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Abstract: In this paper some recent research on active control of very long suspension bridges is presented. The presentation is based on research work at Aalborg University, Denmark. The active control system is based on movable flaps attached to the bridge girder. Wind loading on bridges with and without flaps attached to the girder is briefly presented. A simple active control system is discussed. Results from wind tunnel experiments with a bridge section show that flaps can be used effectively to control bridge girder vibrations. Flutter conditions for suspension bridges with and without flaps are presented. The theory is illustrated by an example.

Key words : Suspension Bridges, Active Control, Flutter, Wind Tunnel Tests, Bridge Flaps, Aeroelastic Forces.

1. Introduction

There is a growing need for extremely long suspension bridges. Such bridges have already been designed for the future, but are not yet constructed. The longest suspension bridge today is the Akashi Kaikyo Bridge in Japan (main span 1991 m) and the second largest is the Great Belt East Bridge in Denmark (main span 1624 m), see figure 1. It is believed that in the future designs with improved girder forms, lightweight cables, and control devices may be up to 5000 m long. For such extremely long bridges, girder stability in the wind may be a serious problem, especially when the girder depth-to-width ratio is small compared with existing long bridges.

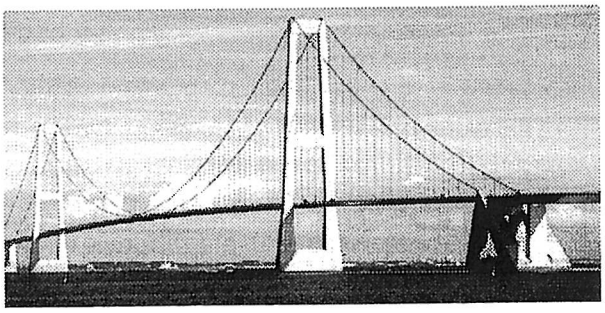


Figure 1. Great Belt East Bridge, Denmark

The main problem is the aeroelastic phenomenon called flutter. Flutter occurs when the bridge is exposed to a wind velocity above a critical value – the flutter wind velocity U_{cr}. Flutter oscillations are perpendicular to the direction of the wind. The flutter problem becomes more serious with increasing span length since U_{cr} decreases with decreasing stiffness and damping.

Passive and active control devices seem to be a solution to the girder stability problem. A large number of proposals for such devices have already been given, e.g. viscoelastic damping elements, turned damping elements and eccentric masses. However, in this paper only actively controlled long suspension bridges will be discussed in detail.

In 1992 Ostenfeld and Larsen [1] proposed to ensure the aerodynamic stability of slender girders by attaching actively controlled flaps along the girder. When these flaps are exposed to wind they exert forces on the bridge girder. The intention is to control the rotation of the flaps in such a way that these forces counteract the aerodynamic forces and therefore damp the oscillations. The motion of the girder is measured by a number of sensors attached to the girder. The signal is transmitted to a control unit, which will rotate the flaps so that an optimal rotation of the flaps is obtained. 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.

At Aalborg University two topics within this area have been investigated in recent years, see the Ph.D. thesis by Hansen [2] and Huynh [3]. The results of these studies are published in several papers e.g. by Hansen & Thoft-Christensen [4], [5], [6], Hansen, Thoft-Christensen, Mendes & Branco [7], and Huynh & Thoft-Christensen [8] ,[9].

In the first thesis, wind tunnel experiments with a sectional model of a girder are performed. Control flaps are installed as integrated parts of the leading and trailing edges of the girder. The experiments with the sectional model confirm that the flap control system is a very efficient way to limit the vibrations. An estimate of the flutter wind velocity for a section with flaps can be obtained simply by replacing the aerodynamic derivatives by expressions including the parameters describing the flap configuration. The theoretical effect of the flaps is confirmed by the experiments. On the basis of the experiments it can be concluded that the trailing flap is more efficient than the leading flap. However, moving both flaps is more efficient than using only the trailing flap. It is also shown that it is theoretically possible to eliminate the flutter problem for the investigated bridge section model by using the active flap control system. The effect of the trailing flap is probably overestimated since separation of the flow around the bridge section is not taken into account.

