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The flutter performance study for a suspension bridge based on numerical analysis and wind-tunnel test

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ABSTRACT

The flutter stability of Maputo Bridge was investigated via both numerical analysis based on the 2D coupled flutter theory and sectional model wind-tunnel test. The bridge with a main span of 680 m is located in the south coast of Africa where meteorological conditions are very complex, thus the wind parameters of the bridge site is a key issue for bridge wind-resistance design. The basic wind speed of the bridge is obtained by Gumbel extreme distribution on the basis of meteorological data of Maputo. Then the research of flutter stability is conducted by theoretical and experimental investigations respectively. The results obtained by the two methods are basically the same, which indicate the availability of the pure flutter theoretical analysis. The research suggests that the flutter stability is well when the attack angle is 0° while the flutter stability cannot satisfy the need when the attack angle is +3°. The flutter stability performance can be promoted when horizontal guide plates are installed on the girder tuyere. The research fruits could act as a reference for the wind-resistance design of the same type of bridges.

1. INTRODUCTION

With the span of modern bridge is becoming longer, the stiffness and damping ratio of structures decrease clearly, thus modern bridge are becoming highly wind sensitive structures. The wind-resistant design becomes one of the key issues for successful construction of bridge. Therein flutter is a major type of wind-induced vibration; which is a kind of divergent self-excited vibration and will cause a destructive failure of bridge. The aim of designing for wind-resistance is to ensure the enough aerodynamic stability for the main girder, and the flutter must be avoided for bridge. At present, evaluation methods for bridge flutter include theoretical method, the direct wind tunnel test method and the combination method of theoretical models and experimentally identified

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parameters.

Mary of the theoretical method were based on the Scanlan's expressions of self-excited aerodynamic force (Scanlan and Lin 1978) which aims at determining the flutter critical state and its corresponding flutter critical wind speed. The two most widely used methods are two-dimensional coupled flutter analysis (Jain et al. 1996) and three-dimensional flutter analysis (Xie and Xiang 1985; Ding et al. 2002). However, wind tunnel test is one of the relatively direct methods compared with the theoretical analysis. This method can be the true representation of the actual wind vibration response of the real bridge. There are sectional model, taut strip model and full bridge model experiments in direct experimental methods. Sectional model experiment (Diana et al. 2013) can measure the actual flutter critical wind speed of the main girder directly based on strip theory. In the preliminary design stage, the aerodynamic performance of long span bridge is always evaluated via sectional model test.

Before flutter analysis, the wind parameters of the bridge should be determined, and the most widely used method is based on the Gumbel extremal distribution. In order to obtain the wind parameters of Maputo Bridge, this paper introduces a method which can fit the Gumbel extremal distribution curve with the method of least square according to the weather data of Maputo. Then, 2D coupled flutter analysis method is used for computationally determining aerodynamic instability of Maputo Bridge. And the aerodynamic instability of the bridge is further studied via wind-tunnel test involving sectional model. On this basis, the analysis of theoretical analysis and experimental results are compared.

2. ENGINEERING BACKGROUND

The proposed Maputo Bridge, located in the capital of Mozambique, is a two-tower suspension bridge with main span 680 m (Fig. 1). The sag-to-span ratio of main cable is 1/10. Transverse direction spacing of main cables is 20.6 m. For the tower, the shape is gantry tower made of reinforced concrete. The height of the tower in Maputo side is 136 m while the Katembe side is 138 m. Its deck of closed streamline cross-section of single box with two wind-fairings is 3 m high and 25.6 m wide (Fig. 2).

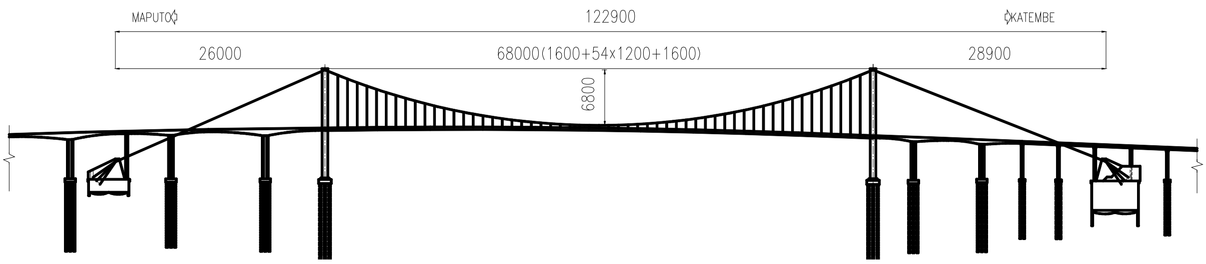

Fig. 1 General layout of bridge (unit: mm).

