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RELATION BETWEEN THE TURBULENT INTENSITY ON THE CREST OF A RIDGE AND WIND DIRECTION RELATIVE TO THE RIDGE LINE - PART 1: FIELD EXPERIMENTS

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1. Introduction

Turbulence affects the efficiency of power generation and the life time of wind turbines. Many wind turbines have been constructed on the crest of ridges or hills. Therefore, predicting turbulence as well as average wind speed is one of the subjects for the wind power generation. Many studies have focused attention on the airflow and turbulence for a 2-D ridge or a circular hill. These include theoretical works of Jackson and Hunt (1975), Hunt et al.(1988a, 1988b), Lemelin et al.(1988), Finnigan (1988); and field experiments of Bradley(1980), Mason and King (1985), Mason (1986), Taylor and Teunissen (1987) and Salmon et al.(1988). A review on boundary-layer flow over hills was written by Taylor et al. (1987). On the crest of a 2-D ridge, the wind speed is larger than upstream at the same height above the ground as a result of the stream convergence occurring when wind blows perpendicular to the ridge line. Therefore, on the crest of a ridge, wind speed is larger when the prevailing wind blows perpendicular to the ridge line as compared to that blowing parallel to it (Wegley et al. 1982). However, the relation between the turbulence intensity on the crest and the prevailing wind direction to the ridge line has not been studied.

Therefore we studied this subject because it is important for siting wind energy conversion systems. The average wind speed and turbulence data obtained from field experiments were used for the analysis. The measurements were performed for a year. Because the measurements were performed by using 3-cup anemometers, we have to study whether these 3-cup anemometers could observe the turbulence generated by the topography and surface obstacles. Therefore the response of a 3-cup anemometer to wind speed fluctuations was investigated by comparing it with sonic data.

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2. Response of 3-cup anemometer

2.1 Instrument

The 3-cup anemometer has inertia. It responds more quickly to an increase in wind speed than to a decrease of the same magnitude (Bush and Kristensen, 1976). The response time to fluctuating wind speed depends on the type of cup anemometers. We investigated the response time of the 3-cup anemometer NRG #40, which was used in the field measurement at Mt. Hyonosen. According to the specifications of NRG #40 (NRG Systems, 2006), the measure of response time is a distance constant (=d, 63% recovery) and the value d is 3.0 m. The distance constant is a measure how much air mass pass the sensor in order for the response to reach 63% of the step increase. Therefore, when the change of wind speed Δv is 1 ms^{-1}, the response time $\tau = d/\Delta v = 3$ s. For comparison, the sonic anemometer SAT-550 (KAIJO) was also used.

2.2 Field experiment of response

Wind speed was measured simultaneously with a 3-cup anemometer NRG #40 and a sonic anemometer SAT-550 (KAIJO). The sampling interval of the sonic anemometer data was 0.02 s (frequency = 50 Hz). The sampling interval of the 3-cup anemometer data depended on the wind speed U; the sampling intervals were 0.4～0.08 s (frequency = 2.5～12.5 Hz) for 1 < U < 10 m s^{-1} and 1.8 s (frequency = 0.56 Hz) for U = 0.5 m s^{-1}. Two sets of experiments were carried out for measuring U. (a) One set of experiment was carried out by mounting sensors on a microwave tower located in Himeji city (Fig. 1). The tower was 73 m high, and the sensors were mounted at a height of 53 m from the ground at the southern side of the tower. For 3 days, U was recorded. Moderate to strong winds were observed during the observation period. Three windy runs in south wind were selected from the experiment. The average values of U were 2.9, 5.5, and 7.1 m s^{-1} for an interval of 10 minutes. (b) The other set of experiment was carried out in a playing field of area 100 m × 100 m in the campus of University of Hyogo (Fig. 2). The sensors were mounted on poles at a height of 2.5 m from the ground, and U was recorded for 6 h. Weak winds were observed during the period. Winds with U equal to 0.5 and 0.7 m s^{-1} and blowing from the north to the east were observed in experiment (b). There were no tall buildings along the north and the east. Two-storey houses were located outside the campus. The distances between the measurement site and the nearest house were 50 m (north) and 100 m (east).

Fig. 1. The microwave tower in Himeji city on which sensors are mounted for the response experiment carried out using a 3-cup anemometer and a sonic anemometer under windy conditions.

