Session 1. **Equivalent Aerodynamic Derivatives and their Influences on Coupled Flutter Instability**

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1. ABSTRACT - Flutter instability is a catastrophic oscillation and its stabilization is an important issue in the design of long span bridges. In this study, a strategy for coupled flutter stabilization of long-span bridges is presented. The approach is based on the reduction of the absolute values of the aerodynamic derivatives A_1^* and H_3^*, by a proper arrangement of multiple bridge girders along the span direction of the bridge, which was proved effective through wind tunnel tests.

2. INTRODUCTION - Since the old Tacoma Narrows Bridge failure, in 1940, the role of the aerodynamic effects on the general behavior of large structures, e.g. long span bridges, has increased in importance. In this context, an effect to be considered is the flutter instability that may arise in bridge decks, due to the interactions wind-structure. With the ever-increasing bridges span lengths, their natural frequencies have gotten closer and closer, making room for the arising of the 2-DOF coupled flutter instability, instead of the more common 1-DOF torsional flutter. Thus, the development of better tools for the assessment of these effects is needed. In order to fill this gap, this study brings a new approach by using the Step-by-Step Analysis (SBSA), in which the use of the *Equivalent Aerodynamic Derivatives* [1], is shown as an efficient strategy for evaluating the aerodynamic effects on long span bridges.

3. FLUTTER ANALYSIS AND STABILIZATION - The investigations on flutter on long span bridges are usually conducted by using the Complex Eigen-Value Analysis (CEVA). This technique is based only on a mathematical approach for a 2 DOF dynamic instability, not considering the generation mechanism of the phenomenon itself. In order to fill this gap, a method based on the flutter generation mechanism, namely Step-by-Step Analysis (SBSA), was developed. So a better understanding of the flutter characteristics, necessary for the proposition of better strategies for its mitigation, can be attained.

Previous studies using SBSA have demonstrated that coupled flutter can be stabilized by reducing the absolute values of the aerodynamic derivatives A_1^* and H_3^* [2][3]. So introducing the equivalent aerodynamic derivatives, Eq.1 and Eq.2, as the form of the product of modal integral and aerodynamic derivatives, the 2-DOF equations of motion can be expressed as Eq.3 and Eq.4.

$$H_{1,eq}^* = \frac{\int \mu_{\eta i}^2 H_1^* dx}{\int \mu_{\eta i}^2 dx}, H_{2,eq}^* = \frac{\int \mu_{\eta i}\mu_{\phi j} H_2^* dx}{\int \mu_{\eta i}^2 dx}, H_{3,eq}^* = \frac{\int \mu_{\eta i}\mu_{\phi j} H_3^* dx}{\int \mu_{\eta i}^2 dx}, H_{4,eq}^* = \frac{\int \mu_{\eta i}^2 H_4^* dx}{\int \mu_{\eta i}^2 dx} \tag{1}$$

$$A_{1,eq}^* = \frac{\int \mu_{\eta i}\mu_{\phi j} A_1^* dx}{\int \mu_{\phi j}^2 dx}, A_{2,eq}^* = \frac{\int \mu_{\phi j}^2 A_2^* dx}{\int \mu_{\phi j}^2 dx}, A_{3,eq}^* = \frac{\int \mu_{\phi j}^2 A_3^* dx}{\int \mu_{\phi j}^2 dx}, A_{4,eq}^* = \frac{\int \mu_{\eta i}\mu_{\phi j} A_4^* dx}{\int \mu_{\phi j}^2 dx} \tag{2}$$

$$\ddot{p}_i + 2\zeta_i\omega_i\dot{p}_i + \omega_i^2 p_i = \frac{\rho b^2\omega_F}{m_{ei}}\frac{\int \mu_{\eta i}^2 H_1^* dx}{\int \mu_{\eta i}^2 dx}\dot{p}_i + \frac{\rho b^3\omega_F}{m_{ei}}\frac{\int \mu_{\eta i}\mu_{\phi j} H_2^* dx}{\int \mu_{\eta i}^2 dx}\dot{q}_j + \frac{\rho b^3\omega_F^2}{m_{ei}}\frac{\int \mu_{\eta i}\mu_{\phi j} H_3^* dx}{\int \mu_{\eta i}^2 dx}q_j + \frac{\rho b^2\omega_F^2}{m_{ei}}\frac{\int \mu_{\eta i}^2 H_4^* dx}{\int \mu_{\eta i}^2 dx}p_i \tag{3}$$

