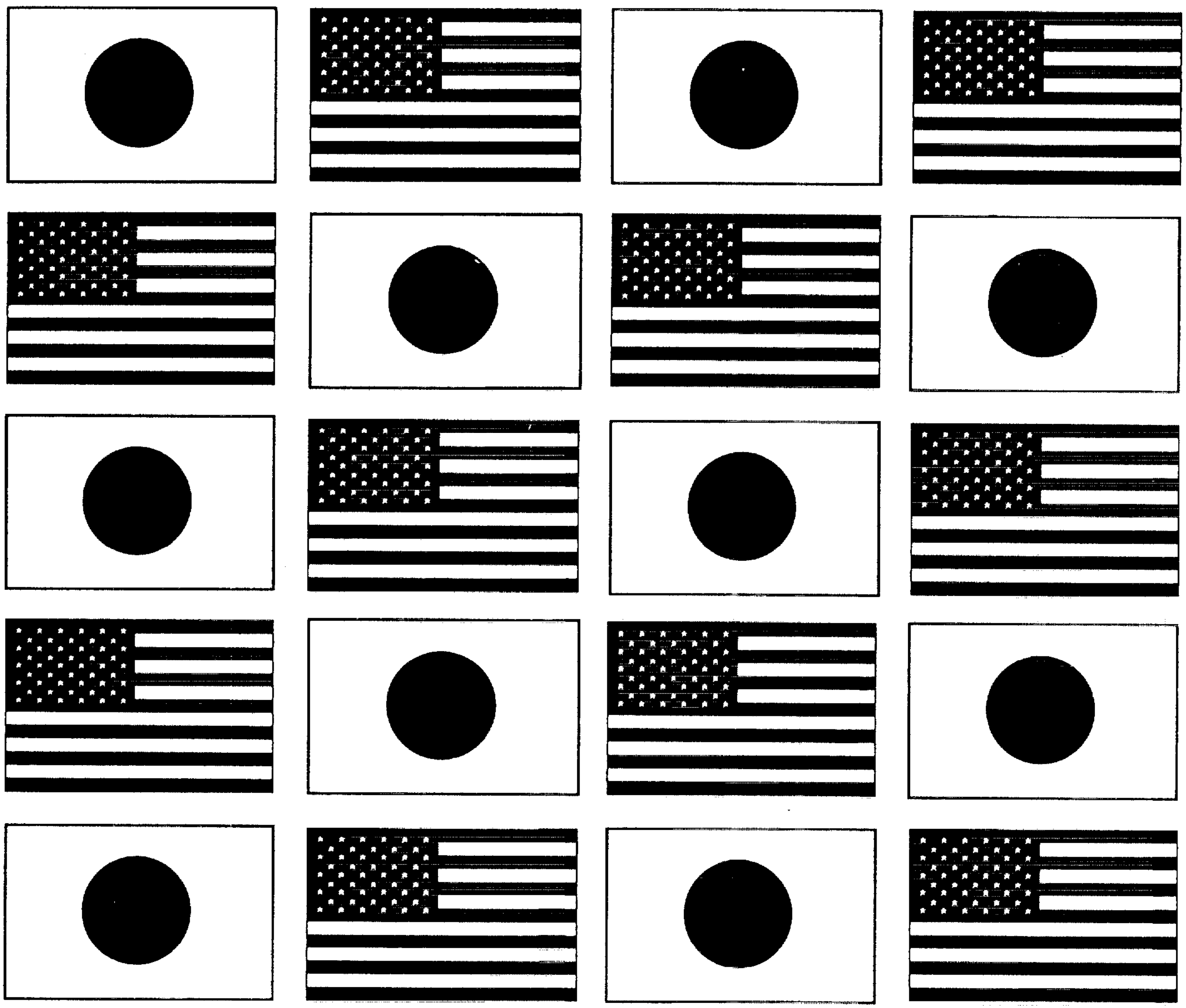
Wind and Seismic Effects

Proceedings of the 30th Joint Meeting

NIST SP 931



U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology

Wind and Seismic Effects

NIST SP 931

PROCEEDINGS OF THE 30TH JOINT MEETING OF THE U.S.-JAPAN COOPERATIVE PROGRAM IN NATURAL RESOURCES PANEL ON WIND AND SEISMIC EFFECTS

Issued August 1998

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WIND ENGINEERING

Consideration on Flutter Characteristics of Super Long-Span Bridges

by

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ABSTRACT

Aerodynamic stability is one of the most important themes in the design of a super long-span bridge. To improve the aerodynamic stability of a super long-span bridge, a series of wind tunnel studies and analytical studies were conducted, and it was found that slot at the center of girder was effective to improve the aerodynamic stability. The relationship between flutter characteristics and unsteady aerodynamic forces was discussed, and it was found that flutter characteristics were closely correlated with unsteady aerodynamic force coefficients M_{ZI} $L_{\theta R}/M_{\theta I}$ and $M_{\theta R}$.

KEYWORD: flutter, super long-span bridge, slotted box girder, unsteady aerodynamic force

1. INTRODUCTION

The Akashi Kaikyo Bridge has the world-longest span length of 1990m. In Japan and in the world, there are several plans or ideas to construct bridges longer than the Akashi Kaikyo Bridge. In the design of such super long-span bridges, aerodynamic stability is one of the most important themes. The approaches to improve aerodynamic stability can be classified into structural one and aerodynamic one. This paper deals with the latter approach.