In the second thesis analysis of a full span suspension bridge is performed. Separate control flaps are installed in front of and under the leading and the trailing edges of the girder. The full span-bridge computation shows that the girder vibrations can be reduced depending on the following three factors concerning the control flaps: the total sectional length of the flaps, the rotational directions and the rotational magnitudes of the flaps. The girder used in the Great Belt Bridge is used for the analysis. For a given configuration of the flaps it is shown that the flutter wind velocity U_{cr} can be increased by 50% compared with the case with no flaps. Not only the flutter response can be limited by the flap rotations, but also the buffeting response can be reduced in the mean square value. The flap rotations in turbulence conditions will change the angle of attack of the wind to the flaps so that the total buffeting induced forces acting on the girder system are reduced. The stochastic buffeting responses can be derived by a conventional stochastic response analysis in modal coordinates, and in accordance with the wind load consisting of a stochastic buffeting term and an aeroelastic term.

Controlling the vibrations of civil engineering structures using active control systems has been used primarily to fulfil serviceability and comfort requirements. For such cases failure of the control system is not critical for the users of the structures or the structure itself. The situation is completely different with regard to controlling the safety of a long-span bridge using a control system. In such a case a passive control system is preferred.

2. Wind Loads on Suspension Bridges

The three most important vibrations of a suspension bridge girder are motion-induced vibrations, buffeting-induced vibrations and vortex-induced vibrations. The motion-induced wind loads (aeroelastic forces) depend directly on deformations and deformation velocities of the girder, and are the subject of this paper. The buffeting-induced wind loads are the fluctuating wind loads due to the turbulence of the wind.

For thin airfoils in incompressible flow assuming potential flow theory Theodorsen [10] has shown that the motion-induced vertical load $L_{ae}(x,t)$ and the motion-induced moment $M_{ae}(x,t)$ on the airfoil are linear in theoretical displacement and the torsional angle and their first and second derivatives. Scanlan and Tomko [11] introduced this formulation into the bridge area. Let x, y and z be coordinates in the direction of the bridge, across the bridge and in the vertical direction, and let t be the time. The aeroelastic forces L^{deck} and M^{deck} per unit span and for small rotations can then be written, see Similu & Scanlan [12]

$$L^{deck}(x,t) = \frac{\rho U^2 B}{2}\left[KH_1^*(K)\frac{\dot{v}_z}{U} + KH_2^*(K)\frac{B\dot{r}_x}{U} + K^2H_3^*(K)r_x + K^2H_4^*(K)\frac{v_z}{B}\right]$$

$$M^{deck}(x,t) = \frac{\rho U^2 B^2}{2}\left[KA_1^*(K)\frac{v_z}{U} + KA_2^*(K)\frac{Br_x}{U} + K^2A_3^*(K)r_x + K^2A_4^*(K)\frac{v_z}{B}\right]$$

K is the non-dimensional reduced frequency $K=B\omega/U$ where B is the girder width, U is the mean wind velocity, ω is the bridge oscillating frequency in radians at the wind velocity U, and ρ is air density. $H_i^*(K)$ and $A_i^*(K)$ (i=1,2,3,4) are non-dimensional aerodynamic derivatives determined in a wind tunnel. The quantities r_x, $\dot{v}_z/U$ and $B\dot{r}_x/U$ are non-dimensional, effective angles of attack. An example of an aerodynamic derivative for the Great Belt girder is $H_1^*(u) = 7u^3/649664 - 82u^2/5959 - 593u/4718 + 82/11989$, where $u=2\pi/K$.

3. Bridge Girders with Flaps

Two types of actively controlled flaps are shown in figure 2: Flaps arranged on pylons below the leading and trailing edge of the streamlined bridge girder and flaps integrated in the bridge girder so each flap is the streamlined part of the edge of the girder.

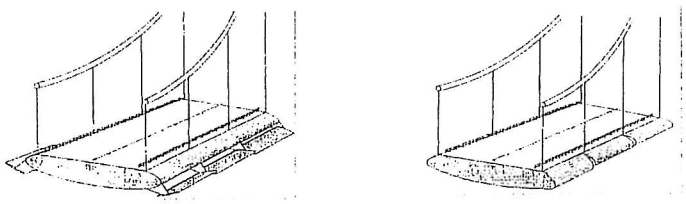


Figure 2. Sections with flaps on pylons and integrated in the section

When the flaps are exposed to the wind they exert forces on the bridge girder. Regulating the flaps can control the directions and sizes of the forces. 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 active control system is shown in figure 3.

