

Aerodynamic effects on streamline box girder in active wind tunnel with multiple fans and vibrating airfoils

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ABSTRACT: The aerodynamic behavior of a streamline box section model is characterized in an active wind tunnel with multiple fans and vibrating airfoils in Miyazaki University, Japan. A series of single harmonic fluctuating wind with discrete frequencies are generated. The aerodynamic admittance components obtained via cross spectral identification method for different oncoming flows present obvious deviation between each other, which implies the limitation of traditional buffeting theory. More attention is emphasized on the relationship between aerodynamic forces and wind turbulence components, along- and cross-wind, in sinusoidal flow conditions. It is found that the cross-wind turbulence has dominant influence on lift and pitching moment forces. With the strengthening of along-wind turbulence, the lift force increases, while the drag and pitching moment forces vary with different trend in different range of frequency. Moreover, it is found that the contribution of along-wind turbulence to lift and pitching moment forces is neglectable compared with that of the cross-wind turbulence, while for the drag force, the two turbulence components present comparative contributions.

KEYWORDS: Active wind tunnel; Two-dimensional harmonic fluctuating flow; Streamline box section; Aerodynamic admittance; Turbulence statistics; Aerodynamic effects

1 INTRODUCTION

Buffeting is a kind of stochastic forced vibration caused by the turbulence existing inherently in natural wind. Buffeting is hence inevitable for any bridges exposed to the natural wind. To ensure the safety of the construction for long-span bridges, the buffeting analysis is necessary to be refined. Many previous studies have made great contribution to the development of buffeting theory [1-4]. For the consideration of the non-stationarity and incompletely spanwise coherence of natural turbulence, the aerodynamic admittance was employed to modify the quasi-steady aerodynamic forces. On buffeting analysis, Sears's function for a vertical wind gust [1] and Devenport's formula for an along wind gust [2] are usually employed. The accuracy of the result depends largely upon the accurate estimation of aerodynamic admittance. Wind tunnel testing is the most popular method to investigate the effects of wind on long-span bridges. Some studies focused on aerodynamic admittance have been conducted in conventional boundary-layer wind tunnels [3-4]. Considering the limits like the adjustment of wind power spectral density and the integral length scale in passive turbulence generation method, a few actively controlled wind tunnels have been proposed [5-8].

Multiple-fan wind tunnel is a relatively fine active generation technique in Japan. In the active wind tunnel in Miyazaki University, 99 fans arranged in a 9 wide by 11 high matrix has been used to generate only along-wind turbulence (u -turbulence), which coincide well with the natural turbulent flow [9]. Then in this wind tunnel, a series of single harmonic fluctuating wind were generated to research the relationship between aerodynamic forces induced by sinusoidal fluctuating wind with discrete frequency and broadband turbulence, which verifies the principle of

superposition of aerodynamic forces for sinusoidal flows in some specified frequency range (Fig. 1)[10,11]. However, active wind tunnel with only multiple-fan equipment could not produce sufficient cross-wind turbulence (w -turbulence), which may result in significant effects on buffeting forces. In contrast, there is some testing conducted in a wind tunnel equipped with only a series of wings to produce w -turbulence, while the u -turbulence is neglected [12]. However, the contribution of u -turbulence and w -turbulence to aerodynamic forces has not been clearly understood. Based on the limits of the existing active wind tunnels, additory active vibrating airfoils are equipped in the wind tunnel of Miyazaki University together with the multiple-fan equipment to produce two-dimensional (u - and w -) active turbulence. Based on the superposition principle of aerodynamic forces referred above, more attention is emphasized on the relationship between aerodynamic forces and wind turbulence components in sinusoidal flow condition.