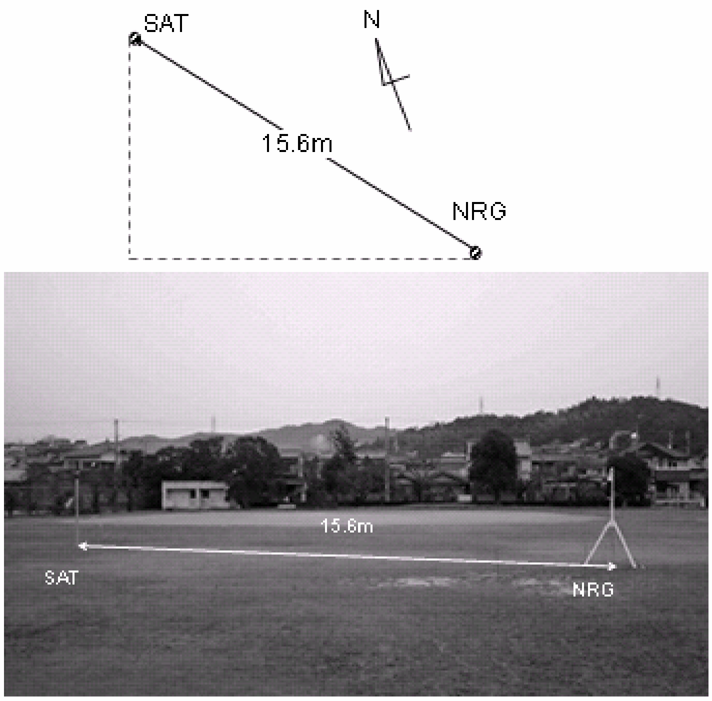

Fig. 2. Site for response experiment carried out using a 3-cup anemometer and a sonic anemometer under calm wind conditions: Playing field in University of Hyogo campus.

2.3 Results and discussion

The results of the three runs under windy conditions are presented in Table 1 and Figure 3. The sampling period is 10 min in Table 1 and 2 min (120 s) at the beginning, as shown in Figure 1. The σ_h values measured by using the 3-cup anemometer NRG #40 are 86% to 93% of those measured by using the sonic anemometer, where σ_h is the standard deviation of the fluctuations in U in the horizontal direction. The sonic anemometer data includes the fluctuations of higher frequency as compared with the 3-cup anemometer. The running averages of the sonic anemometer are shown in Figure 3. Comparing the 3-s and 5-s running averages with the 3-cup anemometer, for $U > 5$ m s^{-1}, the 3-cup anemometer measures the fluctuations of frequencies lower than 0.3 Hz (3-s running average). However, it dose not respond to a rapid decrease in the wind speed for frequencies higher than 0.3 Hz. This was discussed by Bush and Kristensen (1976) for a different type cup anemometer. For $U < 2$ m s^{-1}, the difference between the 3-cup anemometer and the sonic anemometer increases and the 3-cup anemometer cannot respond to the fluctuations above 0.2 Hz (5-s running average). Comparing the results with NRG #40 specification of the response time $\tau = d/\Delta v = 3$ s, present results approximately agreed with the specification. The ratio of σ_h of NRG #40 to σ_u of the sonic anemometer is 72 to 97% in Table 1 for wind speed ranging from 2.9–7.1 m s^{-1}.

The results under calm wind ($U < 1$ m s^{-1}) were shown in Figure 4. Because the threshold of NRG #40 is 0.8 m s^{-1} (NRG Systems, 2006), the instrument repeatedly stopped and rotated with the fluctuations in the wind speeds for $U < 1$ m s^{-1}. When wind speed becomes less than 1m s^{-1}, NRG #40 showed lower values than the sonic anemometer. This was discussed by Mitsuta (1970) with regard to other types of cup anemometers. As a result, apparent turbulent intensity in the longitudinal direction (σ_h /U) increases under U < 1 m s^{-1}.

Table 1. Comparison between the 3-cup anemometer and the sonic anemometer. (m s^{-1})

run		NRG		SONIC	NRG/SONIC
run 1–10	U	2.85	U	2.90	1.02
	σ_h	0.63	σ_u	0.58	0.93
	σ_h/U	0.22	σ_u/U	0.20	0.91
run 2–10	U	6.4	U	5.5	1.15
	σ_h	1.54	σ_u	1.79	0.86
	σ_h/U	0.24	σ_u/U	0.32	0.75
run 3–10	U	6.3	U	7.1	1.12
	σ_h	1.80	σ_u	1.59	0.88
	σ_h/U	0.28	σ_u/U	0.22	0.79

