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Recent topics on bridge aerodynamics

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Abstract. This paper aims to describe the aerodynamic vibrations of various structural elements of bridges, which are particular issues at present. The aerodynamic countermeasures for those vibrations are also discussed considering the generation mechanisms of the aerodynamic instabilities. In this paper, an example of vortex-induced oscillation of bridge deck and its lesson are discussed. Next, the wind-induced cable vibration and its aerodynamic countermeasures are reviewed. Then, the aerodynamic characteristics on two edge girders and their feasibility for application to long span cable-stayed bridges are considered. Furthermore, the bridge decks for future long span bridges are proposed and their aerodynamic characteristics are also discussed.

Key words : bridge aerodynamics; vortex-induced vibration; cable vibration; flutter; two-edge girders; super long span bridges.

1. Introduction

The wind-induced vibrations of bridge structures have been investigated for almost 60 years, initially motivated by Tacoma Narrows Bridge collapse in 1940. During this long term, a lot of wind tunnel tests and the related analyses have significantly developed the safety of bridges against strong winds. However, to find out more reasonable bridge structural systems, the many problems still remain. For example, the design method of super long span bridges for the next century, the development of very economical and safe bridges, the proposal of more effective and reasonable vibration control methods against wind induced vibration of structural elements of bridge and so on, should be investigated. Furthermore, the accurate evaluation of wind induced behavior at wide wind velocity ranges are more greatly required now than before to accomplish the performance based wind resistance design of bridges.

In this paper, the recent topics on the wind-induced vibrations of bridge elements are explained. Especially, following contents are discussed: 1) An example of vortex-induced vibration of a bridge deck, which was an important lesson, 2) Wind-induced vibration of cables, which is a very serious problem on cable-stayed bridges all over the world, 3) Fundamental aerodynamic characteristics of the “edge girder bridges” which are expected to realize more economical bridges and 4) Some proposals about the bridge girders of the future super long span bridges.

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2. An example of vortex-induced vibration

The box girder bridge (see Fig. 1), which has been recently constructed in Japan, showed the vortex-induced vibration just before its completion (see an article in Nikkei Construction 1995). Notwithstanding the wind tunnel tests had indicated the possibility of appearances of wind induced vibration, this bridge had been constructed without any vibration control devices. The bridge designers seem to judge rather quite low the possibility of appearance of aerodynamic vibration. They had a lot of experiences of no appearance of wind induced vibrations on the prototype bridges in the natural wind, even if the results of the wind tunnel tests indicated the appearance of the vibration quite in advance. Also, the structural damping was rather small comparing with its expected value. After the appearance of the wind-induced vibration, the TMD devices have been installed inside the box girder.

This phenomenon suggests the importance of an accurate evaluation of the turbulence effects on the vortex induced vibration, which highly depends upon the geometrical shape of bridge girder and the turbulent characteristics, and also the importance of the evaluation of the structural damping in advance. The mechanism of this vortex-induced vibration seems to be the vortex generation at the leading edge and its convection on the deck surface. Therefore, as the alternative countermeasure, the installation of the aerodynamic countermeasure devices, such as the flap plates, deflector or so on, at the bridge deck edges might have been effective. Furthermore, another shape of bridge girder with less sensitivity to the vortex-induced vibration should have been adopted at the primary design stage.

3. Wind-induced cable vibration of cable-stayed bridges

Recently, many cable-stayed bridges suffer from wind-induced stay cable vibrations, which frequently occurs at comparatively low wind velocity, such as less than 20 m/s, and under the precipitation condition. Therefore, they are called rain-wind induced vibrations. Mechanical countermeasures have been used for the vibration control in many cases, such as the installation of damper at the joint part on the bridge girder or the cable wire connection. However, it has been found that some of the latter were damaged and didn't work well. As an alternative vibration control, the geometrical shape of the cables could be changed, so that the flow field around the cable would be controlled.

