

Numerical studies on the behaviors of wind-structure interaction for membrane structures

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ABSTRACT: In this paper, a combined numerical approach on the time-dependent fluid-structure interaction for tension structures with large displacements is presented. The general idea of this approach is to divide the structural response under wind actions into three components: mean response, background response and resonant response. The first component is a static interaction process, which is due to the change of structural geometry under mean wind pressure. The second component can be regarded as a steady interaction process, which relates to the motion of large scale eddies. The last component can be called as a transient interaction process, in which the dynamic magnification effect should be considered mainly. Due to the different characteristics of each component, different methods should be adopted respectively. For static and steady interaction, the suitable method is CFD simulation, in which the wind pressure change due to structural deformation will be considered mainly; for transient interaction, the suitable method is nonlinear random vibration analysis in time domain. Based upon the combined procedure, some numerical examples include one-way type roofs and saddle-shaped membrane structures are carried out finally. From the comparison with direct numerical method, which can be seen as an accurate method, it can be concluded that the results obtained from the combined procedure are very close to the direct numerical method; moreover, the combined procedure seems easier for application.

KEYWORDS: membrane structures; wind-structure interaction; CFD numerical simulation; aeroelastic effects; aerodynamic response; geometrical nonlinearity

1 INTRODUCTION

Membrane structures are the most widely used long-span tension structures. As being characterized by lightweight and flexible, they are highly susceptible to the wind action. How to determine the aerostatic and aerodynamic response due to the wind action is a major concerned problem for the design of tension structures. Up to now, comprehensive studies have been performed, but the mechanism of wind-induced vibration of membrane structures has not been recognized in enough detail. The main reasons lie in two aspects: one is the strongly geometrical nonlinearity,

which make the dynamic characteristics of tension structures are obviously different from those of bridges and high-rising buildings, so traditional methods of random vibration analysis in frequency domain can not be used directly. The other reason is the weak local rigidity, which can make membrane structures produce rather large vibration under wind excitation. Sometime, these large vibrations can even affect the surrounding fluid field remarkably; that is to say, the wind-structure interaction or the aeroelastic effects can not be neglected. To solve the previous problem, some nonlinear random vibration analysis methods in time domain have been developed successfully [1]. But all those methods are based on the condition that the inlet flow or the wind pressure process has been determined beforehand, so they can not consider the fluid-structure interaction actually. To determine the actual wind loads on tension structures, especially to reveal the mechanism of wind-structure interaction, some semi-empirical methods have been developed [2], also some wind tunnel tests has been carried out [3]. However, some unavoidable errors will occur when using simplified methods, and wind tunnel tests are too expensive to carry out extensive studies, therefore those methods are only limited to certain special structures.

In recent years, with the development of high speed computer and numerical computational methods, it has been available to integrate computational fluid dynamics (CFD) and computational structure dynamics (CSD) technique to simulate structures and surrounding flow simultaneously, which is called as numerical wind tunnel method. Comparing to those simplified methods and wind tunnel tests, numerical wind tunnel method can solve flowing problems of complex geometrical bodies without disturbing the fluid field, construct computational models whose dimension are same as that of original structures so as to avoid the similarity requirements in wind tunnel test, completely control the properties of fluid and provide great flexibility for selecting flowing parameters to carry out parametric analysis. Because of these superior characteristics, numerical wind tunnel method is highly valued by researches and developed quickly. Now this method has been applied to solve some aeroelastic problems, such as for bridges [4] and also for membrane structures [5]. But due to the tremendous calculate work, this method also can not be used in engineering practice.

In this paper, an overview of the studies on wind-structure interaction of tension structures is provided firstly. Then a combined numerical approach based on CFD simulation method and random vibration analysis method is presented. Finally, Base upon the combined procedure, some numerical examples include one-way type roofs and saddle-shaped membrane structures are carried out.

2 METHODOLOGY

Wind-induced response of tension structures can be theoretically described as a problem of unsteady coupling vibration between incompressible viscous fluid and geometrical nonlinear elastic body. Due to the fluid forces and structure displacements on the interface between fluid and structure are unknown, it is impossible to solve the fluid field and structural field separately, so we have to find some methods that can solve these two fields simultaneously. Undoubtedly, the numerical wind tunnel method provides a good platform for solving this problem.

