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Experimental study on spanwise correlation of vortex-induced forces for the long span bridge girder

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ABSTRACT

The existing section model wind tunnel test method and semi-empirical mathmatic models are two-dimensional theory, however, for an actual structure, it is a three-dimensional problem. Incomplete spanwise correlation of vortex-induced forces leads to the inconsistency between test results and prototype response. For studying the spanwise correlation of classic blunt body, several section models are made for pressure measurement tests by using free vibration method. The spanwise correlation of vortex-induced forces and its influence are studied in details. The correlation is closely related to the amplitude and the speed of oncoming flow. The correlation of lift force is better than the wake's, and the correlation of streamline section is better than other models'.

1.INTRODUCTION

Long-span bridges often suffer from vortex-induced vibration (VIV) due to its flexibility, light weight and low damping etc. At present, wind tunnel testing for section model is a general methodology to evaluate its VIV performance. However, wind tunnel tests methodand the existing semi-empirical modelsare based on two-dimensional (2-D) theory, the section model in wind tunnel tests is assumed to behave in a 2-D manner, for

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an actual structure, it is a three-dimensional (3-D) problem. In addition to the differences in vibration mode, the aerodynamic forces are not perfectly correlated along its span. The consistence between the observation of prototype and predictions based on 2-D model testing is still uncertain due to the contribution of spatial correlation of vortex-induced aerodynamic forces.

Obvious oblique vortices were found in the towing tank and wind tunnel experiments by flow visualization technique (Williamson 1988, Miller 1994). Partial correlation of vortex-induced forces may be attributed partly to asynchronous trail vortices along span behind a bluff cylinder immersed in 2-D smooth oncoming flow. With considering the effect of vibration mode but ignoring the partial correlation of vortex-induced aerodynamic forces along the span, Irwin (1998), Zhu (2005), Huera Huarte (2006) and Zhang (2011) proposed some methods to estimate VIV response of the bridge. The correlation of vortex-induced force acting on square cylinders along the span was studied in detail by Wilkinson (1981), and then correlation of vortex-induced force varied with amplitude was found through direct pressure measurement on rigid cylinder section model, and after that a double exponential correlation semi-empirical formula was fitted (see Fig.1). On the basis of Scanlan's semi-empirical nonlinear model and Wilkinson's correlation function, Eshan (1990) discussed the vortex-induced force along the span roughly, and proposed a relatively simple method to estimate the response of VIV. Xian (2008) designed a taut stripe model of box girder to test spanwise vortex-induced response, and got the response correlation effect function to analyze the VIV of long-span bridges. A linear and a nonlinear method which were used to estimate prototype bridge by the result of section model wind tunnel tests, were proposed by Li (2011) and Sun (2014) respectively based on Scanlan's semi-empirical model. But their correlation function comes from the pressure tests of square cylinders (Wilkinson 1981), and it is not suitable for VIV analysis ofbridge.

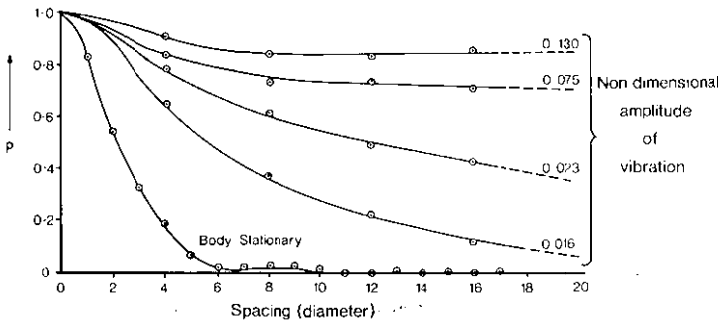

Fig.1 Research results of Wilkinson (1981) (Symbol: η=amplitude; D=depth of girder)

Several section models with classic blunt body (including rectangular, trapezoidal, and streamlined box girder) are made for pressure measurement tests by using free vibration method. The spanwise correlation of vortex-induced forces and the influence of spanwise space, vibration amplitude, and attack angle et al. are studied in details.

2.TESTS DESCRIPTION

The wind tunnel (Type: XNJD-1) of Southwest Jiaotong University, a closed circuit wind tunnel with two tandem closed test sections, was used to carry out the investigation. The dimension of the test section is 2.4m×2.0m×16.0m (*W*×*H*×*L*), with wind speed adjustable from 0.5m/s to 45.0m/s (turbulent intensity<0.5%). A test set-up, which was specially designed to carry out wind-induced vibration testing of bridge girder section and mounted on the outside walls of wind tunnel, was used in this investigation. The model was suspended by four pairs of linear springs and it could vibrate vertically and torsionally.

Three section models were made for pressure measurement tests. One is rectangular, one is trapezoidal, and another is a streamlined box girder.The three were made of high quality lightweight wood and plastics. The length of three models (L) is 2.095m, and the other dimensions are shown in Fig. 2. In order tobe close tothe actual structures, and to observethe VIV phenomenon easily, railings were installed on the trapezoidal and streamlined model.5rows measurement points withdifferentrow spacing were set in every model, and10 sets spanwise spacing weregenerated. There are 34 measurement points in every row of rectangular model, 34points in trapezoidal model, and 50 points in streamlined box girder.5 groups pressure scanning valve (type: DSM-3400) were used for pressure tests. The valveswere fixed in the internal model，and the data lines were led out from the end plates at both sides (see Fig.3)

The VIV tests were conducted by free vibrating method in smooth flow at three different attack angle 0º, 3º and 5º. The vibration amplitude were recorded by laser displacement meters and the lock-in area were found, theacquisition of pressure data were proceeded in the three stages(before the VIV region, in the VIV region and after the VIV region). In the VIV region,pressure data were acquired at different amplitudes which depend on three different damping levels, and the effects of VIV amplitude on the correlation of vortex-induced force were studied in detail. In addition, the pressure distribution characteristics of different cross sections were analyzed detailed, especially the points near the wake.

