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## Coupled Flutter Behavior of Ultra Long-Span Suspension Bridges

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### Summary

The realization of ultra long-span bridges with center span length of 2,500 to 3,000 m depends on the aerodynamic stability. In order to develop ultra long-span suspension bridges with streamlined stiffening box-girders that have excellent structural characteristics, the torsional stiffness should be improved within the limits of the advantage in cost. This study dealt with two cable systems: mono-duo shaped main cable and rigid hanger frame, the latter of which is a newly proposed auxiliary hanger system. In order to investigate the aerodynamic characteristics of the proposed cable systems, a multi-mode flutter analysis was performed using four analytical models based on a trial design of ultra long-span suspension bridge with center span length of 2,500 m. The results demonstrated that rigid hanger frames and mono-duo shaped main cables are effective on the aerodynamic stability.

### 1. Introduction

The Akashi-Kaikyo Bridge with center span length of 1,990 m will be opened for service soon, and a part of the channel-crossing-road project that was developed as a next-generation project is proceeding to the implementation stage. Thus, an era of ultra long-span bridges whose span length considerably exceeds that of the Akashi-Kaikyo Bridge is about to begin. Under this circumstance, the research and development of ultra long-span suspension bridges with center span length ranging from 2,500 to 3,000 m has recently been underway. For the realization of such bridges, detailed investigations will be conducted using actual examples.

To construct ultra long-span suspension bridges successfully, it is important to ensure the aerodynamic stability of the bridges, in addition to realizing high economic performance. Therefore, major research subjects are the increase of the torsional stiffness of girder cross sections as well as that of the entire bridge and the improvement of the aerodynamic characteristics of girders.

In order to apply suspension structures with streamlined stiffening box-girder to ultra long-span bridges, we have performed a research focused on cable systems that increase the torsional stiffness of the entire bridge (Maeda, Iwamoto and Fujino et al. 1996, 1997). In the research, we investigated wind-resistant countermeasures through the use of mono-duo shaped main cable system and auxiliary hanger cable systems, based on the results of Astiz and Andersen (1990) and Ostenfeld and Larsen (1992) about the influence of auxiliary cable systems on flutter critical wind velocity.



The aim of this paper is to clarify the applicability as wind-resistant countermeasures for ultra long-span bridges of two cable systems: mono-duo shaped main cable and rigid hanger frame, the latter of which is a newly proposed auxiliary hanger system. We investigated in detail the changes in the characteristics of natural vibration modes due to these cable systems. Then, we conducted a multi-mode coupled flutter analysis and compared the results with the values calculated from the conventional basic two-mode analysis. In addition, we attempted to find the dominant modes other than the basic two modes that affected the critical wind velocity.

### 2. Wind-Resistant Countermeasures

Figure 1 shows the concept of mono-duo shaped main cable system used in this study. Conventional suspension bridges have the relative displacement of both sides of the main cable in the bridge axis direction at the tower top due to symmetric torsional deformation. On the other hand, mono-duo shaped main cable system restricts the relative displacement, leading to the increase in the torsional stiffness of the entire bridge. This restriction effect is the main effect. The effect resulting from the reduced polar moment of inertia of the main cable compared to that for conventional suspension bridges is relatively small.

Figure 2 shows the newly proposed auxiliary hanger systems named rigid hanger frames. The rigid hangers have bending stiffness and include hanger cables. They are installed concentratedly at several locations in the center span. We investigated the three types of rigid hanger frames shown in Fig. 2 and confirmed that there is almost no difference in their effects. Therefore, hereafter we deal with the rigid frame c).