In Ref. [6], the author had developed a FEM program for calculating two-dimension problem. There were three modules included in this program, each for CFD, CSD and CMD (Computational Mesh Dynamics) calculation, respectively. The flowchart is shown in fig.1. The dynamic fluid-structure interaction was performed by a partitioned solution approach, and the time-dependent simulation process was controlled by an iteration procedure between these three modules until convergence was reached in each time-step. Based on this program, the aeroelastic re-

sponse of one-way type pretensioned membrane roofs has been studied. The effects of several factors, such as height-span ratio, roof slope, roof mass and pretension force et al, were investigated. From these studies, some preliminary but very important conclusions about the mechanism of wind-structure interaction were obtained [7].

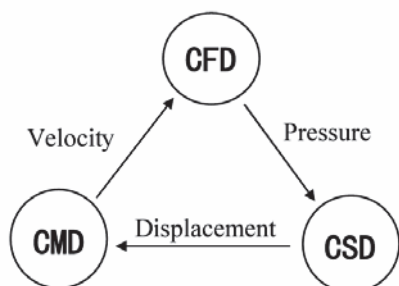


Fig. 1 Flowchart of CFD simulation program

The practical cable/membrane structures are 3-dimensional with complicated surfaces. Using the CFD simulation approach as mentioned above to study the aeroelastic effects of 3-D structures has theoretically possible, but will be very difficult in practice at present. Firstly, the time-consuming of simulating 3-D problem is hundreds times of 2-D problem, which can not be tolerated for systemically studies. Secondly, the increasing computing time will cause lots of numerical dissipation and error cumulation. So if we use the method proposed in Ref. [9] to solve 3-D problem, it means that all the numerical methods in this 2-D program should be improved to get more computing efficiency and precision, however the work is obviously enormous. At the same time, there are two facts: (1) Various CFD commercial software are developing quickly, they have provide more efficient numerical platform to solve fluid problem, however, the problem of fluid-structure interaction can hardly be resolved by these software. (2) From the viewpoint of engineering, engineers usually don't concern about the details of coupling vibration process but some statistic information, such as the mean and peak value, and whether or when will the aeroelastic instability occur. So it is possible to solve the coupling problem by another new method, which is to adopt some simplified analytical methods and numerical methods to get the statistical information of the coupling process, and give up the simulation on wind-structure interaction in detail. The precondition of this method is to give a reasonable explanation about the coupling mechanism of wind-structure interaction.

According to the wind-induced structural vibration theory proposed by Davenport [8], the structural response can be broken into three components: mean response $\bar{r}$, background response $\tilde{r}_b$ and resonant response $\tilde{r}_r$ (Fig.2). The mean response is induced by average wind pressure, and does not change with time. The background responses relates to the motion of large scale eddies, and vary slowly and irregularly with time. It is essentially a quasi-static process and has no dynamic amplificatory effect. The resonant response usually happens at frequencies adjacent with the structural natural frequency, and has obvious dynamic amplificatory effect. If we assume that the wind-induced vibration response of membrane structures has the same characteristics as mentioned above, then different methods can be adopted for different components to get the statistic information separately.

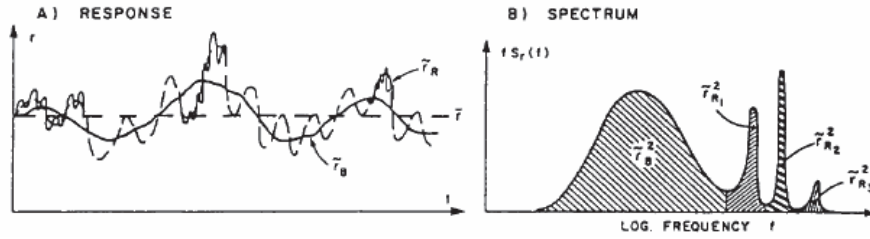


Fig. 2 Response to wind

For the mean response, the coupling effects are mainly induced by the structural average deformation, which will make the mean wind pressure change consequently. It is a static process and can be solved directly by steady CFD numerical simulation with several iterative steps. For the background response, the coupling effects are mainly induced by the effect of the spatial correlation of fluctuating wind, that is to say, we have to find these critical distributions of fluctuating wind pressure which can make structure produce maximum or minimum steady response. It is a quasi-static process in which the dynamic amplificatory effect can be ignored and only some modes of steady deformation are considered. For the resonant responses, dynamic coupling between the higher frequency parts of fluctuating wind and structure is mainly considered, it means that the resonant response of structure is mainly induced by those small-scale eddies. Due to the effect of those small-scale eddies is a random process, the suitable method for solving the resonant responses is nonlinear random vibration analysis methods in time domain. It is worth to explain that the calculation of each component will be based on the result of the calculation on the former component.

