August 27-31, 2023
FLORENCE - ITALY
ICWE 16
16th International Conference on Wind Engineering

Spanwise layout optimization for aerodynamic measures against multi-mode vortex-induced vibration on bridges

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SUMMARY:
Aerodynamic countermeasures are commonly used to control vortex-induced vibration (VIV) on bridges. Due to lack of appropriate three-dimensional (3-D) VIV analysis method, these countermeasures are usually installed along the full span of the bridge deck, resulting in excessive costs. Here we propose a method to reduce the use of aerodynamic countermeasures by optimizing their spanwise layout along the bridge deck. A mode-by-mode 3-D VIV analysis method based on the generalized polynomial vortex-induced force model is developed to compute the VIV response of the bridge with different spanwise layout of countermeasures during optimization. The genetic algorithm is then adopted to search the most economic layout scheme with constraints of limited multi-mode VIV response. We offer two alternative types of search space for the optimization. This method is applied to a long-span suspension bridge in conjunction with numerical simulation and wind tunnel test. The optimized results show that a significant reduction in the total spanwise length of the aerodynamic countermeasures can be achieved.

Keywords: multi-mode vortex-induced vibration, aerodynamic countermeasure, spanwise layout optimization

1. INTRODUCTION

Long-span bridges are susceptible to vortex-induced vibration (VIV). Large-amplitude VIV threatens the serviceability and fatigue life of the bridge and therefore needs to be mitigated. Aerodynamic countermeasures are commonly used for the control of VIV. Due to lack of appropriate three-dimensional (3-D) VIV analysis method, these countermeasures are usually installed along the full span of the bridge deck, resulting in excessive costs for construction and maintenance. According to previous study (Ehsan and Scanlan, 1990), the vortex-induced force (VIF) is dominated by the self-excited force component, the magnitude of which increases with the structural vibration amplitude. Therefore, installing aerodynamic countermeasures at the spanwise locations where the deck response is small has little contribution to mitigating the overall VIF and thus the VIV response on the full bridge deck. It is possible to reduce the use of aerodynamic countermeasures by optimizing their spanwise layout on bridge. To accomplish the optimization, a mode-by-mode 3-D VIV analysis method for the bridges with multiple cross-sections deck is developed based on the generalized polynomial VIF model. The genetic algorithm (GA) is then adopted to search the most economic layout scheme with constraints of limited multi-mode VIV response. A long-span suspension bridge is chosen as the application example to show the effectiveness of the proposed method.

2. SPANWISE LAYOUT OPTIMIZATION METHOD FOR COUNTERMEASURES

A 4th-order generalized polynomial model following the framework of Xu et al. (2018) is adopted to describe the vertical VIF acting on the bridge deck per unit length:

$$f_{VI}(\dot{y}) = \rho U^2 D\left[Y_1(U_r) + Y_2(U_r)\frac{|\dot{y}|}{U} + Y_3(U_r)\frac{|\dot{y}|^2}{U^2} + Y_4(U_r)\frac{|\dot{y}|^3}{U^3}\right]\frac{\dot{y}}{U} \tag{1}$$

where f_{VI} is the vertical VIF; ρ is the air density; U is the wind speed; D is the depth of the bridge deck section; y is the vertical displacement; the over-dot denotes differentiation with respect to time t; Y_i (i = 1, 2, 3, 4) are the aerodynamic parameters which vary with the reduced wind speed $U_r = U/f_sD$ and the section shape; f_s is the structural frequency. Define the cross-sections without and with aerodynamic countermeasures as CsA and CsB respectively, and the aerodynamic parameters of the full bridge deck with both CsA and CsB should be expressed as

$$Y_i(x, U_r) = \begin{cases} Y_{i,CsA}(U_r),\ x \in L_{CsA} \\ Y_{i,CsB}(U_r),\ x \in L_{CsB} \end{cases} ; \quad \mu(L_{CsA}) + \mu(L_{CsB}) = L \tag{2}$$

where x is the location along the span L of the bridge deck; $Y_{i,CsA}$ and L_{CsA} are respectively the aerodynamic parameters and spanwise location set of CsA, while $Y_{i,CsB}$ and L_{CsB} are for CsB; $\mu(\cdot)$ denotes the length of location set. Assuming that the VIF is fully correlated along the bridge deck, the governing equations for vertical VIV of single structural mode can be expressed as

$$y(x,t) = \phi(x)v(t) ; \quad M = \int_0^L m\phi^2(x)dx ; \quad \tilde{Y}_i(U_r) = \int_0^L Y_i(x, U_r)|\phi|^{i+1}(x)dx \tag{3a}$$