It was proposed by the authors that slotted box girders were effective to increase flutter speeds of super long-span bridges [1]. In this paper discussed is the relationship between flutter characteristics and unsteady aerodynamic forces of slotted box girders.

2. FLUTTER CHARACTERISTICS OF SLOTTED BOX GIRDERS [1]

The effect of location and size of slot on aerodynamic characteristics was examined through section model wind tunnel tests. Considering a super long-span bridge which has center span length of 3,000m with two side spans of 1,500m, the structural conditions were assumed. Reduced mass μ (=m/(ρ B^2), m: mass per unit length, ρ: air density, B: girder width), reduced polar moment of inertia ν (=I/(ρ B^4), I: polar moment of inertia per unit length), and natural frequency ratio ε (=f_θ/fz, f_θ: torsional natural frequency, fz: vertical bending natural frequency) were 16, 2.1, and 2.1, respectively. The cross section of the model is shown in Fig.1. From the test results, it was found that the slot at the center increased the flutter onset wind speed. It was also found that the flutter onset wind speed was increased with the width of slot at the center of the girder (Fig.2).

In order to understand the effect of slot at the center of girder, preliminary analysis was conducted for slotted plate. For the analysis, aerodynamic forces acting on each plate was calculated using the Theodorsen's function. The aerodynamic interference between the 2 boxes was neglected. Using these aerodynamic forces, two degree-of-freedom flutter analysis was conducted by U-g method [2]. The result of the flutter analysis (Fig.2) indicated that the flutter onset wind speed increased with size of slot. The differences between the analysis and the experiment seemed to be caused by aerodynamic interference between the 2 boxes.

Although wide slot at the center of the girder improves flutter characteristics, narrower slot

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would be preferable from the viewpoint of construction cost of towers and foundations. To improve aerodynamic characteristics, the effect of some devices was studied by section model tests. The tested devices are illustrated in Fig.3. The results showed that the center barrier and guide vanes improved flutter characteristics very well (Fig.4). However, the flutter speed was not so high when angle of attack was -3 deg. It was found that the guard rails at the bottom deck increased the flutter speed considerably at this angle of attack (Fig.5).

3. UNSTEADY AERODYNAMIC FORCES OF SLOTTED BOX GIRDERS

From the above studies, it was found that slotted plates and slotted box girders have better flutter characteristics than single plates and single box girders. It was also found that the devices such as center barrier and guide vanes are effective to improve flutter characteristics of slotted box girders.

In order to understand causes of flutter characteristics of slotted plates and box girders more precisely, unsteady aerodynamic forces were measured for three models: model A (single box girder, b=0 in Fig.1), model B (slotted box girder, b=0.22B in Fig.1) and model C (slotted box girder with devices, Fig.3). The measurement was made by forced oscillation method [3] with angle of attack 0 degree. Coefficients of the unsteady aerodynamic forces were defined as follows:

$$L=\pi\rho\{B^2[L_{ZR}\omega^2 z+L_{ZI}\omega z'] +B^3[L_{\theta R}\omega^2\theta+L_{\theta I}\omega\theta']\} \quad (1.1)$$

$$M=\pi\rho\{B^3[M_{ZR}\omega^2 z+M_{ZI}\omega z'] +B^4[M_{\theta R}\omega^2\theta+M_{\theta I}\omega\theta']\} \quad (1.2)$$

where, L: lift (upward positive), M: aerodynamic moment (head up positive), z: vertical displacement (upward positive), θ : torsional displacement (head up positive), ω : circular frequency, ( )': d( )/dt, L_{xx} or M_{xx}: coefficients of unsteady aerodynamic forces ($_Z$: caused by vertical vibration, $_\theta$: caused by torsional vibration, $_R$: in phase with displacement, $_I$: in phase with velocity).

Among measured unsteady aerodynamic force coefficients, the most effective coefficients for flutter, which will be explained next, are shown in Fig. 6. For comparison, theoretical coefficients for single plate and slotted plate, which were calculated from the Theodorsen's function, are shown in the same figures. The slot ratio of the slotted plate was the same as the Model B and C.

In general, it is difficult to predict coupled flutter characteristics directly from these coefficients. For 2-degrees of freedom system, Nakamura [4] showed approximate relationship between unsteady aerodynamic coefficients M_{ZI} , $M_{\theta I}$, $L_{\theta R}$ and $M_{\theta R}$ and some flutter properties as follows:

$$\delta a \fallingdotseq -\pi^2 M_{ZI}X/\nu - \pi^2 M_{\theta I}/\nu \quad (2.1)$$

$$X \equiv z_0/\theta_0/B \fallingdotseq \pi L_{\theta R}/(-1+(f_Z/f_\theta)^2\sigma^2)/\mu \quad (2.2)$$

$$\sigma^2 \equiv (f_\theta/f)^2 \fallingdotseq 1+\pi M_{\theta R}/\nu \quad (2.3)$$

where, δ a: aerodynamic damping in logarithmic decrement.

These equations were derived by assuming that absolute value of aerodynamic damping and phase angle are small, and that absolute value of the amplitude ratio X is small. As is shown here, $M_{\theta R}$ affects the frequency ratio σ. $L_{\theta R}$ and σ affect the amplitude ratio X. M_{ZI} , $M_{\theta I}$ and X affect the aerodynamic damping.

