P65

ON THE ROLE OF AIR FLOW SEPARATION FOR MOMENTUM FLUX TRANSFER AT WATER SURFACE

Natsuki Mizutani[1], Masahiro Kaji[2], Masahiro Miyajima[3]
1, 3, Osaka Sangyo University, Osaka, Japan
2, Graduate School of Osaka Sangyo University, Osaka, Japan

1. INTRODUCTION

Since the report of Powell *et al.*(2004), it has been considered that a drag coefficient C_D is reduced under high wind speed conditions, which is over 30m/s, like in a hurricane. However, the mechanism that a drag coefficient is reduced is still not clear.

One of the concepts is that sea spray due to wave breaking affects air flow turbulence near water surface. However, it was still unknown how droplets of sea spray reduce a drag coefficient.

Donelan *et al.*(2004) indicated the reappearance that a drag coefficient was reduced under high wind speed conditions in the laboratory tank. They also mentioned that the mechanism of the reduction of the drag coefficient might be due to air flow separations. Letchford and Zachry(2009) also proposed the classification of air flow regimes divided by wave geometries and air flow patterns.

We also have focused attention on air flow separations over wind waves, but it is very difficult to measure air flow over wind waves under high wind speed conditions in a laboratory tank. On the other hand, air flow separations occur even under low wind speed conditions and at short fetch like in a laboratory tank (see Fig-1). There is a constant value region of a drag coefficient under low wind speed conditions as shown in many previous studies. We are considering that the reduction mechanism of a drag coefficient is same under low as well as high wind speed conditions.

The purpose of this study is to investigate an occurrence frequency of air flow separations over short wind waves, and relationships between the occurrence frequency of air flow separations and various parameters of wind waves.

1 *Corresponding author address:* Natsuki Mizutani, Osaka Sangyo Univ., Department of Civil Engineering, 3-1-1 Nakagaito, Daito, Osaka, 574-8530 Japan;
email: mizutani@ce.osaka-sandai.ac.jp.

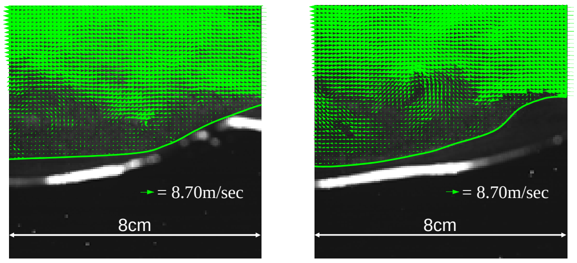

Fig-1 Sample of air flow separations

2. EXPERIMENTAL PROCEDURE

2.1 Experimental setup and conditions

The PIV measurements were conducted to acquire video images of air flow patterns including water vapor as tracer particles. The laboratory wind wave tank used has 8.0m long, 0.2m width and 0.7m height as shown Fig-2. The water depth was set at 0.45m during all the measurements. Therefore, the height of the air flow section was 0.25m.

The time series of water surface elevation were measured by using a capacitance type wave gauge at the measurement points from P01 to P07 with sampling frequency of 200Hz. In order to make a vertical profile of mean wind speed, the instantaneous wind speed also was measured at the same points by a heat type anemometer with sampling frequency of 10Hz for 120 seconds. The video images to compute air flow vector maps were acquired at the measurement from P02 to P06.

A pair of video image which has monochrome 8bit gradation and the resolution of 1M pixel were acquired with sampling frequency of 12Hz. 713 vector maps were computed from the series of the video images for one case.

2.2 How to count air flow separations

A main purpose of this study is to count the number of air flow separations on the air flow vector maps to investigate an occurrence frequency of air flow separations.