$$M\left(\ddot{v} + 2\omega_s\zeta_s\dot{v} + \omega_s^2 v\right) = \rho U^2 D\left[\tilde{Y}_1(U_r) + \tilde{Y}_2(U_r)\frac{|\dot{v}|}{U} + \tilde{Y}_3(U_r)\frac{|\dot{v}|^2}{U^2} + \tilde{Y}_4(U_r)\frac{|\dot{v}|^3}{U^3}\right]\frac{\dot{v}}{U} \tag{3b}$$

where $\phi(x)$ is the mode shape; $v(t)$ is the generalized coordinate; M is the modal mass; m is the mass per unit length; $\tilde{Y}_i$ are the modal aerodynamic parameters; $\omega_s = 2\pi f_s$ and ζ_s are respectively the modal circular frequency and damping ratio. According to Eq. (3b), VIV is not going to occur in the considered mode if the linear damping ratio ζ_l of the aeroelastic system satisfies

$$\zeta_l(U_r) = \zeta_s - \frac{\rho U D \tilde{Y}_1(U_r)}{2M\omega_s} \geq 0,\ U_r \in \text{lock-in range} \tag{4}$$

To reduce the use of aerodynamic countermeasures with constraints of zero VIV amplitudes, the distribution of L_{CsA} and L_{CsB} is to be optimized, which influences the value of $\tilde{Y}_1$. For the control of single-mode VIV, the spanwise locations with larger mode shape values are given priority to install the countermeasures. The minimum required length of countermeasures can then be deduced from min(ζ_l) = 0. To control multi-mode VIV, the GA is adopted for the optimization. The full bridge deck is divided into N location sets of equal length along the span as [L_1, L_2, …, L_N]. The individual of GA is then defined as a certain prioritization of the location sets to install countermeasures. The expressions of the individual **C** and the objective function J are as follows:

$$\mathbf{C} = \left[L_{\delta 1},\ L_{\delta 2},\ \ldots,\ L_{\delta n},\ L_{\delta(n+1)},\ \ldots,\ L_{\delta N} \right] \tag{5}$$

$$J(\mathbf{C}) = J_1 + J_2 = \mu\left(\bigcup_{k=1}^{n} L_{\delta k} \right) + \mu(L_N)\frac{d}{n} \tag{6}$$

where $[L_{\delta 1}, L_{\delta 2}, \ldots, L_{\delta N}]$ is a permutation of $[L_1, L_2, \ldots, L_N]$; n is the minimum number of location sets required to install the countermeasures for the control of all target modes; d is the number of discontinuities in the set $\bigcup_{k=1}^{n} L_{\delta k}$. J_1 denotes the minimum required length of countermeasures to control all target modes under the current prioritization of spanwise location sets. J_2 is introduced to make the optimized countermeasure installation locations as continuous as possible. J_1 is priority to J_2 in the optimization because $0 \leq d/n < 1$. The optimum individual with minimum value of Eq. (6) can be searched using GA from all permutations of $[L_1, L_2, \ldots, L_N]$. Alternatively, the search space can be reduced with the results of single-mode optimization (see section 3).

3. APPLICATION EXAMPLE

A suspension bridge with semi-closed box deck (see Fig. 1) is taken as the example to evaluate the application effect of the proposed method. The to-be-optimized aerodynamic countermeasure is the additional baffle installed in the lower slot of the bridge deck. According to the results of wind tunnel test on the bridge deck section model (see Fig. 2), application of this baffle can completely suppress the vertical VIV of the original bridge deck at +3° wind attack angle. The structural and aerodynamic parameters required for optimizing the spanwise layout of baffles on the bridge were obtained from numerical simulation and wind tunnel test.

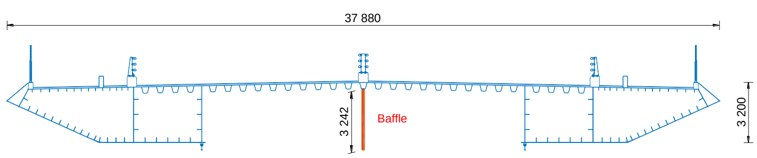

Figure 1. Cross-section of the bridge deck (unit: mm).

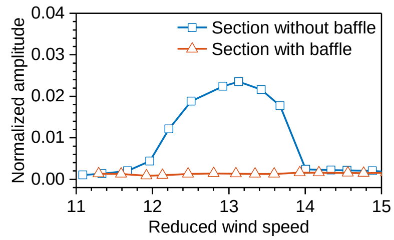

Figure 2. Recorded amplitudes of VIV.

