POLISH MARITIME RESEARCH Special Issue 2018 S2 (98) 2018 Vol. 25; pp. 17-22
10.2478/pomr-2018-0068

EXPERIMENTAL STUDY OF THE AERODYNAMICS OF SAIL IN NATURAL WIND

Zeng Xiangming, Associate Professor
Zhang Huawu, Lecturer
Merchant Marine College, Shanghai Maritime University, Shanghai, China

ABSTRACT

In order to evaluate the impacts of a motor vessel after installing wind sails, the aerodynamics of the sail should be accurately calculated. However most of the research on sails are based on stable wind instead of natural wind which is changing horizontally and vertically. In this paper wind tunnel tests are carried out based on stable wind field and simulated natural wind field, the results shown that there are 16–44% decrease in natural wind in terms of lifting coefficient and 11–42% decrease for drag coefficient. This would provide a valuable reference to the effectiveness evaluation of the impact of sails for sail assisted ships.

Keywords: Natural wind, Wind sail; Aerodynamics; Sail assisted ship

INTRODUCTION

With the rising of oil price and the enter into force of IMO (International Maritime Organization) regulations on Green House Gas emission control, sail assisted shipping technology once again becomes a hot topic of shipping researches. Undoubtedly sails could be used as ship propulsion source to reduce the fuel consumption of engine, however, modern motor ship has tremendous differences compared with traditional sail ship in terms of structure and propulsion system. For sail assisted motor ship, sail is just an auxiliary propulsion plant, the working principle of wind sail is also different with pure sail ship because sails on motor ships are mainly working under transverse wind similar to aerofoil [1]. It makes the aerodynamic characteristics of the sail crucial to the efficiency of propulsion, i.e. to provide as much as possible thrust force and at the same time reduce the transverse force to limit the adversely impact to the ship stability and maneuvering.

By literatures [2, 3, 4, 5, 6], researches of sail for motor ships in recent years mainly focus on sail model selection and the interaction between sail and ship, including design, optimization of model and aerodynamic analysis of sails of different structures and materials, routing plan and economic performance forecast, computation analysis of sail structure strength and its influences on ship stability, and interaction between sail and ship and between sails. The core of all these researches is to develop an accurate recognition of sail's aerodynamic performance. That is to say, if sail's stress situation is unclear, subsequent study of structure, stability, controllability and economic benefit is nothing but a false proposition.

Sail aerodynamic performance is an important basis for selection of sail model. Good sail type can make a sail of the same size generate higher ship thrust. During initial researches, Japanese scholars M. Ueno proposed a soft-hard-combined compound sail design, which is proven able to reach a thrust coefficient of 2.46 by wind tunnel experiment researches [7]. Fujiwara T. did the research of square soft sail's aerodynamic performance by both CFD and wind tunnel test[8]. Ouchi K. carried out research of optimization of sail type, and proposed that hard sail has the aerodynamic performance better than that of soft sails and will be the direction of development in the future [9]. French scholar Armand J. L. carried out wind tunnel experiment of 3100-ton product oil tanker with sail by the 1/50 proportion of reduction to research the ship model's aerodynamic performance, and proposed an initial scheme for adoption of sail for sail assistance in modern commercial ship [10]. Spanish scholar Guerri O. used numerical simulation model to CFD simulation research of the turbulence of elliptic sail [11]. British scholar Burden A. proposed a design concept of feeder container vessel with sail assistance, which has the sail system able to save energy by 6% at the 15-knot sailing speed [12].