Fig. 1 Box girder bridge where the vortex-induced oscillation was observed during construction

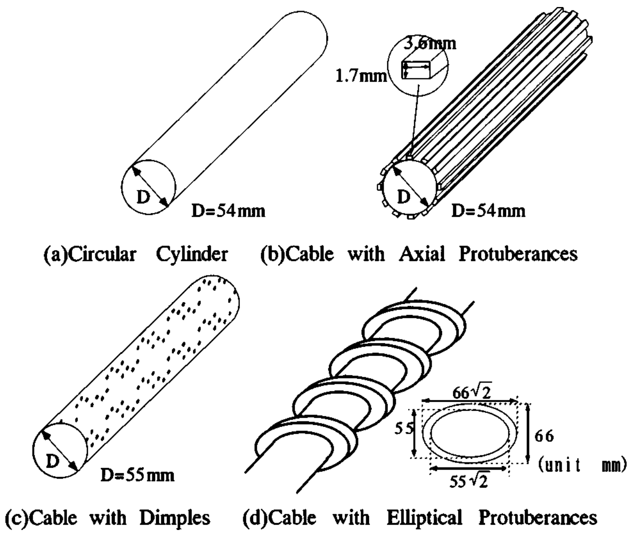


Fig. 2 Cable models

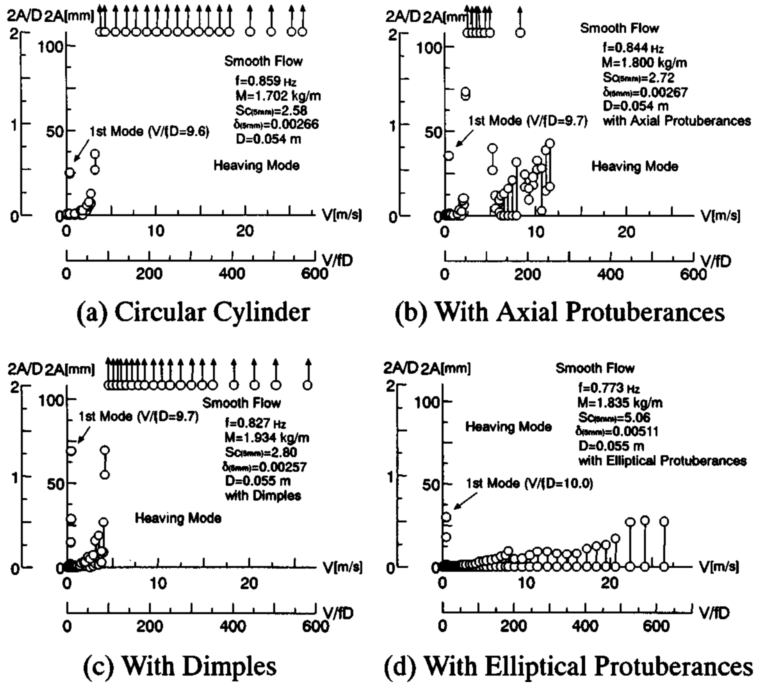


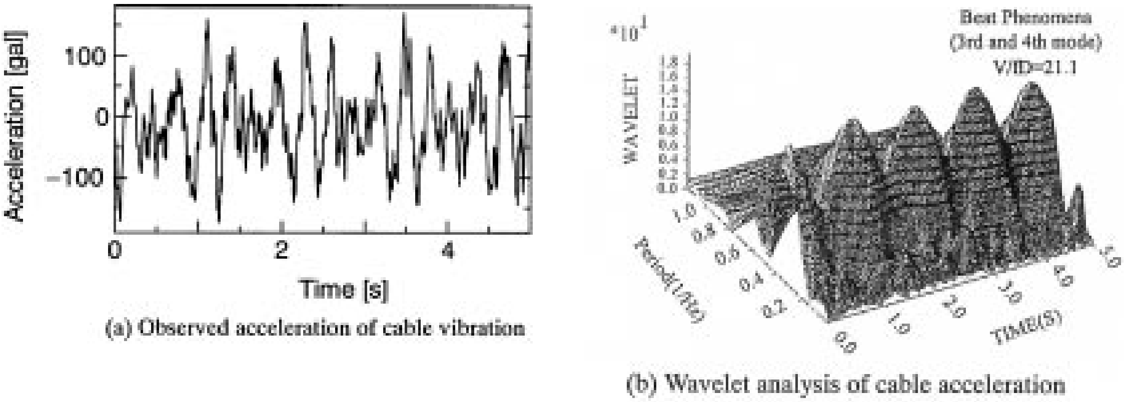
Fig. 3 Velocity - amplitude diagrams of cable models

For example, the protuberated cables for Higashi Kobe Bridge (l = 485 m), the dimpled cable surface for Tatara Bridge (l = 890 m) and the cables with helical wires on those surfaces for Normandy Bridge (l = 875 m) were tried.