### 3. Analytical models

In this study, we used four types of analytical models shown in Fig. 4 based on an example design, the general design plan of which is shown in Fig. 3 and sectional values of structural members listed in Table 1. The four models contain a conventional model (PARA model), a basic mono-duo model (MONO model) and two rigid hanger frame models (PARA-RIGID and MONO-RIGID) in which rigid hanger frames are

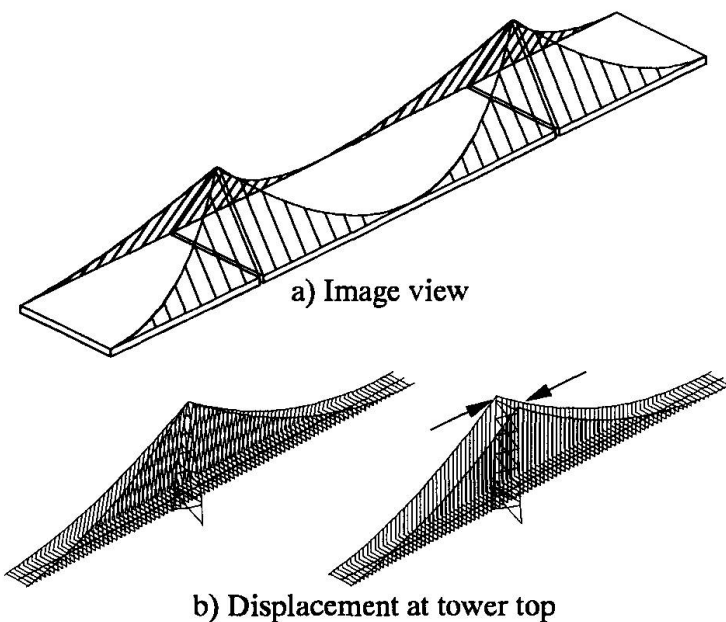


Fig. 1 Concept of mono-duo shaped main cable

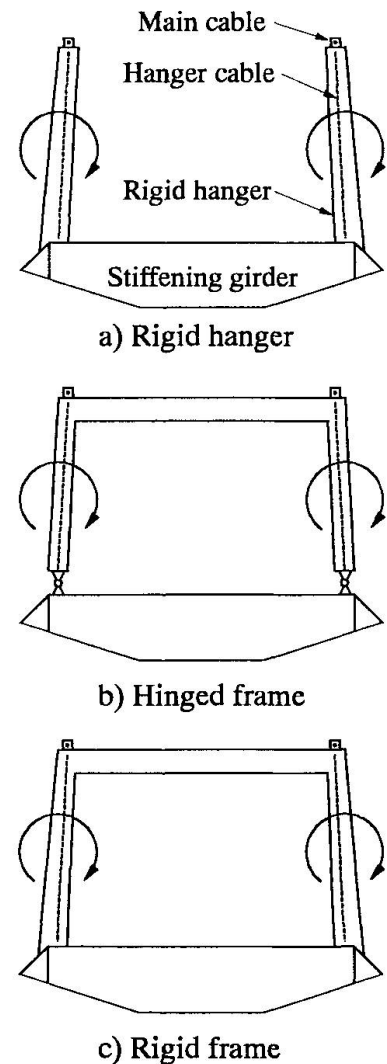


Fig. 2 Rigid hanger frames

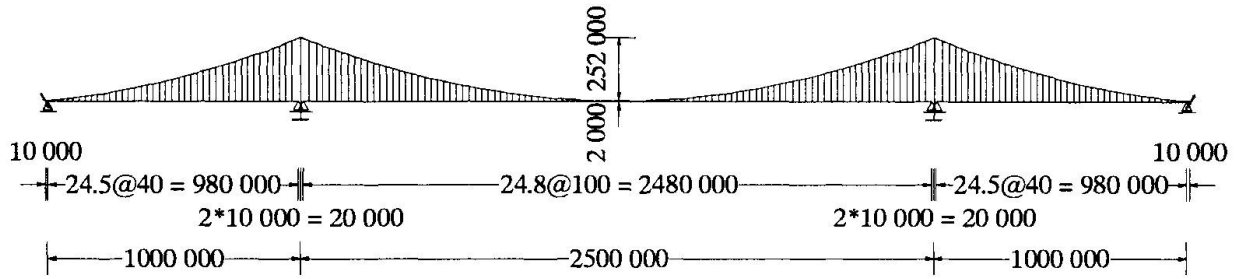


Fig. 3 Trial design

Table 1 Sectional values of structural members

Main cable	$A_C$	0.5564 m <sup>2</sup> /cable