The spanwise layout of the baffles was first optimized with the single-mode optimization method. Fig. 3 shows the minimum required length and location range of the baffles to completely control the VIV of each vertical mode. The optimized layout schemes of the 4 modes differ in the length and location due to variation of modal mass and shape. All the first 4 vertical modes are prone to VIV below the designed wind speed and therefore need to be controlled in the optimization. The optimum layout was searched using the GA, where the full bridge deck is divided into several 4 m segments along the span. Fig. 4 shows the search space and optimized results of the global and local optimization. The search space of the global optimization includes the full bridge deck, while that of the local optimization is limited to the location sets that covers all the single-mode optimization results shown in Fig. 3. The total spanwise length of baffles in the symmetric optimum layout scheme is slightly larger than that in the asymmetry one due to more constraints, but both are much smaller than the full span. The local optimization can yield the solution with very close or even the same length of baffles compared to the global optimum solution, and it is more efficient for practical application due to the significant reduction in search space.

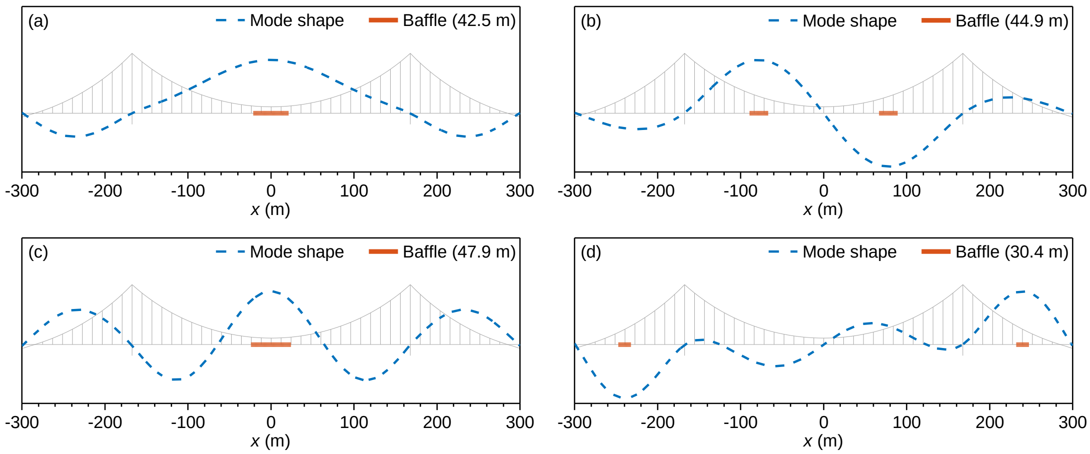

Figure 3. Optimized spanwise layout of the aerodynamic countermeasures with constraints of zero single-mode VIV amplitudes: (a) 1st vertical mode; (b) 2nd vertical mode; (c) 3rd vertical mode; (d) 4th vertical mode.

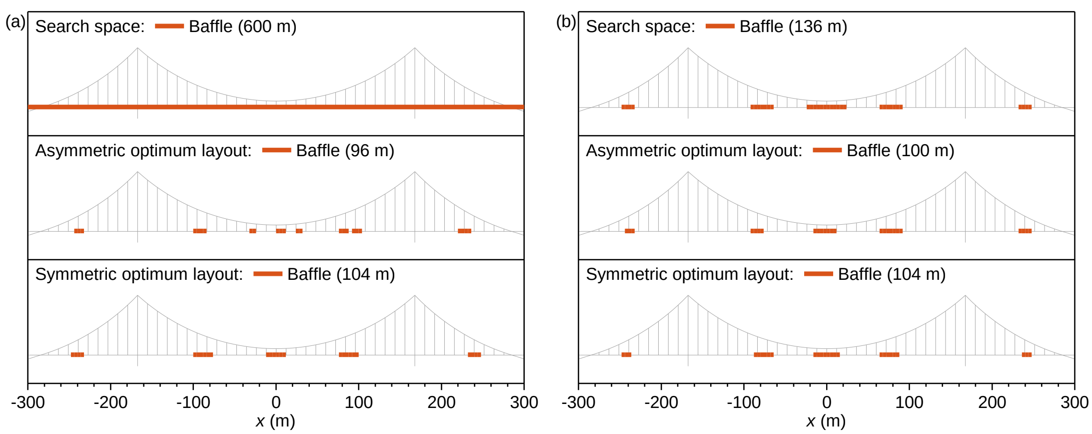

Figure 4. Optimized spanwise layout of the aerodynamic countermeasures with constraints of zero multi-mode VIV amplitudes: (a) global optimization; (b) local optimization.

4. CONCLUSIONS

A spanwise layout optimization method for the aerodynamic countermeasures against VIV is proposed to reduce the use of them on the bridge. The optimized results of the application example with constraints of limited multi-mode VIV response show that a significant reduction in the use of aerodynamic countermeasures can be achieved. The proposed global and local optimization methods yield the layout schemes with very close spanwise lengths of aerodynamic countermeasures, and the latter is more efficient for practical application.

ACKNOWLEDGEMENTS

The work described in this paper was jointly supported by the National Natural Science Foundation of China (Grant 51938012), to which the authors are very grateful.

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