Assuming ε , μ and ν as 2.0, 15 and 2.0, respectively, frequency ratio, amplitude ratio and aerodynamic damping were calculated for three Models, single plate and slotted plate. The results are shown in Fig. 7. The critical reduced frequency of slotted plate and slotted box girder, where aerodynamic damping turns negative, is smaller than that of single plate and single box girder. It means that slotted plate and slotted box girder have better flutter characteristics than single plate and single box girder. It is also found that flutter speed of single plate is higher than single box girder (Model A), and that flutter speed of slotted plate is higher than slotted box girder (Model B).

Comparing unsteady aerodynamic force coefficients of single plate and single box girder (Model A), it is found that they are almost identical except for $M_{\theta I}$. Since $M_{\theta I}$ produces positive aerodynamic damping as can be seen in eq.(2.1) and Fig. 6, it is found that the difference of $M_{\theta I}$ explains the different flutter speeds of single plate and single box girder (Model A). In a similar way, it is found that the difference of M_{ZI} explains the different flutter speeds of slotted plate and slotted box girder (Model B), because M_{ZI} produces negative aerodynamic damping. Therefore, Nakamura's equations are effective to explain flutter characteristics. However, flutter characteristics such that slotted plate and slotted box girder have better flutter characteristics than single plate and single box girder, can not be explained directly from these equations.

4. INEQUALITY FOR FLUTTER ONSET

If onset of flutter is defined as $\delta a \leqq 0$, simpler inequality for onset of flutter can be derived from (2.1)-(2.3) as follows:

$$\alpha M_{ZI} L_{\theta R}/M_{\theta I} + \beta M_{\theta R} \geqq 1 \qquad (3.1)$$

$$\alpha \equiv (\varepsilon^2/(\varepsilon^2-1))(\pi/\mu) \qquad (3.2)$$

$$\beta \equiv (1/(\varepsilon^2-1))(\pi/\nu) \qquad (3.3)$$

The left hand side of inequality (3.1) was calculated for the Models A, B and C using measured unsteady aerodynamic forces, as well as for single plate and slotted plate using the Theodorsen's function. ε, μ and ν were assumed as 2.0, 15 and 2.0, respectively. The results are shown in Fig.8. The slotted box girders and slotted plate show higher flutter speed than the single box girder or single plate. Since the first term of the left hand side of inequality (3.1) is much larger than the second term, it can be said that this higher flutter speed was caused mainly by the property of $M_{ZI} L_{\theta R}/M_{\theta I}$.

In Fig.8, reduced flutter speed U/(fB) of slotted box girder with devices is almost identical with that of slotted box girder. In Fig.9, the results are plotted with $f_\theta B/U$. Flutter speed of slotted box girder with devices is higher than that without devices. It means that the effect of devices came from small value of $M_{\theta R}$, which affected apparent frequency in wind.

5. CONCLUSION

Slotted box girders have good flutter characteristics, and they can be improved by some devices like center barrier and guide vane. In this paper, the relationship between flutter characteristics and unsteady aerodynamic forces of the slotted box girders was discussed. The main findings are as follows:

(1) Flutter characteristics of single plate, slotted plate, single box girder and slotted box girder can be explained by their unsteady aerodynamic forces through Nakamura's equations and the following inequality for flutter onset:

$$\alpha M_{ZI} L_{\theta R}/M_{\theta I} + \beta M_{\theta R} \geqq 1$$

(2) The higher flutter speed of slotted box girders and slotted plate than the single box girder or single plate was caused mainly by property of $M_{ZI} L_{\theta R}/M_{\theta I}$.

(3) The effect of the devices like center barrier and guide vane came from small value of $M_{\theta R}$, which affected apparent frequency in wind.

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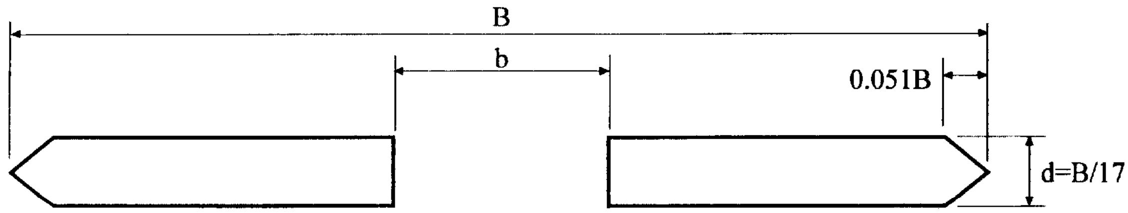