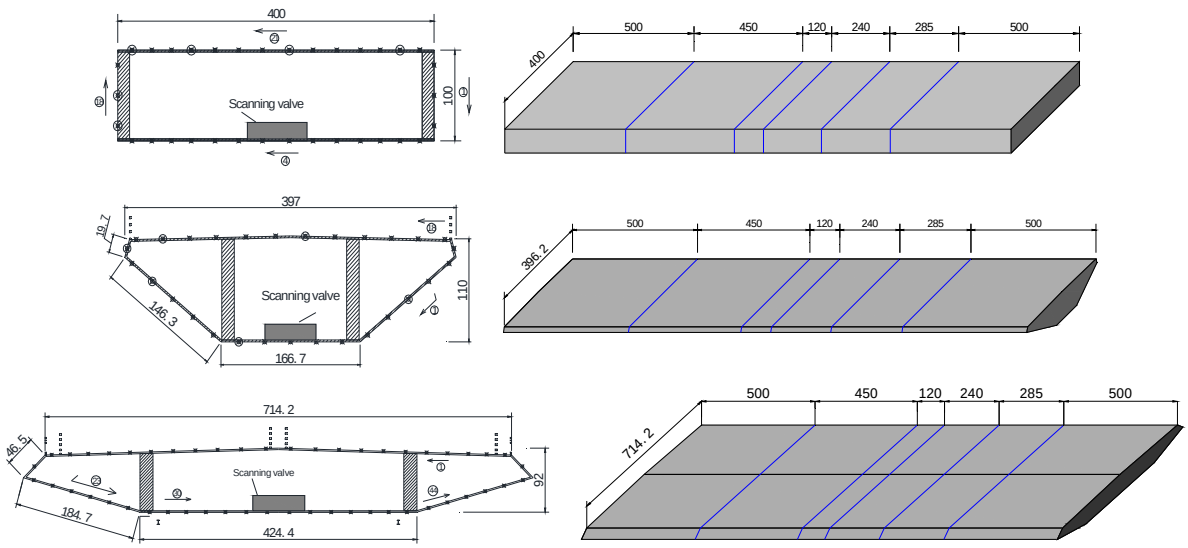

Fig.2Layouts of measurement points

3.ANALYSIS OF DISPLACEMENT RESULTS

Obvious VIV was observed at 0º, 3º, 5º attack angles in the tests of three models. VIV of rectangular and trapezoidal models occurred at three different damping, and VIV of streamlined model only occurred at the lowest damping at the 0º attack angle. VIV response of three models at different damping ratio and different attack angles are shown in Fig.3~Fig.5, in which X axis represents the reduced wind speed U/*f*D, and Y axis represents VIV amplitude *η*=*y*/D (U is the wind speed of oncoming flow, D is the height of model, *f* is the system frequency, and *y* is VIV amplitude).

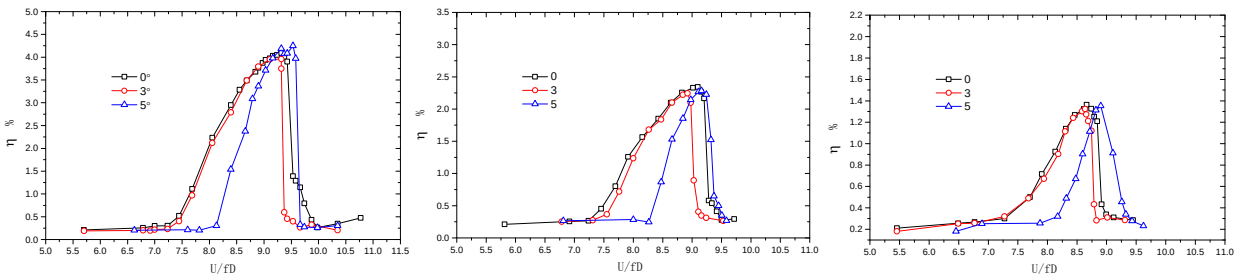

Fig.3 The VIVdisplacements of rectangular model
(left: damping 1, middle: damping 2, right: damping 3)

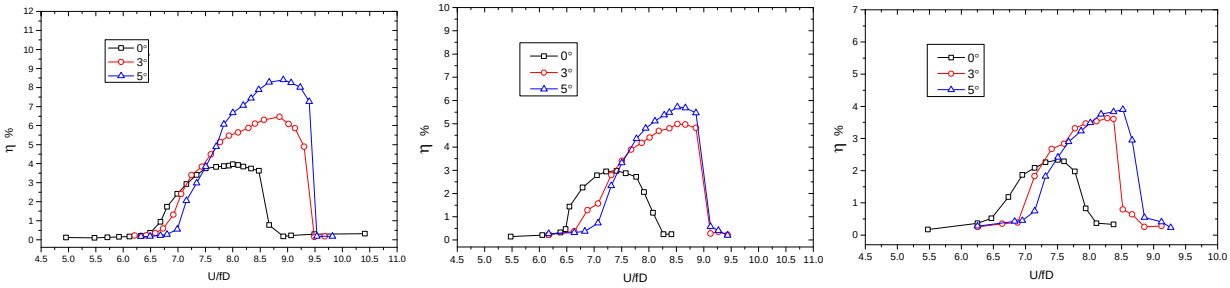

Fig.4 The VIV displacements of trapezoidal model
(left: damping 1, middle: damping 2, right: damping 3)

