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Torsional Flutter of a Suspension Bridge

Effets de la turbulence du vent sur les vibrations de torsion dans les ponts suspendus

Torsionflattern von Hängebrücken

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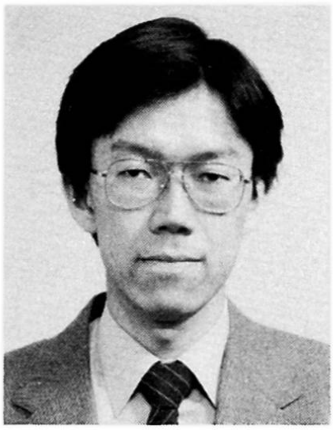

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SUMMARY
The effects of two types of phenomena existing under strong wind on the torsional flutter of a suspension bridge are discussed; one is the effects of wind-induced deformation of the structure, and another is those of the limited-amplitude cross-wind oscillation due to, for instance, vertical component of turbulent air flow. With the aid of sectional model experiment in a wind tunnel, it was found that the both effects mentioned above might raise the critical flutter speed to some extent.

RESUME
Cet article décrit les deux causes des vibrations torsionnelles des ponts suspendus sous l'effet de vents violents. L'une est due à la déformation de la structure créée par le vent et l'autre aux turbulences. Ce fait a été mis en évidence en soufflerie par des essais sur modèle.

ZUSAMMENFASSUNG
Zwei Arten von Erscheinungen, die bei starkem Wind auf das Torsionsflattern von Hängebrücken einwirken, werden diskutiert: der Einfluss von windinduzierten Verformungen des Tragwerkes und die beschränkte Amplitude von Querwindschwingungen, bedingt z.B. durch die lotrechte Komponente der turbulenten Windströmung. Mit Hilfe von Modellversuchen im Windkanal wurde festgestellt, dass beide genannten Einflüsse die kritische Flattergeschwindigkeit zu erhöhen vermögen.

1. INTRODUCTION

Self-excited vibrations of very flexible structures subject to wind, if occurred, are most catastrophic. Although various investigations concerned have been conducted since the well-known collapse of the old Tacoma Narrows Bridge, more realistic considerations seem to be needed to achieve the rational design of these structures.

This contribution deals with the effects of two types of phenomena existing under the action of strong wind on the torsional flutter of a suspension bridge; one is the effects of wind-induced deformation of the structure, and another is those of the limited-amplitude cross-wind oscillation due to, for instance, vertical component of turbulent air flow. The torsional flutter dominates often the design of a long-span suspension bridge, the stiffening frame of which is a truss with closed deck or a relatively shallow plate girder type.

2. EFFECTS OF WIND-INDUCED DEFORMATION

2.1 Coupled Free Oscillations

The dynamic characteristics of a long-span suspension bridge under strong wind will be more or less different from those at unloaded state, because the structure is so flexible as to cause considerable deformations due to wind pressure (Fig. 1). Fig. 2 shows an example of the first torsion-dominant vibration mode of a suspension bridge subject to very strong wind. It is found that the torsional component and the corresponding natural frequency under wind loading are not so much different from those at unloaded state, whereas the coupling between torsional, lateral and vertical components tends to be introduced by the static deformations due to wind force.

These coupled oscillations are associated with the rotational motion about a certain axis shown in Fig. 3. This centre of rotation locates at the point shifting from the shear centre of the bridge deck cross section as seen in the same figure. Fig. 4 shows the range of possible position of the centre of rotation, S_V and S_H, versus the maximum lateral displacement in the centre span of the bridge. Here we can find that the horizontal shift of rotation centre increases almost linearly with increasing lateral deflection while vertical shift changes slightly. It was also observed that the equivalent polar moment of inertia, that is the generalized mass for torsional mode, increased notably with increasing lateral deflection of the bridge.