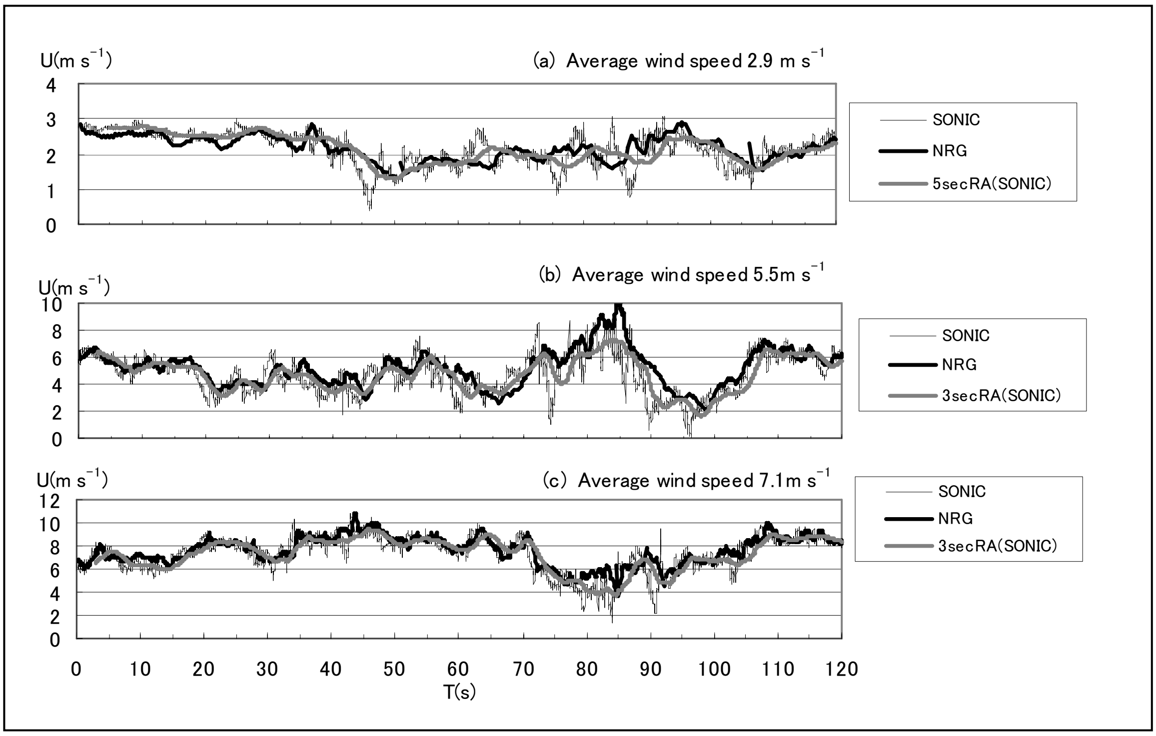

Fig. 3 Wind speed measured with the 3-cup anemometer and the sonic anemometer. (a) Average wind speed of 2.9 m s^{-1}. (b) 5.5 m s^{-1}. (c) 7.1 m s^{-1}. Running averages of the sonic anemometer are also shown.

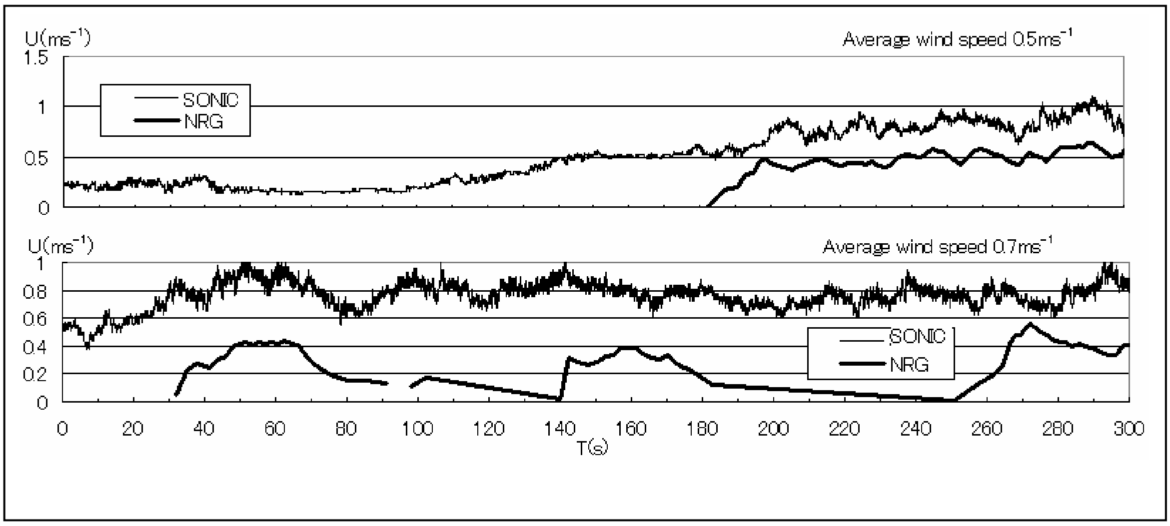

Fig.4. Wind speeds measured with the 3-cup anemometer and the sonic anemometer under calm wind speeds less than 1 m s^{-1}.

