A LONG-SPAN BRIDGE AERODYNAMIC REPRESENTATION

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INTRODUCTION

Until the middle of the last century, the aerodynamic actions of wind on bridges were not well understood. The dramatic failure of the Tacoma Narrow Bridge in the US in 1940 initialized a great impetus to study bridge aerodynamics, in which the wind-induced forces and the bridge deck's motions interact significantly. This interaction was found analogous to those happening to airfoils in aeronautics. The understanding of the aerodynamics of bridge decks thus traditionally borrowed many ideas from the airfoil problem. For example, the coupled response of bridge decks has been thought to be due to the couple between different primary vibration modes (see Simiu and Scanlan, 1996). However, rigorous studies, both analytical and experimental, have revealed that the aerodynamic response of bridge decks is not simple like that.

In this paper, a modern understanding and interpretation of the aerodynamic response of bridge decks is presented. Then by using the concept of aeroelastic complex modes (Nguyen, et al., 2000), the aerodynamic behaviors of the Akashi Kaikyo Bridge in Japan, which is the longest suspension bridge in the world at present, are effectively interpreted in line with this modern understanding.

AEROELASTIC PHENOMENON

A coming wind flow to a bridge deck induces a wind force, which applies on the bridge deck and makes the deck response (see **Fig. 1**). However, when the deck vibrates in the wind flow, its movement will change the condition of the flow around itself, and hence will inversely affect the wind force. This interaction is called aeroelastic phenomenon for bridge decks, which is similar to that in case of airfoils. As such, the feed back of the response to the wind force can be modeled as a 'self-excited force'. Because of depending on the deck's motions, this force alters the dynamic properties, and hence plays an ultimate role in the stability of the deck. The fundamental question is how such matters happen.

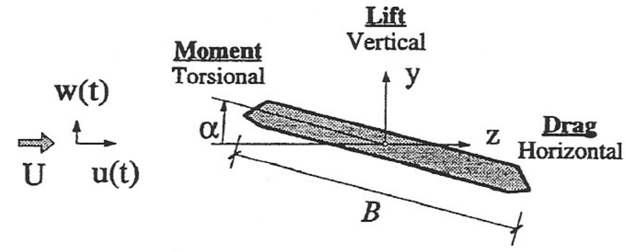


Figure 1 3-DOF section of a bridge deck (z-direction is excluded for 2-DOF section)

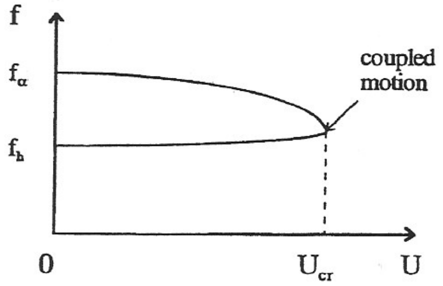


Figure 2 Classical interpretation of aeroelastic coupling for 2-DOF airfoils

As understood from the well-known classical airfoil problem (Bisplinghoff and Ashley, 1962), there is a potential of flutter instability of a 2-DOF airfoil at a certain wind speed. The phenomenon is characterized by a strongly coupled response of the 2 DOFs – vertical and torsional – at the same frequency, which can lead the system to the negative damping state and hence the divergent oscillation. In the classical understanding, it was interpreted that the self-excited force significantly alters the natural frequencies of the vertical motion f_h and the torsional motion f_α, so that they change with the wind speed as illustrated in **Fig. 2**. The flutter wind speed U_{cr} was defined corresponding to the cross point between f_h and f_α, at which the coupled response was thought to occur.