Fig.1 Cross Section of Slotted Girder

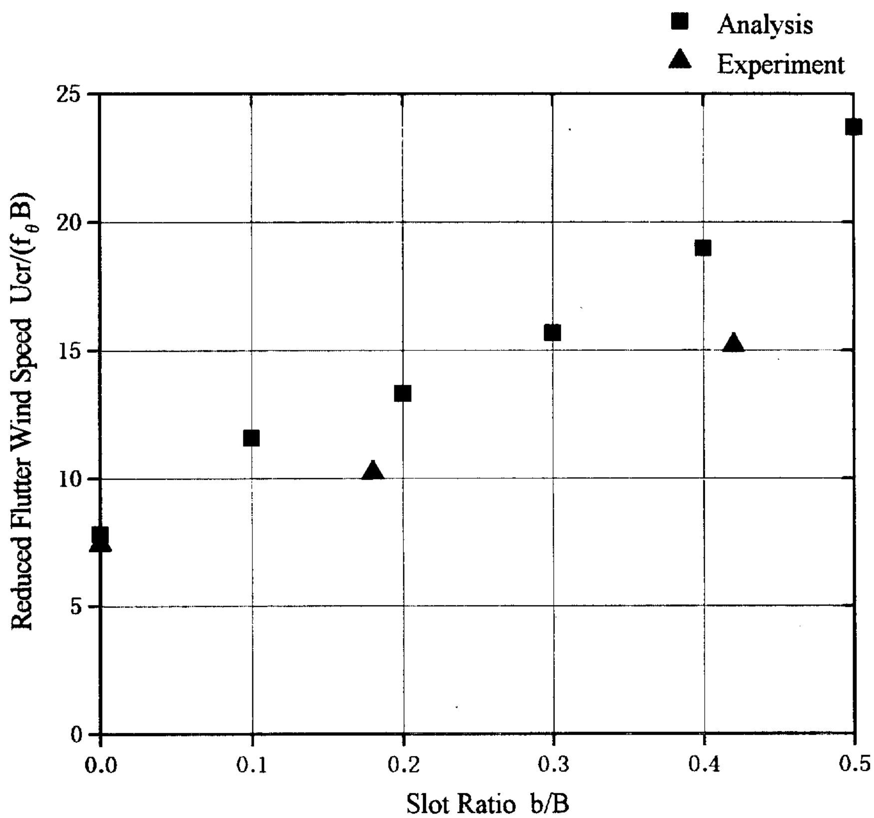


Fig.2 Flutter Onset Speed and Slot Ratio

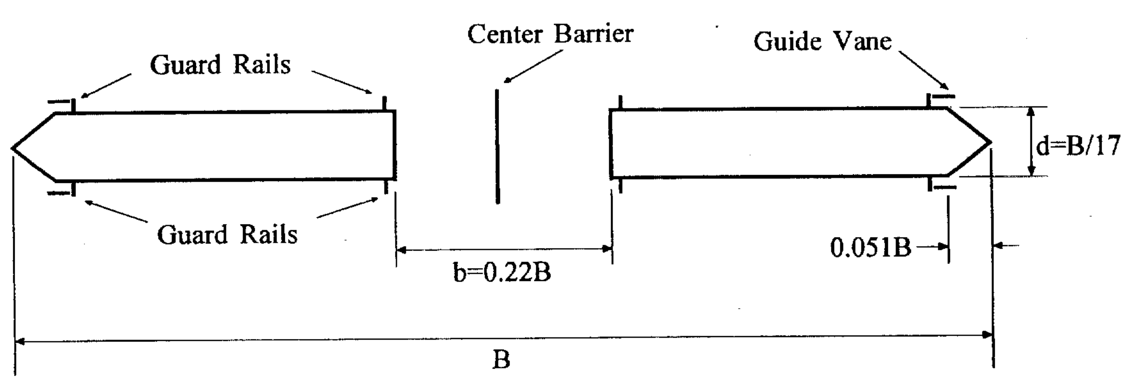


Fig.3 Slotted Box Girder with Devices