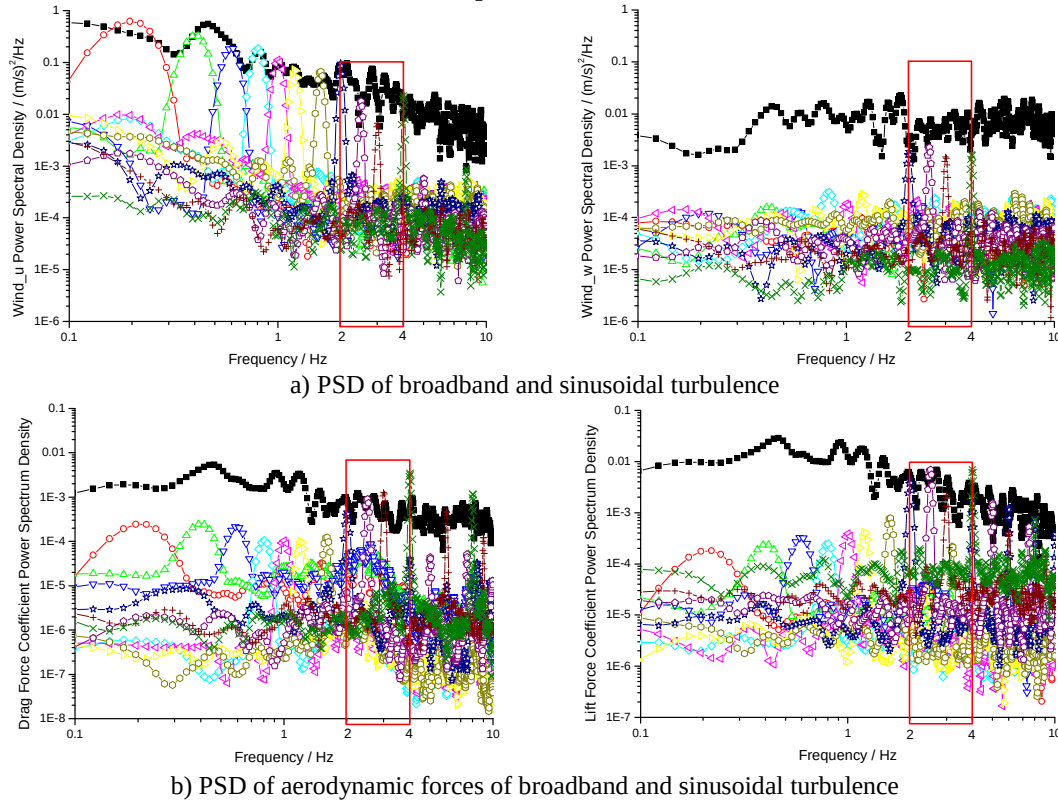


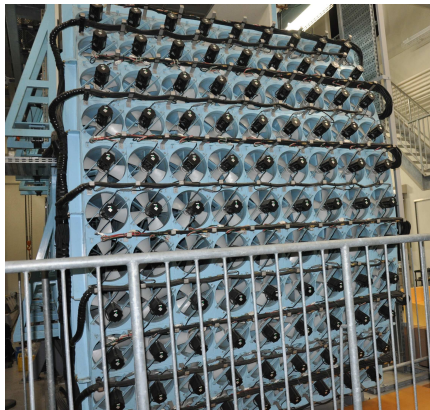
Figure 1 Linear superposition of sinusoidal flow for Streamline Box Girder section