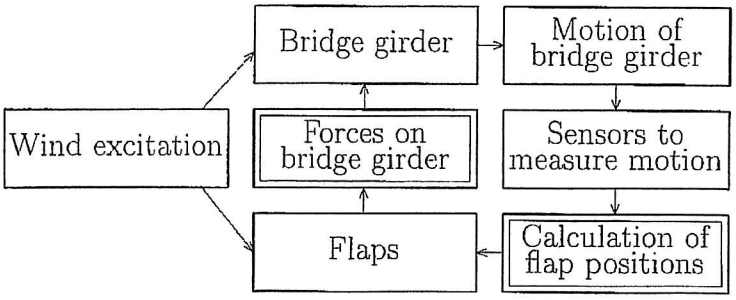


Figure 3. Active Control System.

As for the airfoils, 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.

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

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

where α_t and α_l are the angles of the trailing and leading flap, respectively, and $H_i^*(K)$ and $A_i^*(K)$ $(i = 5,6,7,8)$ are additional aerodynamic derivatives. The angles of the flaps are expressed in terms of the torsional angle of the bridge section as follows $\alpha_t(t) = a_t e^{-i\varphi_t}\alpha(t)$ and $\alpha_l(t) = a_l e^{-i\varphi_l}\alpha(t)$, 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. For a bridge section with the same parameters as the model used in the wind tunnel tests, see section 3, the theoretical effect of the flaps is illustrated in figure 3. 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 reduced. The flutter wind velocity 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 reduced 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. The trailing flap is much more efficient than the leading flap.

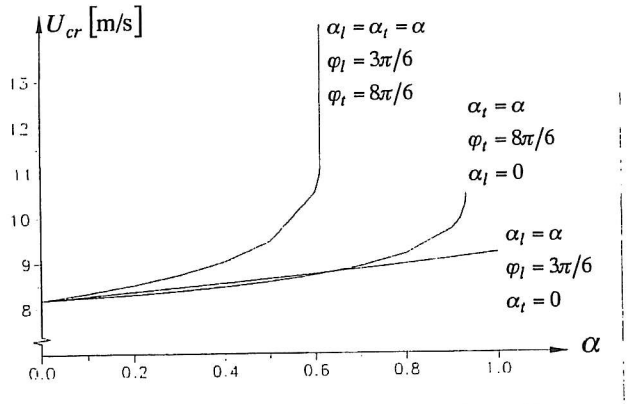


Figure 4. Theoretical effect of flaps.

3. Wind Tunnel Tests

Wind tunnel testing of a bridge section model has been performed in a wind tunnel at Instituto Superior Téchnico in Lisbon, Portugal. The model is shown in figure 4. The regulation system to move the flaps consists of three parts: a servo system, regulation software to position the flaps, and control software to calculate the desired positions of the flaps. A servo system consists of a servo amplifier, a servomotor and a reduction gear. Two servo systems are used so that the flaps can be regulated independently. The reduction gears and servomotors are fixed inside the bridge section model. Each reduction gear is connected to the flaps via cables. Each servomotor is connected to a servo amplifier, which is placed outside the model.

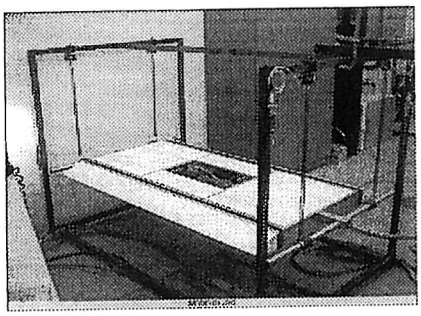


Figure 5. Wind tunnel model.

Figures 6 and 7 show the torsional movement of the model when the flaps are not regulated (configuration 0) and when they are regulated (configuration 2). The wind speed is 6.1 m/s. Note that the units on the x-axis are different in the two figures. The conclusion is that configuration 2 is very efficient to control the torsional motion of the model. During the first second the torsional motion is reduced from 2.7^0 to 11^0, i.e. 62%.

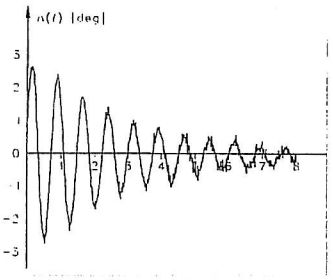


Figure 6. Torsional motion for flap configuration 0 and wind speed 6.1 m/s.