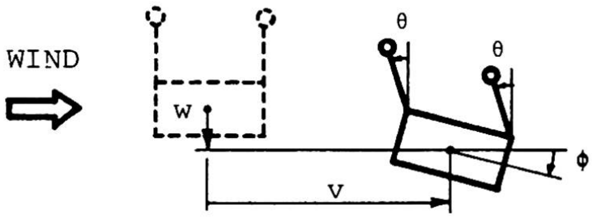


Fig. 1 Static deformation due to strong wind

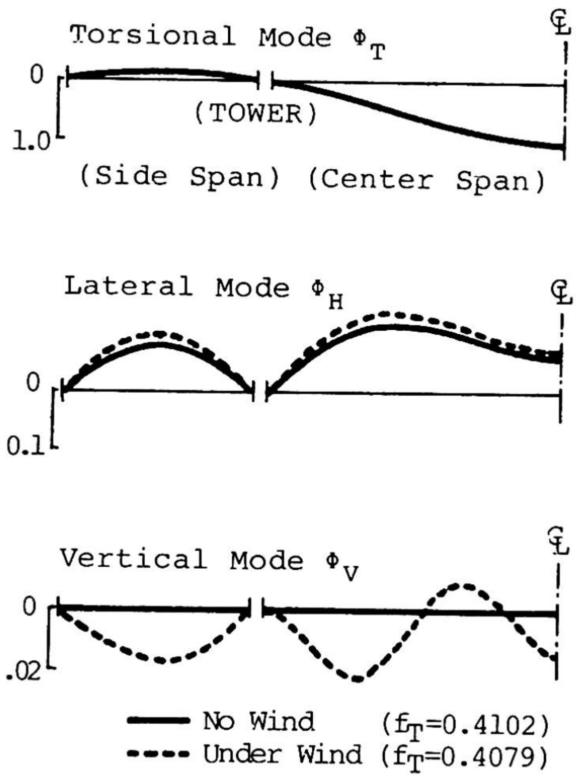


Fig. 2 Coupling in the first torsional mode of vibration

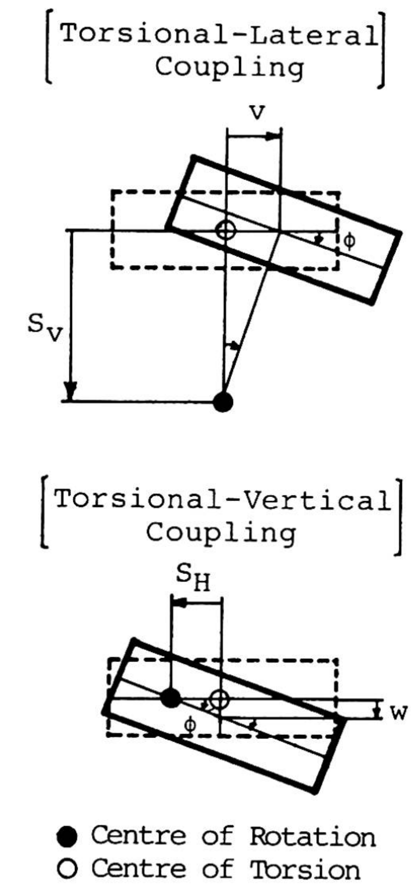


Fig. 3 Centre of rotation in coupled motion

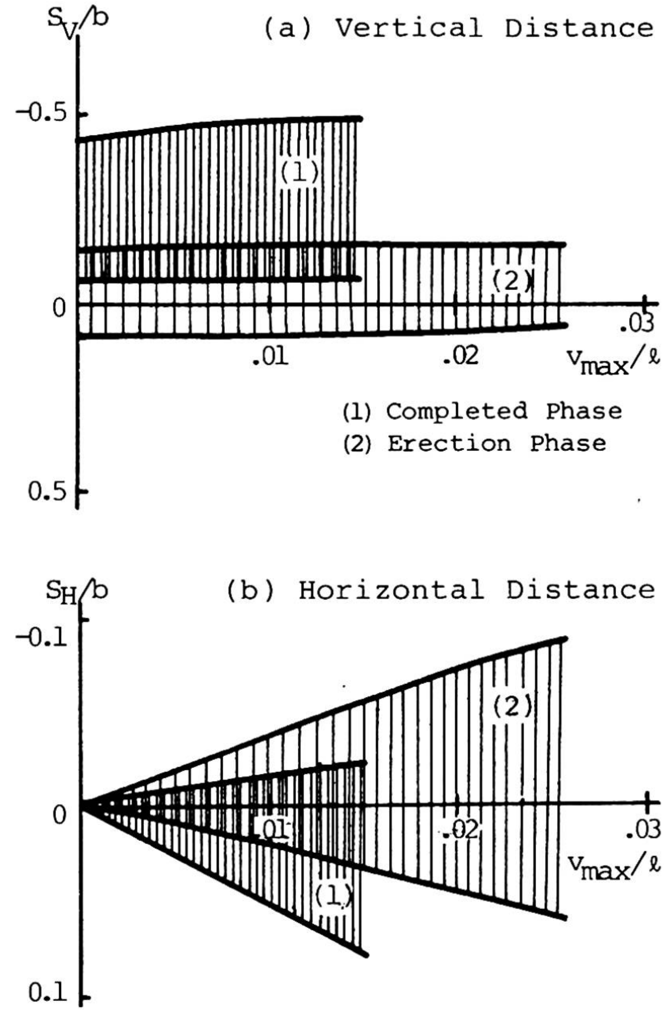


Fig. 4 Position of centre of rotation under static deformation

2.2 Critical Wind Speed for Torsional Flutter

As found in the preceding section, when a flexible suspension bridge deforms due to wind force, its dynamic characteristics change from those at unloaded state. In consequence the aerodynamic stability of the structure may also change to some extent. In order to verify these situation, utilizing the analytical results for static deformation and coupled vibration modes, the aeroelastic wind tunnel test with the sectional model of a truss-stiffened suspension bridge was conducted in a smooth air flow. The prototype bridge has a main span length of about 800m and the structural damping was set at $\delta_s = 0.01$ in logarithmic decrement.

Fig. 5 (a) and (b) show the relation between the reduced wind speed $U_r = U/f_T B$ and the double amplitude in torsion for different values of vertical and horizontal shift, respectively, of centre of rotation, where U is wind speed, f_T is the natural frequency of torsion, and B is the width of bridge deck. These experimental results indicate that the vertical shift of centre of rotation gives no significant effect on the aerodynamic stability of the structure. This agrees with the past experiences conducted elsewhere [1], [2]. On the other hand, the critical wind speed for flutter is clearly increased with the horizontal shift of centre of rotation which may be accompanied by lateral deformation of the structure. As also seen in Fig. 5(b), the slope of response curve becomes more gentle as the centre of roration moves away from the centre of section to upstream side ($S_H/B > 0$), and vice versa.