2.4. Discussion on eddy size and response time of a 3-cup anemometer

The 3-cup anemometer responds to wind speed fluctuations with frequencies lower than 0.3 Hz for U > 5 m s^{-1}. Using the frozen wave hypothesis of Taylor (1938), the 0.3-Hz fluctuations for U > 5 m s^{-1} corresponds to eddy sizes in the longitudinal direction of λ_x > 7 m. It is known from the spectrum analysis of turbulence observed on a flat terrain under neutral atmospheric condition that the eddy size in the vertical direction which has the maximum kinetic energy λ_{zm}, is approximately z, where λ_z = U/2f, f is the cycle frequency of the wind speed in the vertical direction and z is the height above the ground. (Kaimal and Finnigan, 1994) The eddy size in the longitudinal direction λ_{xm} is larger than that in the vertical direction λ_{zm}. As the heights of wind measurements were 20 m and 30 m above the ground, the eddy sizes which had the maximum kinetic energy were 20m and 30m. The size of eddies induced by topography are expected to be larger than λ_{zm}. Therefore, NRG #40 measures most of the eddies generated by roughness elements on the ground surface and topography.

3. Analysis of turbulence on field measurement

We analyzed the average wind speed and turbulence which were measured at two sites. One of the sites was at Mt. Hyonosen and the measurements were carried out in cooperation with NEDO, Sekinomiya-town and Meidensha (2003); the other site was at Mt. Taiko and the measurements were carried out in cooperation with NEDO and Kyoto Prefectural Government (1999).

3.1. Field measurement sites

The field measurement sites are located on the eastern ridge of Mt. Hyonosen in Hyogo Prefecture and the northern ridge of Mt. Taiko in Kyoto Prefecture, Japan. They are shown in Figure 5. The crest of the eastern ridge of Mt. Hyonosen are shown in Figure 6. The trees were cut down within a radius of 40 m from the mast. The trees in the picture are 10 to 12 m high. The crest site for the wind measurement at Mt. Taiko is shown in Figure 7.

3.2. Instrumentation, data processing and observation period

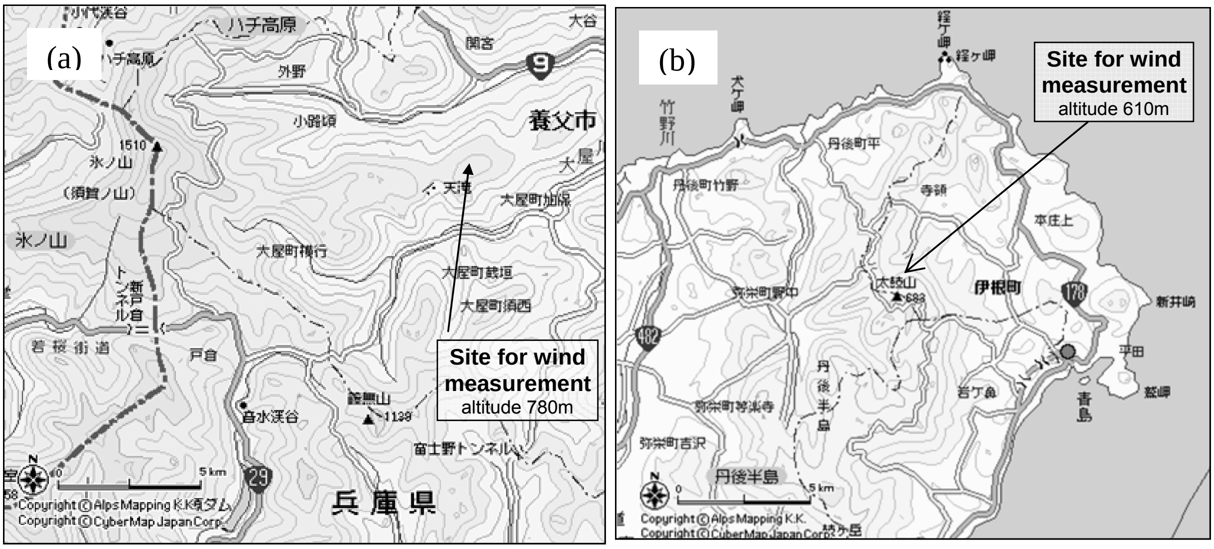

Fig. 5. The sites for wind measurement and the surrounding terrain. (a) The eastern ridge of Mt. Hyonosen. (b) The northern ridge of Mt. Taiko.