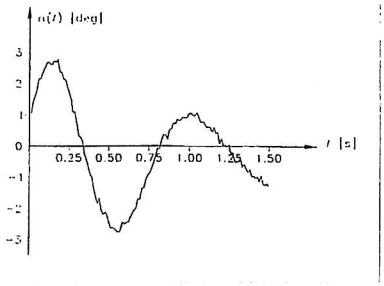
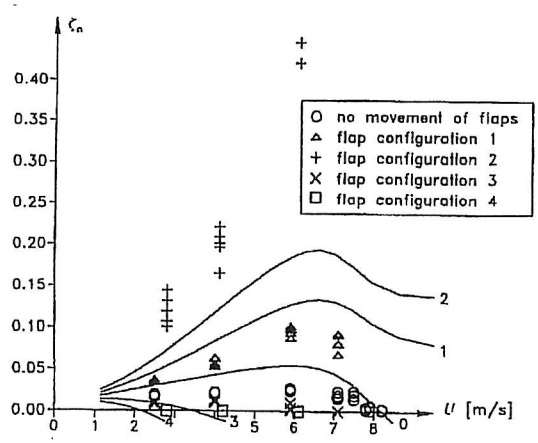


Figure 7. Torsional motion for flap configuration 2 and wind speed 6.1 m/s.

As seen in figure 8, the experimental damping ratio is smaller for flap configurations 0 and 1 than the theoretical damping ratio, but the shape of the curve is almost the same. For flap configuration 2 the experimental damping ratio exceeds the theoretical one. For flap configurations 1 and 2, the theoretical curves show that no binary flutter will occur.



Configu-ration	a_t	a_l
0	0	0
1	1.9	2.0
2	3.4	3.6
3	2.0	2.0
4	3.4	3.6

Figure 8. Theoretical (solid lines) and experimental damping ratio for torsional motion with wind for flap configuration 0-4. The number at the end of a solid line denotes the actual flap configuration.

5. Suspension Bridge with Controlled Separate Flaps

In this section the flutter vibration is considered where the first vertical vibration mode and the first torsional vibration mode are coupled together in one vibration. The wind velocity that causes this coupling is called the critical wind velocity U_{cr} , and the associated frequency is called the critical frequency ω_{cr}. Determination of U_{cr} and ω_{cr} is based on the modal analysis. The vertical displacement $z_i(x,t)$ in mode i and the rotation $\alpha_j(x,t)$ in mode j are given by

$$M_z\left(\ddot{z}(t)+2\omega_z\zeta_z\dot{z}(t)+\omega_z^2 z(t)\right)=F_z^{deck}=H1\,\dot{z}(t)+H2\,\dot{\alpha}(t)+H3\,\alpha(t)+H4\,z(t)$$

$$M_x\left(\ddot{\alpha}(t)+2\omega_\alpha\zeta_\alpha\dot{\alpha}(t)+\omega_\alpha^2\alpha(t)\right)=F_x^{deck}=A1\,\dot{z}(t)+A2\,\dot{\alpha}(t)+A3\,\alpha(t)+A4\,z(t)$$

where ω_z, ζ_z and ω_α and ζ_α are the natural frequencies and the damping ratios of the vertical and torsional modes. For coupled vertical-torsional motion, the vertical and torsional modal responses are proportional to $e^{i\omega t}$, when the critical wind velocity is acting on the bridge, i.e.

$z(t) = z_0 e^{i\omega t}$ and $\alpha(t) = \alpha_0 e^{i\omega t}$. When this is introduced in the equations above the following matrix equation can be derived

$$A\begin{bmatrix} z/B \\ \alpha \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

where the matrix A depends of the natural frequencies, the damping ratios, the derivatives, the vibration modes and the wind velocity. This matrix equation has non-trivial solutions when

$$Det(A) = \mathrm{Re}\,Det(A) + i\,\mathrm{Im}\,Det(A) = 0$$

resulting in the following two flutter conditions for a bridge *without flaps*

$$\begin{aligned}\mathrm{Re}\,Det(A) = {} & \frac{\omega^4}{\omega_z^4}\left(1 + \frac{\rho B^4 A_3^*}{2J} + \frac{\rho B^2 H_4^*}{2m} + \frac{\rho^2 B^6}{4mJ}\left(-H_1^* A_2^* + H_4^* A_3^* + \frac{\Xi\Xi}{\Phi\Psi}\left(-A_4^* H_3^* + A_1^* H_2^*\right)\right)\right) \\ & + \frac{\omega^3}{\omega_z^3}\left(\frac{\rho B^4 A_2^*}{J}\zeta_z + \frac{\rho B^2 H_1^*}{m}\frac{\omega_\alpha}{\omega_z}\zeta_\alpha\right) \\ & + \frac{\omega^2}{\omega_z^2}\left(-1 - \frac{\omega_\alpha^2}{\omega_z^2} - 4\zeta_z\zeta_\alpha\frac{\omega_\alpha}{\omega_z} - \frac{\rho B^4 A_3^*}{2J} - \frac{\rho B^2 H_4^*}{2m}\frac{\omega_\alpha^2}{\omega_z^2}\right) + \frac{\omega_\alpha^2}{\omega_z^2} = 0\end{aligned}$$