Because a separation bubble in air flow is

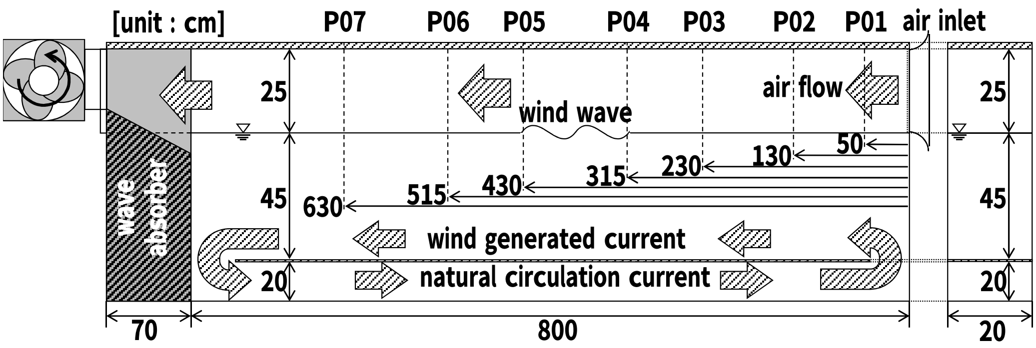

Fig-2 Schematic of the wind wave tank

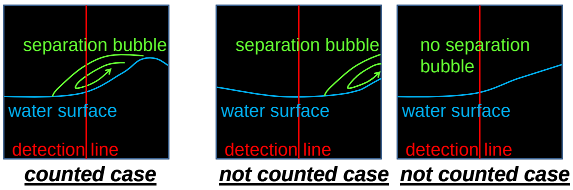

Fig-3 How to count separation bubbles

generated at leeward of a wave crest, the bubbles were counted on the vector map by the visual observation. As shown Fig-3, a vertical detection line was placed at a center of vector map. If a separation bubble overlaps with the vertical detection line, the case is counted as a separated case. Even if a separation bubble appears on a vector map, the case that the bubble does not overlap with the detection line is not counted as a separated case.

3. RESULTS AND DISCUSSION

3.1 Wind speed and wind waves

Wind speed in the laboratory wind wave tank was changed to four conditions. The maximum wind speed of each case at all the measurement points is shown in Table-1. Fig-4 shows the distribution of the friction velocity calculated from the vertical mean wind profile by fitting a log-law profile. The distributions of the significant wave height and the significant wave period are shown in Fig-5 and Fig-6 respectively.

Table-1 Maximum wind speed of each case

Case	U_{max} [m/s]
01	5.13 - 5.48
02	6.67 - 7.33
03	8.40 - 8.95
04	10.14 - 11.04

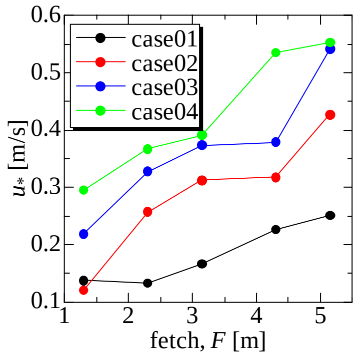

Fig-4 Distribution of the friction velocity

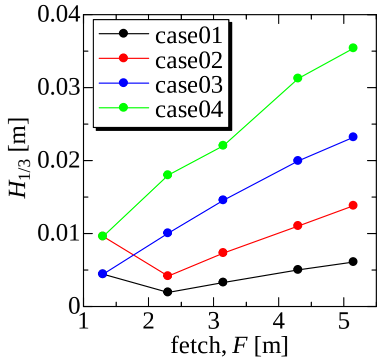

Fig-5 Distribution of the significant wave height

To check whether the generated waves in the small scale laboratory tank have characteristics of wind waves, the relationship between the non-dimensional wave height and the non-dimensional wave period was checked as shown in Fig-7. Some of Case01 and Case02 with the short fetch depart from the regression curve called 3/2 power law defined by Toba(1972).

3.2 Occurrence frequency of air flow separations

Fig-8 shows the distributions of the occurrence

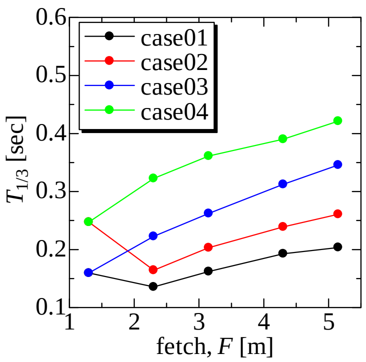

Fig-6 Distribution of the significant wave period

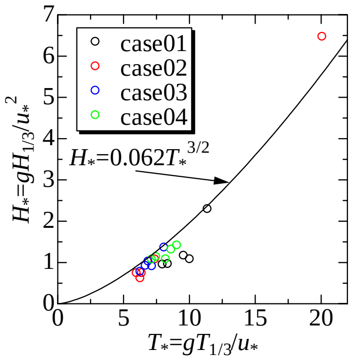

Fig-7 Relationship between the non-dimensional wave height and the non-dimensional wave period