2 EXPERIMENTAL ARRANGEMENT

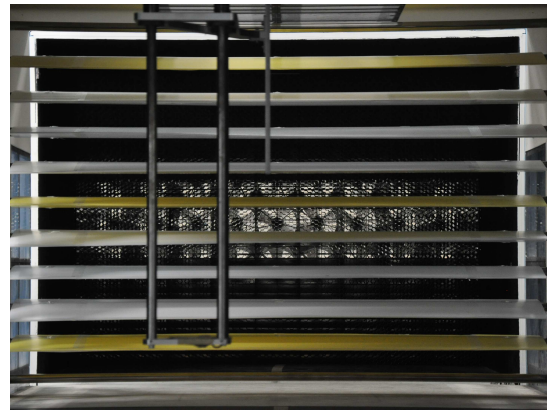
2.1 Active turbulence generator

Fig.1 shows the active wind tunnel with multiple fans and vibrating airfoils in Miyazaki University, Japan. This wind tunnel is an open-circuit one with 99 fans of 270mm in diameter at the front. The fans are arranged in a 9 wide by 11 high matrix (Fig. 1(a)). The vibrating airfoils are set to be 1.5m downstream from the honeycomb (Fig. 1(b)). The test section is 15.5m long (maximum), 2.538m wide and 1.804m high. The maximum wind velocity is about 15m/s, while 9m/s for sinusoidal flows with fluctuating amplitude of 3.5m/s. The maximum fluctuating frequency can reach to 5Hz. In this experiment, active fans and vibrating airfoils are combined to produce

sinusoidal turbulent flows of different dominant frequencies and different values of power spectral density (PSD) of u - and w - turbulence, denoted as S_u and S_w respectively.



(a) Multiple fans

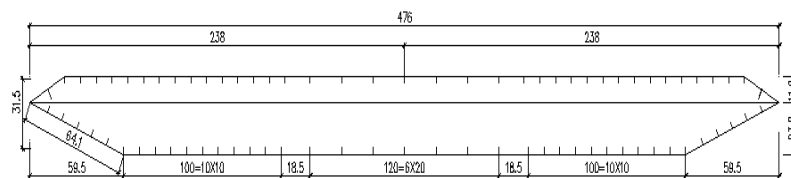


(b) Vibrating airfoils

Fig. 2 Active wind tunnel with multiple fans and vibrating airfoils

2.2 Fixed model tests

The deck section adopted for tests is a 1:60 scale section model of a streamline box shape. Fig. 3 shows the cross section of the section model and the model in tests. A pressure measurement system was set up for the measurement of aerodynamic forces. There are 80 points around the section under measurement and for each testing process two sections (section 1 and section 2) are simultaneously measured. The static angle of attack of the bridge section is 0° .



(a) Cross section of the section model



(b) Section model in tests

Fig. 3 Streamline box section model

In this experiment, special study about the turbulence statistics along the test section is conducted to identify the relatively steady section for model tests. Fig. 4 shows the variation of PSD,

integral scale, turbulence intensity and average wind velocity of two measure points. It illustrates that when the distance from the honeycomb ranges between 4.1m and 4.6m, the turbulent flows keep relatively steady. The section model is finally fixed 4.4 meters away from the honeycomb.