$$\begin{aligned}\mathrm{Im}\,Det(A) = {} & \frac{\omega^3}{\omega_z^3}\left(\frac{\rho B^4 A_2^*}{2J} + \frac{\rho B^2 H_1^*}{2m} + \frac{\rho^2 B^6}{4mJ}\left(H_1^* A_3^* + A_2^* H_4^* + \frac{\Xi\Xi}{\Phi\Psi}\left(-A_1^* H_3^* - A_4^* H_2^*\right)\right)\right) \\ & + \frac{\omega^2}{\omega_z^2}\left(-2\zeta_z - 2\zeta_\alpha\frac{\omega_\alpha}{\omega_z} - \zeta_\alpha\frac{\rho B^2 H_4^*}{m}\frac{\omega_\alpha}{\omega_z} - \zeta_z\frac{\rho B^4 A_3^*}{J}\right) \\ & + \frac{\omega}{\omega_z}\left(-\frac{\rho B^4 A_2^*}{2J} - \frac{\rho B^2 H_1^*}{2m}\frac{\omega_\alpha^2}{\omega_z^2}\right) + 2\zeta_z\frac{\omega_\alpha^2}{\omega_z^2} + 2\zeta_\alpha\frac{\omega_\alpha}{\omega_z} = 0\end{aligned}$$

where ($\phi_1(x)$ and $\psi_1(x)$ are the vertical and torsional modes

$$\Phi = \int_0^L \phi_1^2(x)dx \;,\; \Xi = \int_0^L \phi_1(x)\psi_1(x)dx \;,\; \text{and} \;\; \Psi = \int_0^L \psi_1^2(x)dx$$

The flutter conditions for a girder *with* flaps are similar to the flutter conditions shown above, but F_x^{deck} and F_z^{deck} are replaced by $F_x^{total} = F_x^{deck} + F_x^{flap}$ and $F_z^{total} = F_z^{deck} + F_z^{flap}$.

6. Example

In this section the theory presented above is illustrated by an example taken from Huynh [3]. The suspension bridge shown on figure 9 is considered. It has a streamlined cross- section similar to the cross section of the Great Belt Bridge. The cable sag is 265 m, the pylon top is 360 m, the girder depth is 4 m, and the girder cross- sectional area is 1056 m^2. The data concerning mass and damping etc. can be found in [3].

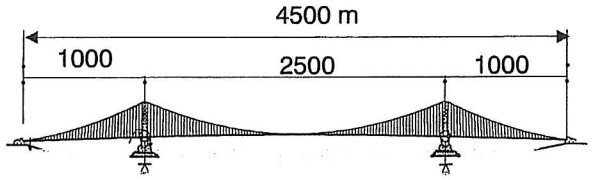


Figure 9. Suspension bridge used in the example.

The natural frequencies of the first symmetrical vertical and torsional modes are 0.404 rad/s and 1.276 rad/s, respectively. The solution of the flutter conditions is performed graphically for the girder without flaps. The critical wind velocity is U_{cr}= 58.21 m/s and the corresponding critical frequency is ω_{cr} = 0.853 rad/s.

The flutter solutions for the girder with flaps are investigated for four different configurations of the flaps. The most interesting configuration is theconfiguration "Minus – Plus", where the leading flap rotates against the girder, and the trailing flap rotates with the girder, see figure 10.

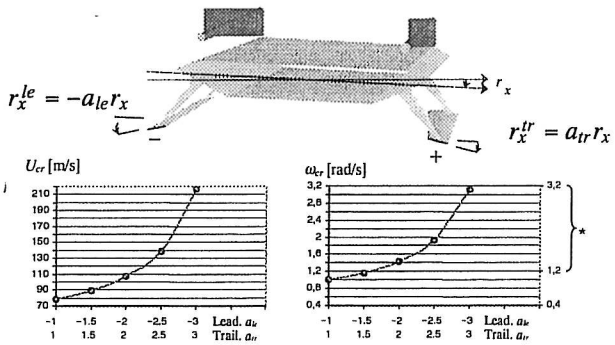


Figure 10. Configuration "Minus-Plus".