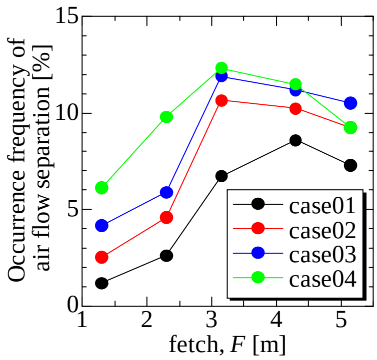

Fig-8 Distribution of the occurrence frequency of air flow separations

frequency of air flow separations. The occurrence frequency of air flow separations has a peak value at the fetch of around 3-4m. The friction velocity (Fig-4) also has distinctive change there, but the significant wave height (Fig-5) and the significant wave period (Fig-6) show nothing there.

Fig-9 shows the relationship between the drag coefficient and the occurrence frequency of air flow

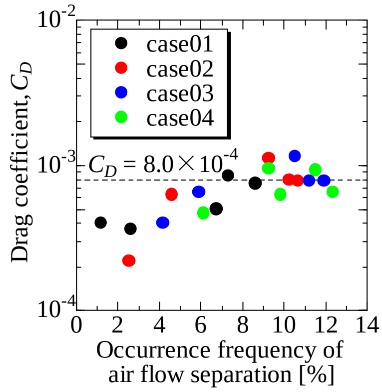

Fig-9 Relationship between the drag coefficient and the occurrence frequency of air flow separation

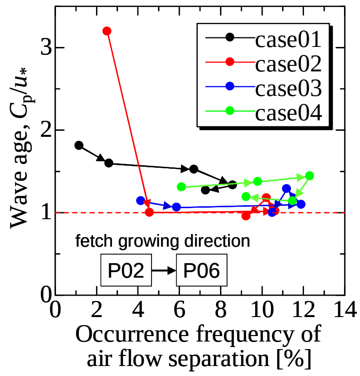

Fig-10 Relationship between the wave age and the occurrence frequency of air flow separation

separation. The drag coefficient leads to a constant value when the occurrence frequency of air flow separations is greater than 8%. This result supports our concept that the air flow separations might make the drag coefficient be a constant value even under law wind conditions.

Fig-10 shows the relationship between the wave age and the occurrence frequency of air flow separations. The wave age has a lower limit value of a unity and also fluctuates between 1.0 and 1.5. In fact, the value of the wave age comes close to a unity first, and then it gets back to a little bit large value. After that it comes close to a unity again. This suggests that wind can not input momentum to water side in excess of the wave speed in this stage. Air flow might control the momentum transfer using air flow separations at air side.

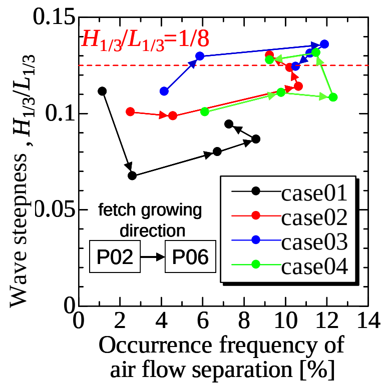

Fig-11 Relationship between the wave steepness and the occurrence frequency of air flow separation

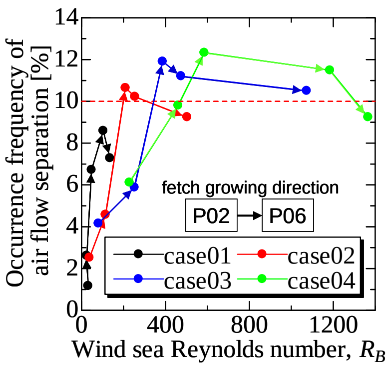

Fig-12 Relationship between the occurrence frequency of air flow separations and the wind sea Reynolds number

For the wave steepness, the measured value moves as same as the change of the wave age. Fig-11 shows the relationship between the wave steepness and the occurrence frequency of air flow separation. The wave steepness also gathers around a constant value of 1/8 as growing of the fetch. The wave steepness of 1/8 might make the occurrence frequency of air flow separations be a constant value of 10%.