$$\ddot{q}_j + 2\zeta_j\omega_j\dot{q}_j + \omega_j^2 q_j = \frac{\rho b^3\omega_F}{I_{ej}}\frac{\int \mu_{\eta i}\mu_{\phi j} A_1^* dx}{\int \mu_{\phi j}^2 dx}\dot{p}_i + \frac{\rho b^4\omega_F}{I_{ej}}\frac{\int \mu_{\phi j}^2 A_2^* dx}{\int \mu_{\phi j}^2 dx}\dot{q}_j + \frac{\rho b^4\omega_F^2}{I_{ej}}\frac{\int \mu_{\phi j}^2 A_3^* dx}{\int \mu_{\phi j}^2 dx}q_j + \frac{\rho b^3\omega_F^2}{I_{ej}}\frac{\int \mu_{\eta i}\mu_{\phi j} A_4^* dx}{\int \mu_{\phi j}^2 dx}p_i \tag{4}$$

where: p and q are the generalized coordinates of heaving and torsional motion, ω_F is the modal flutter frequency, m_e and I_e are the modal mass and mass inertia per unit length, μ_η and μ_ϕ are the modal displacements of heaving and torsional motions.

So considering both the mode shape and the aerodynamic derivatives, the reduction of the equivalent aerodynamic derivatives, $A_1^*{}_{,eq}$ and $H_3^*{}_{,eq}$, can be attained by a proper combination of two different kinds of girders along the span direction.

4. WIND TUNNEL TESTS - In order to validate the above proposition, a three-span parallel type suspension bridge with center span of 2780m and side spans of 1075m was investigated (Fig.1). Two kinds of grating girders (Type 1, Type 2) with opening ratio around 35% and opposite signs of A_1^* was optimally arranged in its span direction. The structural logarithmic damping δ_0 was 0.02 and the first symmetric and asymmetric vibration modes shapes as well as the structural parameters used in flutter analyses are shown in Fig.2.

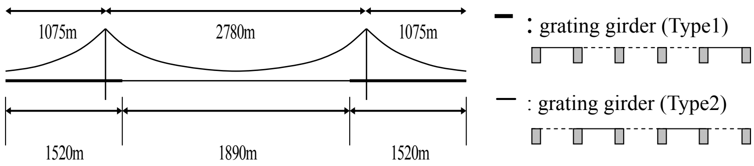
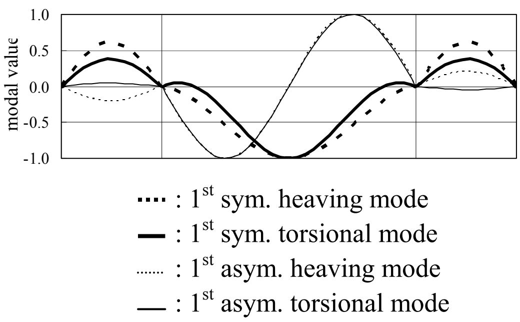


Fig.1 - Arrangement of multiple bridge girders



Span configuration	Main cable	1100,2800,1100 m
	Stiffened girder	1075,2780,1075 m
Main cable	Sag ratio	1/10
	Spacing	28 m
	Area	0.59 m^2
	Mass of inertia	5×10 ton/m/g
Stiffened girder	Depth	4.0 m (I-shape)
	Area	1.0 m^2
	Bending stiffness (EI)	6×10^7 ton·m^2
	Torsional stiffness (GJ)	8×10^5 ton·m^2
	Mass of inertia	18.3 ton/m/g
	Mass moment of inertia	1.8×10^3 ton·m^2/m/g

Fig. 2 - Modal shape and structural parameters of the suspension bridge

The coupled flutter analyses using the aerodynamic derivatives of thin plate pointed for the occurrence of flutter in both vibration modes, at low velocity range. However the hybrid proposed arrangement did not show any flutter instability, mainly due to the reduction of absolute values of equivalent aerodynamic derivatives $A_1^*{}_{,eq}$ and $H_3^*{}_{,eq}$.

5. CONCLUSION - The coupled flutter instability of super long-span suspension bridge can be effectively controlled by the reduction of absolute values of the equivalent coupled aerodynamic derivatives $A_1^*{}_{,eq}$ and $H_3^*{}_{,eq}$, with the use of a proper combination of two different kinds of girders, which have opposite sign of aerodynamic derivatives, even when their isolated usage does not show any advantage for flutter stabilization.

6. REFERENCES – 1) Matsumoto et al "Flutter stabilization method based upon effects of equivalent aerodynamic derivative", *Proc. of 19th KKCNN Symposium on Civil Engineering*, 2006; 2) Matsumoto, M., et al "Flutter mechanism and its Stabilization of Bluff Bodies", *Proc. of 9th ICWE*, 1995; 3) Matsumoto, M. "Flutter instability of structures", *Proc. of 4th EACWE*, 6-11, 2005;