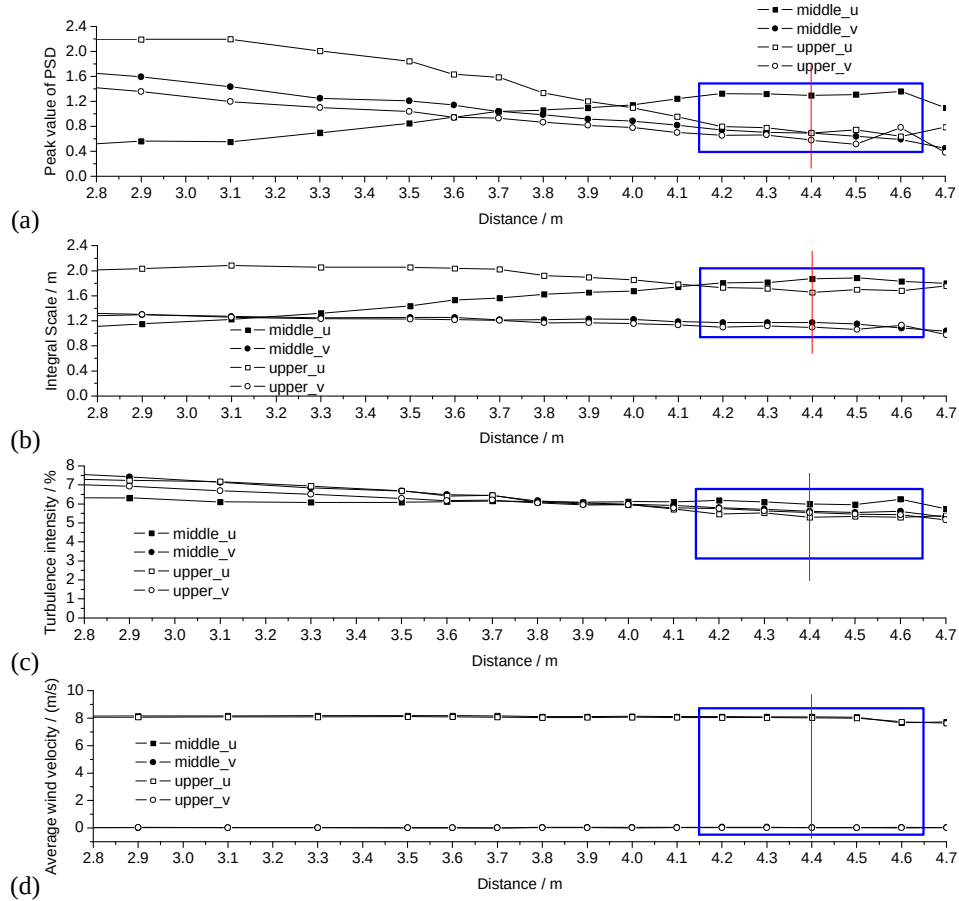


Fig. 4 Variation of (a) PSD, (b) integral scale, (c) turbulence intensity and (d) average wind velocity along test section

In order to study the relationship between aerodynamic forces and wind turbulence components, the active fans and vibrating airfoils are combined to produce a series of sinusoidal fluctuating winds. The detailed testing conditions are listed in Table 1. There are totally three kinds of combination between active fans and vibrating airfoils. In Table 1, f means the dominant frequency of the sinusoidal flow.

Table 1 Different combination of motion for active fans and vibrating airfoils

Testing serial No.	Description of fluctuating flows in entrance section
1	Multiple fans: $f=0.2-4.0\text{Hz}$; $\Delta f=0.1\text{Hz}$ Average wind velocity $U=8\text{m/s}$; Amplitude $A1=2\text{m/s}$ Airfoils: Vibrating with the same frequency as active fans Amplitude $A2=10^\circ$
2	Multiple fans: $U=8\text{m/s}$; $A1=0$ Airfoils: $f=0.2-4.0\text{Hz}$; $\Delta f=0.2\text{Hz}$; $A2=10^\circ$
3	Multiple fans: $f=0.2-4.0\text{Hz}$; $\Delta f=0.2\text{Hz}$; $U=8\text{m/s}$; $A1=2\text{m/s}$ Airfoils: static

3 EXPERIMENTAL RESULTS

3.1 Identification of aerodynamic admittance

Based on the traditional buffeting theory, the aerodynamic admittance functions have been employed to modify the quasi-steady aerodynamic forces. For example, the lift component is expressed as [2]

$$L_b(t) = \rho UB(C_L(\alpha)\chi_{Lu} + 1/2(C'_L(\alpha) + C_D(\alpha))\chi_{Lw}w(t)) \quad (1)$$

where ρ =air density; U =mean wind velocity; $B=2b$ is the bridge deck width; C_L and C_D =mean lift and drag coefficients, respectively; $C'_L = dC_L / d\alpha$; α is the mean static angle of attack of the bridge section; and χ_{Lu} , χ_{Lw} = aerodynamic admittance functions for lift force.

The aerodynamic admittance components here are identified by cross spectral admittance identification method. The aerodynamic admittance for lift force can be expressed by

$$\chi_{Lu}(f) = \frac{S_w(f)S_{Lu}(f) - S_{wu}(f)S_{Lw}(f)}{\rho U B C_L(\alpha) [S_u(f)S_w(f) - S_{uw}(f)S_{uw}(f)]} \quad (2a)$$

$$\chi_{Lw}(f) = \frac{S_u(f)S_{Lw}(f) - S_{uw}(f)S_{Lu}(f)}{1/2 \rho U B [C'_L(\alpha) + C_D(\alpha)] [S_u(f)S_w(f) - S_{uw}(f)S_{uw}(f)]} \quad (2b)$$

where $S_{Lu}(f)$, $S_{Lw}(f)$ = cross power spectrum between lift force and u - , w - turbulence respectively; $S_{wu}(f)$, $S_{uw}(f)$ = cross power spectrum between u - and w - turbulence; $S_u(f)$, $S_w(f)$ = PSD of u - and w - turbulence.