Fig. 6. Views at the crest of the eastern ridge of Mt. Hyonosen. (a) A northward view. (b) An eastward view. (c) A westward view. (d) A southward view.

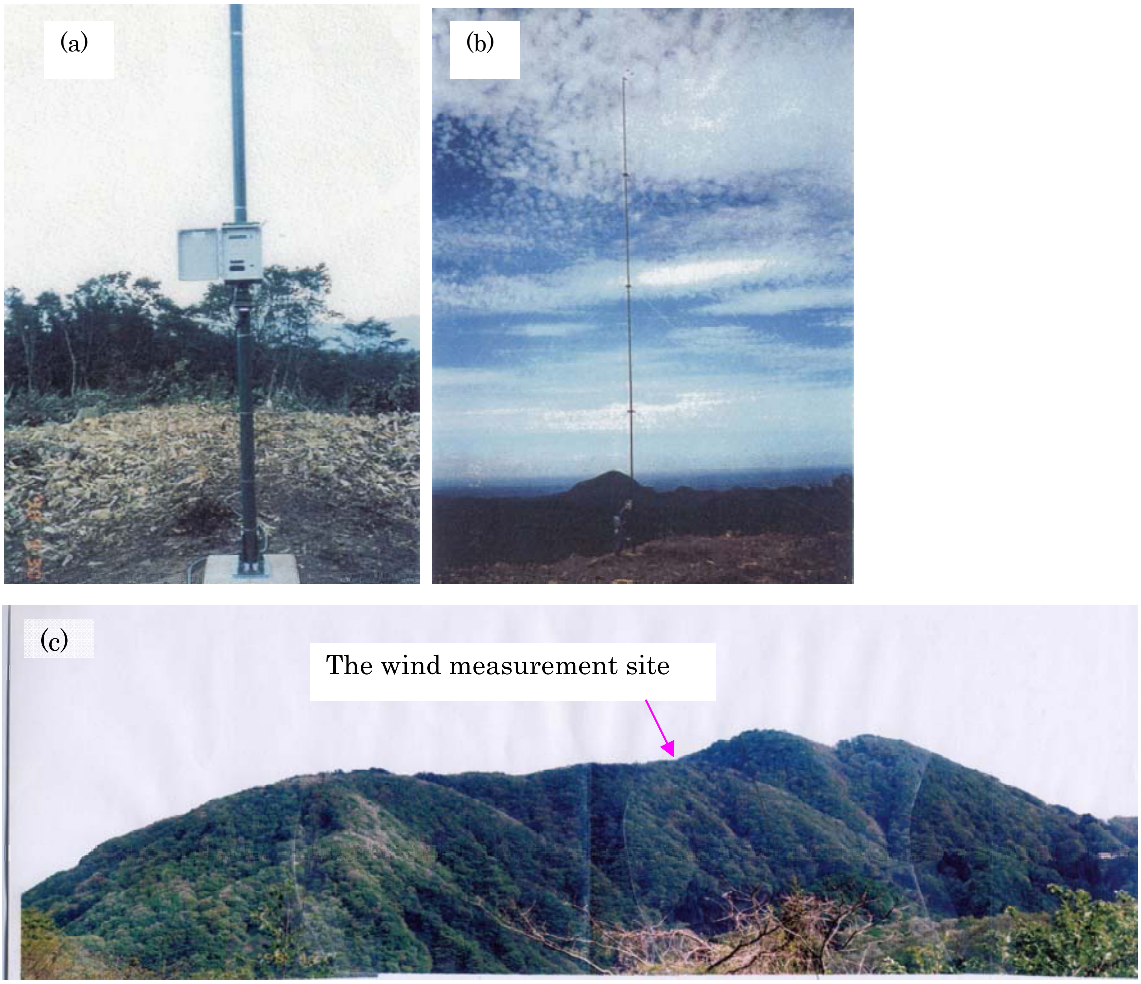

Fig. 7. The crest of the north ridge of Mt. Taiko. (a) The mast at the crest looking northwest. (b) The mast and view looking north-northwest. (c) View from the west looking the north ridge of Mt. Taiko.

3.2.1. Mt. Hyonosen

The wind speed was measured continuously on a mast at 20 m and 30 m high above the ground (Fig. 4). The 3-cup anemometers NRG #40 and the wind direction vane NRG #200P were used for these measurements. The sampling interval of 3-cup anemometer was 1- 3 s, which varied with wind speed. The ten-minute average and standard deviation of wind speed, and the ten-minute average of wind direction were recorded. The measurement was carried out for one year (11/1/ 2002 –10/31/ 2003).