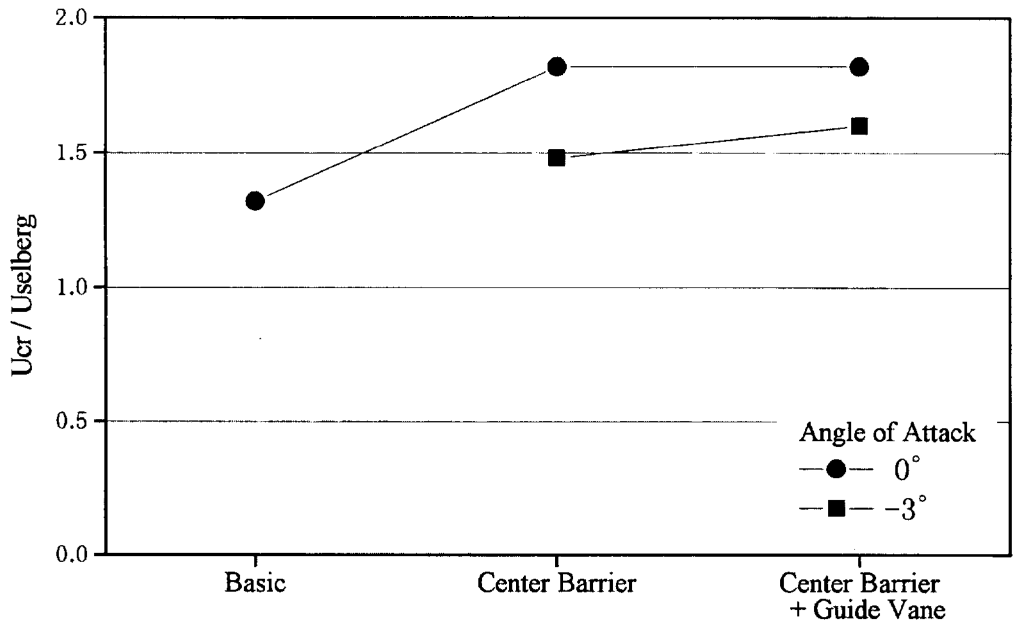


Fig.4 Effect of Tested Devices

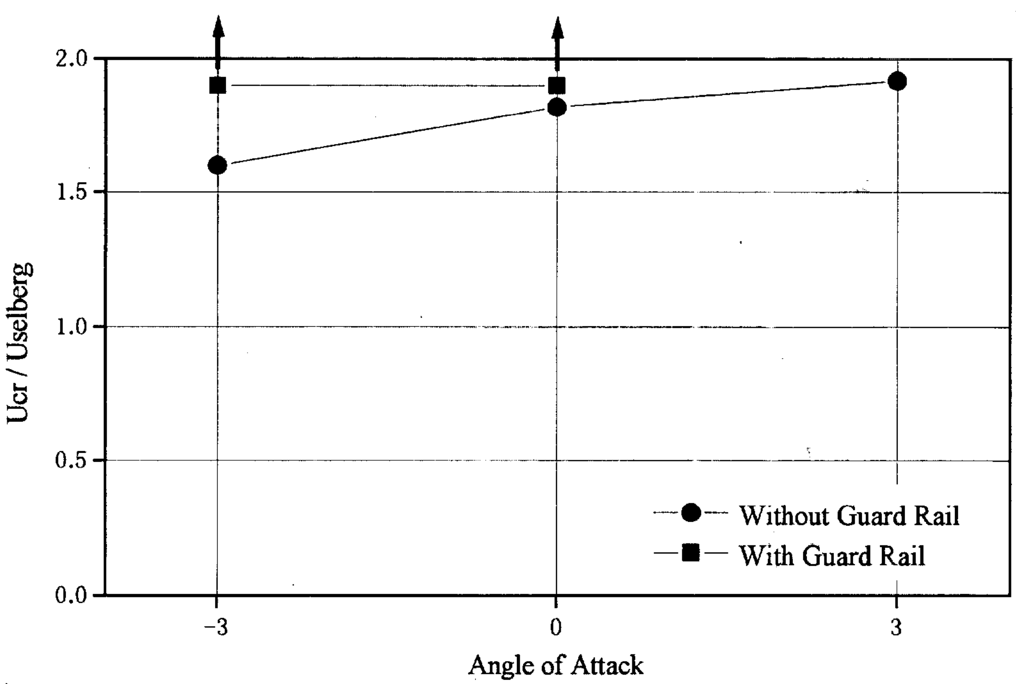
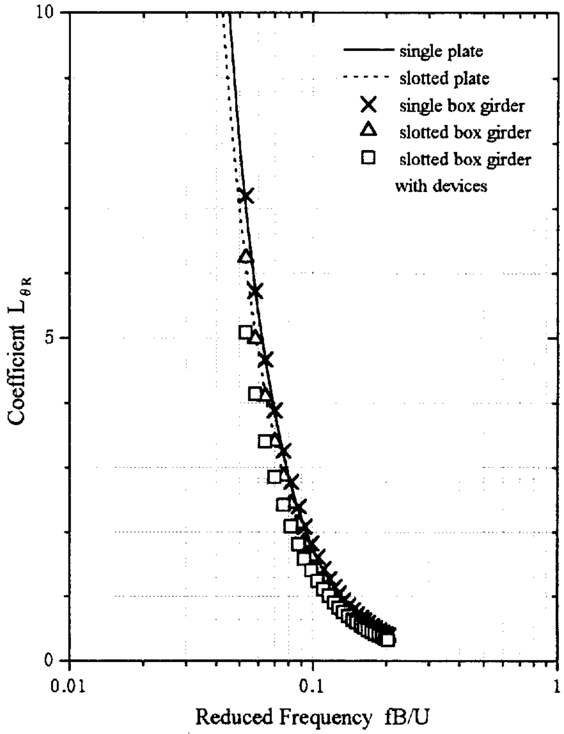
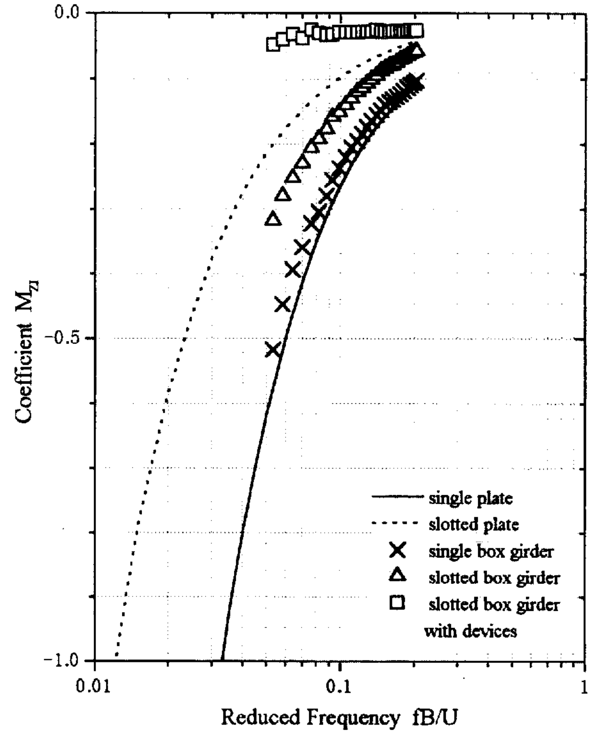