Hanger cable	$A_H$	0.006 m <sup>2</sup> /cable
Center stay	$A_S$	0.2 m <sup>2</sup> /cable
Stiffening Girder	$A_G$	1.3 m <sup>2</sup>
	$I_{G,in}$	11.0 m <sup>4</sup>
	$I_{G,out}$	132 m <sup>4</sup>
Main tower	$J_G$	23.7 m <sup>4</sup>
	$A_T$	2.6-4.2 m <sup>2</sup> /column
	$I_{T,in}$	13.5-23.2 m <sup>4</sup> /column
	$I_{T,out}$	26.0-85.3 m <sup>4</sup> /column
	$J_T$	17.6-37.3 m <sup>4</sup> /column

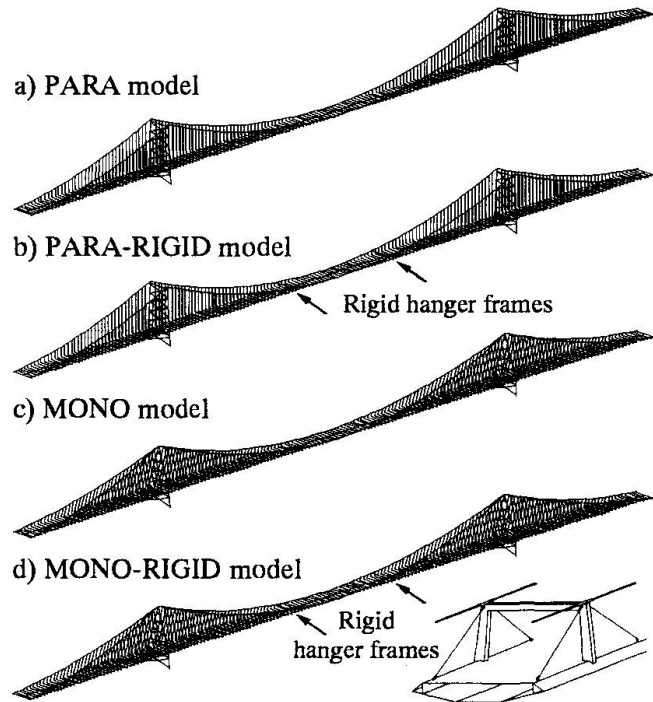


Fig. 4 Analytical models

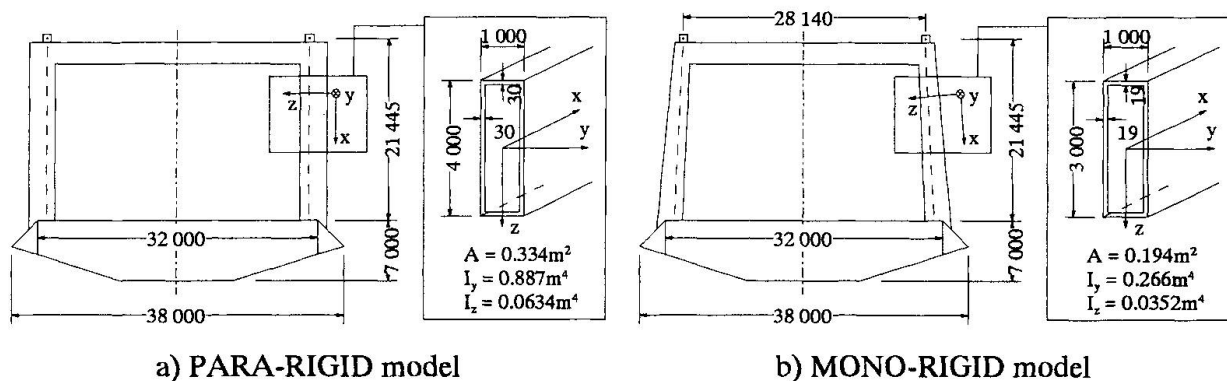


Fig. 5 Sectional values of rigid hanger frames

installed at 0.36 L and 0.64 L (L : center span length) of the center span of the former two models (Fig. 4). Figure 5 shows the rigid hanger frames used in this study and their sectional values.