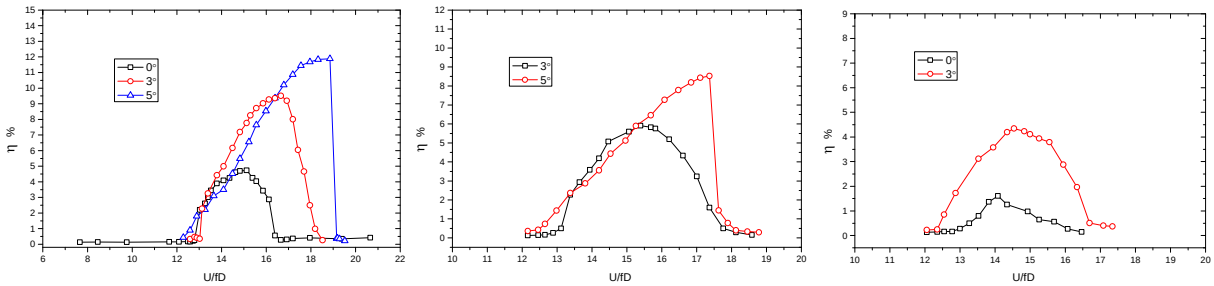

Fig.5 The VIV displacements of streamlined model
(left: damping 1, middle: damping 2, right: damping 3)

The VIV responses at 0º attack angle are summarized in Fig.6, and the parameters of VIVtest results are listed in Table 1. The marks of the curve in Fig.6 stand for the acquired wind speed in the pressure measurement tests. WA1 and WA2 are the acquired wind speed before VIV region, W1, W2 and W3 are the acquired wind speed in VIV region, in which W3 is the wind speed of maximum amplitude, and WB1 and WB2 are the acquired wind speed after VIV region.

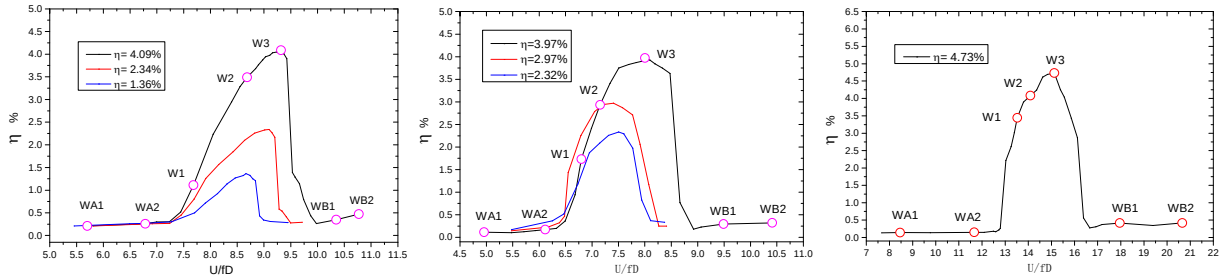

Fig.6 The VIV responses at 0º attack angle
(left: rectangular model 1, middle: trapezoidal model, right: streamlined model)

Table 1Parameters of VIVtests at 0 º attack angle

Model	Case	Freq.(Hz)	Velocity of start vibration (m/s)	*St* Number
Rectangle	η=4.09%	3.788	2.74	0.1382
	η=2.34%	3.716	2.69	0.1381
	η=1.36%	3.959	2.87	0.1379
Trapezoid	η=3.97%	3.851	2.75	0.1540
	η=2.97%	3.817	2.68	0.1566
	η=2.32%	3.768	2.72	0.1524
Streamline	η=4.73%	3.263	3.84	0.0782

4.PRESSURE DISTRIBUTION CHARACTERISTICS ANALYSIS

In order to have a better understand of the force of the model in VIV region, pressure distribution characteristics on the model surface is studied, which is the direct reason that causes VIV. The surficial distribution of the average wind pressure coefficient of three models at different attack angelsis shown in left column of Fig.7~Fig.9, and the root mean square (RMS) of wind pressure coefficient is shown in right column of Fig.7~Fig.9.

When the airstream flow across a bluff body, the vortex will separate and reattach along the surface of model. It can be drawn from the test results that the obvious flow separation and attachment phenomenon is observed, and this is the main reason thatmakes the models vibrate. In addition, the distribution of surficial pressure changes with attack angle, and the lock-in region and amplitude of VIV change as well.

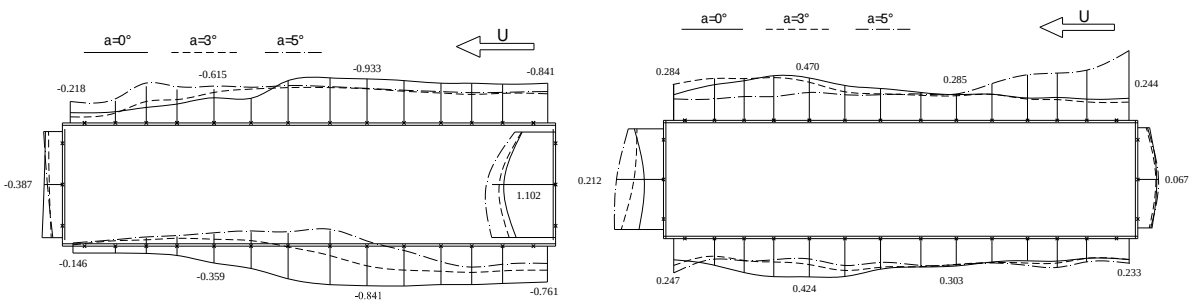

Fig.7The pressure coefficient distribution of trapezoidal model (left: mean, right: RMS)

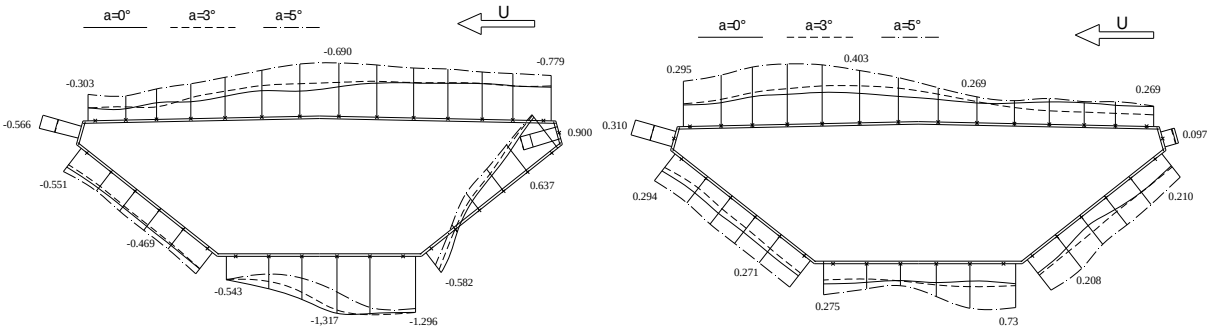

Fig.8 The pressure coefficient distribution of rectangular model (left: mean, right: RMS)