However, this classical interpretation in **Fig. 2** is found to be incorrect and inadequate to represent the phenomenon. From extensive observation of wind tunnel test for section model of bridge decks, it was learned that the coupled response and the definition of flutter wind speed U_{cr} must be represented by two **Figs. 3a** and **3b** simultaneously. **Fig. 3a**, similar to the classical interpretation, shows the change of the frequencies of the vertical mode f_h and the torsional mode f_α with the wind speed. Both of them decreases, showing a more flexible system at higher wind speed due to the aeroelastic effect. However, the cross point between them does not always occur and also does not have any particular meaning. The coupled response happens and develops gradually with wind speed in the torsional mode f_α only. At wind speed $U = 0$, this mode is purely torsional. As the wind speed increases, the vertical motion will appear and gradually develop in the mode, to make it more and more 'torsional-vertical' coupled mode. The vertical mode f_h, on the contrary, keeps being purely vertical, and has no interference to the evolution of the torsional mode. On the other hand, the flutter wind speed U_{cr} is obtained in **Fig. 3b**, which shows the change of logarithmic decrement δ of response (representing for the system's damping) with wind speed. The flutter wind speed corresponds to the state of zero logarithmic decrement, after which the system divergently oscillates.

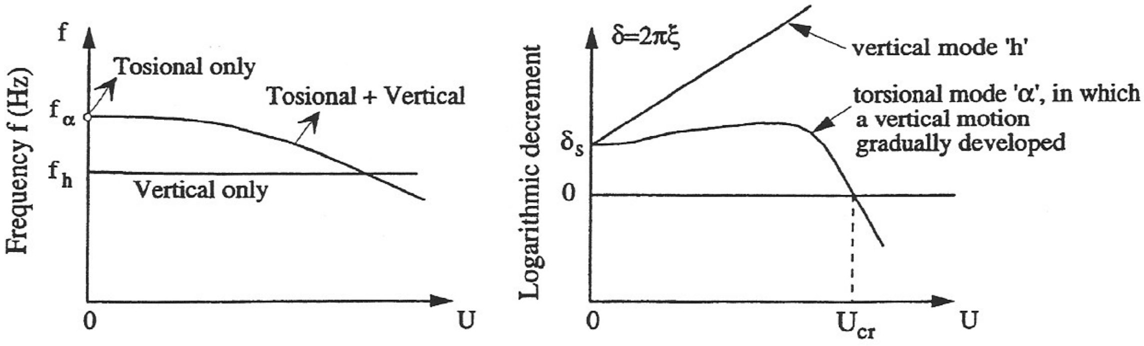


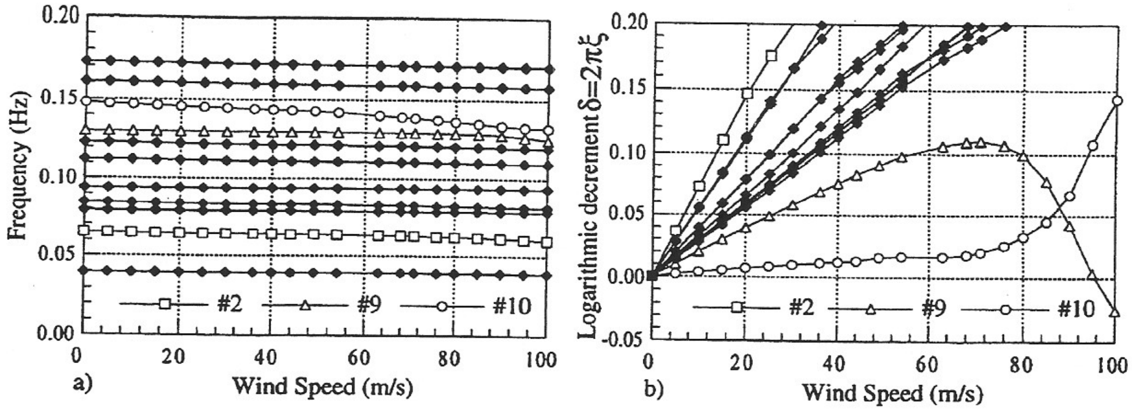
Figure 3 Modern interpretation of aerodynamic phenomena of bridge decks

COUPLED GUST RESPONSE BY AEROELASTIC COMPLEX MODE APPROACH

The Aeroelastic Complex Mode (ACM) approach (Nguyen, et al., 2000) can be used to analyze and interpret the phenomenon mathematically. Instead of employing much complicated mathematical formulation to incorporate the aeroelastic effect like many other methods, the ACM method offered a direct way to see the aeroelastic effect explicitly in the modal properties. A successful application of the method for the Akashi Kaikyo Bridge in Japan has been made elsewhere (Nguyen, et al., 2000). The objective in this part is to investigate the aerodynamic behaviors of the bridge in line with the above modern understanding.

