Experimental research on wind flows severely interfered by sea waves

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Keywords: Sea wave; Aerodynamic interference; Wind tunnel test; Non-Gaussian performance.
Abstract. Rough waves may be incurred by strong wind over ocean, and the wind field behind the wave fluctuates violently, which can induce extraordinary impacts on bridges, offshore structures and vessels. The severely interfered performances of wind flows near sea surface by two patterns of rough waves are studied via wind tunnel tests. The research results indicate that the apparent influential region by wave ranges from the wave crest to 15 times of wave height downwind horizontally and 4 times of wave height upward vertically. For different waveform, the difference in the approaching region is more obvious, and it fades away slowly with farther distance. Behind the wave, the wind velocity and direction fluctuate violently and remarkable non-Gaussian property can be detected. The observations may present reference for wind-resistant design of bridges and offshore platforms.

Introduction

For bridges spanning across seas, long and even ultra-long span schemes may be adopted to satisfy the requirement of vessels navigation. In deep water area, the number of piers and pylons can be reduced to save engineering cost. Under this condition, large span bridge is preferred. In order to improve the structural seimic- and wind-resistance performance, the pylon and deck heights should be as low as possible. For some long-span bridges, the navigation requirements can be satisfied with the deck bottom above 15-20m over the sea surface. However, under extreme climatic conditions (e.g., 100-year recurrence), rough sea waves (wave peak may be higher than 8m) may be incurred by strong wind. Under the combined actions of wind, sea wave and flow, adverse influence may be imposed on bridges and offshore platforms. Under such extreme climatic conditions, the velocity of sea waves are usually lower than the wind velocity. The sea waves can then be regarded as obstacles which influence the characters of wind flows. The impacts of rough sea waves can be significant, remarkable changes regarding turbulence intensity and angle of attack may be brought on the wind flow field, which in turn bring extraordinary impacts on wind load on offshore structures[1-3]. Traditional method of wind resistance disign may lose its efficiecy under such conditions. Accurate prediction and assessment of wind field characteristics are needed to be conducted.

To evaluate the aerodynamic behavior of bridge in wind flows interfered by sea waves, 3-D large eddy simulations (LES) have been conducted by the authors[4]. The purpose of the present work is to investigate the characteristics of wind fields behind the sea waves via wind tunnel tests. As the velocity of sea waves are far lower than the wind velocity, the sea waves could be regarded as static.

Shapes of Sea Waves

Sea waves in real world have numerous kinds of forms, and they are difficult to be accurately quantified. Rough sea waves (eg. wave peak higher than 8m) are considered in the present work, which are usually regular in forms, and the distances between waves are wide (e.g., may be more than 500m). Hence, it is unnecessary to consider the condition of two or more waves coexist in wind flow, and only the condition of one single wave in wind flow is taken into account. Wind tunnel tests were performed on geometrical scale of 1:40 models of two sea wave forms. Profile curves of the two tested waves are reported in Fig. 1. Tests could be done on waves of more forms or wave groups in order to better understand the impacts of sea waves on wind flows.

Wave 1: Profile is got through translation and scale transformation from x=exp(0.25*z)，y=(normpdf(0,4,x)， plot(x,y)) ($3 \le x \le 9.9$):

$$y = \frac{689.6552}{(0.3255x+4)\sqrt{2p}} e^{\frac{-8}{(0.3255x+4)^2}} - 21.7241 \qquad (5.7849 \le x \le 24.2151) \tag{1}$$

Wave 2: Profile is got through translation and scale transformation from the probability density function of standardized normal distribution:

$$y = 50\frac{1}{\sqrt{2p}} e^{\frac{-x^2}{288}} \quad (-30 \le x \le 30) \tag{2}$$

The width and height are 60 cm and 20cm, respectively.