To investigate the effects of aerodynamic countermeasures, various kinds of rigid cable models shown in Fig. 2, have been examined by spring supported tests in a wind tunnel. The wind tunnel used in this study is a room circuit type, whose working section is 1.8 m height and 1.0 m width. These cable models were installed in the wind tunnel with horizontal yaw angle $\beta = 45^{o}$ under smooth flow condition. The velocity-amplitude (V-A) diagrams for these results are shown in Fig. 3. In each plot, the following experimental conditions are denoted; structural frequency f, mass per length M, logarithmic decrement δ, diameter of model D and Scruton number $Sc = 2M\ \delta / (\rho D^2)$, where ρ is the air density. From the obtained results, the dimples on the cable surface are not effective to reduce the galloping. On the other hand, the cable with the axial protuberances has rather stable characteristics except a velocity restricted response at the lower wind speed. Furthermore, it becomes clear that the cable with the elliptical protuberances is the most stable through the all wind velocity range in these three models.

Generally, the mechanism of the inclined cable vibration seems to be the galloping instability or the velocity restricted type. Under smooth flow condition, this mechanism depends upon the combination of the cable inclined angle to wind and the location of the water rivulet on the cable surface. On the other hand, the galloping instability could be stabilized and only velocity restricted vibrations appeared in turbulent flow. (Matsumoto *et al*. 1990) These velocity restricted vibration appeared at particular reduced velocity ranges, defined by $Vr = V/fD$ (V: wind velocity, f: cable frequency, D: cable diameter), such as 40, 80, and so on. Furthermore, using the elastic inclined cable model in the wind tunnel, the beat vibrations have been observed. (Matsumoto 1998) These vibrations could occur not only for the inclined cable with the artificial rain or the artificial fixed rivulet on the cable surface, but also for the one with smooth surface, that is without rain condition. From the field observation results, the prototype inclined cables have shown the velocity-restricted vibration and the beat vibration in many cases, similarly to the ones observed during the wind tunnel tests. Fig. 4 shows acceleration data observed on a prototype cable and its wavelet analysis. The beat phenomena between 3rd and 4th mode is clearly observed.

In order to develop a more effective vibration control method for the inclined cables, the precise clarification of vibration mechanisms and the evaluation for the unsteady aerodynamic forces must be very important. At present, some generation factors of this cable vibration have been reported, those are (1) the formation of water rivulet on cable surface, (2) the coupling effect between the water rivulet motion and the cable motion, (3) the axial flow behind the inclined cable, (4) three



(a) Observed acceleration of cable vibration

(b) Wavelet analysis of cable acceleration

Fig. 4 Observed cable vibration at a prototype cable-stayed bridge dimensional Karman vortex shedding in the wake of the inclined cables and (5) the axial vortex along cable axis in the near wake. (Matsumoto *et al*. 1999) As a matter of fact, the realistic mechanism is a complex combination of these exciting factors, and the unsteady forces on the cable would be sensitively affected by the rivulet condition, the flow condition, the relative cable attitude to wind and so on. Therefore, further investigations should establish reasonable cable vibration control methods considering these complicated mechanisms.

4. Aerodynamics of two edge girders

The two edge girders are going to be attracted again as the girders of the long span cable stayed bridges because of their economical advantages. One of the concerning problems on designing the two edge girders for the long span bridges is their aerodynamic instability. It was believed that the edge girder has a disadvantage to the aerodynamic stability, because Tacoma Narrows Bridge so drastically and sensationally collapsed in 1940. In fact, after Kessock Bridge in Scotland (l = 240 m) showed the vortex induced vibrations, the tuned-mass dampers were installed under the bridge deck, which were however damaged and replaced. (Owen *et al*. 1994) However, the application of the two edge girders to the modern long span cable stayed bridges was motivated by the completion of the Alex Frazer Bridge with the two edge girders.