Fig-12 shows the relationship between the occurrence frequency of air flow separations and the wind sea Reynolds number, defined by Koga and Toba(1986). The occurrence frequency of air flow separations leads to a constant value of about 10% when the wind sea Reynolds number is higher than 200. Toba *et al.*(2006) shows that air flow separation occurs frequently over R_B=200.

3.3 Wind wave development process in a laboratory tank

From all the results, our concept of wind wave development process in a laboratory tank is indicated as follows.

(1) In a laboratory tank, at the initial stage of wind wave growing process, waves are very small. Wave steepness is less than 1/8. Air flow separations do not occurs frequently. As the result, a drag coefficient will be large value and the wave steepness will come to 1/8 as growing of wind speed or fetch.

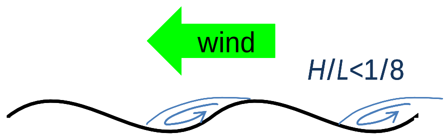

Fig-13(1) Wind wave development process in stage 1

(2) The wave steepness will be nearly 1/8. The occurrence frequency of air flow separations becomes a constant value. The drag coefficient also leads to a constant value.

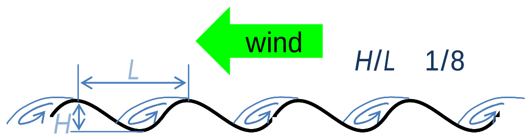

Fig-13(2) Wind wave development process in stage 2

(3) The wave steepness is over 1/8. The air flow travels from a crest to next crest of the each wave. There is no separation bubble between the crest and the trough of the waves. The drag coefficient becomes small value like it on a smooth wall.

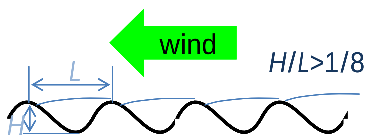

Fig-13(3) Wind wave development process in stage 3

(4) The wave steepness will be back to nearly 1/8 again. The wave steepness adjusts the momentum transfer using the air flow separations.

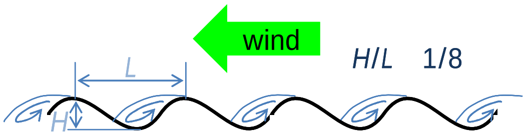

Fig-13(4) Wind wave development process in stage 4

4. CONCLUSIONS

The occurrence frequency of air flow separations has been investigated.

The process of momentum transfer under low wind speed conditions was indicated. Wind speed in a laboratory tank and that under a hurricane is much different, but hurricane wind must develop wind waves in the same process. However, wave steepness under hurricane condition is less than about 1/20. There is a case that the wave steepness of a freak wave is nearly 1/8, but a freak wave doesn't have successive high wave crests.

We do not have a reasonable explanation for hurricane condition. Further studies are needed.

REFERENCES

Donelan, M. A., B. K. Haus, N. Reul, W. J. Plant, M. Stiassnie, H. C. Graber, O.B . Brown and E. S. Saltzman, 2004: On the limiting aerodynamic roughness of the ocean in very strong winds, *Geophys. Res. Lett.*, 31, L18306, doi:10.1029/2004GL019460.

Letchford, C.W. and B.C. Zachry, 2009: On wind, waves, and surface drag, Proceedings of 5th European – African Conference on Wind Engineering, www.lawe.org.

Powell, M. D., P. J. Vickery and T. A. Reinhold, 2003: Reduced drag coefficient for high wind speeds in tropical cyclones, *Nature*, 422, 279-283.

Toba, Y., 1972: Local balance in the air-sea boundary processes I. On the growth process of wind waves, J. Oceanography Soc. Japan, 29, 209-220.

Toba, Y. & M. Koga, 1986: A parameter describing overall conditions of wave breaking, whitecapping, sea-spray production and wind stress, *Oceanic Whitecaps*, D. Reidel, 37-47.

Toba, Y., S. Komori, Y. Suzuki & D. Zhao, 2006: Similarity and dissimilarity in air-sea momentum and CO2 transfers: the nondimensional transfer coefficients in light of the windsea Reynolds number, *Ocean-Atmosphere Interactions*, WIT Press, vol. 2, 53-82.