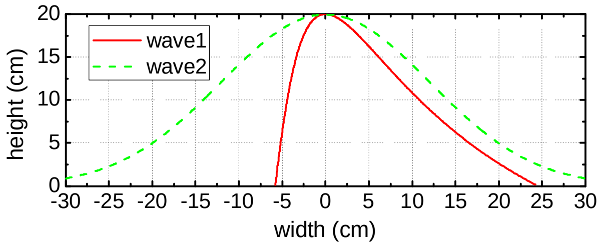


Fig.1 Wave shape graphs

Fig.2 Wave model in wind tunnel

Introduction of Wind Tunnel Test

Measurements of wind field characters can be arranged into two shemes. For Scheme 1, serval groups of measuring points are positioned behind the fixed model of wave, and the measuring points are meaured group by group. As comparisons, for Scheme 2, the model of wave is moving with measuring points fixed, and the measuring points are synchronously measured. The measured time-histories of Scheme 2 are non-stationary processes and are complicated in the process of data analysis. So the first scheme is taken in the present work. The model is 2.5m in length and the skins of waves are made of aluminum sheets and the ribs are made of balsa woods. The model of wave in wind tunnel is shown in Fig.2. The time-histories of wind speeds and static wind pressure are measured by using 3-dimentional fluctuating anemometer. The positions of measuring points are shown in Fig. 3. The heights of measuring points are 30, 40, 50, and 60cm, respectively. The horizontal distances to wave peak are distributed in (50, 150) cm, with a interval of 25cm, and (250, 1250)cm, with a interval of 100cm. The total number of measuring points is 17×4=68. The testing wind velocity 10m/s, and the sampling frequency and sampling length of time are 200 Hz and 41 s, respectively. The Reynolds number effect is tested to be insignificant and tend to be negligible.

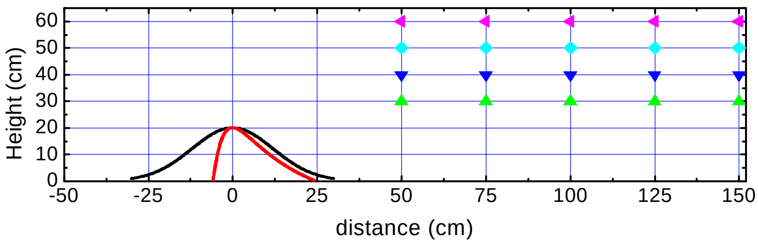


Fig.3 Measuring points arrangement

Experimental Results and Analyses

The First Four Order Statistical Parameters

The mean values and the variances (or standard deviations) can fully depict the probability density functions (PDF) of Gaussian signals, while the PDF of non-Gaussian signals can not be fully depicted by the first two order moments. Statistical moments of first four orders of wind speeds of the flow incoming direction and vertical dirction, angle of attack and static wind pressure are statistically analyzed. The mean values, standard deviation, skewness and kurtosis are the quantities to depict the likehood score, dispersion degree, asymmetry degree and tailedness of the probability distribution of a real-valued random variable, repectively. Skewness of a random variable reflects the degree of asymmetry of its probability distribution curve. The random variable is left-skewed (left-tailed) if its skewness is negative, and it is right-skewed (right-tailed) if its skewness is positive. Kurtosis of a random variable reflects the degree of evenness of its probability distribution curve. Distributions with kurtosis less than 3 are said to be platykurtic, which are relativly even in thier probability distribution curves; distributions with kurtosis greater than 3 are said to be leptokurtic, which are relativly uneven in thier probability distribution curves. The skewness and kurtosis of Gaussian distribution are 0 and 3, respectively. Therefore, skewness and kurtosis can depict the non-Gaussian characteristics of signals to some extent.