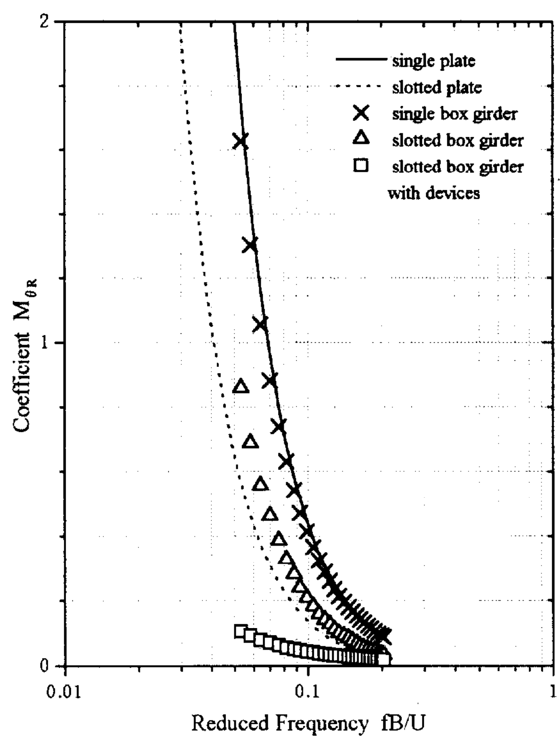
Fig.5 Effect of Guard Rails at the Bottom Deck