To sum up, the wind-structure interaction can be divided into three parts (Fig.3): static interaction, steady interaction and transient interaction. Mean response belongs to the static interaction, background response belongs to the steady interaction, and resonant response belongs to transient interaction. The static interaction and the steady interaction should be studied specially by means of CFD numerical simulation. The transient interaction should be studied by means of nonlinear random simulation in time domain.

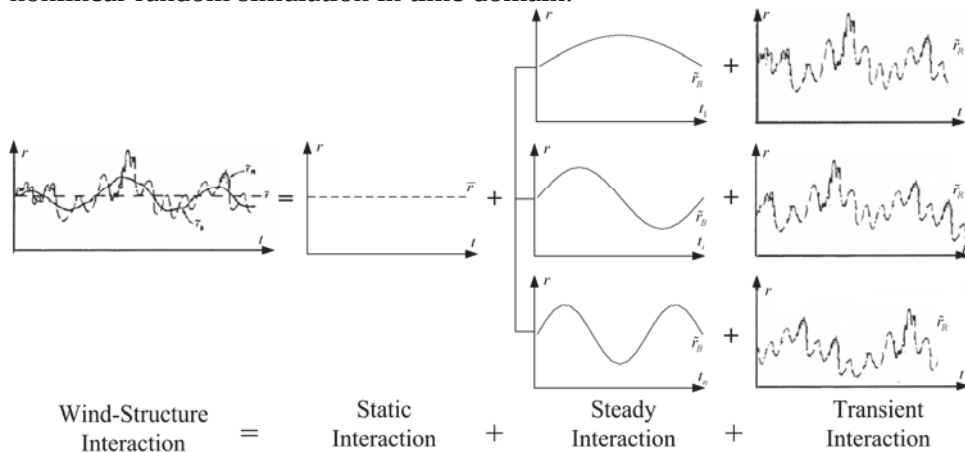


Fig. 3 the sketch of wind-structure interaction

3 GENNERAL FORMULATIONS

3.1 Static Interaction

Static interaction is expressed as follow:

$$K_{s0} \cdot \bar{x}_0 = \bar{p} \quad (1)$$

Where $\bar{x}_0$ is the mean response; K_{s0} and $\bar{p}$ are the stiffness and mean wind pressure corresponding to the mean deformation respectively; $\bar{p}$ can be calculated by means of CFD simulation.

3.2 Steady Interaction

Steady interaction is expressed as follow:

$$K_{s1} \cdot x_1(t) = p(t) \quad (2)$$

Where $p(t)$ is the fluctuating wind pressure, which can be calculated by CFD simulation.

According to the Proper Orthogonal Decomposition (POD) technique, $p(t)$ can be decomposed as follow:

$$p(x, y, z, t) \approx \sum_{i=1}^n \hat{p}_i(x, y, z, t) = \sum_{i=1}^n a_i(t) G_i \quad (3)$$

where G_i is the i th eigenmode of the wind pressure field, $a_i(t)$ is the corresponding principal coordinate, $\hat{p}_i(t)$ is the wind pressure time history corresponding to the i th eigenmode, represents the dominant wind pressure distribution on structural surface.

Substitute Eq.(3) into Eq.(2), Eq.(2) can be rewritten as:

$$K_{s1} \cdot x_1(t) = \sum_{i=1}^n \hat{p}_i(t) \quad (4)$$

Assuming the steady deformation is the summation of the effects of each eigenmode

$$K_{s1} \cdot x_{1i}(t) = \hat{p}_i(t), \quad x_1(t) = \sum_{i=1}^n x_{1i}(t) \quad (5)$$

where $x_{1i}(t)$ is defined as the time-history of the quasi-static response induced by the i th eigenmode. Then the variance of background response σ_1 can be expressed as

$$\sigma_1 = \sqrt{\sum_{i=1}^n \sigma_{1i}^2} \quad (6)$$

where σ_{1i} is the variance of steady deformation $x_{1i}(t)$ induced by the i th eigenmode. So the following formula can be used to estimate the contribution of each eigenmode to the whole steady deformation.