Experimental Results of Statistics

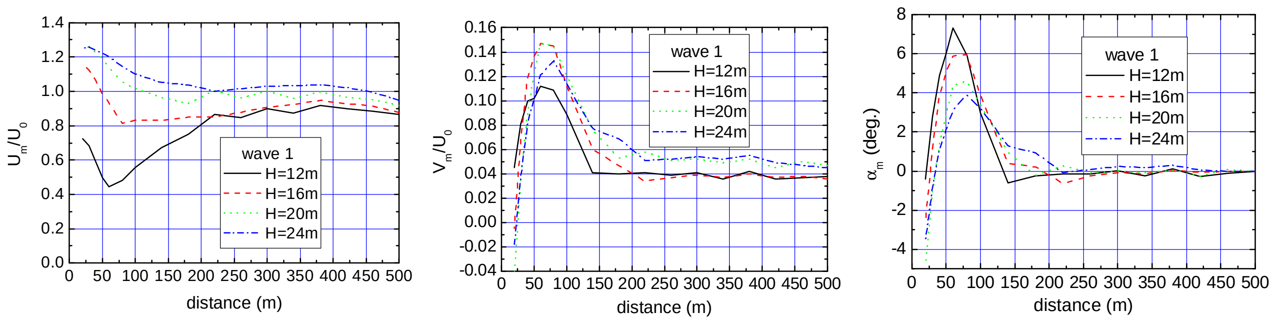
For the convinent and intuitive comparisons, the means and standard deviations of longitudinal and vertical components are divided by the uninterfered wind speed, i.e., 10 m/s. The means, standard deviation, skewness and kurtosis of measured parameters of measuring points are shown in Figs. 4-7, respectively. Distances on the horizontal ordinates are transformed into the practical conditions.

Characteristics of mean values

(1) The waves blocked the wind flow when $U_m/U_0<1$ and accelerated the wind flow when $U_m/U_0>1$. In the range of 16-24 m (2h-3h, h is the height of the wave) behind the wave, the acceleration effect is more obvious for aera higher above the sea surface. The range of 0-1.5h behind the wave is the range of blockage, in which the wind velocities are decelerated. The maximum blockage rate of wave 1 and wave 2 are 50% and 30%, respectively. For areas beyond the range of 3h, the area closer to the wave (e.g. 50 m) is range of acceleration, the maximum acceleration coefficient is around 1.2. Wind velocity of different height gradually approaching together as the measuring points move further from the waves, and a blockage effect is preformed in this range. In the range of 200 m behind the waves, characteristics of wind field are significantly influenced by the waves and vary dramatically, which may bring adverse effects to the wind loads of bridges. Impacts of waves on characteristics of wind field beyond the range of 200 m behind the waves are relatively lower and are negligible in view of engineering. Characteristics of wind field behind the tested two wave forms are similar in trend, while distinct significantly in some local aeras.

(2) For aeras close to the waves, mean values of vertical wind velocities can not be neglected. Mean values of angle of attack for aeras close to the waves can be 5°or even larger. Instantaneous angle of attack can be extremly large, which has significant impact on wind loads of bridge. Attention should be paid to the abovementioned phenomenon.

In general, wind fields that closely behind waves are extremely complex, mean values of vertical wind velocities are nonnegligible and the instantaneous angle of attack can be large. Wind flows are severely interfered by sea waves even beyond 3h behind the waves. Impacts of waves on wind field beyond the range of 200 behind the waves are relatively lower. The residuals of vertical wind velocities and changes in angle of attack may be ascribed to measurement error.