However, in terms of literatures, current simulation researches of sail's aerodynamic performance are all based on the premise of stable wind field. Previous sail test researches were basically executed in low-speed wind tunnel with even wind speed and stable wind direction and did not simulate the influence of wind field change on sail stress situations under natural wind state [7, 8, 9, 10, 11]. However, actual sail working environment is natural wind field, the wind speed is fluctuating, and can be classified into stable average wind speed and fluctuating wind speed with characteristics of zero-mean stationary random process. In addition, in order to obtain higher thrust, sails of ships are always designed to be very large. For example, in the research of design of sail-assistance feeder container vessel by British University of Southampton, the sail had the width and height of 26.5 m and 25 m as an upright structures [12]. In natural wind environment, as surface boundary layer exists, wind speed in vertical direction often presents logarithmic or exponential distribution, namely wind speed will decrease strikingly with the fall of the height. Therefore, in actual sailing, the wind speed and direction on sail is under the action of wind force changing in the horizontal direction, but also the change of wind force in vertical direction, which will surely make great influence on sail stress. For this reason, to accurately understand stress situation of sail in actual use, aerodynamic performance of sail in natural wind environment must be studied.

This paper, on the basis of initial researches of the sail assistance research group of Shanghai Maritime University, explored natural wind simulation researches and carried out aerodynamic performance test of the elliptic aerofoil sail designed by the research group under natural wind state.

NATURAL WIND SIMULATION

Simulation experiment of natural wind is generally realized through boundary layer wind tunnel. By wind tunnel design characteristics, the experiment method could be divided into natural simulation and artificial simulation [13]. The natural simulation method relies on extension of the test section of common wind tunnel to let wind form certain turbulence and wind profile in the test section, thus to simulate characteristics of natural wind. This method is not used generally, because it needs changing of wind tunnel structure. The artificial intervention can be carried out through passive simulation or active simulation [14]. The passive simulation mainly features adding some components generating turbulence before the test section of wind tunnel, such as baffle and spire, so as to generate the wind field characteristics similar to atmospheric boundary layer. As shown in Fig. 1., in wind tunnel, plate-type grilles are mounted with different intervals [15]. By adjusting grille distance distribution and plate-type scale, different atmospheric boundary layer characteristics can be simulated. This method is commonly used in early atmospheric boundary layer simulation wind tunnel.

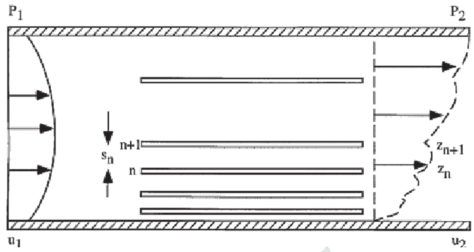

Fig. 1. Boundary Layer Wind Tunnel with Plate-type Grille

Relatively recent atmospheric boundary layer wind tunnels mostly use spires and roughness elements to simulate wind field characteristics of atmospheric boundary layer [16]. As shown in Fig. 2., spires were arranged in wind tunnel in a row, to make turbulence in wind tunnel. Meanwhile, with the structure as shown in Fig. 3., the spires can form wind profile. In addition, according to actual situations of the scene to be simulated in the experiment, some rectangular blocks can be arranged at the bottom of the wind tunnel, to increase surface roughness.

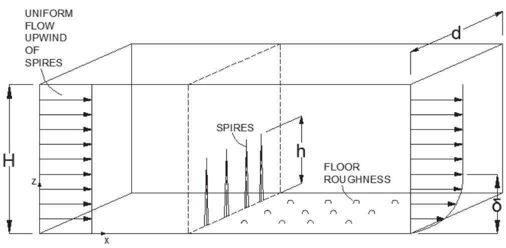

Fig. 2. Boundary Layer Wind Tunnel with Spire and Roughness Element

Active simulation method features adding jet or deformed spire block in wind tunnel, tests the flow field wind speed spectrum in the test section to control the additional incoming flow energy provided by jet or multiple fans or change shape of spire blocks, for example, letting spire be able to vibrate under computer control, to generate experiment-needed turbulence and realize accurate simulation of wind field characteristics. For example, University of Miyazaki's multi-fan wind tunnel adopts 11 conversion-controlled small fans, and relies on adjustment of the rotating speed of every fan to generate the wind simulating characteristics of atmospheric boundary layer wind field. In the test section, the hot-wire anemometer collects the wind speed spectrum of downstream wind field as the feedback information for control system and finally obtain the wind field needed for test [17]. Active simulation method is characterized by high requirements for wind tunnel hardware and control and high initial investment. Therefore, it is rarely used in actual application.