The aerodynamic characteristics of the two edge girders are quite sensitive to the geometrical shapes of the bridge decks, in particular the edge shape, and to the vertical angle of wind. (Matsumoto *et al.* 1999) The flutter instability depending on the edge girder shapes, the location of the edge girder from the bridge deck and the angle of attack of wind are summarized in Fig. 5 and Fig. 6. The aerodynamic derivatives used in these analyses were measured by wind tunnel forced vibration tests under smooth flow. The cable-stayed bridge with center span length 610 m is virtually assumed for these flutter analyses: its deck width B, the natural frequency for bending $f_{\eta 0}$

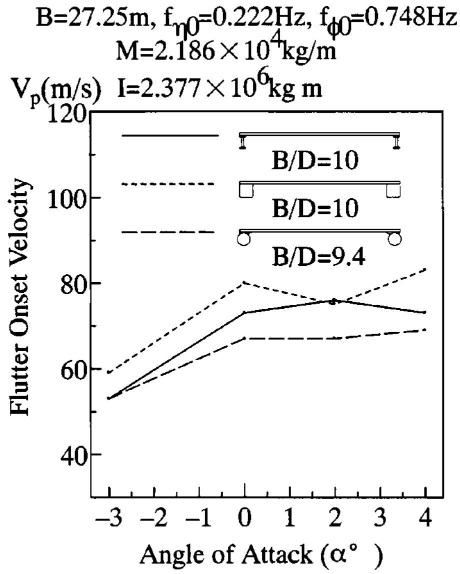


Fig. 5 Flutter instability depending on the edge girder shape and the angle of attack of wind

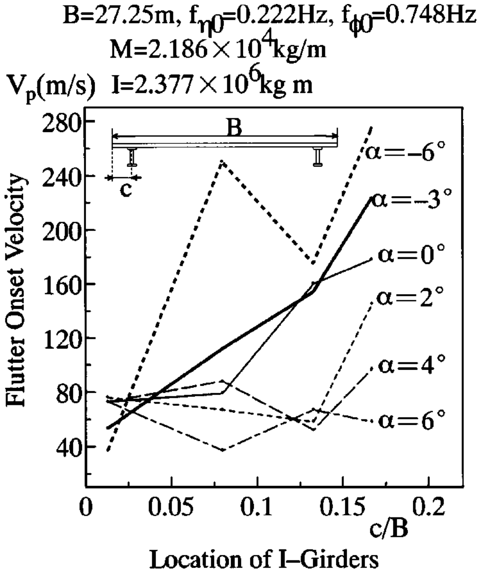


Fig. 6 Flutter instability depending on the location of edge girders and the angle of attack of wind

and torsion $f_{\phi 0}$, the mass per length M and inertia per length I are shown in the figures. These analyses are meant for the comparison of their aerodynamic instability, then the structural damping is assumed as zero. The flutter onset velocity against angle of wind attack for various edge girder shapes are compared in Fig. 5. It is clear that the negative angle of attack causes lower flutter onset velocity in the all cases. Also, the square shape of edge girder has better flutter characteristics than the other shapes of edge girders. In Fig. 6, the relation between the flutter instability and the location of I-girders for various angles of attack is shown. Generally, higher flutter onset velocity can be expected if the I-girders are installed inward. Also, the results from spring supported tests are shown in Fig. 7. These tests are torsional 1DOF tests and are conducted under smooth flow condition. The experimental conditions, as the inertia per length I, structural frequency f, logarithmic decrement δ, Scruton number $Sc = 2I\ \delta / (\rho D^4)$, where D is the deck height and ρ is air density, are shown in the figure. The torsional flutter is vanished if the *I*-girders are located inward, which is the same results from the previous flutter analyses. Furthermore, the vortex-induced oscillation occurs at a different wind velocity region. Therefore, it becomes clear that the location of edge girders can easily change the flow pattern around the body.

From the points of the flutter onset reduced velocity Vp / fB (Vp : flutter onset velocity, f : flutter frequency, B : full deck chord length), their flutter properties are much poorer than those of a thin plate, truss stiffened girders or thin box sections, which are frequently used for the long span suspension bridges or cable stayed bridges. However, the torsional frequencies of multi-cable stayed bridges with two edge girders are unexpectedly high, for example more than 0.5 Hz for the long span cable stayed bridge with main span length of 600 m or a little more. This fact can make long cable stayed bridges with the two edge girders possible from the flutter instability points of view. On the other hand, the edge girder decks frequently show vortex induced vibrations, but they might be suppressed by the slight change of the edge geometry with the installation of flap plates, deflector plates and so on, or even by TMD under the decks.