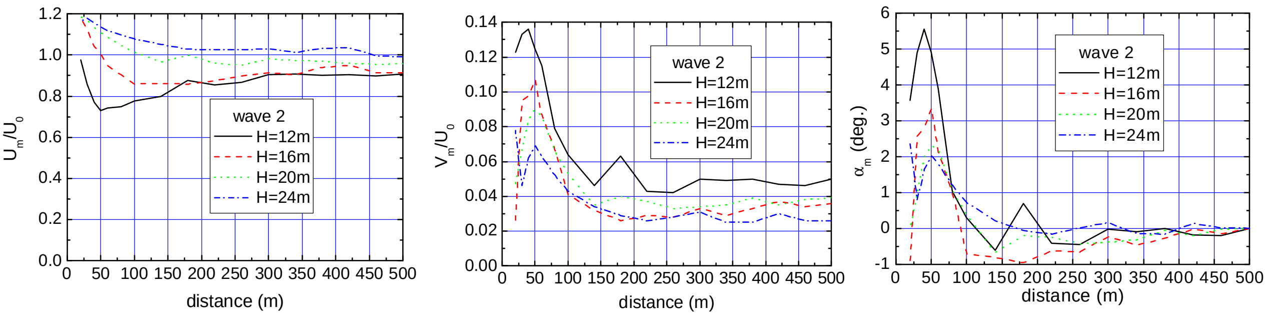


Fig.4 Means of each parameter

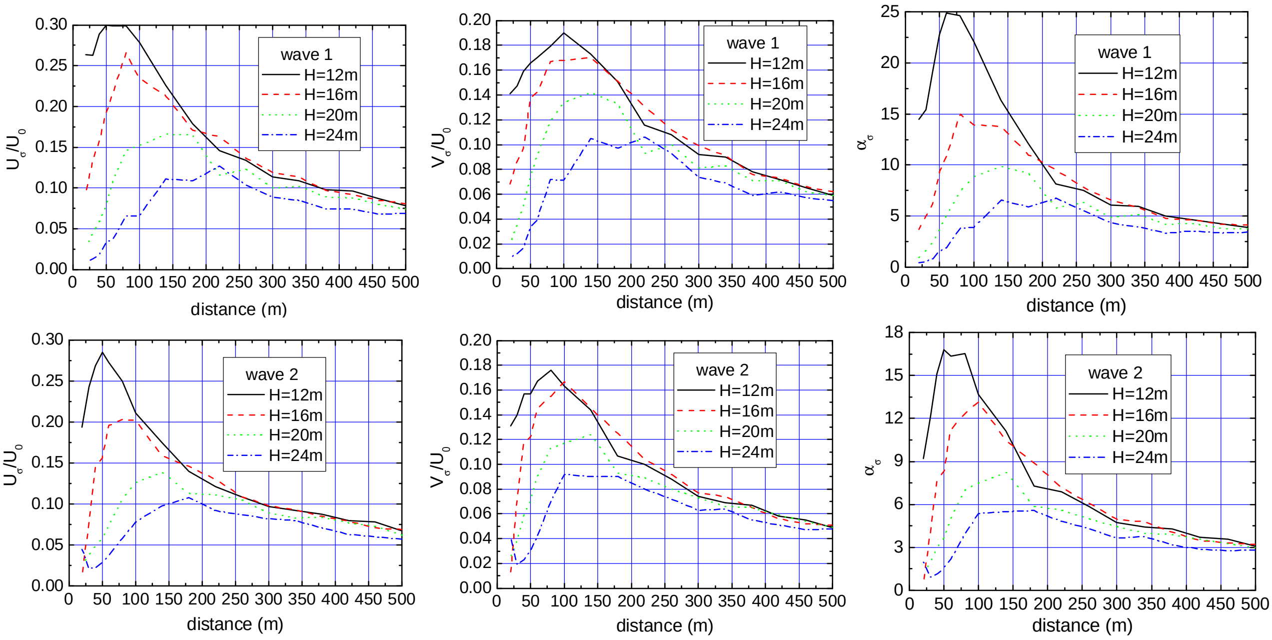


Fig.5 Standard deviation of each parameter

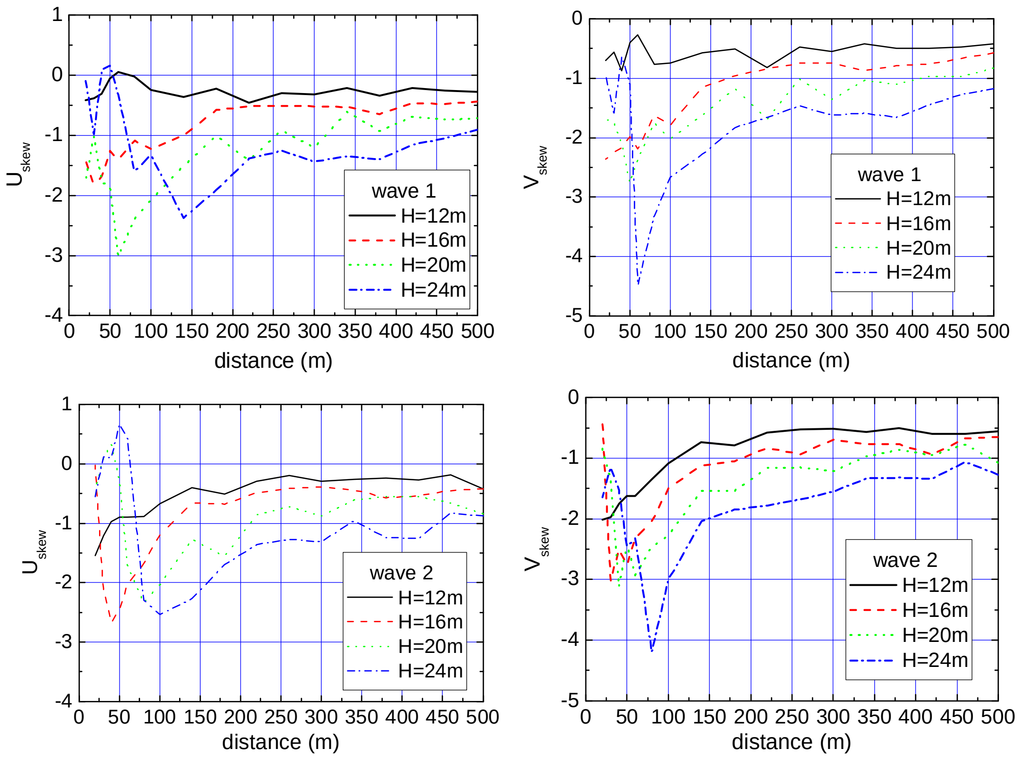


Fig.6 Skewness of each parameter

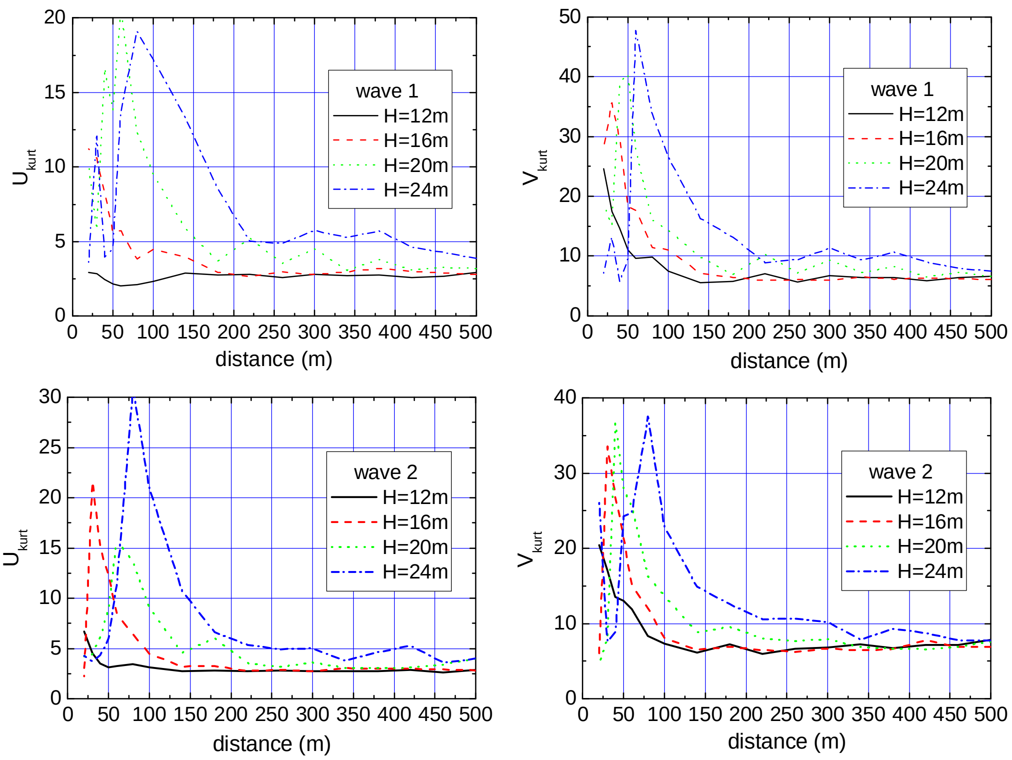


Fig.7 Kurtosis of each parameter

Characteristics of standard deviations

(1) The maximum value of horizontal turbulence intensity of coming flow is about 30% and the turbulence intensity increases downwards to the sea surface. Turbulence intensity firstly increases and then decreases behind the waves. Turbulence intensity of different waves at different height reach their maxima at different distances from the waves.