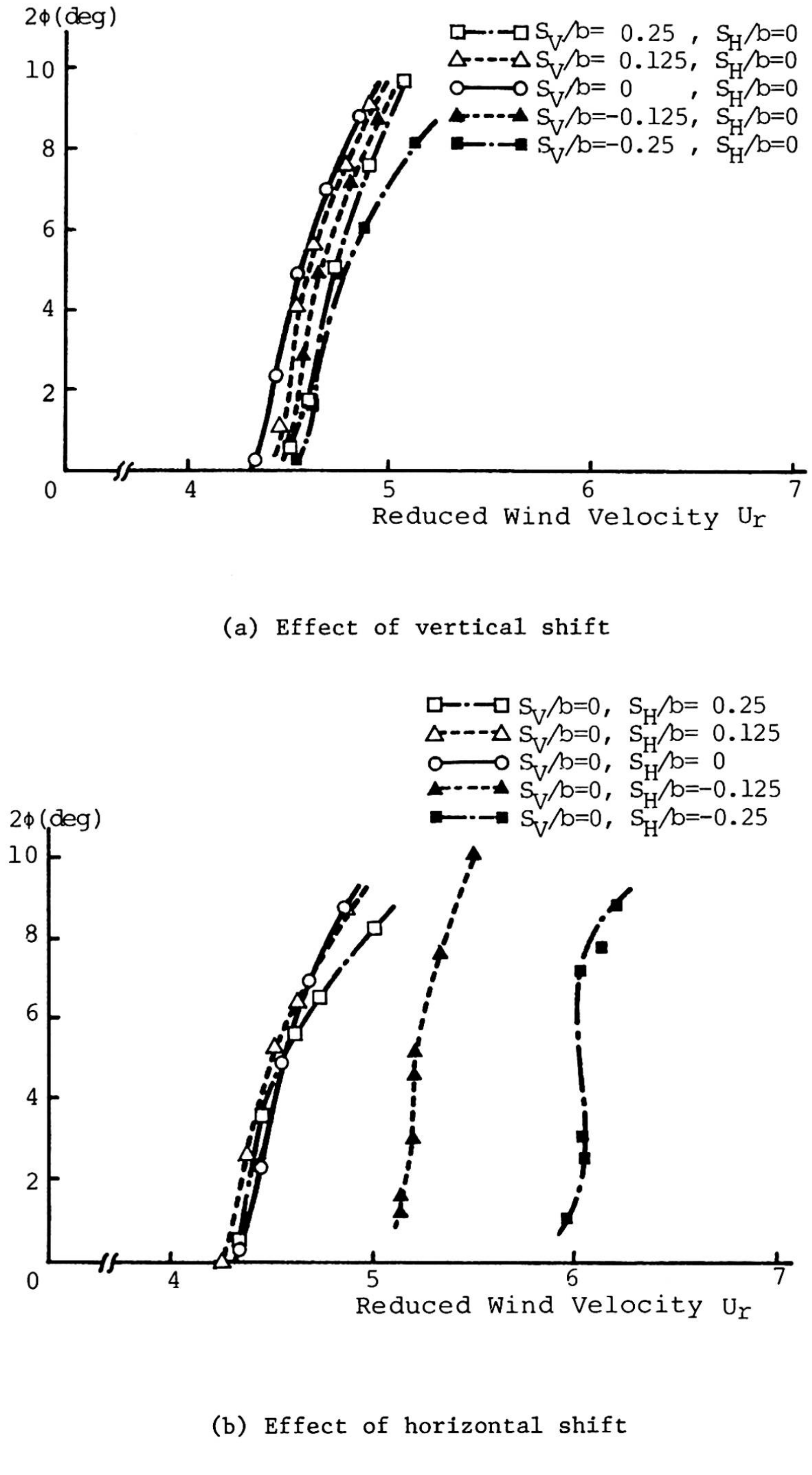


Fig. 5 Effects of position of centre of rotation on flutter response

Fig. 6 illustrates the critical reduced velocities for flutter for different structural damping. In the case of small damping, the critical velocity changes slightly when the centre of rotation moves forward, while it is substantially increased when the centre of rotation moves backward. With large structural damping, however, the increase of critical velocity is achieved by the horizontal shift of rotation centre irrespectively of its direction.