For the comparison with Sears function, the aerodynamic admittance components shown in Eq. (2) are transformed into equivalent aerodynamic admittance (EAA) with an expression as follows

$$|\phi_{LL}(K)|^2 = \frac{4C_L^2(\alpha)|\chi_{Lu}|^2 S_u(K) + (C'_L(\alpha) + C_D(\alpha))^2 |\chi_{Lw}|^2 S_w(K)}{(4C_L^2(\alpha)S_u(K) + (C'_L(\alpha) + C_D(\alpha))^2 S_w(K))} \quad (3)$$

where $|\phi_{LL}(K)|$ is EAA for lift force; $K=2\pi Bf/U$. EAA for drag and pitching moment forces, denoted as $|\phi_{DD}(K)|$ and $|\phi_{MM}(K)|$, have similar expression as Eq. (3).

3.2 Aerodynamic admittance of streamline box section

In this experiment, the time histories of buffeting forces components, i.e. lift, drag, and pitching moment components are obtained by integration of pressure measured around the model section. Three equivalent aerodynamic admittances are identified for each different testing condition listed in Table 1. Fig. 5 shows the comparisons of equivalent aerodynamic admittance (EAA) between different fluctuating flows for section 1. It is clearly shown that the aerodynamic admittance components obtained by cross spectral identification method present obvious deviation between different fluctuating flows. This indicates the limitation of traditional buffeting theory.

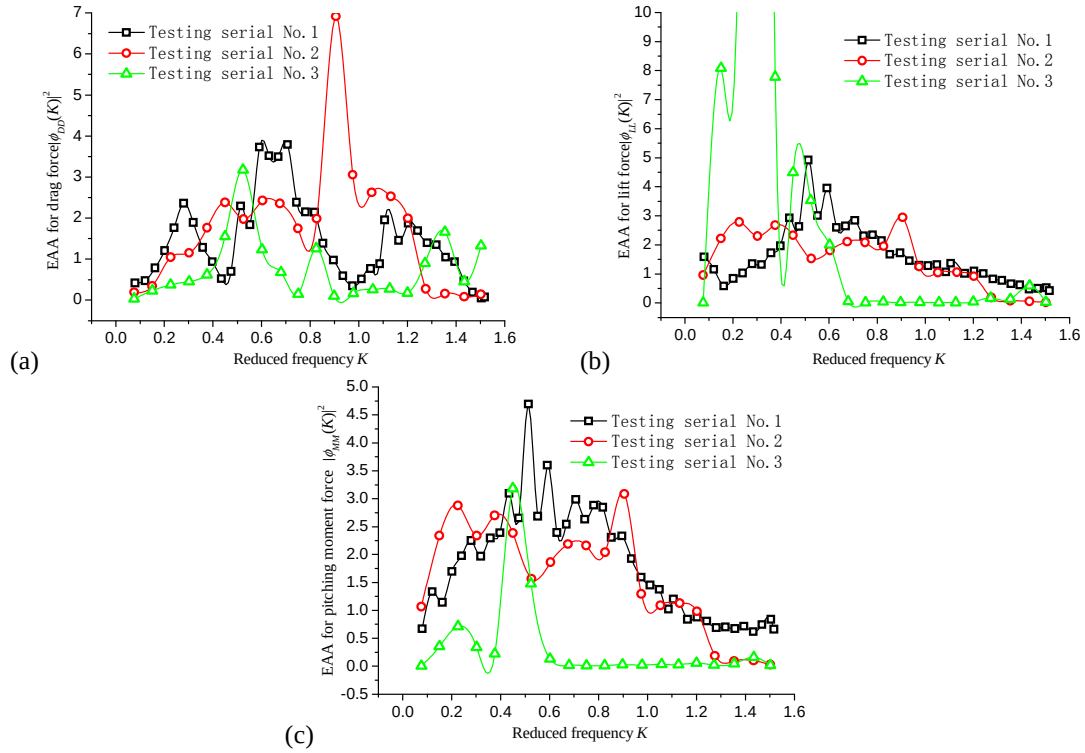


Fig.5 Comparison of equivalent aerodynamic admittance (EAA) for (a) drag force, (b) lift force, and (c) pitching moment force