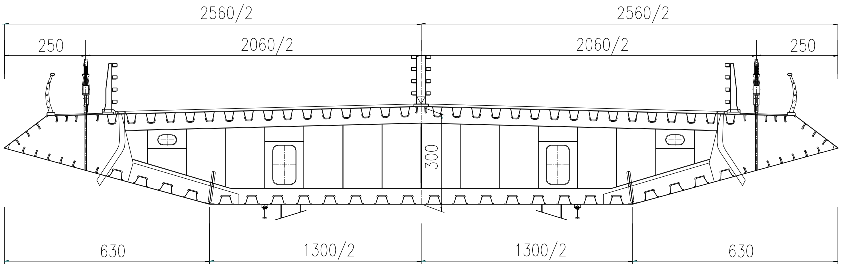

Fig. 2 Deck cross-section (unit: mm).

3. DESIGN WIND PARAMENTERS

Maputo Bridge is located in Maputo bay (Fig. 3), the meteorological condition of the bridge site is very complex, the weather is easily be affected by the subtropical and tropical monsoon and typhoon.

Fig. 3 The bridge site

The maximum wind speed in the past 37 years for Maputo could be observed from the weather data provided by National Weather Bureau between the year of 1973 and 2010 (Table 1). According to the data, the maximum wind speed in Maputo in 2001 is as high as 32.5 m/s, which is significantly greater than the suggested value 27 m/s of southern African specification (SATCC 1998). Thus the design wind speed should be obtained by the probabilistic method based on the weather data.

The most concerned thing is the extreme wind speed in statistical analysis; meanwhile, statistical inference will ultimately determine a value which is the maximum wind speed of a return period. Then, it is reasonable to choose Gumbel extremal distribution as mathematical statistics method. Gumbel extremal distribution function is:

$$F_I(x) = P(X_{\max} < X) = \exp\{-\exp[-a(x-u)]\} \tag{1}$$

Where x is the maximum wind speed, α is the scale parameter, u is the location parameter. Rearranging Eq. (1) into the following form:

$$\alpha\left(x-u\right)=y \qquad (2)$$

Where $y = -\ln(-\ln P)$ is reduction variable. The value of two parameters is connected with the first two moments of the distribution. If the sample size is large enough, there will be a relationship between them:

$$E\left(x\right)=\frac{0.5772}{\alpha}+u \qquad (3)$$

$$\sigma^2=\frac{1.6449}{\alpha^2} \qquad (4)$$

Table 1 The maximum annual wind speed at Maputo

year	maximum wind speed (m/s)	year	maximum wind speed (m/s)
1973	19.4	1992	24.4
1974	23.1	1993	/
1975	16.7	1994	20.8
1976	22.2	1995	18.1
1977	23.6	1996	22.8
1978	21.4	1997	21.7
1979	23.9	1998	20.6
1980	19.2	1999	23.6
1981	25.6	2000	/
1982	19.4	2001	32.5
1983	24.4	2002	26.7
1984	30	2003	18.1
1985	22.2	2004	13.9
1986	19.4	2005	15
1987	21.7	2006	15.6
1988	19.4	2007	18.1
1989	20.6	2008	18.6
1990	25	2009	16.1
1991	17.5	2010	12.2

The maximum wind speed can be obtained by substituting Eq. (3) and (4) into Eq. (2). However, the sample size is limited in reality, so some other methods should be used to determine the value of two parameters (Simiu and Scanlan 1996). In order to obtain the wind parameters of Maputo Bridge, the least square method is introduced to fit the Gumbel extremal distribution curve according to the weather data of Maputo. These steps are as follows:

Step 1: Sort data in order big to small, the sequence number is repeat number (N, N-1, … , m, … , 1).
Step 2: P is obtained by the function P≈1-m/ (N+1) and y also can be obtained by the function y = - In (- In P).
Step 3: By substituting data (x, y) into Eq. (2), the least square method is used to compute the value of two parameters.