In order to understand the difference of stress situation of sail between natural wind environment and stable wind field, this paper, on the basis of initial research by the sail assistance research group of Shanghai Maritime University, modified the University's low-speed revolution wind tunnel with the size and performance as follows:

- Test section size: 6 m (L) × 1.4 m (W) × 2 m (D)
- Area covered by the wind tunnel: L × W=22 m × 7.08 m
- Wind tunnel use: research of sailing ship, particularly sail stress
- Design wind speed: 1~40 m/s
- Factory building space: W 12 m × D 7.7 m× L 24 m
- The air-flow pressure in the wind tunnel is 1 bar and operates under normal pressure.
- Wind speed adjustment range and control accuracy
- 1.0~25 m/s, measurement accuracy: (error < 0.1%)

In this test, two spires as shown in Fig. 3. are added before the wind tunnel test section to increase test section turbulence and form wind speed profile. To test the aerodynamics of ship sails, we should simulated wind field on the sea, which is based the landforms with the lowest surface roughness. Therefore, roughness element is not used to increase roughness. Spire size is as shown in Fig. 3., and the front view shows the windward side of spire. The spire has a base 250 mm wide and 1800 mm high. The bottom supporting board behind the spire is trapezoidal, and the trapezoidal bottom's length of side is 318 mm. In order to better support spires, an adjustable carrier role is designed at the top of spires, to firmly fasten spires and take advantages of some inclination and rely on wind tunnel body to clamp spires firmly.

Before experiment execution, test spire firmness, which should be able to bear at least 30 m/s wind speed and satisfy the whole range of wind speed needed in this experiment. Spires are erected in the following manner: Spires are erected at the entrance to the experimental section of wind tunnel. In order not to influence normal wind speed control and adjustment of wind tunnel, spires are arranged behind the entrance wind tunnel hot-wire anemometer, with two spires erected at the place 30 cm from wind tunnel side, by the interval of 30 cm. Experimental spires are erected as shown in Fig. 4.

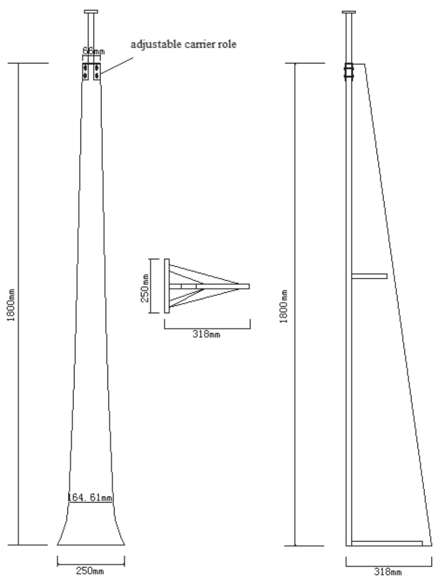

Fig. 3. Spire shape and size

Fig. 4. Real picture of spire erection

Tab. 1. Turbulivity Distribution at Different Wind Speeds before and after Modification

Wind speed		15 m/s	20 m/s	25 m/s
Turbulivity at the Height of 40 cm	Original	2.42	2.56	1.49
	Modified	27.68	27.39	27.39
Turbulivity at the Height of 50 cm	Original	1.49	0.93	0.76
	Modified	24.41	24.92	23.84
Turbulivity at the Height of 60 cm	Original	0.83	1.09	2.57
	Modified	22.05	20.31	20.31
Turbulivity at the Height of 70 cm	Original	1.53	0.58	1.74
	Modified	21.18	19.65	19.41
Turbulivity at the Height of 80 cm	Original	3.36	3.63	2.32
	Modified	18.16	19.75	18.16