In figure 10 the variation of the critical wind velocity U_{cr} and the corresponding frequency ω_{cr} for several combinations of a_{le} and a_{tr} is shown. U_{cr} strongly increases with a small rotation of the flaps. For full flaps in the main span and the side spans, and for $r_x^{le} = -1.5 r_x$ and $r_x^{tr} = 1.5 r_x$, U_{cr} increases from 58.2 to 89.6m/s, i.e. 54%. The critical frequency ω_{cr} increases to the ST1 frequency (symmetrical torsional frequency) and indicates the torsional divergent flutter. By increasing a_{le} and a_{tr} up to –3 and 3, U_{cr} and ω_{cr} can still be found, but ω_{cr} exceeds the ST1 frequency indicating that the higher modes can be involved in the flutter.

7. Control of Vibrations

Several authors have treated control of structures; see e.g. Meirovitch [13]. The general theory will not be discussed here, but some results from applying the theory to the example suspension bridge in section 5 will be presented.

Consider n vertical and m torsional vibration modes. Then the state vector $q(t) = [a(t)\ \dot{a}(t)\ ]$ is determined by the state equation

$$\dot{q}(t) = Aq(t) + BF^{flap}(t)$$

where the system matrix A depends on the mean wind velocity U and the frequency ω of the bridge subjected to the wind. B depends of the modal masses.

The steady-state solution of the optimal control problem involving a quadratic performance measure can be obtained in closed form. The performance measure can be written

$$J = \sum_{i=1}^{n+m} J_i$$

where

$$J_i = \int_0^{t_f} \left[\underbrace{w_i^T(t) Q_i w_i(t)}_{\text{control state}} + \underbrace{W_i^T(t) R_i W_i(t)}_{\text{control force}} \right] dt$$

is the modal performance measure in mode i, $i=1,2,...,n+m$. $w_i(t)$ is the modal displacement vector and $Q_i(t)$ is the state weighting matrix. $W_i(t)$ is the modal control force vector and $R_i(t)$ is the control weighting matrix for mode i defined by

$$R_i^{-1} = \begin{bmatrix} R_{i1}^{-1} & 0 \\ 0 & R_{i2}^{-1} \end{bmatrix}$$

The physical responses in the vertical and the torsional mode at the centre of the main span are shown in figures 11 and 12 for different values of the control parameters R_1 and R_2. The responses and the response velocities are quickly reduced with reducing control-weighting factor $R = R_1 = R_2$ (more control forces required). The maximum vertical response is approximately 0.8 m and the maximum torsional response is about 2 degrees at the centre main span. The associated maximum velocities are about 0.6 m/s and 2 deg/s.

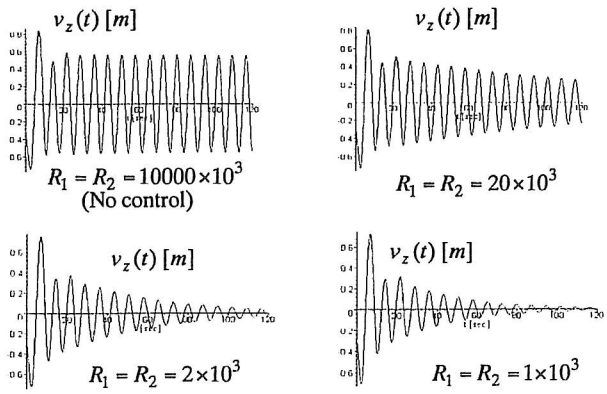


Figure 11. Control of vertical response in the main span centre.

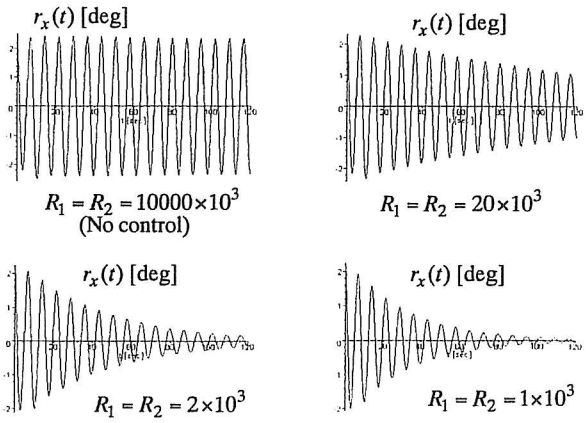


Figure 12. Control of torsional response in the main span centre.

8. Literature

Detailed information on wind loading and vibration of long suspension bridges may be obtained from the references mentioned above and from excellent contributions in books like references [14] to [22].

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