Table 2 lists assurance rate P, reduction variable y and the maximum wind speed of the bridge. Wind speed calculating formula in various return periods could be obtained as shown in Fig. 4. From the curve above, the maximum wind speed 10 meters above water surface for the return period of 100 years in the bridge site is about 35.77 m/s, which is significantly greater than the suggested value 27 m/s of southern African specification. Obviously, as a result of the calculation above, the value of the wind parameter is closer to the actual situation.

The height for bridge deck above the water surface is 64 m. Based on European specification (CEN 2004), the design wind speed in the deck height is:

$$V_m\left(60\right)=35.77\times0.19\times\text{In}\left(64/0.05\right)=48.62\text{m}/\text{s} \quad (5)$$

The flutter critical wind speed of the deck is obtained using logarithmic ratio (AASHTO 2010). The design wind speeds of Maputo Bridge are listed in Table 3.

Table 2 statistical parameter of the maximum wind speed at the bridge site

repeat number	maximum wind speed (m/s)	P	y	repeat number	maximum wind speed (m/s)	P	y
36	12.2	0.027	-1.284	18	20.8	0.5135	0.4058
35	13.9	0.0541	-1.0708	17	21.4	0.5405	0.4858
34	15	0.0811	-0.9212	16	21.7	0.5676	0.5685
33	15.6	0.1081	-0.7996	15	21.7	0.5946	0.6542
32	16.1	0.1351	-0.6939	14	22.2	0.6216	0.7436
31	16.7	0.1622	-0.5984	13	22.2	0.6486	0.8373
30	17.5	0.1892	-0.5098	12	22.8	0.6757	0.9364
29	18.1	0.2162	-0.4262	11	23.1	0.7027	1.0418
28	18.1	0.2432	-0.3462	10	23.6	0.7297	1.1549
27	18.1	0.2703	-0.2688	9	23.6	0.7568	1.2776
26	18.6	0.2973	-0.1931	8	23.9	0.7838	1.4121
25	19.2	0.3243	-0.1187	7	24.4	0.8108	1.562
24	19.4	0.3514	-0.0449	6	24.4	0.8378	1.732
23	19.4	0.3784	0.0285	5	25	0.8649	1.9298
22	19.4	0.4054	0.1022	4	25.6	0.8919	2.168
21	19.4	0.4324	0.1763	3	26.7	0.9189	2.4703
20	20.6	0.4595	0.2514	2	30	0.9459	2.8901
19	20.6	0.4865	0.3278	1	32.5	0.973	3.5973

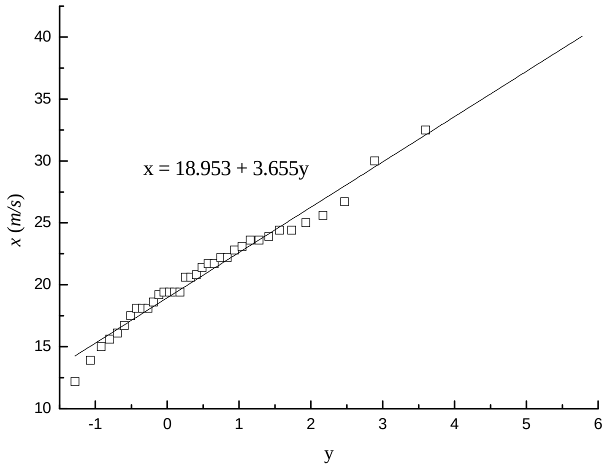

Fig. 4 Wind speed regression curve

Table 3 Design wind speeds (deck height: 64 m)

wind speed	return period (years)	intervene time (years)	wind speed (m/s)
design	100	100	48.62
flutter	10,000	100	71.54

3. STRUCTURAL DYNAMIC CHARACTERISTIC ANALYSIS

The structure dynamic characteristics are the basis of wind resistance analysis and thus they needed to be conducted in advance. By the analysis of structural dynamic characteristics, the structural frequency distribution and vibration mode could be obtained and therefore the basic data for wind tunnel test is provided. The structure dynamic characteristics are calculated by adopting the finite element software ANSYS. The bridge deck was modeled with spatial beam elements and a single spine girder model because of the little warping effect due to the adoption of closed-box cross section (Zhu et al., 2000). The bridge towers were also modeled with spatial beam. The main cables and suspender cables were modeled with spatial links, their tension stiffness represented by the initial strain on the basis of the data provided by planning department. Diaphragm, deck pavement and other added mass and mass moment of inertia are simulated by using equivalent mass points. The natural frequencies of some major modes of the bridge are listed in Table 4, where L is lateral bending of deck, V is vertical bending of deck, T is torsional bending of deck, number is mode order, S is symmetric mode shape, A is asymmetric mode shape.

