) = \frac{1}{4k^2}\left[-k^2 T_1 - 2F(k)T_{10} + kG(k)T_{11}\right]$$

$$A_5^*(K) = \frac{1}{8k}\left[-\left(T_1 - T_8 - cT_4 + \frac{T_{11}}{2}\right) + \frac{F(k)T_{11}}{2} + \frac{G(k)T_{10}}{k}\right]$$

$$A_6^*(K) = \frac{1}{8k^2}\left[-(T_4 + T_{10}) - k^2(T_7 + cT_1) + F(k)T_{10} - \frac{kG(k)T_{11}}{2}\right]$$

Additional aerodynamic derivatives for a leading flap.

$$H_7^*(K) = \frac{T_4}{4k} \quad A_7^*(K) = -\frac{1}{8k}\left[T_1 - T_8 - cT_4\right]$$

$$H_8^*(K) = -\frac{T_1}{4} \quad A_8^*(K) = \frac{1}{8k^2}\left[-T_4 - k^2(T_7 + cT_1)\right]$$

where the T-constants are defined by Theodorsen, c is the location of the flap hinge relative to mid chord and k is the reduced frequency based on the half chord, i.e. $k = K/2$.

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