Before and after modification, hot-wire anemometer was used to measure wind speed at all points on the 60 cm plane ahead of the test component. The comparison of turbulivity and standard variance at different wind speeds before and after modification is shown as in Tab. 1. and Tab. 2. The data indicate that before modification, the wind field in the wind tunnel had a very good evenness, low turbulivity and very low wind speed average variance. After the spires are added, the turbulivity in the wind tunnel increase by more than 10 times, and the average variance also increased by nearly 10 times, indicating that after modification, the flow field in the wind tunnel was no longer even and developed the fluctuating characteristics similar to natural wind.

Tab. 2. Wind speed Standard Variance Distribution at Different Wind Speeds before and after Modification

Wind speed		15 m/s	20 m/s	25 m/s
Turbulivity at the Height of 40 cm	Original	0.39	0.54	0.39
	Modified	3.73	4.88	5.95
Turbulivity at the Height of 50 cm	Original	0.22	0.19	0.19
	Modified	3.57	4.84	5.83
Turbulivity at the Height of 60 cm	Original	0.13	0.23	0.68
	Modified	3.48	5.34	5.34
Turbulivity at the Height of 70 cm	Original	0.23	0.12	0.45
	Modified	3.47	4.3	5.29
Turbulivity at the Height of 80 cm	Original	0.52	0.8	0.62
	Modified	5.29	4.61	5.29

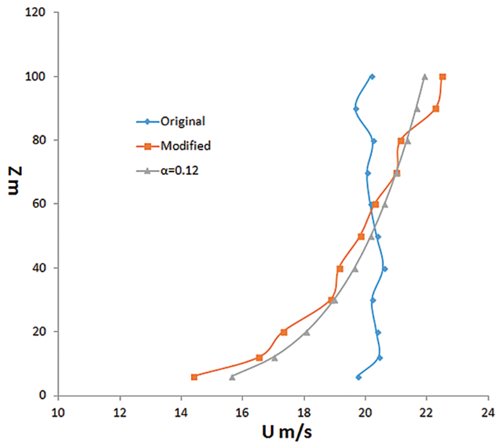

Fig. 5. Comparison of wind speed at Different Height

In vertical direction, Fig. 6. shows the speed distribution before and after modification within the testing height which is 6–100 cm as the height of model is only 62 cm in this experiment. Under the setting speed of 20 m/s, the original wind speed in the wind tunnel test section is closely constant in vertical direction. After modification, due to influence of spire shape, wind speed presented fundamental change at the testing height, very close to the wind profile curve with the index of α=0.12 if the height of atmospheric boundary layer is set at 300 m and the scale is 1:100, just enough conforming to the surface distribution law of natural wind on the sea [18].

Tab. 3 shows the mean speed distribution at different transverse positions, namely at different positions 40 cm vertically from the wind tunnel's longitudinal centre line. It is clearly indicated that in the area nearest to sail model, the change of wind speed in transverse distribution was not obvious, which also conforms to the characteristics in maritime natural wind field.

Tab. 3. Wind speed at different transverse positions

Distance to the centre line		0 cm	15 cm	30 cm	50 cm
Set Speed 15 m/s	Original	15.14	15.82	16.12	15.14
	Modified	14.79	15.57	15.14	14.79
Set Speed 20 m/s	Original	20.53	20.64	20.44	20.53
	Modified	20.26	19.84	20.54	20.26
Set Speed 25 m/s	Original	25.13	26.27	25.92	25.13
	Modified	25.55	25.13	24.74	25.55