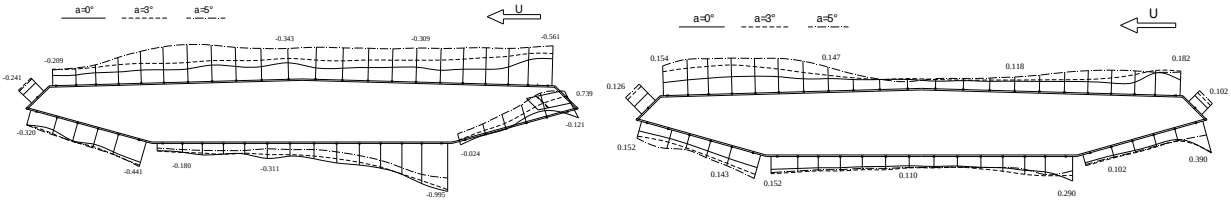

Fig.9 The pressure coefficient distribution of streamlined model (left: mean, right: RMS)

5. THE VORTEX-INDUCED FORCE TIME HISTORY ANALYSIS

For analysis of vortex-induced force at different positions, pressure-time curve and its spectrum of some typical measurement points at the maximum VIV amplitude are shown in Fig.10~Fig.12. By the time history data and its spectrum analysis, vortex-induced force of windward points compose mainly of 1st mode component, and the 2nd mode component is observed at the points near the wake side. The 3rd mode component appears at the measurement points on the inclined web of trapezoidal model and streamline model. As a result, the nonlinear high mode components exist in the vortex-induced force and cannot be ignored, it is reasonable that the influence of high mode component is taken into account in the mathematical models of VIV.

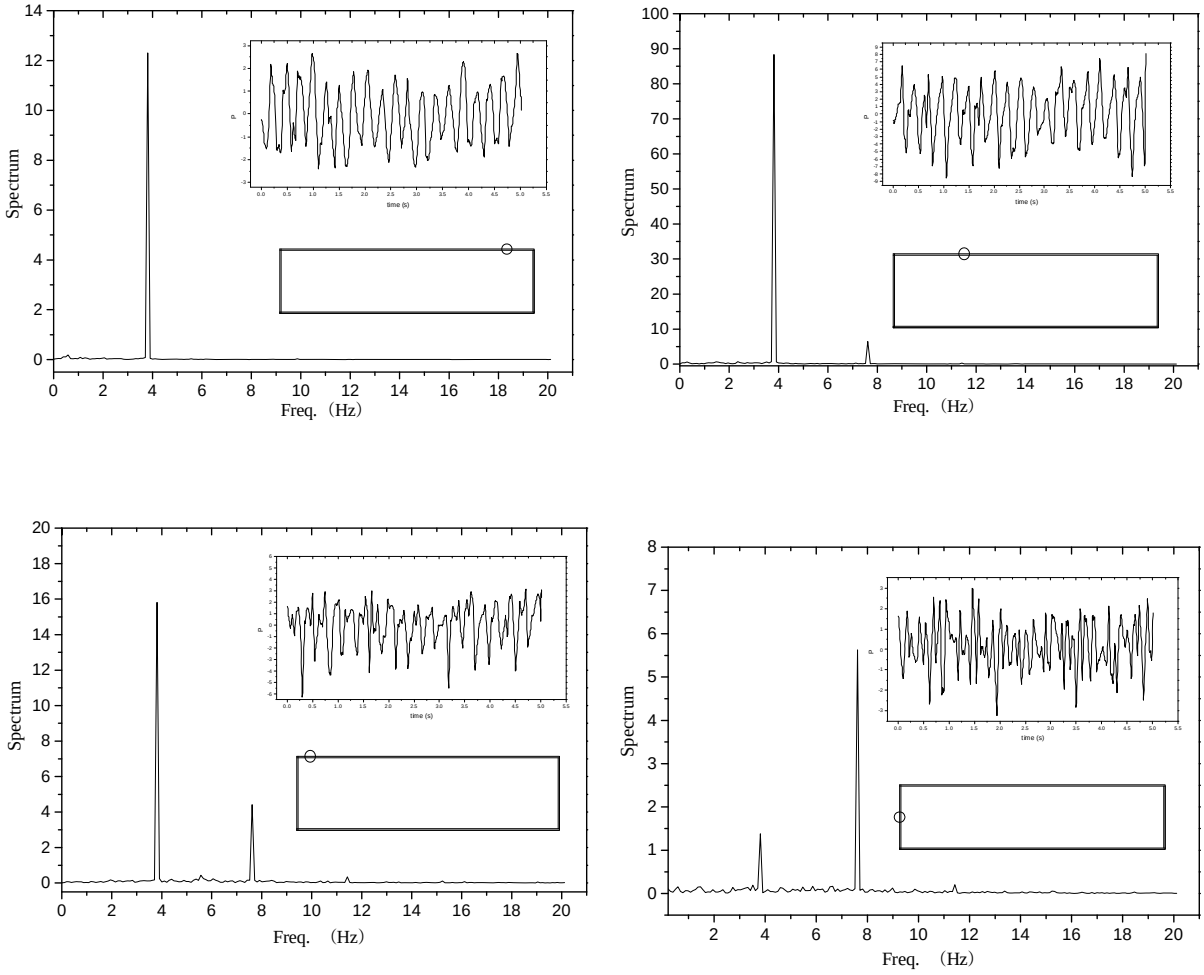

Fig.10 Pressure-time curve and spectrum of typical points
（ “O”represents the position of measurement points）