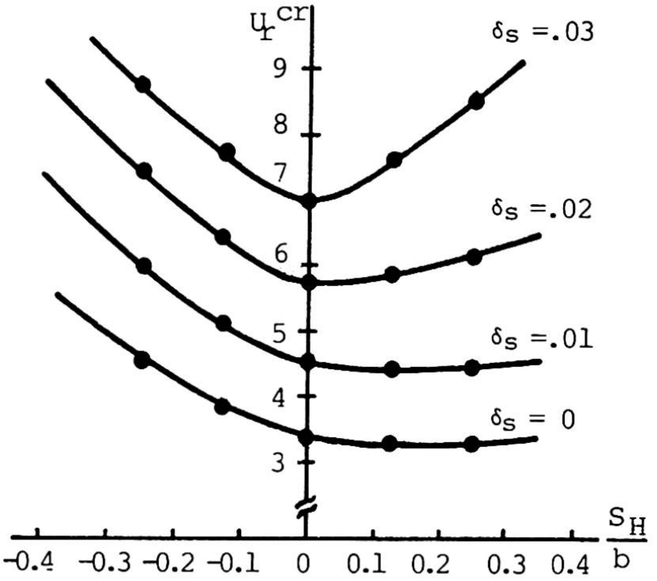


Fig. 6 Critical flutter speed vs. horizontal shift of centre of rotation

3. EFFECTS OF CROSS-WIND MOTION

The second aspect of the present contribution is the effect of the limited-amplitude oscillations, such as turbulence or vortex excitation, on the torsional flutter of a suspension bridge. For the sake of simplicity, given one-mode vertical oscillation of constant amplitude and specified natural frequency, the sectional model tests in the wind tunnel were carried out. The configuration of the bridge deck model was intentionally selected to cause torsional flutter. The experiment was conducted in a smooth air flow. Thus the vertical forced oscillation and the torsional flutter were dealt with independently.

Expressing the unsteady aerodynamic moment M as

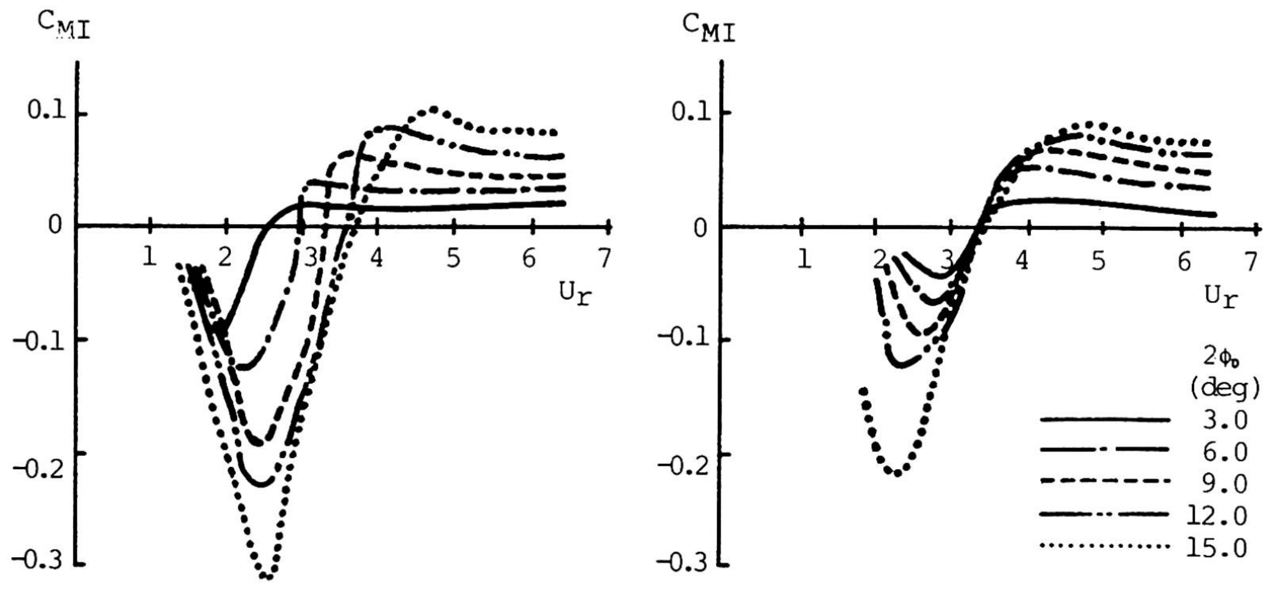
$$M = \frac{1}{2} \rho U^2 B^2 (C_{MR} + i\, C_{MI}) \frac{\phi}{\phi_0}$$

Fig. 7 and 8 show the aerodynamic coefficient C_{MI}, which exerts the aerodynamic damping effect on the structure and was obtained from the sectional model test. In the above equation, ρ is the air density, B is the width of bridge deck, $\phi = \phi_0 \exp(i \cdot 2\pi ft)$ is the torsional displacement and $i = \sqrt{-1}$.