For further understanding of the effects of turbulence on aerodynamic forces, the testing results for both section 1 and section 2 in a sinusoidal flow with dominant frequency of 2Hz are shown in Fig. 6. Although the PSD of horizontal and vertical turbulence, S_u and S_w , around dominant frequency shows much difference, the aerodynamic forces remain almost the same. This indicates that the aerodynamic admittance is related to the turbulent characteristics, which is different from the traditional buffeting theory.

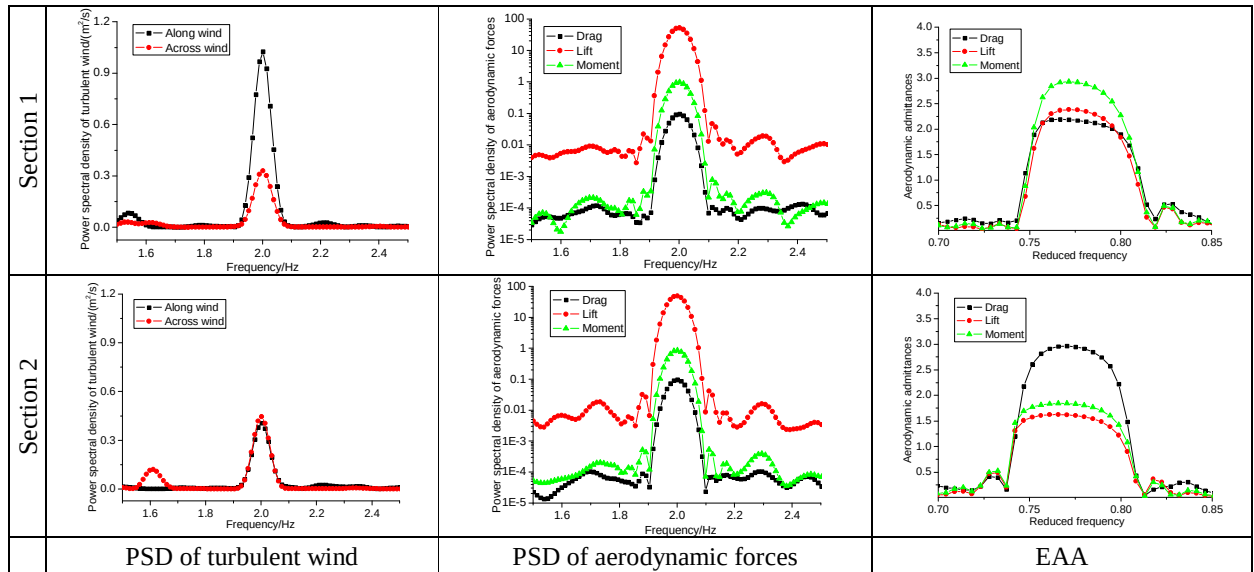


Figure 6 Comparison of the testing results of section 1 and section 2

3.3 Sensitivity analysis of buffeting forces to turbulence

For the sake of the limits in traditional buffeting theory, the effects of u - and w - turbulence (S_u and S_w) on buffeting forces (PSD of buffeting forces: S_L , S_D and S_M) are directly analyzed without the employment of aerodynamic admittance functions. For the purpose of the analysis about the sensitivity of buffeting forces to turbulence, several pairs of results with almost the same values of S_u (or S_w) at the same dominant frequency are selected. In contrast, the values of S_w (or S_u) present relatively obvious differences. The results are listed in Table 2 and Table 3.