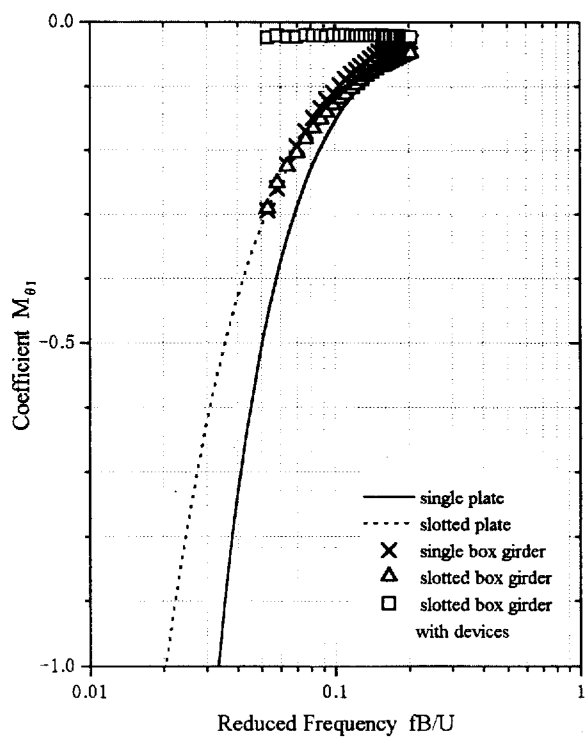
(a) $L_{\theta R}$



(b) M_{ZI}

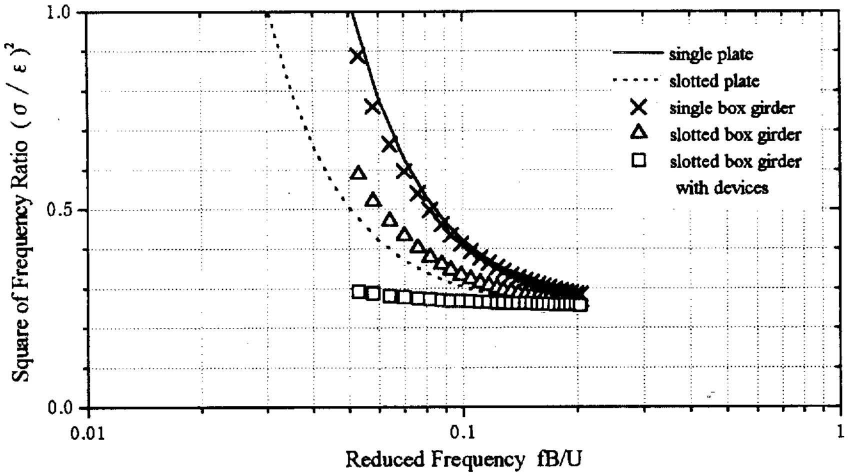


(c) $M_{\theta R}$

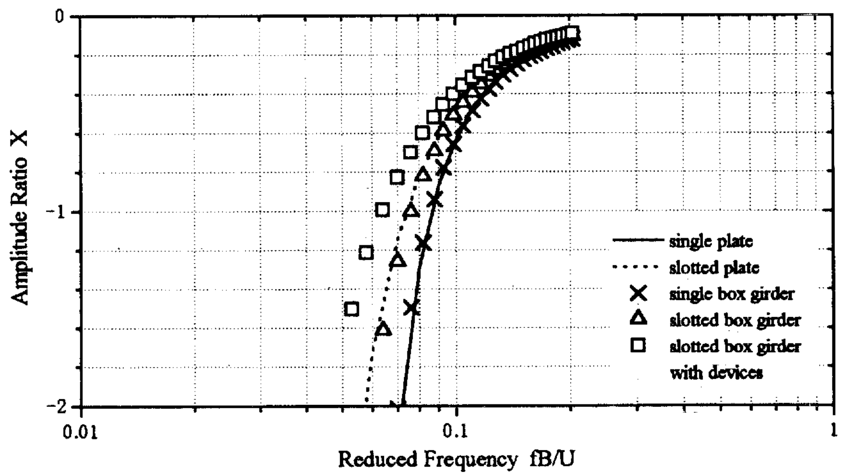


(d) $M_{\theta I}$

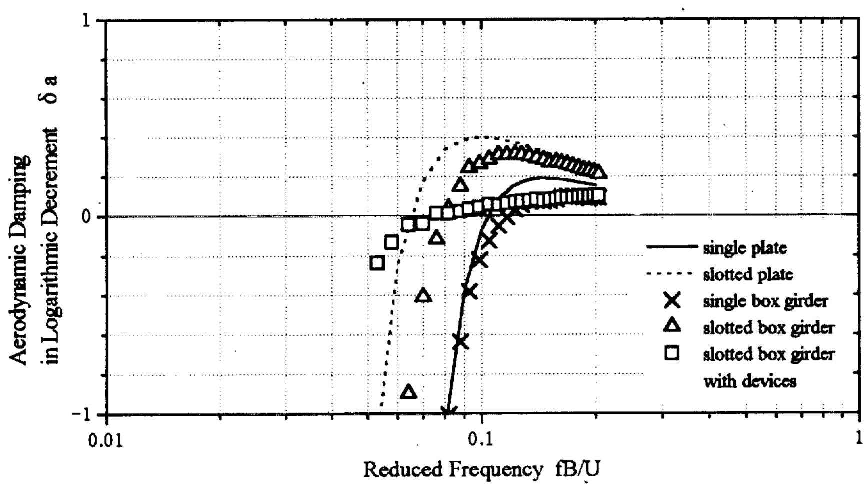
Fig.6 Coefficients of Unsteady Aerodynamic Forces



(a) Square of Frequency Ratio $(\sigma / \varepsilon)^2$

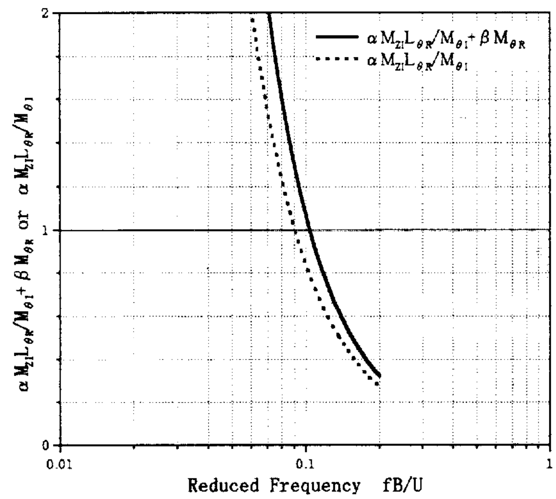


(b) Amplitude Ratio X

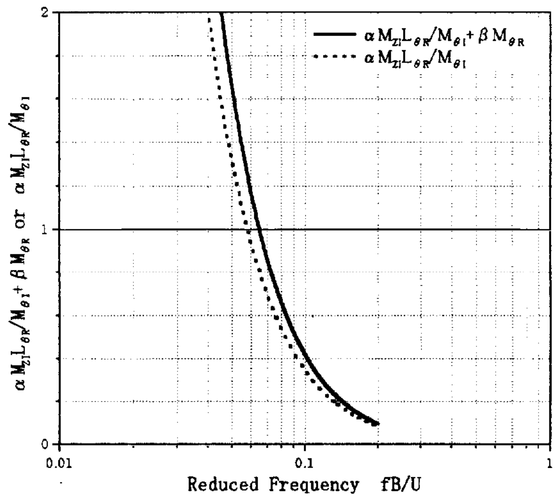


(c) Aerodynamic Damping in Logarithmic Decrement δa

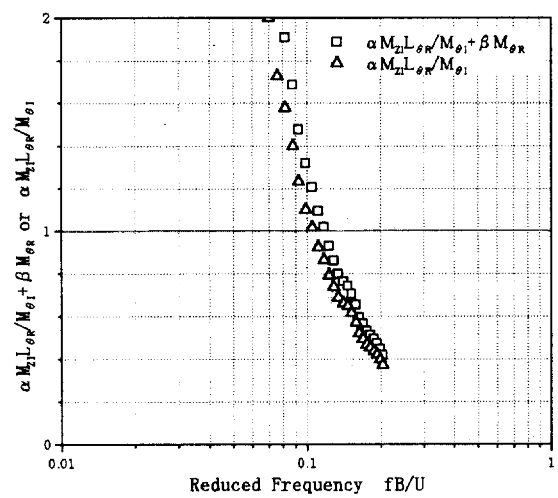
Fig7. Parameters Related to Flutter Characteristics