3.2.2. Mt. Taiko

The wind speed was measured continuously on a mast at a height of 20 m from the ground (Fig.7). Three-cup anemometer NRG #40(S) and wind direction vane NRG 200PG were used for these measurements. The sampling interval of the 3-cup anemometer was several seconds, which varied with wind speed. The recording and processing of data were performed in a manner similar to that at Mt. Hyonosen. The measurements were carried out for one year (10/1/1998 - 9/30/1999).

3.3. Results and discussion

Figure 8 shows the relation between σ_h/U and U, which was measured with the 3-cup anemometer at Mt. Hyonosen (upper) and Mt. Taiko (lower). Both figures are similar in the following ways. (1)When average wind speed becomes larger than 6 m s^{-1}, the variance of σ_h /U decreases and σ_h /U converges into a constant value, because atmospheric stability is neutral under strong wind conditions. (2)When wind speed becomes less than 5 m s^{-1}, σ_h/U increases. (Note that σ_h was fixed to be 0 in the lower figure when U < 0.5 m s^{-1}.) According to the Pasquill and Gifford's stability classification system (Pasquill, 1961), when surface wind speed is less than 3 m s^{-1}, the atmospheric stability becomes unstable in mid sunny day under strong insolation, becomes neutral in cloudiness or rain and becomes stable in clear night. Hence σ_h/U should be highly scattered in weak wind condition according to variations in the atmospheric stability. However, in Figure 8, the apparent turbulent intensity increases when wind speed becomes less than 3 m s^{-1}. The reason is shown in the response experiment of the 3-cup anemometer under calm wind conditions. Therefore, we used the data for U > 5 m s^{-1} in order to study the relation between turbulent intensity and wind directions relative to the ridge orientation. For U > 5 m s^{-1}, the atmospheric stability becomes almost neutral and the effects of the friction of the 3-cup anemometer, which is remarkable under weak wind conditions, may be neglected.

Figure 9 shows the directional profile of the turbulent intensity and the detailed contour map of the ridge at Mt. Hyonosen. It shows the relation between the turbulence, on the crest of ridges, and the wind direction/ridge orientation angle. The turbulent intensity was larger in the wind directions parallel to the ridge line AA' than the wind directions perpendicular to the ridge line, BB'. The turbulent intensity at the height of 20 m varied more with the angles to the ridge line as compared to that at the height of 30 m. Figure 10 shows the vertical cross section through the line AA' and BB' in Figure 9. The slope angle is larger along BB' than along AA'.

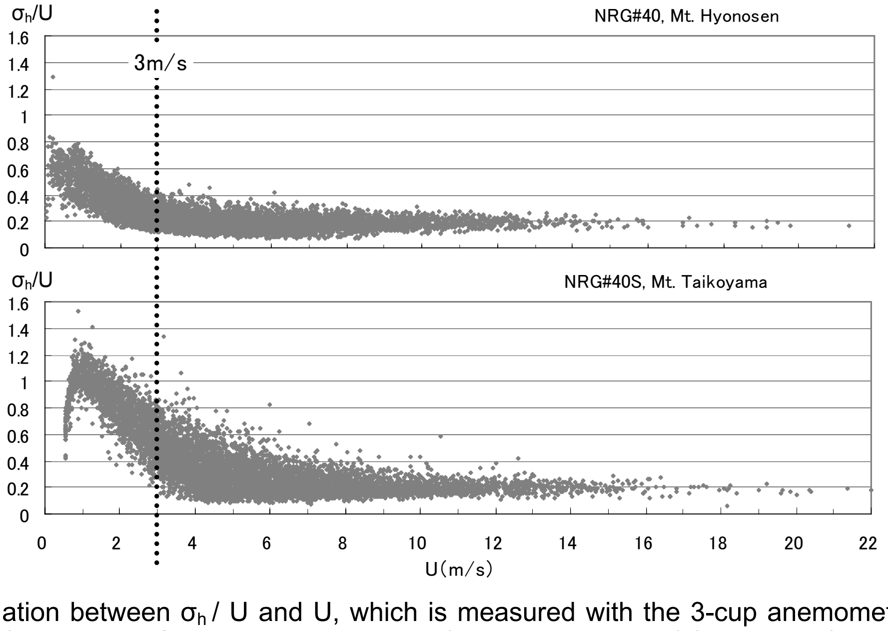

Fig. 8. Relation between σ_h / U and U, which is measured with the 3-cup anemometer at (a) Mt. Hyonosen (at a height of 30 m above the ground) and measured at (b) Mt. Taiko (20 m high).