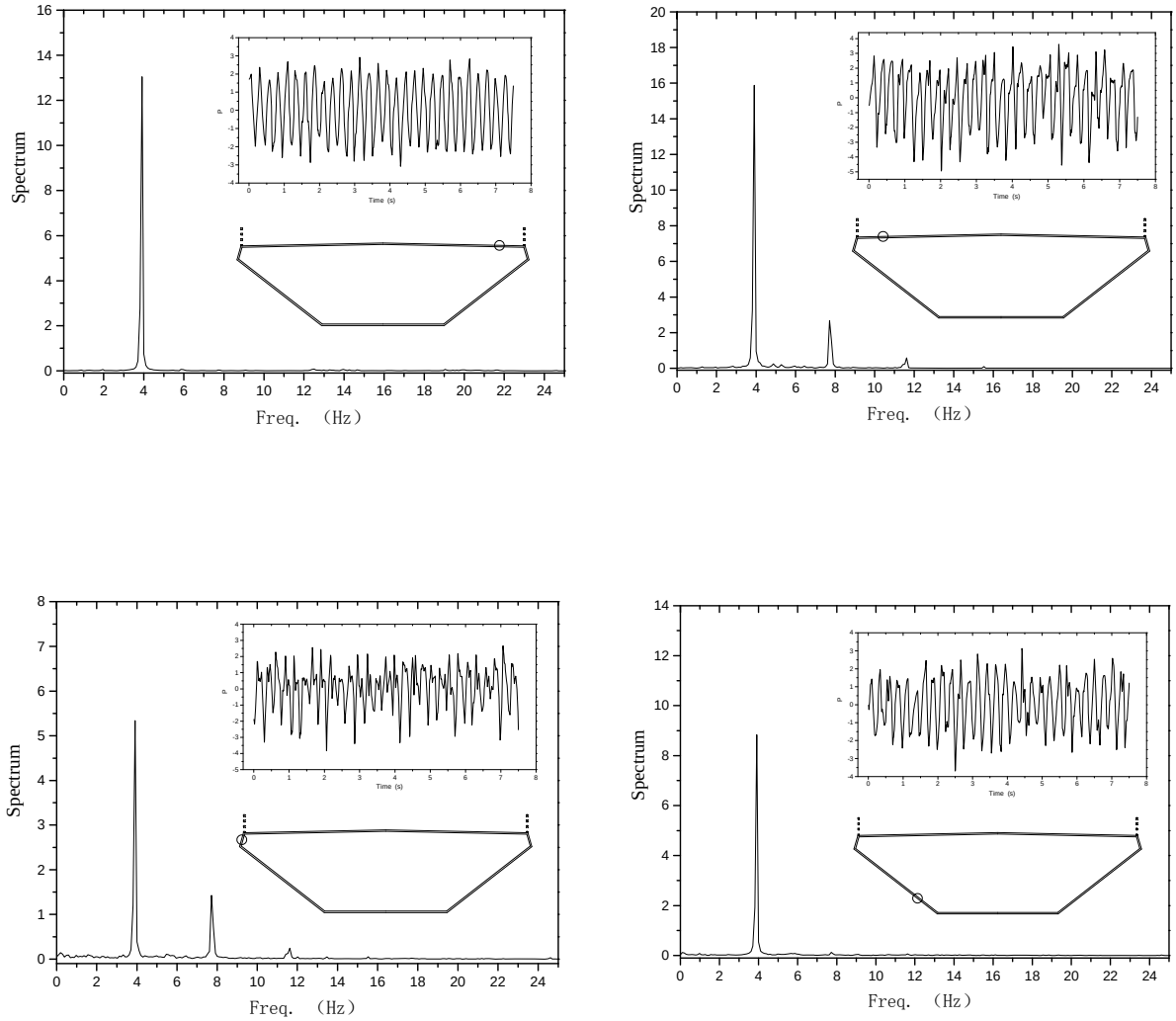

Fig.11 Pressure-time curve and spectrum of typical points
（ “O”represents the position of measurement points）