$$\gamma_{1i} = \frac{\sigma_{1i}^2}{\sigma_1^2} \quad (7)$$

According to the POD technique, Eq. (4) can be expressed as:

$$K_{s1} \cdot x_{1i}(t) = a_i(t) G_i \quad (8)$$

From Eq. (8), it is deduced that the vibration mode of $x_{1i}(t)$ is determined by the stiffness K_{s1} and the i th eigenmode G_i , and the vibration amplitude of $x_{1i}(t)$ is determined by the principal coordinate $a_i(t)$. So the maximal steady deformation $x_{1i}(t_j)$ of $x_{1i}(t)$ can be determined by finding the moment t_j , which is corresponding to the peak value of $a_i(t)$.

3.3 Transient Interaction

Transient interaction is expressed as follow:

$$M_s \ddot{x}_{2i}(t) + C_s \dot{x}_{2i}(t) + K_s x_{2i}(t) = \tilde{p}(t, x_{2i}(t), \dot{x}_{2i}(t), \ddot{x}_{2i}(t)) \quad (9)$$

$$\tilde{p}(t, x_{2i}(t), \dot{x}_{2i}(t), \ddot{x}_{2i}(t)) = \tilde{\tilde{p}}(t) + f(x_{2i}(t), \dot{x}_{2i}(t), \ddot{x}_{2i}(t)) \quad (10)$$

Where $x_{2i}(t)$ is transient deformation relative to the peak steady deformation of the i th eigenmode; $\tilde{p}(\cdot)$ represents the high frequency part in fluctuating wind including the motion-induced aerodynamic force; $\tilde{\tilde{p}}(\cdot)$ can be decomposed into $\tilde{\tilde{p}}(t)$ which does not consider the structure vibration and $f(\cdot)$ which is induced by structure vibration. $\tilde{\tilde{p}}(t)$ is gained from the high frequency parts of results of CFD simulation, which based on the form corresponding to each peak steady response; $f(\cdot)$ is added aerodynamic term which can be transformed into added mass M_a and aerodynamic damp C_a by means of simplified aeroelastic model theory[9]. So Eq.(8) can be rewritten as:

$$(M_s + M_a) \ddot{x}_{2i}(t) + (C_s + C_a) \dot{x}_{2i}(t) + K_s x_{2i}(t) = \tilde{\tilde{p}}(t) \quad (11)$$

It is especially emphasized that transient interaction is based on the possible peak steady deformation of the i th eigenmode $\{\bar{x} + x_{1i}(t_j)\}$, i.e. different $\{\bar{x} + x_{1i}(t_j)\}$ correspond to different transient interaction response.

3.4 Peak Response

The peak response of structure is solved by means of superposition theory after getting $\bar{x}$, $x_{1i}(t)$ and $x_{2i}(t)$:

$$x_{\max} = \bar{x} + \sum_{i=1}^n \sigma_{1i}^2 + \max(\sigma_{2i}^2) \quad (12)$$

Based on the theory mentioned above, the flowchart of the combined numerical approach is shown as figure 4.