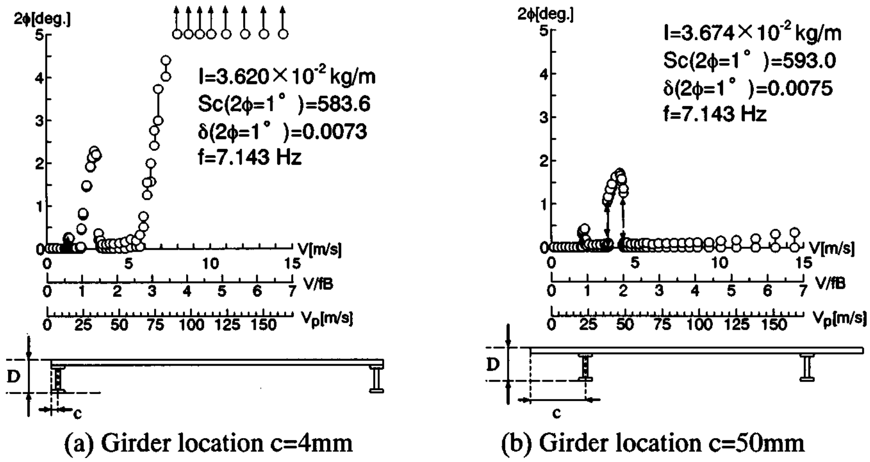


Fig. 7 Velocity - amplitude diagrams of the sections with two different girder locations (width B = 300 mm, height D = 30 mm, angle of attack α = 0 deg, torsional 1DOF, in smooth flow, Vp: field wind velocity on a certain long-span cable-stayed bridge with center span length of 610 m)

5. Flutter stabilization of super long span bridges

Super long span bridges after the Akashi Strait Bridge (l = 1990 m) and the Great Belt East Bridge (l = 1670 m) have been actively examined in Italy and in Japan. The economical and safety designs of those structures are essential factors for their real constructions. The isolated three box girders deck has been proposed for the Messina Strait Bridge (l = 3,300 m) by Diana (1993) as shown in Fig. 8. Its flutter property proves to be rather stable one with the flutter onset velocity of more than 90 m/s in horizontal wind. This deck section has the great advantage of reducing the magnitude of flutter derivatives or the unsteady forces to excite flutter instability. This is due to the suitable arrangement of the air gaps among three box girders and an admirable edge shape modification of the deck.

Increasing the main span length of a bridge, the torsional frequency decreases. Therefore, the designing of super long span bridges requires an aerodynamically much more stable bridge deck section than a thin plate in general. The comparatively stable isolated deck sections against flutter instability are illustrated in Fig. 9, and their flutter characteristics are shown in Fig. 10, respectively. The aerodynamic derivatives of the sectional models in Fig. 9 were measured by the forced vibration