Table 4 Structural dynamic characteristics

frequencies(Hz)	modes
0.0961	L1-S
0.151	V1-A
0.2024	V1-S
0.3033	V2-S
0.3087	L1-A
0.326	V2-A
0.4475	V3-S
0.5746	V3-A
0.5918	T1-S
0.7049	T1-A

4. FLUTTER ANALYSIS

4.1 Numerical identification of aerodynamic derivatives

Before flutter analysis, the aerodynamic derivatives of the deck should be determined. The original approach of the identification of aerodynamic derivatives relies on wind tunnel test using a scaled sectional model of the bridge deck. With the development of computer technology, computational fluid dynamics (CFD) was introduced to identify aerodynamic derivatives (Larsen and Walther 1997). Compared with the experiment method, CFD numerical simulation don't need experimenting equipment, and it is not bound by test conditions, such as the width interference, bracket and model scale, etc. Meanwhile, if the result of CFD numerical simulation is precise enough, it is possible to replace physical wind tunnel experiment to some extent.

The numerical simulation of turbulent flows, involving direct numerical simulation (DNS) and large-eddy simulation (LES) and Reynolds-averaged Navier-Stokes (RANS) approach, is an issue in the computation of numerical identification of aerodynamic derivatives. DNS is the most accurate method of solving turbulence in fluids. But DNS requires so much computer capacity that it is not adaptable for engineering type flows. And LES also requires a huge amount of computer capacity and is not yet applicable to most engineering problems. By contrast, RANS requires a lower amount of computer capacity and can meet the requirements of the engineering calculation. In this simulation, the SST k–ω turbulence model (Ge and Xiang 2008) was adopted in the identification with the FLUENT software.

The forced vibration method is adopted in the numerical simulation of aerodynamic derivatives, which assumes model with pure vertical bending or pure torsion movement respectively. Unsteady aerodynamic forces on the heaving or pitching are computed and the motion of the girder is accounted by the moving grid method. Meanwhile, the aerodynamic derivatives are extracted with the Least Square Method. The amplitudes of harmonic vibration are 0.2m for vertical vibration and 4º for torsional vibration. The numerically identified derivatives are shown in Fig. 5.