Figure 11 shows the directional profile of σ_h /U and the detailed contour map of the ridge at Mt. Taiko. It shows the relation between the turbulence and the wind direction/ridge orientation angle. On Mt. Taiko as on Mt. Hyonosen, the turbulent intensity was larger for the wind direction parallel to the ridge line, NS as compared to the wind direction perpendicular to the ridge line, EW. Figure 12 shows the vertical cross section through the line NS and EW in Figure 11.

The turbulent intensity was larger in wind directions parallel to the ridge line as compared to that perpendicular to it. However the wind speed was larger in wind directions perpendicular to the ridge line as compared to that parallel to it, which was the same result as discussed before by Wegley et al. (1982).

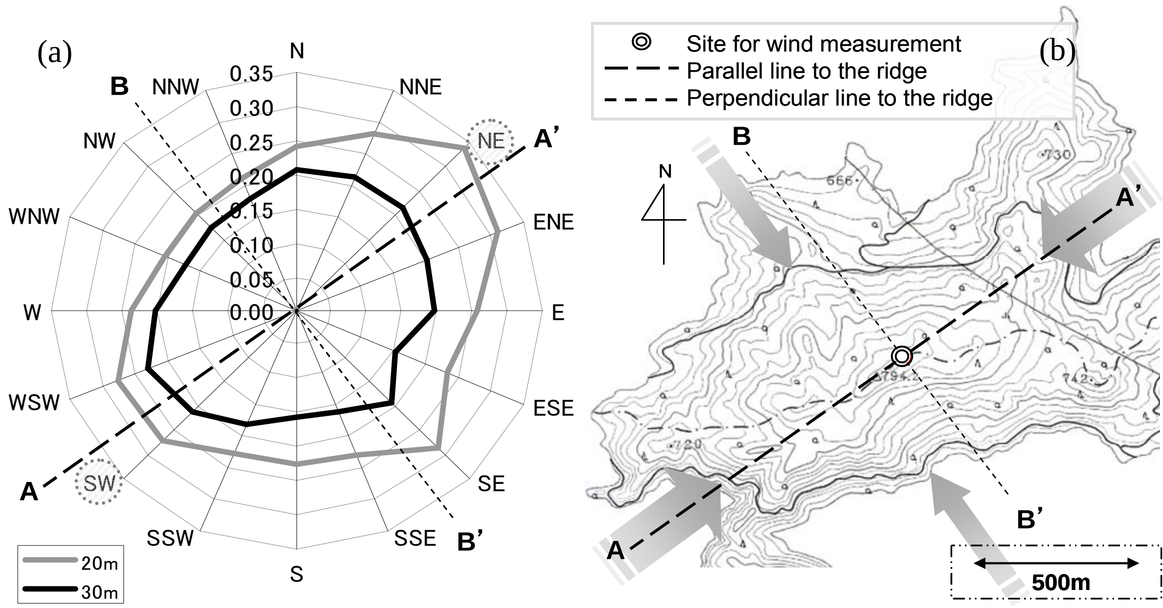

Fig. 9. (a) Directional profile of σ_h /U. (b) The detailed contour map of the eastern ridge of Mt. Hyonosen. Turbulence was measured on the mast at heights of 20 m and 30 m above the ground. The data shown here were measured when U is larger than 5 m s^{-1}. The map is between 650 m and 794 m altitude. (Topographic map of scale 1:25,000 by The Geographical Survey Institute, Government of Japan)

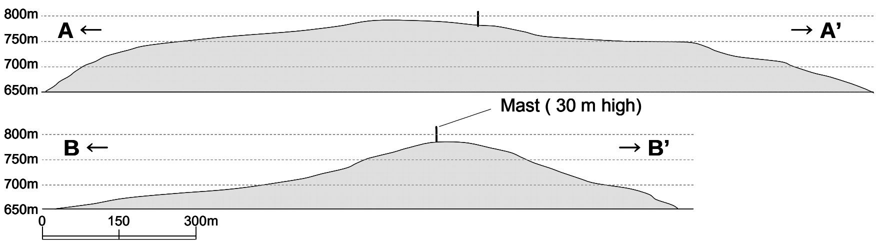

Fig. 10. Vertical cross section on the line AA’ and BB’ in Figure 7. (The eastern ridge at Mt. Hyonosen)