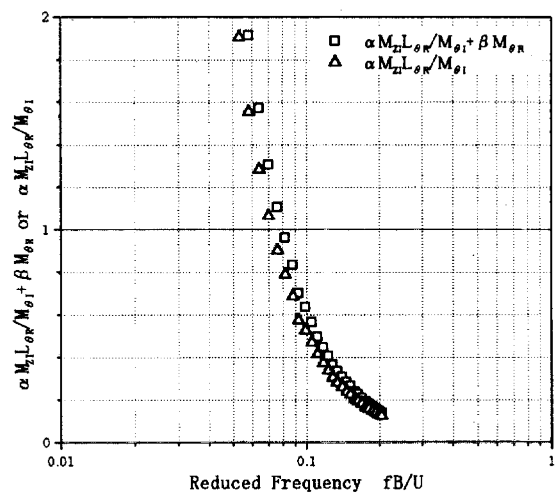
(a) Single Plate



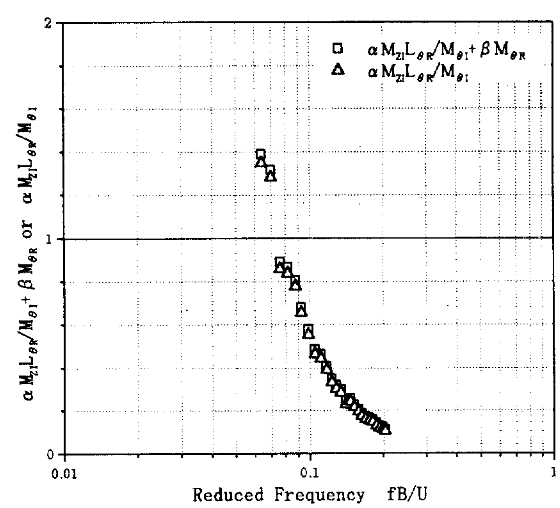
(b) Slotted Plate



(c) Single Box Girder



(d) Slotted Box Girder



(d) Slotted Box Girder with Devices

Fig8. Judgement of Flutter Onset (plotted with fB/U)

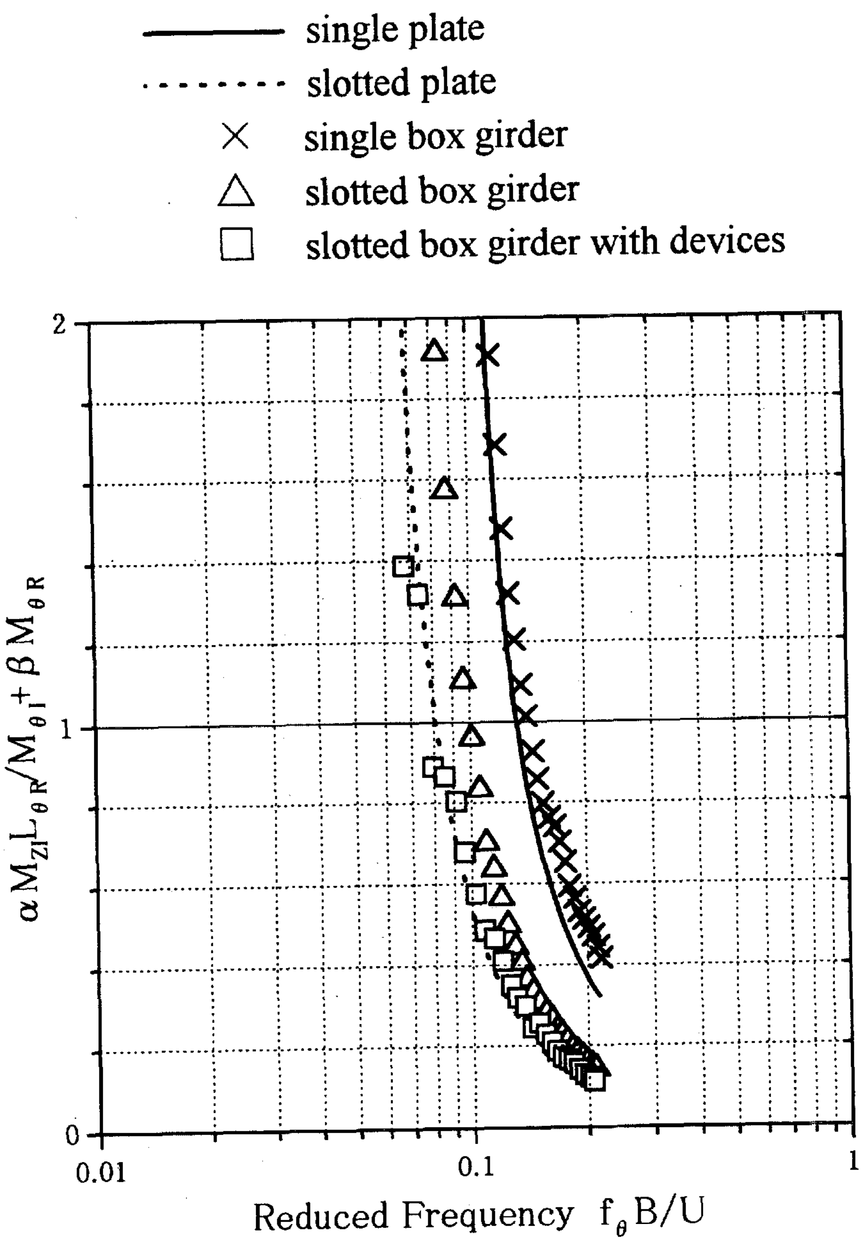


Fig.9 Judgement of Flutter Onset (plotted with f_θ B/U)