Aeroelastic Effects in Aerodynamic Damping Ratio and Frequency

The changes of modal frequencies and logarithmic decrements of the first lowest 12 modes are shown in **Figs. 4a** and **4b**, respectively. Although appearing complicated with many modes for a 3-D model, the basic representation is similar to those in **Figs. 3a** and **3b**. Due to more pronounced self-excited force at higher wind speeds, the modal frequencies and the aerodynamic logarithmic decrements change significantly. In accordance to that in **Fig. 3**, let's consider 3 modes: mode #2, which is the lowest mode containing the 1st vertical motion, and mode #9 and #10, which are the lowest modes including the 1st torsional motion. In **Fig. 4a**, the frequency of mode #9 and especially # 10 considerably decreases, whereas that of mode #2 does not. The intersection of any pair of modal frequency also does not occur. In **Fig. 4b**, the logarithmic decrement (equivalent to damping) of mode #2 just almost linearly increases, whereas those of mode #9 and #10 spectacularly vary not linearly with wind speed. The mode #10 keeps very low logarithmic decrement of at low wind speeds and is then quickly stabilized by increasing values of the logarithmic decrement at high wind speeds. On the contrary, the logarithmic decrement of mode #9 grows up at low wind speeds, but after 80 m/s very quickly reduces to negative value, giving the estimated flutter wind speed at 95 m/s, which is quite close to the experimental result of 90 m/s in the wind tunnel test of the 3-D bridge's model.



a) b)

Figure 4 Trace of a) frequencies and b) aerodynamic logarithmic decrements of lowest 12 modes