Fig. 7 demonstrates that the existence of the vertical oscillation gives little influence on the negative aerodynamic damping in the region $U_r > 5$, while it clearly affects on the aerodynamic characteristics at $U_r = 3\text{-}4$, where the aerodynamic damping turns from positive to negative. This latter effect decreases as the amplitudes of torsional flutter become large. It might be observed that the existence of vertical oscillation tends to weaken the nonlinearity of unsteady aerodynamic force with respect to amplitude.

In order to know the effects of cross-wind motion more thoroughly, the results for the torsional amplitude $2\phi_0 = 3^0$ were rearranged in Fig. 8 (a) and (b) which illustrate the influence of the amplitude and frequency of vertical oscillation, respectively. From these figures, it is found that the critical wind speed for torsional flutter is generally raised with the increase of both the amplitude and the frequency of vertical oscillation.

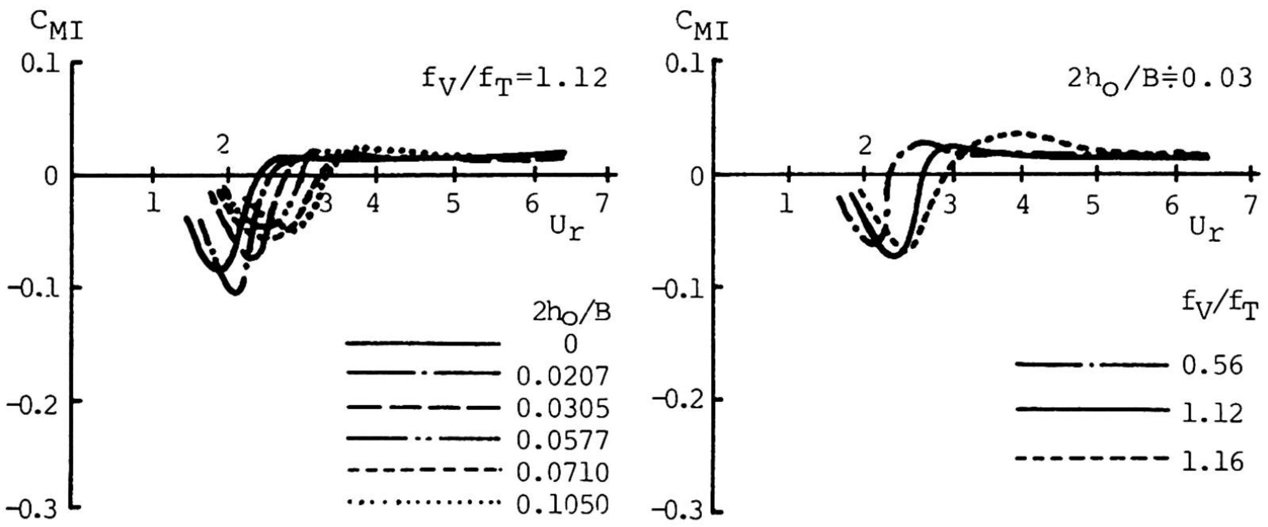
Finally the effect of vertical oscillation modes on the torsional flutter response will be discussed. The response was numerically estimated by applying the unsteady aerodynamic force obtained above to the three-dimensional structure which oscillates vertically. The applicability of strip theory is presupposed here and the structural damping was assumed as $\delta s = 0.03$ in logarithmic decrement. The results are shown in Fig. 9. Again it is observed that the existence of cross-wind oscillation tends to augment the critical wind speed for torsional flutter and this trend is more marked, with some exception, in the



(a) Without vertical motion

(b) Under vertical motion (f_V/f_T = 1.12, $2h_0/B$ = 0.105)

Fig. 7 Unsteady aerodynamic coefficient C_{MI}



(a) Effect of amplitude (f_V/f_T = 1.12)

(b) Effect of frequency ratio ($2h_0/B$ = 0.03)