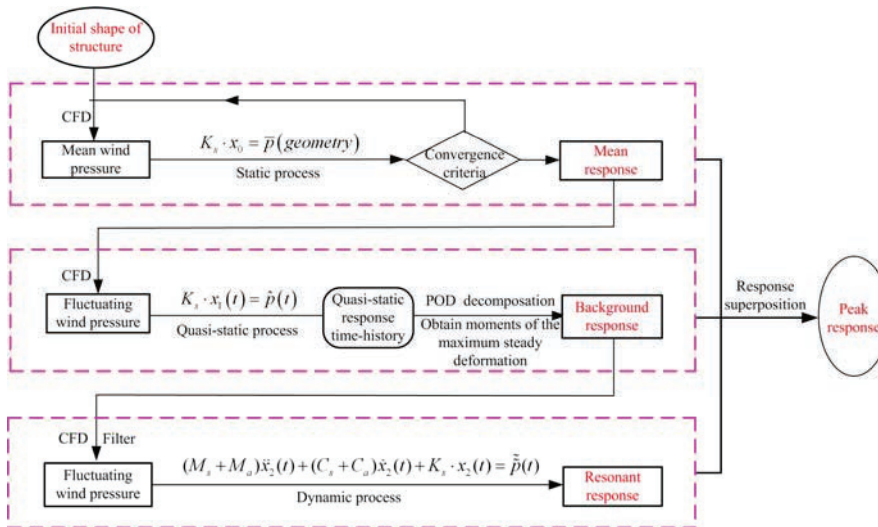


Fig. 4 Flowchart of the combined numerical approach

4 NUMERICAL EXAMPLE

4.1 Coupling Effects of One-Way type roofs

The roof span is 40m and 10m high, the computational domain is shown in figure 5. The inflow velocity profile is defined by $V(y) = 30(y/10)^{0.16}$ m/s, leading to a velocity value of 30m/s at roof level. Thus, the Reynolds number becomes $Re = 2.07 \times 10^7$. The fixed wall is assumed as no-slip flow boundary, local one-way condition is adopted on the boundary of the outlet, and the gradient of flow speed of the outlet is zero; non-dimensional time step $\Delta t = 0.005$. Here we assume the roof is a cable structure, the mass per length g is 5kg/m, the prestressing tension force T is 20kN. According to the results of computation, the first and second frequency of structure is 0.82Hz and 2.34Hz, respectively.

Figure 6 shows the streamline drawing of flow around the fixed roof, it means that the coupling effect does not been considered. Figure 7 shows the streamline drawing of flow around the elastic roof with the consideration of coupling effect. It can be seen that, because the shape of the elastic roof changes with wind action, which directly change the boundary of the fluid field, so the characteristics of flow around a elastic roof is much different from those of rigid roof. For the elastic roof, the separation point of airflow appears at the back of the front of the roof, and the effects of vortex dropping weaken significantly. The whole average wing pressure on the elastic roof is close to that of rigid roof, but the pulse wind pressure decrease significantly, which illustrates that when vortex downstream along the roof, coupling effect induced energy dissipation lead to minor pulse pressure.

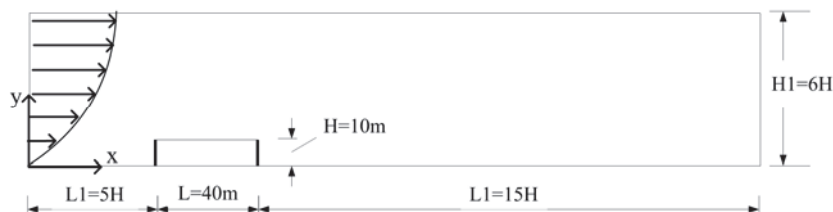


Fig. 5 Computational domain for flow around a one-way type roof

It worth to be explained that the above result was gotten from the method in ref. [6], here we call it as direct numerical method, which can be seen as a accurate method. It can be seen that by the direct numerical method, we can get the entire information of the coupling process. But from the viewpoint of engineering, we usually only concern about those statistic information, such as the mean and peak value, it means that we spend a large amount of time to get those useless information. Next, the combined procedure proposed in this paper will be adopted to calculate that statistic information. The result is shown in figure 8. It can be seen that the result of combined approach seems very close to that of direct numerical method, but quite different to the result of random vibration analysis. It shows that by using the combined approach we can also get fairly accurate result, and the time consuming by this method is quite small compare to the direct numerical method.

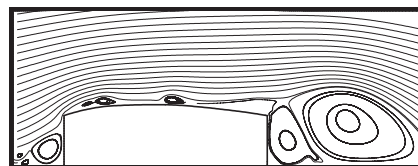
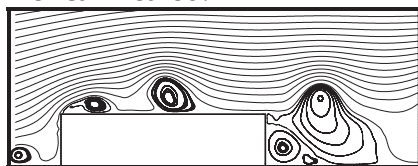


Fig. 6 Streamline around the fixed roof

Fig. 7 Streamline around the elastic roof

We also calculate the one-way type roof with $1/10L$ sag (as shown in fig. 9) and with $1/10L$ rise (as shown in fig. 10). It can be seen that for these two different shape roofs, the combined procedure can get very close results to that of accurate method. For the arch-shaped roof, the effect of fluid-structure interaction seems very small, it can be explained that the roof shape plays an important role to the coupling effect. The coupling effect will change the structural shape from bluff body to streamlined body, if the structural shape close to streamline body, then the coupling effect will be small.