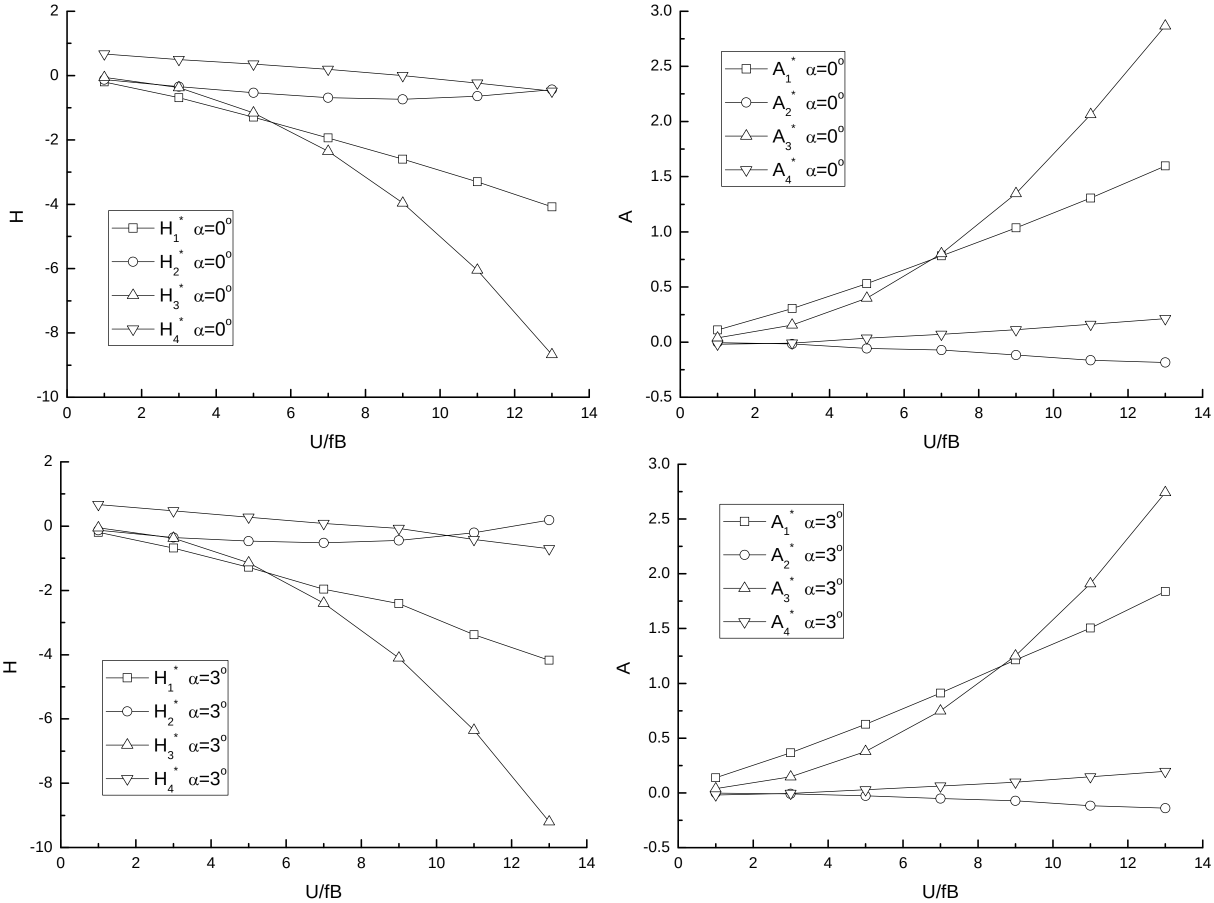

Fig. 5 Identification results of aerodynamic derivatives

4.2 2D flutter analysis

Based on the Scanlan’s expressions of self-excited aerodynamic force (Scanlan and Lin 1978), the most traditional method for flutter analysis is employed on the application of the so-called “strip theory” that the interaction between air stream and the body could be simplified by using a 2D section. The equations of motion are given as follows:

$$m\left[\ddot{h}(t)+2\zeta_h\omega_h\dot{h}(t)+\omega_h^2h(t)\right]=L_{se} \tag{6a}$$

$$I\left[\ddot{\alpha}(t)+2\zeta_\alpha\omega_\alpha\dot{\alpha}(t)+\omega_\alpha^2\alpha(t)\right]=M_{se} \tag{6b}$$

Usually, a restriction assumed in flutter analysis is that the body is performing a simple harmonic motion both in heaving and pitching simultaneously with the same frequency and infinitesimally small amplitudes. It means that the equations are applicable only when the body is performing the following coupled motion:

$$h=h_0e^{i\omega t},\ \alpha=\alpha_0e^{i\omega t} \tag{7}$$

And s and K defined by the following formulas:

$$s = Ut / B\,, \quad K = \omega B / U \tag{8}$$

By substituting Eq. (7) and (8) into Eq. (6), the matrix form equations of motion are given as follows:

$$\mathbf{AY} = 0 \tag{9a}$$

$$A = \begin{bmatrix} -K^2 + 2i\zeta_h K_h K + K_h^2 - \dfrac{\rho B^2 K^2}{m}\left(iH_1^* + H_4^*\right) & -\dfrac{\rho B^2 K^2}{m}\left[iH_2^* + H_3^*\right] \\ -\dfrac{\rho B^4}{I}\left[iK^2 A_1^* + K^2 A_4^*\right] & -K^2 + 2i\zeta_\alpha K_\alpha K + K_\alpha^2 - \dfrac{\rho B^4 K^2}{I}\left(iA_2^* + A_3^*\right) \end{bmatrix} \tag{9b}$$

$$Y = \begin{bmatrix} \dfrac{h_0}{B} \\ \alpha_0 \end{bmatrix} \tag{9c}$$

Where ρ is the air density, U is the mean wind speed, B is the bridge deck width.

Eq. (9) has non-zero solution only when the determinant of coefficient is equal to zero. Consequently, the problem is converted into a standard eigenvalue problem, and the flutter critical condition can be identified by solving the aeroelastic eigenvalue problem. Usually, the eigenvalue of the determinant has a real part a_i and an imaginary part b_i, the real part is circular frequency and the imaginary part is damper ratio. If there is an eigenvalue which is a pure real number, that means $b_i \approx 0$, the eigenvalue is the flutter circular frequency. And the onset wind speed of the flutter can be solved through this condition. According to the principle of the above analysis, the MATLAB software was used to perform the flutter analysis.