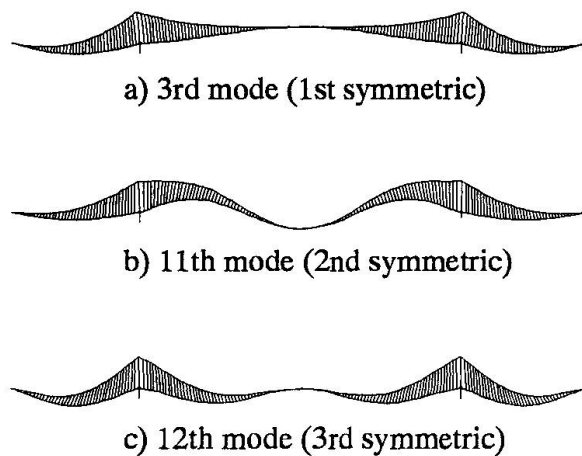


Fig. 6 Symmetric vertical deflection modes (MONO model)

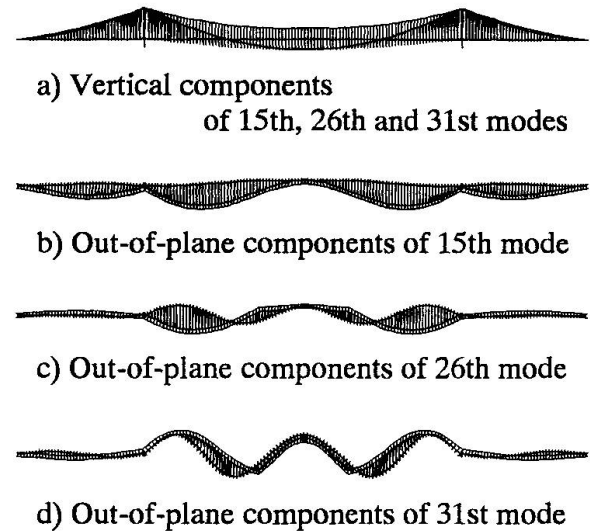


Fig. 7 Symmetric torsional modes (PARA-RIGID model)

#### 4. Natural vibration mode characteristics

Before the coupled flutter analysis, we performed an eigen-analysis for the natural vibration modes of the four models. The results showed that the 1st symmetric vertical deflection mode of both the PARA and MONO models was obtained in the 3rd solution mode. The 1st symmetric vertical mode of the PARA-RIGID and MONO-RIGID models was obtained in the 2nd solution mode instead of the 3rd one, however, the natural frequency was the same as that in the PARA and MONO models. In all the four models, the 2nd and 3rd symmetric vertical modes were obtained in the 11th and 12th solution modes, respectively. The 1st symmetric torsional mode of the PARA model was obtained in the 17th solution mode. In the PARA-RIGID model, it was obtained in the 15th solution mode instead of the 17th one, as well as in the 26th and 31st solution modes while the frequency increased. The 1st symmetric torsional mode of the MONO model was obtained in the 26th solution mode. In the MONO-RIGID model, it was obtained in the same 26th solution mode while the frequency increased, as well as in the 15th, 22nd and 30th solution modes. All these symmetric torsional modes of the PARA-RIGID and MONO-RIGID models had large out-of-plane (in the horizontal direction perpendicular to bridge axis) components. Among them, newly obtained torsional modes in the PARA-RIGID and MONO-RIGID models are the ones that the out-of-plane modes in the PARA and MONO model changed into and the frequencies increased. Figure 6 shows the symmetric vertical modes of the MONO model, and Fig. 7 shows the symmetric torsional modes of the PARA-RIGID model.