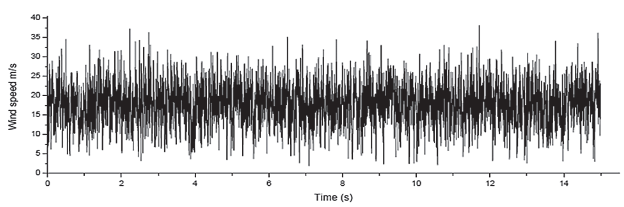

Fig. 6. Curve of the Wind Speed actually Measured in the Wind Tunnel

In order to understand the process of transient change of wind speed, the test adopted measurement of 1000 Hz sampling frequency, to record wind speed change at all points in the wind tunnel with hot wire anemoscope. The wind speed time-interval curve is as shown in Fig. 6. The measurement points were at the centre line of the test section of the wind tunnel, 40 cm away from the ground and 60 cm away from the test piece. The wind speed power spectrum analysis is shown in Fig. 7 and it indicated that measured wind speed power spectrum is similar with Davenport spectrum [19].

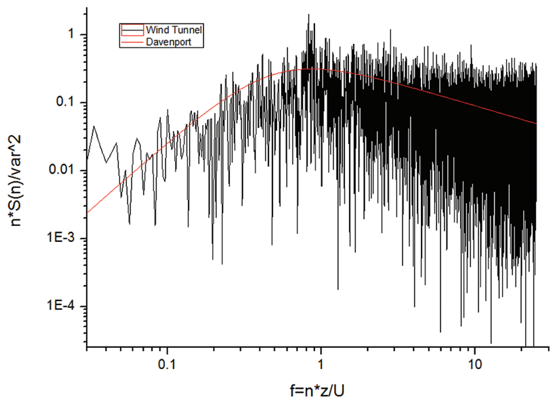

Fig. 7. Wind speed spectrum comparison

WIND TUNNEL TEST

In order to check influences of fluctuating wind field on sail's aerodynamic performance, this paper, on the basis of initial researches by the research group, carried out contrast test of aerodynamic performance in stable wind field and fluctuating wind field of elliptic arc Type D sail model [20]. The testing sail model's geometric size is as shown in Tab. 4. and the sail model is as shown in Fig. 8.

Tab. 4. Geometric Size of Sail Model

Type	Chord	Mast height	Sail height	Max. thickness	Max. camber
Ellipse Arc Wing Sail	36 cm	10 cm	52 cm	4.3 cm	7.2 cm

Fig. 8. Sail model in the wind tunnel

During the test, the wind speed is set at 20 m/s, and the aerodynamic load on the model consists of the forces and moment components decomposed from the wind axis coordinate system. Wind attacking angle α is the included angle between wind speed vector and sail plane direction as shown in Fig. 9.

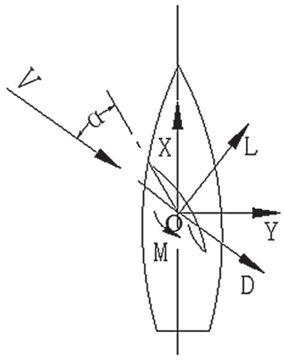

Fig. 9. Wind tunnel test stress coordinate system

Directions of the testing wind and the stress are as shown in Fig. 9, and the wind axis coordinate system is a right angle coordinate system O-LDZ, with the origin O at the center of the model baseboard and Axis Z upward vertically. According to the aerofoil theory, under action of the wind speed with the incoming flow attack angle of α, sail's aerodynamic force is disintegrated into Lifting Force Fl and Drag force Fd as two components, which are expressed as follows with Aerodynamic Coefficient C_L and C_D, respectively:

Lift coefficient

$$C_L = \frac{L}{\frac{1}{2}\rho S V^2} \tag{1}$$

Drag coefficient

$$C_D = \frac{D}{\frac{1}{2}\rho S V^2} \tag{2}$$

ρ — air density;
S — area of the sail;
V — wind speed.