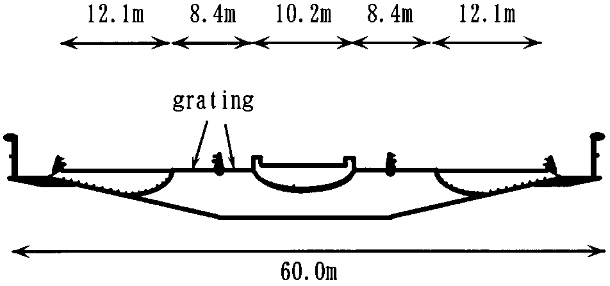


Fig. 8 Deck cross section of the Messina Straits Bridge

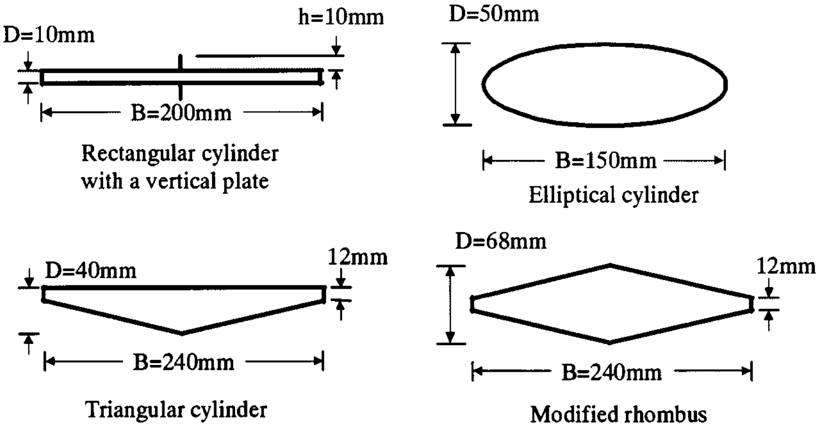


Fig. 9 Comparatively stable isolated deck sections against flutter instability

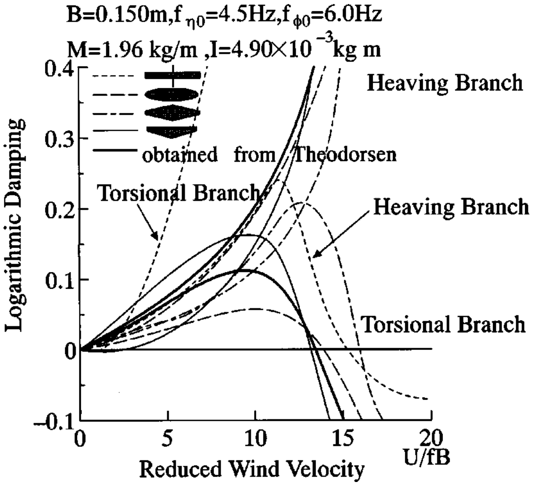


Fig. 10 Velocity - damping curve for the isolated deck sections

tests under smooth flow, and flutter analyses were done for each case. The results of aerodynamic logarithmic decrements are plotted in Fig. 10. Also, the result of using the flutter derivatives of a thin plate is also plotted for the comparison. The conditions for flutter analyses are also shown in the figure. These sections almost have the same or even more stable flutter characteristics than the thin plate. Their stabilization against flutter can be achieved by controlling the unsteady pressure distribution on the deck surface under the heaving or torsional motion by the secondary flow separation. (Matsumoto *et al.* 1996) A brief evaluation of the onset flutter velocity of the long span suspension bridge with these deck sections with a main span length of 3000m is more than 60 m/s or 70 m/s in horizontal wind. Therefore, these isolated deck shapes should be more investigated in detail for future applications.

Also, the aerodynamic flutter characteristics of the separated two box girders have been investigated. (Matsumoto *et al.* 2000) The investigated sections are shown in Fig. 11. Between two box girders, a grating plate is installed. Then, the effects of the angle of attack and the grating opening ratio on the