Table 2 Sensitivity of buffeting forces to w -turbulence

f	S_u	S_w	S_D	S_L	S_M	With the increase of S_w		
						S_D	S_L	S_M
0.8	3.095	0.805	0.155	133.489	2.092			
0.8	3.050	0.004	0.030	1.676	0.003	↑	↑	↑
1	2.377	1.006	0.219	196.360	3.043			
1	2.414	0.001	0.029	0.657	0.001	↑	↑	↑
1.2	1.053	1.478	0.257	254.082	3.995			
1.2	1.130	0.004	0.001	0.006	0.001	↑	↑	↑
1.4	0.301	2.975	0.345	284.919	4.456			
1.4	0.314	0.004	0.026	2.231	0.015	↑	↑	↑
2	0.405	0.445	0.096	49.033	0.856			
2	0.404	0.006	0.025	1.824	0.056	↑	↑	↑
2.2	0.724	0.410	0.055	46.572	0.987			
2.2	0.728	0.007	0.030	1.0603	0.014	↑	↑	↑
3.2	0.520	3.671	0.333	213.520	3.447			
3.2	0.505	0.003	0.127	0.553	0.021	↑	↑	↑

Key: ↑= increase of S_F ($F=D, L, M$)

Table 2 Sensitivity of buffeting forces to u -turbulence

f	S_u	S_w	S_D	S_L	S_M	With the increase of S_u		
						S_D	S_L	S_M
0.2	57.335	0.010	0.222	8.201	0.001			
0.2	52.080	0.012	0.286	3.001	0.025	↓	↑	↓
1.2	0.731	0.001	0.029	0.314	0.001			
1.2	0.274	0.001	0.000	0.002	0.000	↑	↑	↑
2	1.322	0.003	0.042	0.332	0.015			
2	0.140	0.003	0.000	0.005	0.001	↑	↑	↑
2.8	0.117	0.011	0.055	0.579	0.016			
2.8	0.070	0.012	0.086	0.296	0.004	↓	↑	↑

Key: ↑= increase of S_F ($F=D, L, M$); ↓=decrease of S_F ($F=D, L, M$)

It is shown in Table 2 that all the three aerodynamic forces present increase with the increase of S_w . The contribution of S_w is predominant especially for lift and pitching moment forces. The results indicate the importance of correct simulation of w -turbulence in wind tunnels. From Table

3, we can see that the contribution of S_u to buffeting forces is more complex than that of S_w . With the increase of S_u , the lift force increases, while the drag and pitching moment forces present different trend of variation in different ranges of frequency.

Moreover, comparisons about the effects of u -turbulence and w -turbulence on buffeting forces are conducted. The results with regard to turbulent flows with dominant frequencies of 1.2Hz and 2.0Hz are selected from both Table 2 and Table 3. Here we define an average effects index k_u (or k_w) expressed as

$$k_u (or k_w) = \frac{\delta S_F}{\delta S_u (or \delta S_w)} \quad (F=D, L, M) \quad (4)$$

where δS_u , δS_w =variation of PSD of u -turbulence and w -turbulence at the dominant frequency and δS_F is the relative variation of PSD of buffeting forces. Fig. 7 shows the average variation of S_F resulted from the unit change of S_u and S_w .