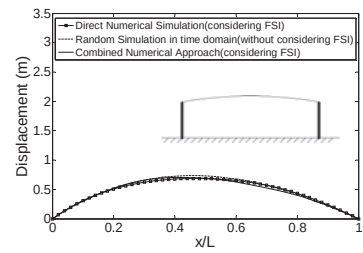
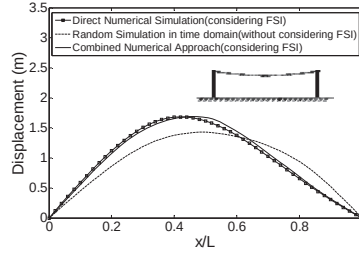
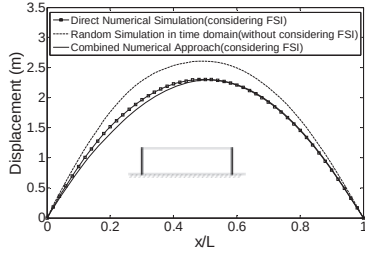


Fig. 8 Maximum response of flat roof

Fig. 9 Maximum response of suspension roof

Fig. 10 Maximum response of arch roof

4.2 Coupling Effects of Shaddle-Shape Membrane Structures

The roof span L is 28m, the ratio of sag to span (f/L) is $1/16$, the mass per area is 1.25kg/m^2 , the tension force is 2.5kN/m . The first and second frequency of structure is 2.26Hz and 3.03Hz , respectively. The calculate model is shown in figure 10. The other calculate parameters are same as the two-way type roof.

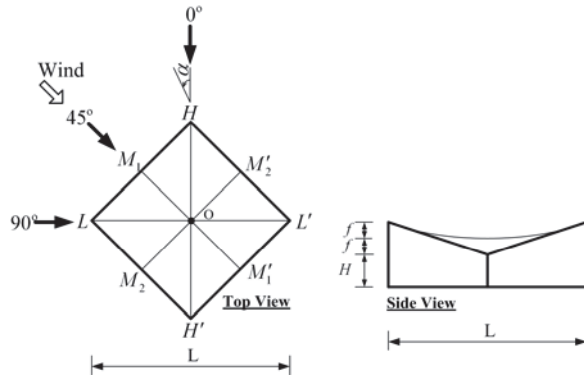


Fig. 10 The calculate model

Figure 11 shows the maximum displacement of membrane structure calculated by these three methods. It can be seen that the coupling effect of 3-D structures seems more complicate than 2-D structures, but if we compare the maximum displacement point between the results of these three methods, it is also show that the result from combined procedure seems fairly close to the direct numerical method, but larger than the result of random vibration analysis.

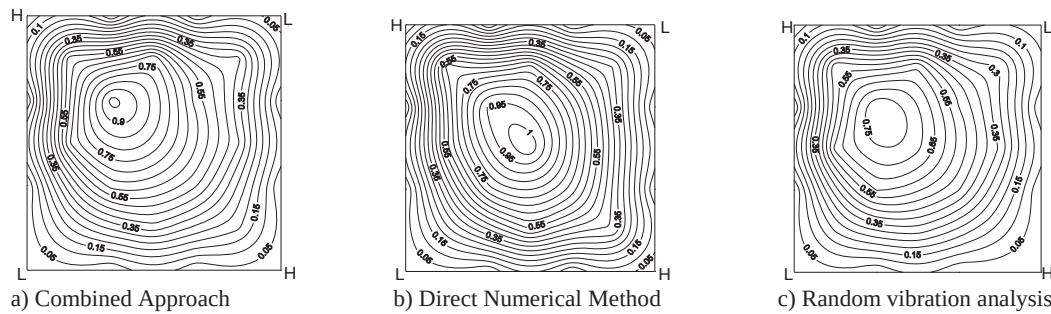


Fig. 11 Maximum displacement on roof by different methods

5 CONCLUSION

In this paper, a combined numerical approach for solving the fluid-structure interaction for tension structures was proposed. With the comparison to the direct numerical method and random vibration method, it can be seen that the combined approach seems more accurate than the random vibration method and more efficient than the direct numerical method.

According to the calculate result of two-way type, it can be conclude that the coupling effect trend to change the structural shape from bluff body to streamlined body, so if the structural shape close to streamline body, then the coupling effect will be small.

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