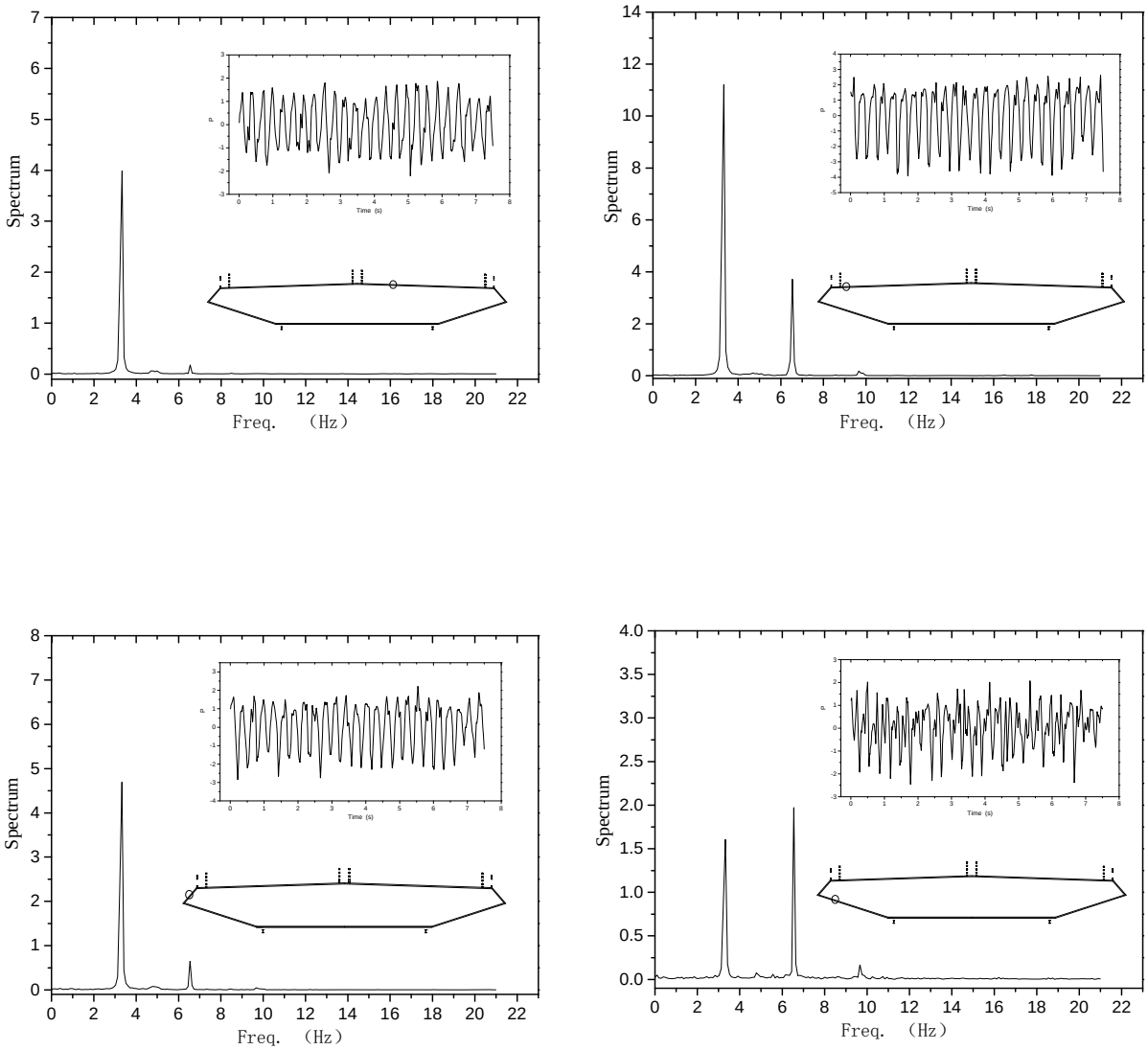

Fig.12 Pressure-time curve and spectrum of typical points
（“O”represents the position of measurement points）

6.SPANWISE CORRELATION ANALYSIS

6.1Effect of VIV Amplitude onCorrelation

The spanwise correlation of vortex-induced force of a square column was studied by using the forced vibration method. It is found that the correlation of vortex-induced forcevaries with amplitude, and the greater of VIV amplitude, the better ofthe correlation is (Wilkinson, 1981).

In the tests, VIV amplitude of models in lock-in region was changed by changing the system damping ratio. The pressures were acquired at the maximum amplitude of VIV region, and the relationship between the VIV amplitude and the correlation coefficient was obtained. The correlation coefficients of three models at different amplitude are shown in Fig.13~Fig.15.

When the model vibrates in lock-in region, the correlation coefficient of rectangularmodel will decrease with the increase of VIV amplitude. The correlation of trapezoidal model is affected at a large extent by the change of attack angel. The correlation coefficient will increase with the increase of amplitude at 0º attack angel, however, the correlation coefficient will decrease with the increase of VIV amplitude at 3º and 5º attack angels. The spanwise correlation of streamlinedmodel is strong, and the correlation coefficient at various amplitudesis relatively close.Additionally, when model is static in VIV region, theaerodynamic force acting on the model does not include self-stimulated force, the pressurecharacteristics has fundamentally changed compared with a vibrating model. Therefore, the correlation is obviously different.

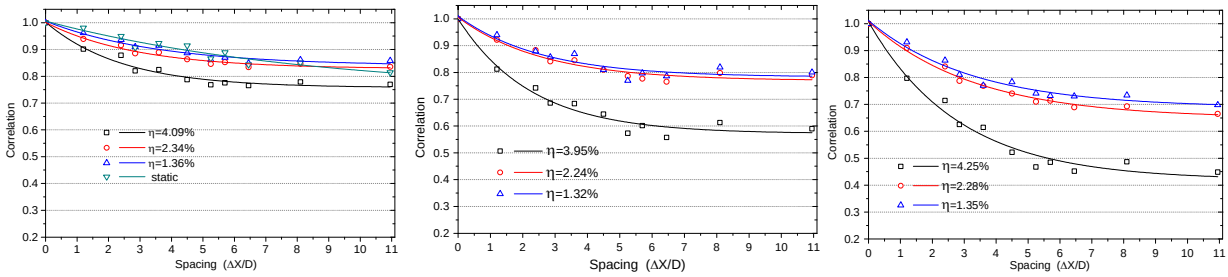

Fig.13The correlation coefficients of rectangular model (left: 0°, middle: 3°, right:5°)

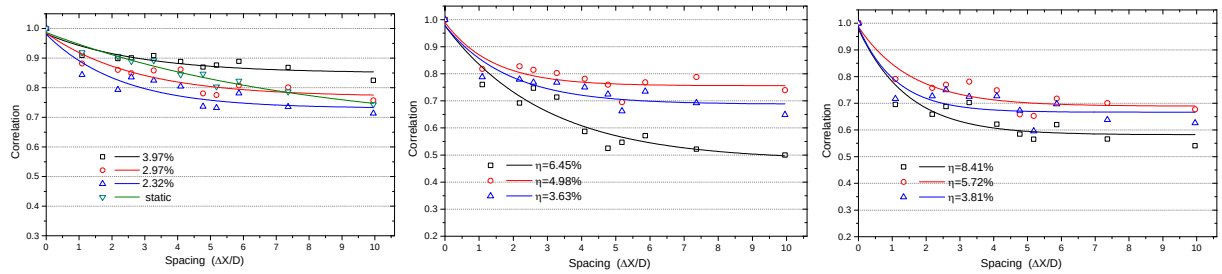

Fig.14The correlation coefficients of trapezoidal model (left: 0°, middle: 3°, right:5°)