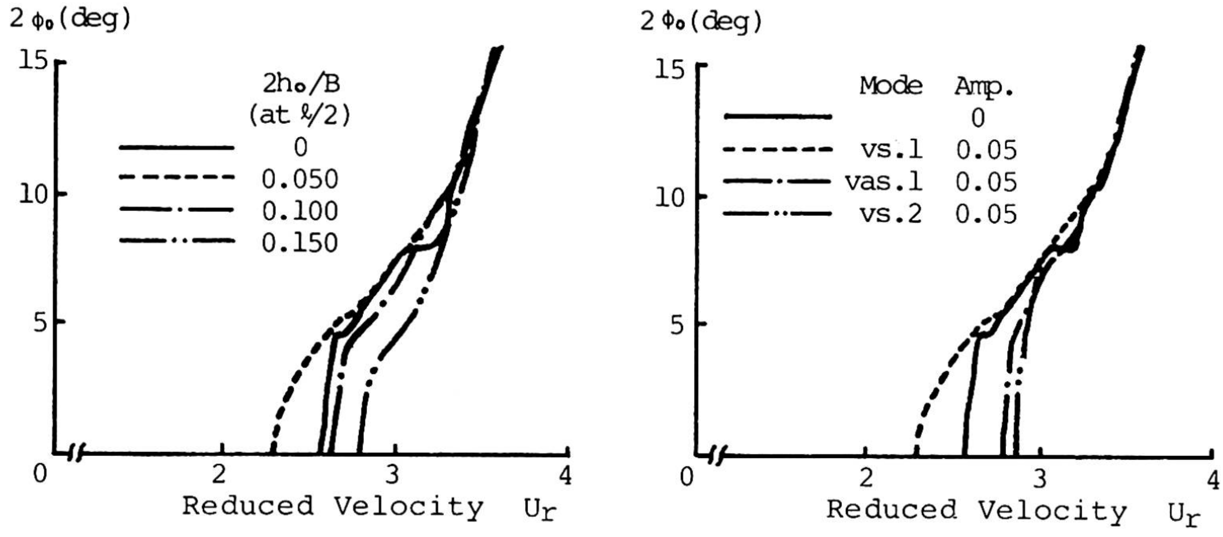
Fig. 8 Effects of vertical motion on C_{MI} at $2\phi_0$ = 3°

case of higher modes of vertical oscillations. Once the flutter occurs, however, the development of flutter response is more rapid in general when the vertical oscillation exists.

4. CONCLUSIONS

When a flexible suspension bridge is deformed by wind force, the coupling between vertical, lateral and torsional displacement component in its oscillatory behaviour is more pronounced. This coupling leads to the horizontal shift of rotation centre, and in its consequence, the critical wind speed for torsional flutter increases to some extent.

The existence of limited-amplitude oscillation of vertical bending may also



(a) Effect of amplitude: 1st symmetric mode of vertical oscillation

(b) Effect of mode of vertical oscillation

Fig. 9 Effects of vertical motion on flutter response

augment the critical wind speed for torsional flutter of a suspension bridge. However, this effect seems not so remarkable in practical sense, whereas the development of flutter response in the range beyond the critical wind speed becomes more abrupt. Therefore, it will be unable to be concluded that the coexistent cross-wind motion, such as due to air turbulence, may improve the torsional instability. If the effect of buffeting on aerodynamic instabilities of a structure is to be studied more realistically, the effect of air turbulence on aerodynamic force and the unsteadiness of buffeting response should be taken into account.

NOTATIONS

- b : half width of bridge deck
- B : width of bridge deck (=2b)
- C_{MR}: real part of aerodynamic moment coefficient
- C_{MI}: imaginary part of aerodynamic moment coefficient
- f_T : natural frequency of torsional vibration
- f_V : frequency of vertical bending vibration
- h_0 : amplitude of vertical bending vibration
- i : unit of imaginary number
- l : span length
- M : unsteady aerodynamic moment
- t : time
- U : wind velocity
- U_r : reduced wind velocity
- δ_s : structural damping in logarithmic decrement
- ρ : air density
- ϕ : torsional displacement
- ϕ_0 : amplitude of torsional vibration

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