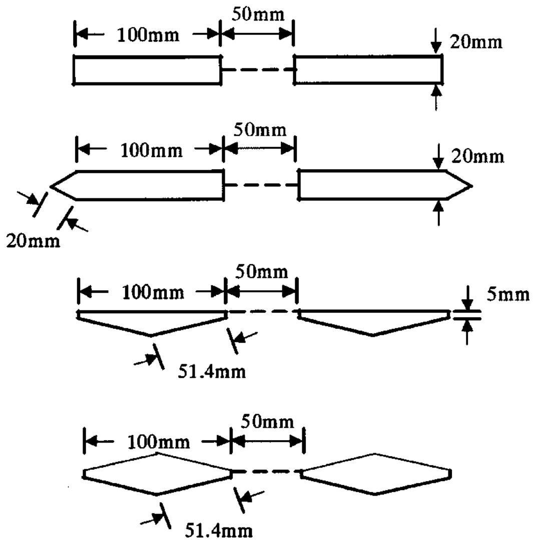


Fig. 11 Separated two box girders

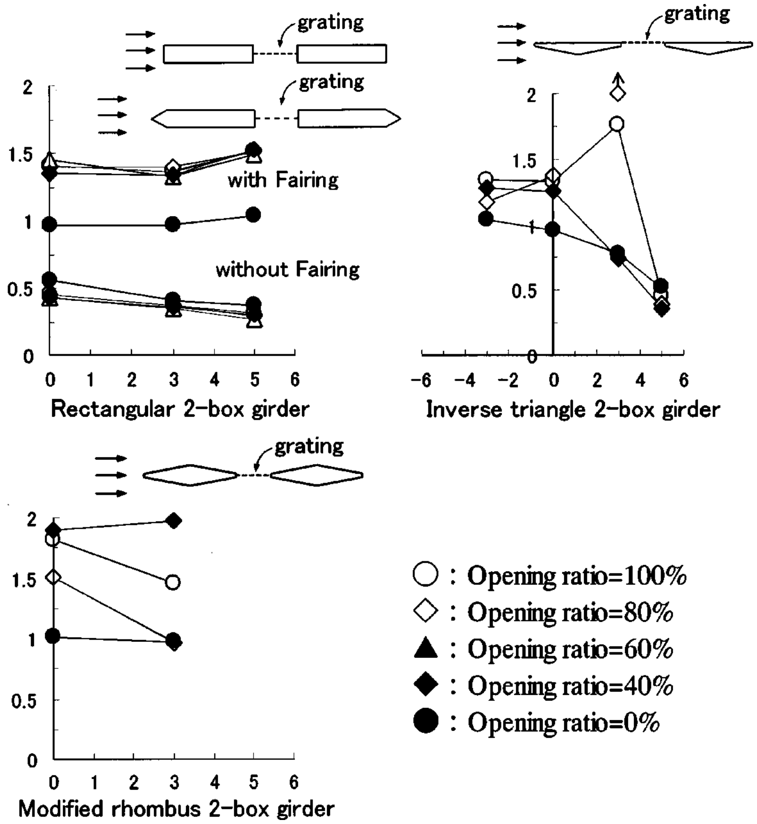


Fig. 12 Influence of angle of attack and grating opening ratio to flutter onset velocity. (horizontal axes: angle of attack (deg.), vertical axes: flutter onset velocity / that of thin plate case)

flutter characteristics were examined by wind tunnel tests and the results are shown in Fig. 12. The vertical axes in these figures show the magnitude of the flutter onset velocity against the results using a thin plate case, and the horizontal axes show the angle of wind attack. For comparison purposes, the width of thin plate is determined as same as the total width of 2-box girder. In general, the nonzero angle of attack of the flow tends to reduce the onset velocity of the flutter instability. And also, the suitable opening ratio of the grating would realize the most stable condition against the flutter. The rectangular 2-box section with fairings has rather stable characteristics through all range of attack angle and the modified rhombus 2-box girder with suitable opening ratio has a rather high flutter onset velocity at zero angle of attack. It becomes clear that the separated two box decks are more stable against the flutter instability than the single box deck. However, the further researches on the separated box girders are necessary for the design of the future super long span bridges.

To establish the more reasonable wind resistance design of bridge structures and to develop new types of bridge structures with more high performance aerodynamics for the coming new century, it is necessary to investigate the present unsolved subjects on the bridge aerodynamics step by step.

6. Conclusions

This paper introduces the recent topics on bridge aerodynamics, that are the vortex induced vibrations of the actual box girder in natural wind, the cable aerodynamics, the edge girder aerodynamics and the introduction on the comparatively stable bridge decks against flutter instability for the future super long span bridges. The conclusions from this study are as follows:

1) An example of vortex-induced vibration of the bridge deck discussed in this paper can be a lesson to wind engineers for the importance of countermeasures against vortex-induced vibration.
2) As to the aerodynamic countermeasure against the rain-wind induced vibration of cables, the elliptical protuberances on the cable is more effective than axial protuberances or dimples. However, the complicated mechanism of this vibration has not been totally clarified yet. Therefore, to develop more rational countermeasures, and further investigation on the problem is needed.
3) The aerodynamic characteristics of bridge decks with two edge girders are quite sensitive to the geometrical shapes of their edges and the vertical angle of wind, and also their flutter properties are rather poor. However, the application of these sections to multi-cable stayed bridges with high torsional frequency could be possible in order to realize less expensive bridges.
4) For future long span bridges, the bridge decks with two flow separation points on their surface and the sections with separated two box girders were considered, and it becomes clear that they have rather stable characteristics against flutter. However, further researches on these bridge decks are necessary for the designing of future super long span bridges.

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