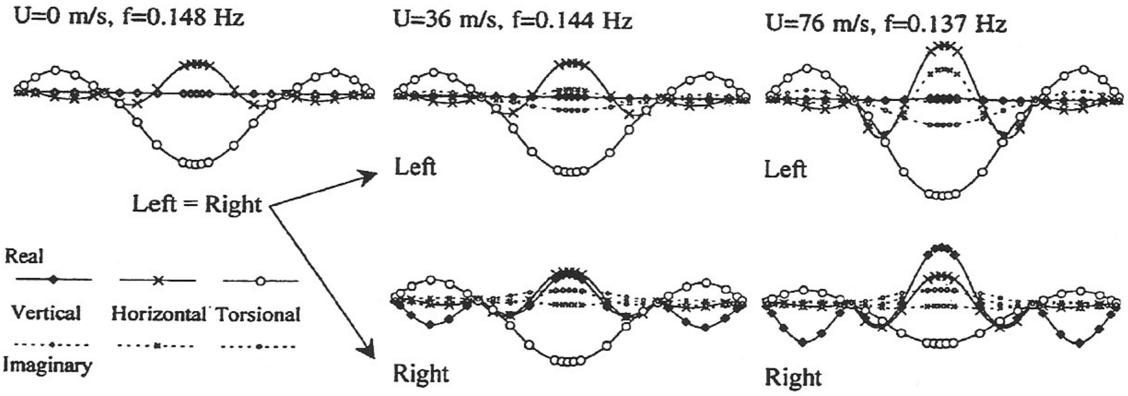


Figure 5 Evolution of mode #10 – typical aeroelastic complex mode

Aeroelastic Effects in Mode Shapes and Response Spectra

The evolution of vibration mode shapes reveals the development of the coupled response. While the mode shape of mode #2 keeps being vertical only, the mode shapes of mode #9 and #10 evolve spectacularly, as typically shown for mode #10 in **Fig. 5**. This mode #10 is a coupling mode between torsional and horizontal motions at U=0. When the wind speed increases, the vertical motion appears and develops, and even becomes the most dominant motion. The mode therefore becomes a three-motion coupling mode. As the result, the vertical gust response spectrum also evolves significantly in **Fig. 6**. At low wind speed, the vertical response is dominated by mode #2. As the wind speed increases, mode #9 and #10 develop, and finally dominate the response. Consequently, the response spectra in **Fig. 7** for all 3 motions – vertical, horizontal and torsional – have peaks of almost the same order of magnitude at the same frequency of mode #10. This coupled gust response – response in all 3 motions at the same frequencies –therefore can be effectively characterized and predicted by the aeroelastic complex modes. The analytical evolutions of the response spectra agree very well with the measured results of the full-model test of the bridge (HSBA, 1992).

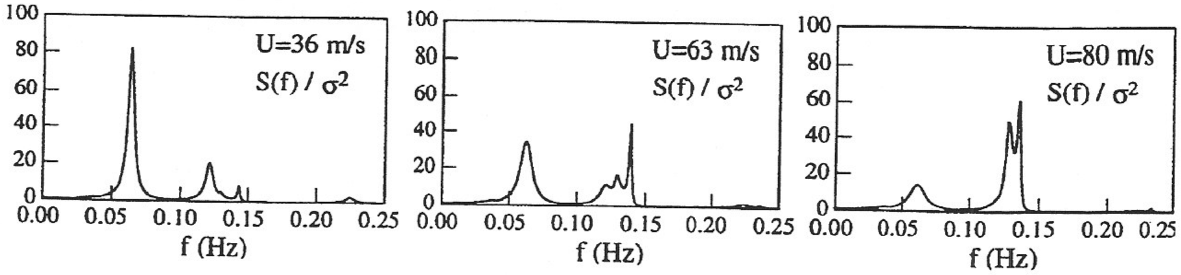


Figure 6 Evolution of vertical response spectrum with wind speed

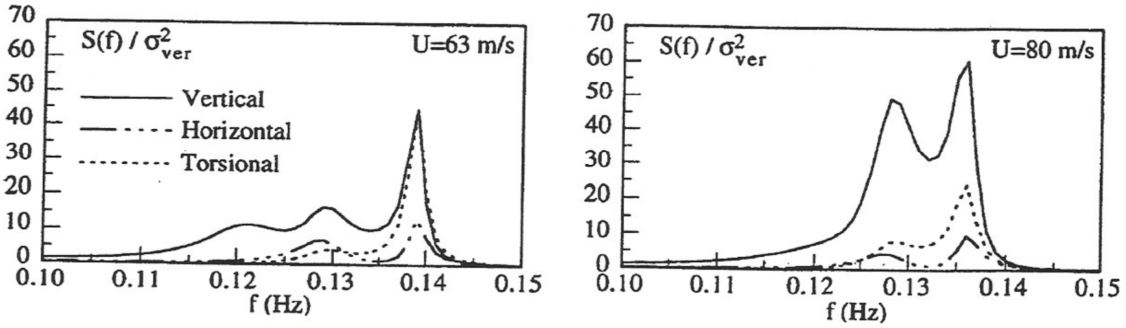


Figure 7 Coupled response spectra

CONCLUSION

(1) A modern understanding of the aerodynamics of bridge deck under wind action has been presented. Due to the aeroelastic effect expressed by the self-excited force, the coupled response happens due to the coupling of motions gradually developing in each mode, not due to coupling between different natural modes.

(2) The aeroelastic complex mode (ACM) was demonstrated to be appropriate to represent the aeroelastic phenomenon. In line with the definition of vibration modes of a dynamic system, the aeroelastic mode is the actual vibration mode shape of the deck in wind flow.

(3) Successful analysis of the aerodynamic behaviors of the Akashi Kaikyo Bridge with a very good agreement to the experimental results has confirmed the correctness of the modern understanding, as well as the effectiveness and accuracy of the ACM method.

(4) This new understanding has provided better insight, and hence better control of the bridge aerodynamic problem. This has led to the development of the 'Mode-shape control' approach (Miyata, 1999), which would be a promising solution for longer span bridges' wind-resistant design in the near future.

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