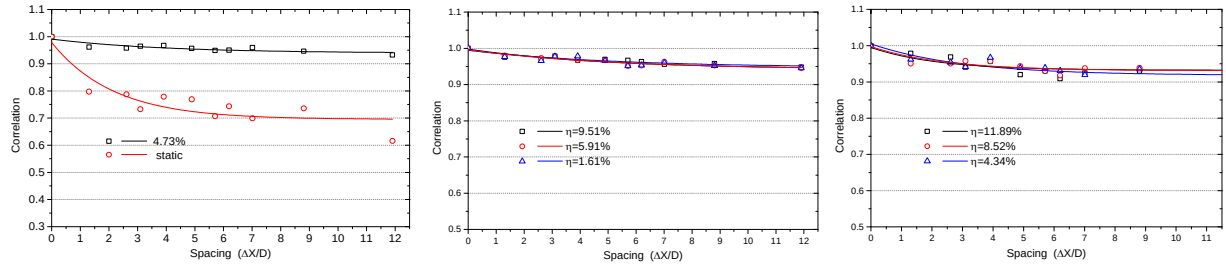

Fig.15The correlation coefficients of streamlined model (left: 0°, middle: 3°, right:5°)

6.2The Correlation Study on Wake Points

The vortex is generated by the airstream which flow across the bluff body, but the separation and attachment of vortex along the span is not fully synchronous, which will cause the spanwise correlation of aerodynamic force inconsistent at different locations of model.The inconsistence ischaracterized by strong correlation at some positions and weak correlation at other positions.

By the results shown in Fig.16, the correlation of different points is quite different, the spanwise correlation of the measuring points which areacted on directly by the flow is stronger than the measuring points at wake side.The correlations of the points at wake side are quite different with the whole section, the correlation coefficients decade rapidly with the increase of spanwise spacing, and the correlation coefficients are much smaller than the vortex-induced force's (whole section). It should be noted that the tendency of the correlation of wake is the same as Wilkinson's research results, but the correlation of lift force is quite different with Wilkinson's.

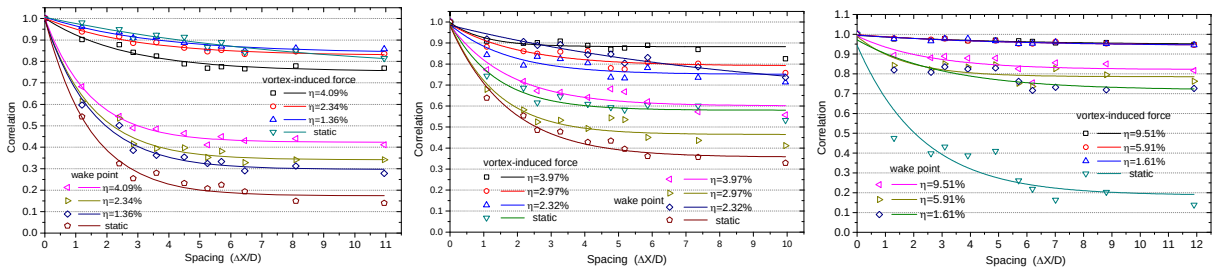

Fig.16 The correlation of vortex-induced force and wake point
(left: rectangular model 1, middle: trapezoidal model, right: streamlined model)

6.3 The Correlation Study on Lock-in and Non-lock-in Region

In the case of minimum damping ratio and the largest VIV amplitude, the correlations of vortex-induced force in the VIV region and out of VIV region are studied respectively. Three wind speed (W1, W2 and W3) are selected to acquire pressure data in the VIV region at different amplitude, in non-lock-in VIV region, two velocities are selected respectively before the VIV region (WA1, WA2) and after the region (WB1, WB2) (non-lock-in region).

The spanwise correlation ofvortex-induced force of the three models in the lock-in regionis better than the correlation of non-lock-in region. The test results at three different velocities show that the correlation coefficients of vortex-induced force at maximum VIV ampliude are smaller than the other two velocities, and the maximum spanwise correlation coefficient is generated at the risingstage of amplitude-velocity curve rather than the maximum amplitude position of the curve (see Fig.17~Fig.18).

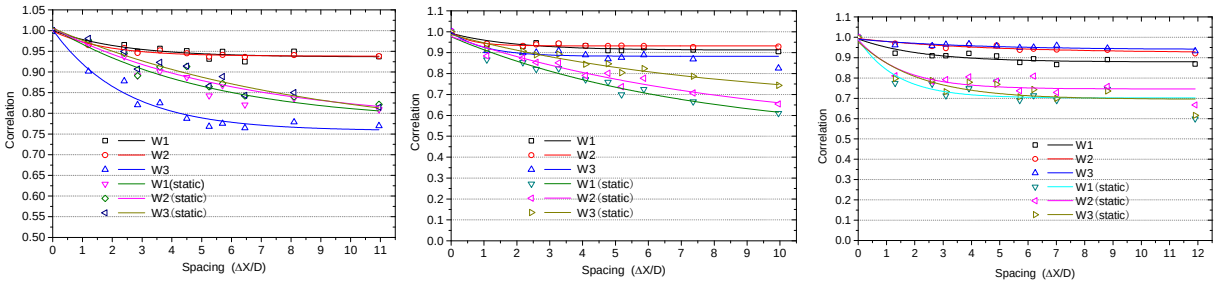

Fig.17 The correlation of vibrating and static model
(left: rectangular model 1, middle: trapezoidal model, right: streamlined model)