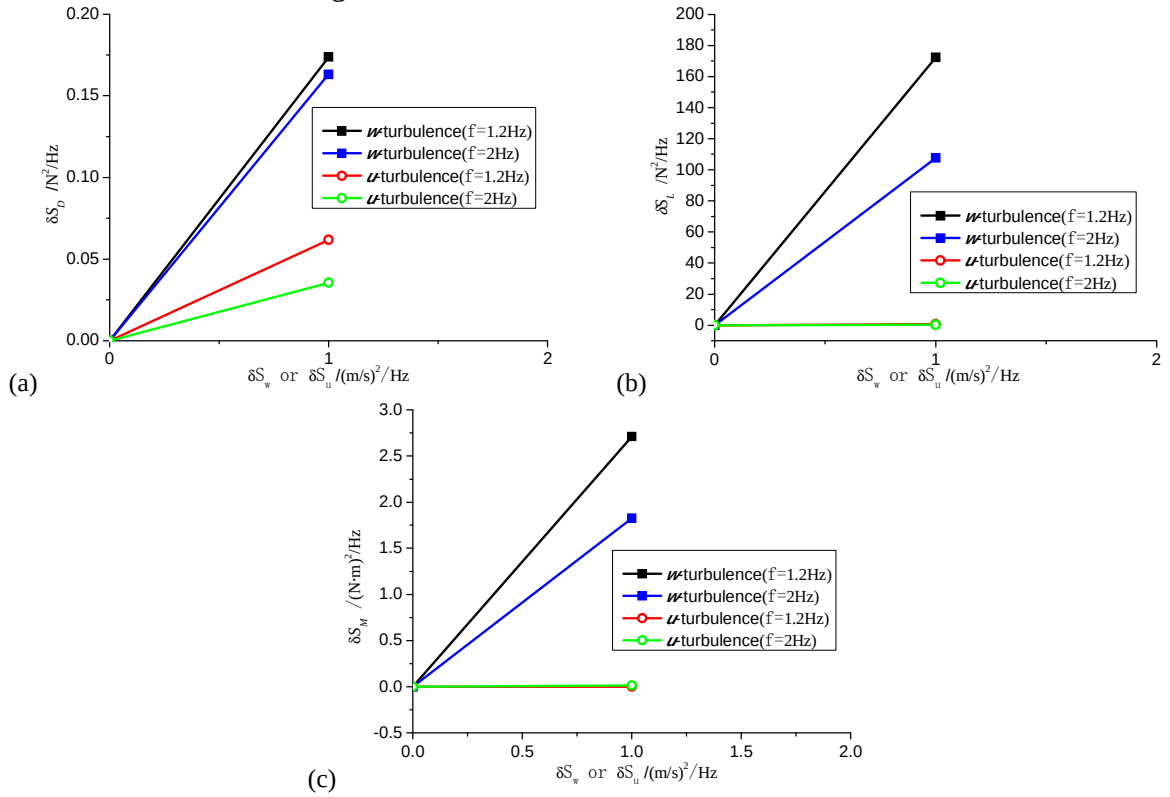


Fig. 7 Average effects of u - and w - turbulence on (a) drag, (b) lift and (c) pitching moment forces

It is clearly indicated in Fig. 7 that the lift and pitching moment forces are much more sensitive to the w - turbulence than u - turbulence. It is acceptable to neglect the contribution of u - turbulence. For the drag force, the contribution of the u - turbulence is less than that of w - turbulence. However, they keep the same order of magnitude, i.e. both the u - and w - turbulence should be corrected simulated for the accurate simulation of drag force.

4 CONCLUSIONS

A series of single harmonic fluctuating winds with different combination of u - and w - turbulence are generated in an active wind tunnel with multiple fans and vibrating airfoils in Miyazaki University. The experimental results about the relationship between flow turbulence and buffeting forces are analyzed. Conclusions of this study are summarized as follows:

- (1) The traditional buffeting theory based on aerodynamic admittances has some limits. The aerodynamic admittance is related to the characteristics of the flow, which is different from the traditional buffeting theory.
- (2) The w - turbulence has positive contribution to all the three buffeting forces, while the u - turbulence presents positive contribution only to lift force. The drag and pitching moment forces present different trend of variation in different ranges of frequency.
- (3) The lift and pitching moment forces are much more sensitive to the w - turbulence than u - turbulence. It is acceptable to neglect the contribution of u - turbulence.
- (4) Both the u - and w - turbulence should be corrected simulated for the accurate simulation of drag force, although the contribution of the u - turbulence is less than that of w - turbulence.

The conclusions above are qualitative ones based on the premise of 0° static angle of attack of the bridge section. More quantitative analyses based on different angle of attack are expected in future.

5 ACKNOWLEDGEMENTS

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