The flutter responses are restrained in symmetry torsion and symmetry vertical bending according to the study of flutter mechanism and the analysis of the dynamic characteristics. Thus the frequencies of first order symmetry vertical bending mode and torsional mode has been chose in the 2D flutter analysis. The results of flutter analysis are listed in Table 5.

Table 5 Results of flutter analysis

attack angle(º)	flutter circular frequency(rad/s)	onset wind speed (m/s)
0	3.18	101
3	3.31	74

5. WIND TUNNEL EXPERIMENT

A geometrical scale 1:50 is chosen to simulate the required details of the girder, and yields blockage less than 3.5% (generally, the blockage should be less than 5% for the wind tunnel testing). The sectional model was designed and manufactured by using the conventional stiff model technology. The model was made of high quality wood (Fig. 6.).

The length of the model is 2.1m, the width 0.512m and the depth 0.06m.

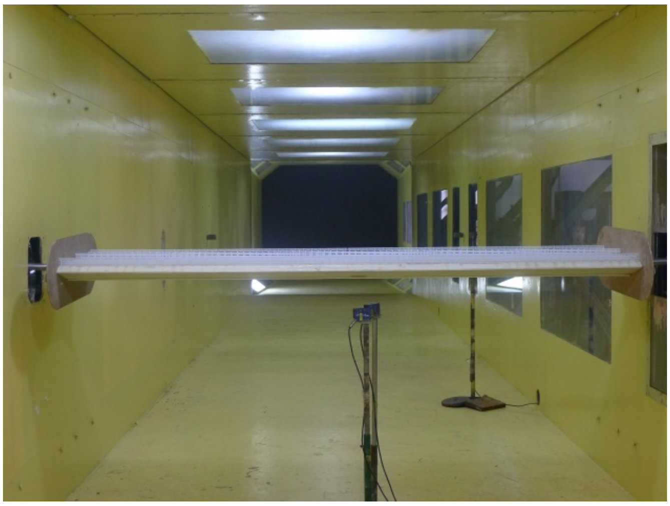

Fig. 6 The sectional model of wind-tunnel test

The testing parameters are shown in Table 7. The damping ratios are within a reasonable range, which are close to that suggested in the literature (MOT 2004) for steel bridge. The table suggests that the model satisfies the need of the test. The sectional model test was conducted to detect the flutter critical wind speeds in different cases. Based on the testing results, the flutter critical wind speeds in the real condition were calculated by wind speed ratios (model testing wind speed/natural wind speed) in each case. The test was conducted in two angles of attack: α = 0°, 3° in the uniform flow. The testing results of the original section are shown in Fig. 7.

Table 7 The design parameters of sectional model

parameter	value of real bridge	model required value	real model value
depth (m)	3.0	0.06	0.06
width (m)	25.6	0.512	0.512
mass (kg/m)	23484	19.68	19.7
mass moment of inertia (kg·m^2/m)	1211106	0.406	0.4593
radius of gyration (m)	7.1813	0.1436	0.153
bending frequency (Hz)	0. 2024	——	2.14
damping ratio of bending (%)	——	——	0.53
torsional frequency (Hz)	0.5918	——	6.44
damping ratio of Torsional (%)	——	——	0.41
torsional-bending frequency ratio	2.924	——	3.01