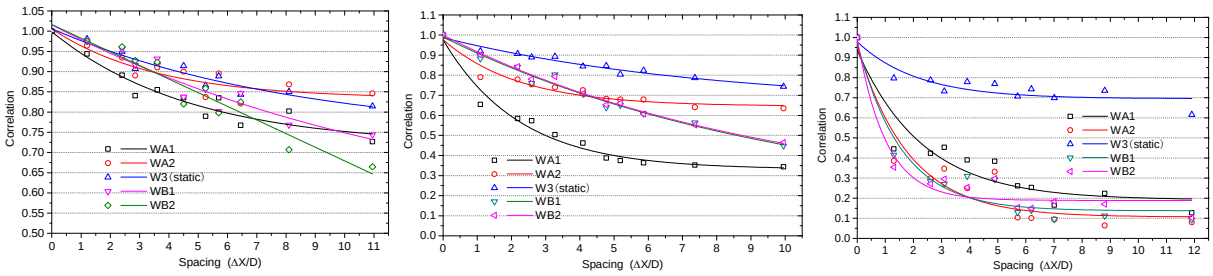

Fig.18 The correlation in lock-in and non-lock-in region
(left: rectangular model, middle: trapezoidal model, right: streamlined model)

6.4Effect of attack angle on correlation

The change of attack angle of oncoming flow will affect the aerodynamic characteristics of section. The change of attack angle means that the flow field of boundary has changed, and the distribution of aerodynamic force on the structure will be different, therefore, Scruton number, VIV amplitude of structureswill also change. It can be drawn from the Fig.19~Fig.21 that with the increase of attack angle the correlation becomes weaker. With the increase of attack angle the points with weak correlation at the wake will reduce the overall correlation, in addition,the law of vortex shedding becomes more disorder, and thus the correlation coefficient becomes small.

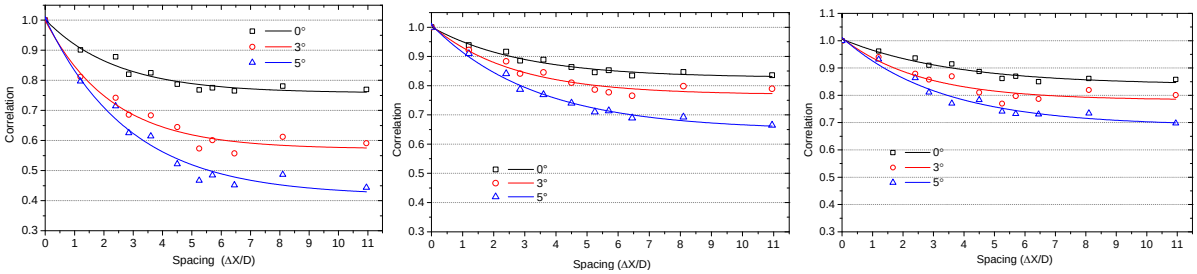

Fig.19 The correlation of rectangular model at different attack angles
(left: damping 1, middle: damping 2, right: damping 3)

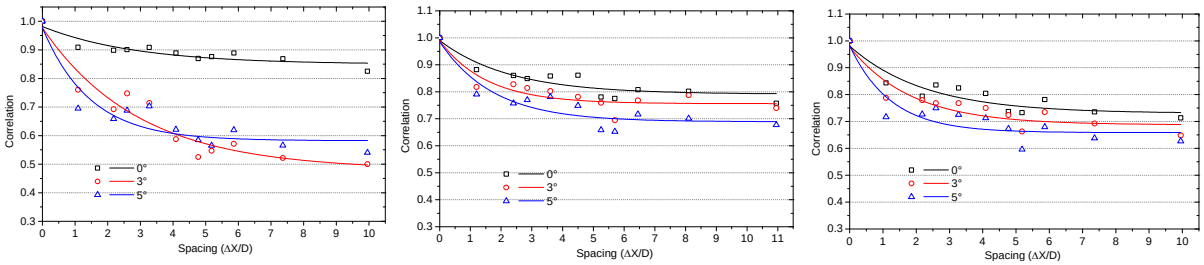

Fig.20The correlation of trapezoidal model at different attack angles
(left: damping 1, middle: damping 2, right: damping 3)

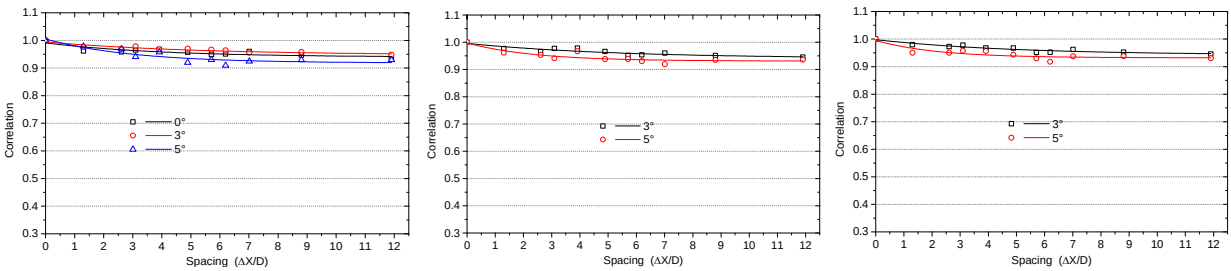

Fig.21The correlation of streamlined model at different attack angles
(left: damping 1, middle: damping 2, right: damping 3)

7. CONCLUSIONS

Several section models were made for pressure measurement tests by using free vibration method, and the spanwise correlation of vortex-induced forces and its influence are studied in details. The nonlinear high mode components exist in the vortex-induced force and cannot be ignored.The correlations of the three model are quite different with each other, and it is difficult to find a general correlation coefficient expression for all kinds of sections based on present studies. The correlation is closely related to the amplitude and spanwise spacing, and it is influenced by the speed and attack angle of oncoming flow as well. The correlation of lift force is better than the wake's, and the correlation of streamline section is better than other models'.

ACKNOWLEDGMENTS

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