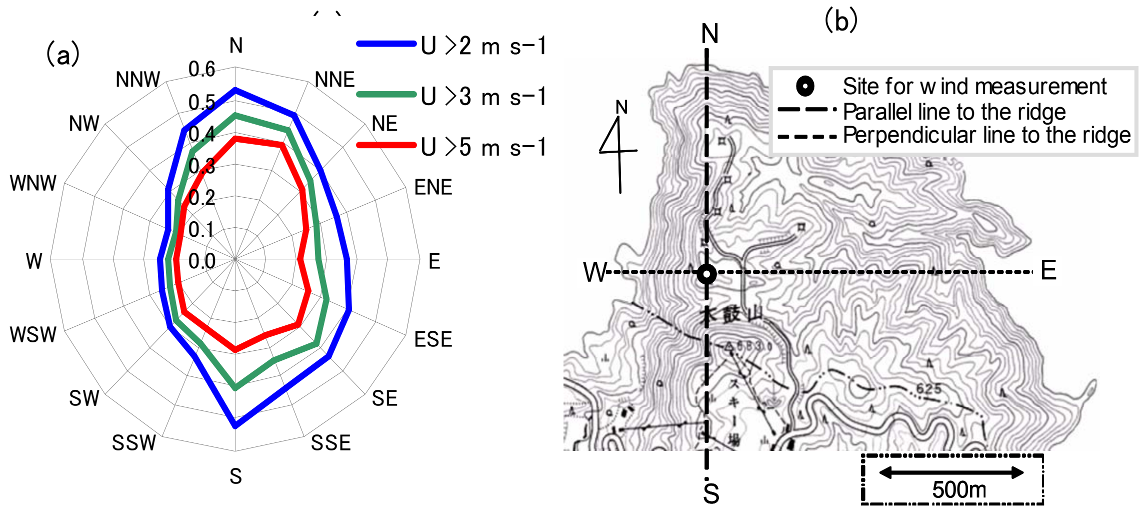

Fig. 11. (a) Directional profile of σ_h / U. (b) The detailed contour map of the ridge at Mt. Taiko. The turbulence was measured on the mast at a height of 20 m above the ground. The map is plotted for altitudes ranging between 450 m and 684 m. (Topographic map of scale 1:25,000 by The Geographical Survey Institute, Government of Japan)

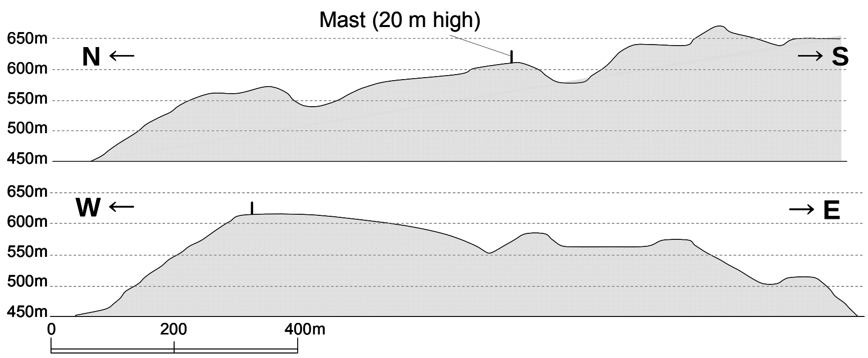

Fig. 12. Vertical cross section through the line NS and EW in Fig. 9. (The northern ridge at Mt. Taiko)

4. Conclusions

(1)The response of a 3-cup anemometer (NRG#40) to fluctuations in the wind speed was investigated by comparing it with a sonic anemometer and with the specification of NRG#40. It was observed that for U > 5 m s^{-1}, the 3- cup anemometer responds to wind speed fluctuations of frequencies lower than 0.3 Hz. The σ_h observed with a NRG 3-cup-anemometer were 86 – 93 % of the σ_u observed with the sonic anemometer.

The 3-cup anemometer NRG#40 is capable of measuring turbulence, except for U< 3 m s^{-1}, and it is better suited for measuring the turbulence for U > 5m s^{-1}.

Therefore, the 3-cup anemometer is capable of measuring the most of turbulence energy caused by surface roughness and complex topography in windy conditions of U > 5 m s^{-1} at 20 m or 30 m high above the ground.

(2)We analyzed the average wind speed and turbulence that were measured at the crests of two ridges for one year. The results are as follows:

On the crest of a ridge, turbulence was larger for winds blowing parallel to the ridge line as compared to those blowing perpendicular to it. Comparing the turbulence measured at two heights, turbulence intensity at a height of 20 m varied more with wind directions than that at a height of 30 m.

The apparent turbulent intensity measured by a 3-cup anemometer increased for low wind speed less than 3 m s^{-1}. This occurred because the 3-cup anemometer repeatedly stopped and rotated when the wind speed becomes less than 1m s^{-1}.

When U become larger than 6 m s^{-1}, the variance of σ_h / U became smaller and converge to a constant value, because the atmospheric stability is neutral under strong wind conditions.

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