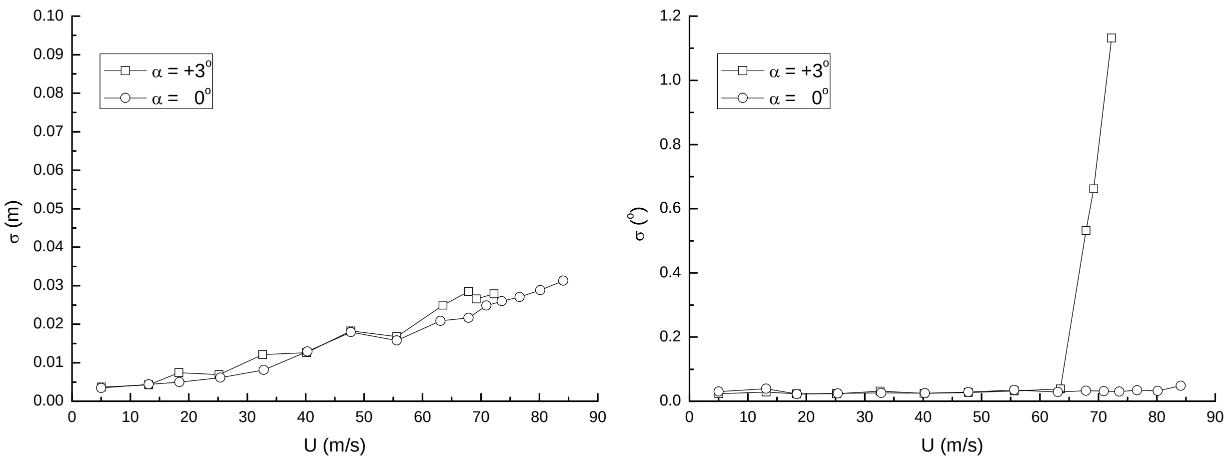

Fig. 7 Flutter test results of the original section

The results show that at 0° attack angle the original girder will suffer flutter within the flutter checking wind speed. However, in the case of 3° attack angle, it can be found form Fig. 7 that the slopes of the response curves with wind speed increase remarkably when wind speed exceeds 68 m/s, which indicating that the critical point of flutter is approached. It also shows that the girder would not suffer the flutter at 3° attack angle. Therefore, it is necessary to carry out aerodynamic optimization for the original girder to improve the flutter stability. According to the existing research results (Simiu and Scanlan 1996), the shape of steel box girder is optimized by adding the horizontal wind deflector whose width is 0.5 m. From the result (Fig. 8.), it can be found that the slopes of the response curves with wind speed increase remarkably when wind speed exceeds 85.9 m/s, which indicating that the critical point of flutter is approached, and the flutter stability performance could be well satisfied.

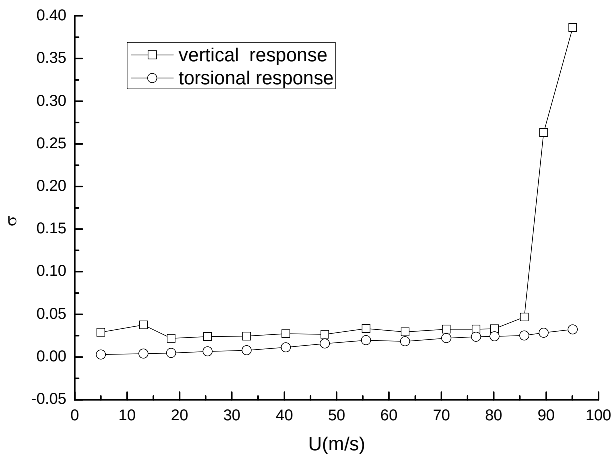

Fig.8 Flutter test results of aerodynamic optimization of main girder （α=3°）

6. RESULTS ANALYSIS

Both 2D flutter analysis method and the sectional model wind tunnel test are based on the strip theory, so they are comparable and we can use the test results to verify the feasibility of the pure theory of flutter analysis. In comparison with test and theoretic results, it can be found that the theoretic result-- 74 m/s is slightly larger than the test result--68 m/s in the case of 3° attack angle. This phenomenon is mainly due to ignoring attachment structure in CFD numerical simulation, such as railing, maintenance track, et al. This attachment structure will aggravate flow separation phenomenon of the cross section. As a result, there is a reduction in the flutter wind speed. Therefore, pure theory of flutter analysis has a certain reference value for engineering in the absence of test conditions.

7. CONCLUDING REMARKS

Maputo Bridge is a typical steel suspension bridge with closed streamline cross-section of single box. This paper studied the flutter performance of the bridge via 2D coupled flutter analysis method and wind tunnel experiment. According to the results, the main conclusions are as follows:
(1)The least square method is introduced to fit the Gumbel extremal distribution curve according to the weather data of Maputo, and the maximum wind speed 10 meters above water surface for the return period of 100 years at the bridge site is about 35.77 m/s.
(2)Through 2D flutter analysis, the onset wind speeds of flutter were 101 m/s and 74 m/s and the corresponding angles of attack were 0° and 3° respectively.
(3)The test results show that the original girder would not suffer the flutter in the case of 3° attack angle. Then the girder shape is optimized by adding the horizontal wind deflector, and the girder has enough aerodynamic stability after aerodynamic optimization.
(4)Through the comparison of the test and the theoretic results, it can be found that the results were similar for both methods. Therefore, pure theory of flutter analysis has a certain reference value for engineering in the absence of test conditions.

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