#### 5. Coupled flutter characteristics

Coupled flutter characteristics were analyzed using a modal analysis technique (Miyata, Yamada and Ota 1989, Iwamoto 1995). Unsteady aerodynamic forces based on the plate-wing theory were used in the analysis. In order to investigate the influence of modes, many cases of analysis with various modal combinations were carried out. Figs. 8 to 11 show the relationship between the wind velocity  $U$  and the logarithmic decrement  $\delta$  of flutter mode branches. In the Fig. 9 for the PARA-RIGID model, the 8th, 10th, 17th and 18th solution modes, which were not described in the previous section, represent the swinging log mode of the side span, the out-of-plane mode and the coupled modes of the 4th symmetric vertical deflection and side span out-of-plane components for the latter two modes, respectively.

Figures 8 to 11 show that there is large difference between the results obtained using the 1st through 40th modes and those using the basic two modes: the 1st symmetric vertical and

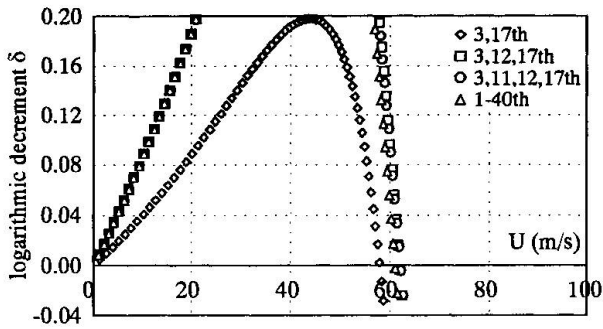
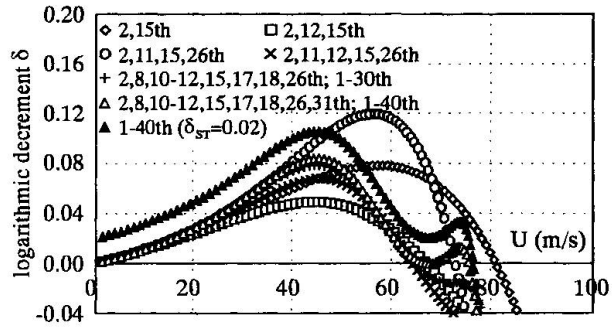
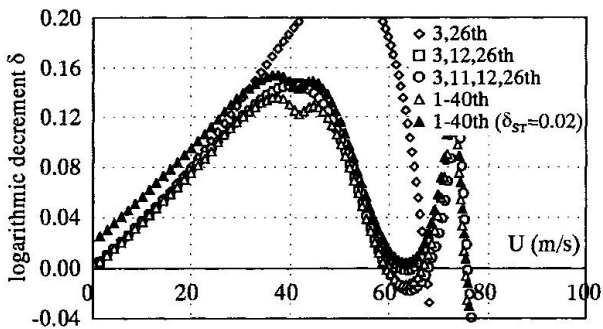
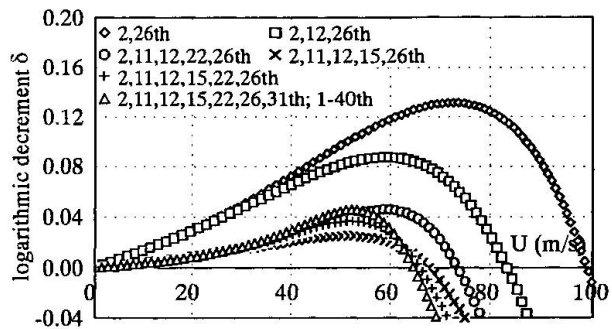

 Fig. 8  $U$ - $\delta$  curve (PARA model)