Though testing, lift coefficient and drag coefficient of the same sail under stable wind field and fluctuating wind field conditions are as shown in Fig. 10. As the wind speed in fluctuating wind field had a high fluctuation, there was certain fluctuation in the lifting force and drag force through the testing. The Table shows the means on the basis of 5000-times automatically acquired data in 60 seconds. The wind speed used in formula 1 and 2 are measured at the height of 40 cm on the center line of the wind tunnel and in 60 cm plane before the model.

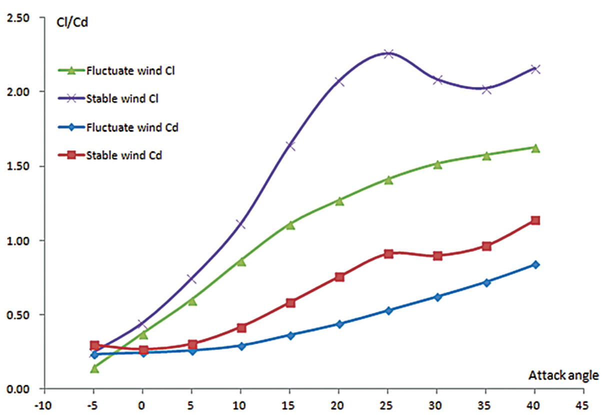

Fig. 10. Lift coefficient and the drag coefficient under stable and fluctuating wind field

As shown in Fig.10 and Tab. 5, there is 16–44% decrease of lift coefficient and 11–42% decrease of drag coefficient of the sail model measured in fluctuating wind field compared with that of stable wind field. The reasons for this phenomena may be of two aspects: on the one hand, with existence of wind profile, fluctuating wind field generally show a wind speed in vertical direction lower than that in stable wind field, so as to reduce sail stress. On the other hand, with existence of massive turbulence and vortex in fluctuating wind field, the distribution of randomly-distributed vortex in sail pressure field will cause loss of some energy and finally leading to decrease of sail stress.

Tab. 5. Comparison of Lift coefficient and the drag coefficient under stable and fluctuating wind field

Attack angle α	Stable wind		Fluctuating wind		Comparison	
	Cl	Cd	Cl	Cd	Cl	Cd
–5°	0.25	0.3	0.14	0.23	44%	23%
0°	0.45	0.27	0.38	0.24	16%	11%
5°	0.75	0.3	0.6	0.26	20%	13%
10°	1.11	0.42	0.87	0.29	22%	31%
15°	1.64	0.58	1.11	0.36	32%	38%
20°	2.07	0.76	1.27	0.44	39%	42%
25°	2.26	0.91	1.41	0.53	38%	42%
30°	2.09	0.9	1.52	0.62	27%	31%
35°	2.03	0.97	1.57	0.72	23%	26%
40°	2.16	1.14	1.63	0.84	25%	26%

CONCLUSIONS

Previous researches of sail's aerodynamic characteristics were carried out in stable wind field, while the real sail is working under natural wind field. By modification of the wind tunnel with stable wind field, this paper simulated the wind field in line with characteristics of natural wind on the sea, and carried out comparison test of sail model's aerodynamic characteristics in two conditions. The results show that in fluctuating wind field, both lift coefficient and drag coefficient of the sail model presented significant falling, which also indicates that to more accurately analyze ship sail's aerodynamic characteristics, natural wind speed fluctuation and wind profile in the atmospheric boundary layer cannot be neglected.

REFERENCES

1. Wang H M, Sun P T, Huang L Z, et al.: *The Analysis of Sail-assisted Ship Based on Aerofoil Theory*. Ship Engineering, Vol. 33(3), pp. 34–37, 2011.

2. Yi-Huai, H. U., Song-Yue, L. I., & Zeng, X. M.: *Study of airfoil sail's aerodynamic characteristics*. Ship Engineering, Vol. 33(4), pp. 20–24, 2011.

3. He, J., Hu, Y., Tang, J. J., & Xue, S.: *Research on sail aerodynamics performance and sail-assisted ship stability*. Journal of Wind Engineering & Industrial Aerodynamics, Vol. 146, pp. 81–89, 2015.