(2) The maximum value of vertical turbulence intensity of coming flow is around 20% and the turbulence intensity increases downwards similar to the horizontal turbulence intensity. Turbulence intensity first increases and then decreases behind the waves. Turbulence intensity of different waves at different height reach their maxima at different distances from the waves.

(3) The maximum value of standard deviation of angle of attack is around 25°and it is more unstable for lower aeras above the sea surface. Angle of attack of different waves at different height reach the maxima at different distances from the waves.

Parameters vary in a similar trend with respect to the distances between measuring points and waves. The impacts on parameters of Wave 1 are more obvious than that of wave 2, which may be caused by the deeper flow seperation due to the shaper wave form of Wave 1.

Characteristics of skewness: Wind fields of aeras closely behind waves are complex, distributions of wind velocity and direction are different from Gaussian distribution, and are mostly left-skewed. Distributions of wind velocity and direction are closer to Gaussian distribution in the range beyond 200 m behind the waves. Moreover, it is interesting to note that distributions are closer to Gaussian distribution at points closer to the sea surface.

Characteristics of kurtosis: Wind fields that closely behind waves are complex. Distributions of wind velocity and direction are closer to Gaussian in the range beyond 200 m behind the waves. Moreover, the distributions are closer to Gaussian distribution at points closer to the sea surface.

The tested two wave forms have similar impacts (both in trent and proportion) on the wind fields of different height. The impacts on wind fields of Wave 1 are more obvious than that of wave 2. The aera most sensative to impacts of waves is within the range of 150 m behind the waves. Extremely adverse effect on bridge structures may be caused by voilent acceleration or fluctuation and huge vortex. Wind flows are severely interfered by sea waves even in the range of 3h behind the waves. Ranges obviously impacted by waves may reach 4h or even 5h behind waves.

It should be stated that there is unavoidable error for calculation of statistical quantities due to various error factors (instrument error, measurement error, ambient noise, etc). The higher-order statistics, and the higher relative error.

Concluding Remarks

The aerodynamic interfered performances of wind flows near sea surface by two patterns of rough waves are studied via wind tunnel tests. The research results indicate that the apparent influential region by wave ranges from the wave crest to 15 times of wave height downwind horizontally and 4 times of wave height upward vertically. Behind the wave, remarkable non-Gaussian property can be discovered for the distribution of wind velocity and direction. The calculation error of mean values and standard deviations of horizontal wind velocity, vertical wind velocity and angle of attack are lower, while error of skewness and kurtosis are relatively higher. The observations may present reference for wind-resistant design of bridges and offshore platforms.

Acknowledgements

This work was financially supported by the Fundamental Research Funds for the Central Universities (DUT14LK29), and the National Program on Key Basic Research Project (973 Program, 2015CB-7705).

References

[1] Bisht, R. S.， Jain, A. K. Wind and wave induced behavior of offshore guyed tower platforms. Ocean Engineering , Vol.25 (1998), p.119.

[2] Li, Xia，Sun Luzhong,, et al. Displacement response of flexible overhead trestle bridge subjected to coupling of wind and wave[J]. Journal of Vibration & Shock, Vol. 30 (2011), p.117.

[3] Li Guoliang, Liu Zhao, Li, Xuemin, et al. Determination of design loads of wind, wave and flow for the construction trestle of Hangzhou Bay Bridge. Journal of Highway and Transportation Research and Development, Vol. 24 (2007), p. 100.

[4] Xu, Fuyou, Ying, Xuyong, Zhang Zhe, et al. 3-D LES numerical simulation researches on wind flows Interfered by rough waves. Seventh International Colloquium on Bluff Body Aerodynamics & Applications, Shanghai,2012.9.