 Fig. 9  $U$ - $\delta$  curve (PARA-RIGID model)

 Fig. 10  $U$ - $\delta$  curve (MONO model)

 Fig. 11  $U$ - $\delta$  curve (MONO-RIGID model)

Table 2 Flutter critical wind velocity [m/s]

Applied modes	Analytical model			
	PARA	PARA-RIGID	MONO	MONO-RIGID
Basic 2 modes ( $\delta_{ST} = 0$ )	58.4	81.4	67.8	99.2
1-40th modes ( $\delta_{ST} = 0$ )	61.1	67.1	59.5	65.5
1-40th modes ( $\delta_{ST} = 0.02$ )	-	76.6	75.7	-
Selberg's equation	55	77	63	89

torsional modes. The flutter critical wind velocity of the former case is considerably lower than that of the latter case, in all the models except the PARA model. The 3rd symmetric vertical mode (the 12th solution mode) has the largest effect on the critical wind velocity, followed by the 2nd symmetric vertical mode (the 11th solution mode). Both modes greatly decreased the critical wind velocity of the other three models than the PARA model. The symmetric torsional modes in the two models with rigid hanger frames also seem to contribute to decreasing the critical wind velocity except the 31st solution mode of the PARA-RIGID model.

The  $U$ - $\delta$  curves of the PARA-RIGID and MONO models obtained from multi-mode flutter analysis have complex shapes, that is, the logarithmic decrement reaches a negative peak right after the flutter occurring and increases to positive value again. In consideration of these shapes of  $U$ - $\delta$  curves, coupled flutter analysis was performed again with the structural damping of logarithmic decrement  $\delta_{ST} = 0.02$  considered. The results demonstrate that, as shown in the figures, the  $U$ - $\delta$  curves shift to the upper side and the critical wind velocity increases by approximately 10 to 15 m/s. In addition, flutter analysis with unsteady drag forces based on the quasi-steady theory considered was performed for all four models. Although the  $\delta$  value tended to increase overall, almost no change was observed in the critical wind velocity.





Table 2 summarizes the estimated values of the critical wind velocity for the four models. In this table, the values obtained from Selberg's equation are also listed as a reference. The final values for the four models are approximately 61, 77, 76 and 65 m/s, respectively. Mono-duo shaped main cable system and rigid hanger frames are found effective as wind-resistant countermeasures. However, it is also found that the flutter characteristics aren't necessarily improved highly even if the two countermeasures are used at the same time. This is a problem to be solved in future investigation.

## 6. Conclusions

This paper discussed the coupled flutter characteristics of the ultra long-span suspension bridges in which mono-duo shaped main cable system and rigid hanger frames are applied as wind-resistant countermeasures. Based on the analytical results, we reached the following conclusions.

- (1) Through the concentrated installation of rigid hanger frames, large degree of coupling of the out-of-plane components was formed in a basic mode in which 1st symmetric torsional components had been previously dominant. In addition, several symmetric torsional modes were obtained by the formation of the coupling of the torsional components in modes in which out-of-plane components had been dominant, leading to the increase in the natural frequencies in all these modes.
- (2) In the flutter analysis using the models with the wind-resistant countermeasures, there was large difference between the  $U$ - $\delta$  curves obtained from the conventional basic two-mode analysis and those from the multi-mode analysis. In addition, there were several dominant modes other than the basic two modes that affected the flutter critical wind velocity, such as the 2nd and 3rd symmetric vertical deflection modes.
- (3) When mono-duo shaped main cable system and rigid hanger frames were applied individually, the flutter critical wind velocity considerably increased as compared with the conventional suspension bridge model if reasonable structural damping was taken into consideration. Thus, mono-duo shaped main cable system and rigid hanger frames are effective as wind-resistant countermeasures. However, the joint use of the two countermeasures didn't necessarily improve the flutter characteristics highly. This is a problem to be solved in future investigation.

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