4. Fujiwara, T., Hearn, G. E., Kitamura, F., Ueno, M., & Minami, Y. *Steady sailing performance of a hybrid-sail assisted bulk carrier.* Journal of Marine Science & Technology, Vol. 10(3), pp. 131–146, 2005.

5. Yang, X., & Li, X. S.:*Analysis and design on course control for sail-assisted ship.* Advanced Materials Research, Vol. 1008–1009, pp. 556–561, 2014.

6. Liu, Y.-F & Huang, L.-Z & Li, Y.-K & Fu, C.: *Analysis on available wind power resources around typical routes of sail-assisted ship*. Journal of Dalian Maritime University Vol. 42. pp. 51–56, 2016.

7. M. Ueno et al.:*Fundamental research for development of an advanced sail-assisted ship.* OCEANS MTTS/IEEE TECHNO-OCEAN 04, Vol. 2, pp. 1102–1109, 2004.

8. Fujiwara T, Hirata K, Ueno M, et al.: *On Aerodynamic Characteristics of a Hybrid-Sail with Square Soft Sail.* Journal of Marine Science & Technology, 2003.

9. Burden A, Hearn G E, Lloyd T, et al.: *Concept design of a fast sail assisted feeder container ship*. Naval Architecture Shipbuilding, Marine Engineering, 2010.

10. Armand J L, Marol P.: *Aerodynamics of Sail-Assisted Propulsion of Commercial Ships: A Preliminary Study.* British Maritime Technology, 1982.

11. Ouchi K, Uzawa K, Kanai A.: *Huge hard wing sails for the propulsion of next generation sailing vessel*. Second International Symposium on Marine Propulsion. 2011.

12. Guerri O, Liberge E, Hamdouni A.: *Numerical Simulation of the Turbulent Flow around an Oval-Sail*. Journal of Applied Fluid Mechanics, Vol. 9(4), 2016.

13. Shui, L. M., Hua, W. W., & Xin, C.: *Boundary layer simulation in the first test section of 8m×6m wind tunnel.* Experiments & Measurements in Fluid Mechanics, Vol. 16(2), pp. 63–66, 2002.

14. Peng, H.: *Research of passive simulation method of atmospheric boundary layer in tj-2 wind tunnel*. Journal of Tongji University, Vol. 27, pp. 136–145, 1999.

15. Owen, P. R, & Zienkiewicz, H. K.: *The production of uniform shear flow in a wind tunnel*. Journal of Fluid Mechanics, Vol. 2(6), pp. 521–531, 1957.

16. Irwin H P A H.: *The design of spires for wind simulation*. Journal of Wind Engineering & Industrial Aerodynamics, Vol. 7(3), pp. 361–366, 1981.

17. Matsuda, Y., Nishi, A., Hirano, K., Ozono, S., Miyagi, H., & Cao, S., et al.: *Control of turbulence in a multiple-fan wind tunnel part5, reproduction of spatial strutures in an atmospheric boundary layer*. Journal of Wind Engineering. Vol. 83(2), pp. 189–196, 2000.

18. Mason, P.: *Atmospheric boundary layer flows: their structure and measurement*. Boundary-Layer Meteorology, Vol. 72 (1–2), pp. 213–214, 1995.

19. Davenport, A. G.: *The spectrum of horizontal gustiness near the ground in high winds*. Quarterly Journal of the Royal Meteorological Society, Vol. 87 (372), pp. 197–198, 1961.

20. Hu, Yihuai; Zeng, Xiangming; Li, Songyue.:*Research on the aerodynamic characteristics of ellipse wing sail.* Advanced Materials Research, Vol. 347–353, pp. 2249–2254, 2012.

CONTACT WITH THE AUTHOR

Zeng Xiangming
e-mail: xmzeng@shmtu.edu.cn
tel: 0086-21-38282979
Shanghai Maritime University
Shanghai 201306
China