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Wind Forces and Peak Wind Pressure Distributions on Wind Turbine Nacelle

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ABSRRACT

In this paper, wind forces acting on a nacelle of wind turbine were measured in the wind tunnel experiments. In order to investigate the validity of application of surface mounted structure data on nacelle enclosure, two kinds of experiments, i.e. model set up on wind tunnel floor and the one apart from floor are carried out. Based on the experimental results, empirical formula of wind force coefficients that are applicable in the design of tower and base of the wind turbine were proposed.

Furthermore a series of local peak pressure measurement was conducted. Based on the results, empirical distributions of local peak pressure coefficients for nacelle enclosures were also proposed.

INTRODUCTION

Wind-generated power that is one of the recyclable energies is expected to beneficial energy for provision against global warming well. In European countries in which numerous wind turbines were constructed, certification systems are maintained well and familiarized.

Although the wind turbines were certified in manufacturers, recently in Japan, a number of serious accidents on wind turbine structures such as collapses of tower and damages on nacelle covers have been reported. These are caused by severe natural conditions, i.e. typhoon wind and highly gusty wind generated by complex terrains which are inherent in Japan. However, aerodynamic data of nacelle which is applicable for the design of tower and base of the wind turbine structure and nacelle enclosure is not well established.

In recently, Germanischer Lloyd , which has been well-known and the most popular

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certification authority, introduces pressure coefficients around the nacelle enclosure in its revised version of guideline (GL2003)[1] for wind turbine certification. Suction values in GL2003 range from –1.0 to –1.2. In GL2003, its design wind speed is defined as a 50 year maximum peak wind speed which is 1.4 times of 50 year annual maximum wind speed, the above values, therefore, should have been multiplied 1.96 to compare with AIJ recommendations [2] in which the coefficients are normalized by mean wind speed. The values in GL2003 appear to be conservative estimation compared with AIJ recommendation in which peak suction coefficient ranges from -2.0 to -5.4.

In the present work, wind forces acting on a nacelle were measured in the wind tunnel experiments. Based on the experimental results, empirical formula of wind force coefficients which are applicable in the design of tower and base of the wind turbine were proposed.

Furthermore a series of local peak pressure measurement was conducted. Based on the results, empirical distributions of local peak pressure coefficients for nacelle enclosures were also proposed.

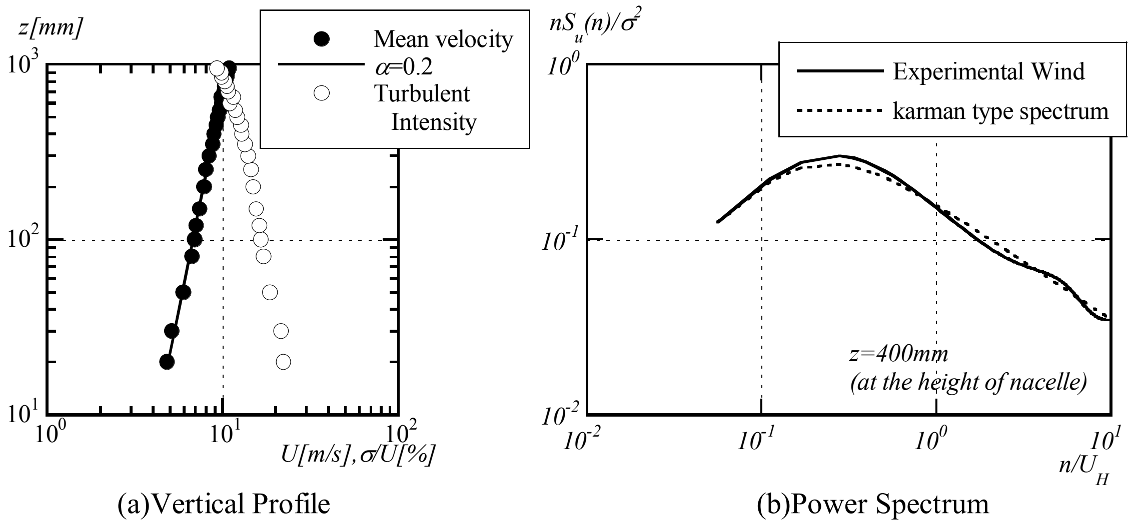
EXPERIMENTAL SETUP

Experimental facilities and wind

Experiments were conducted in a large blower-type low-speed wind tunnel with the test section size of 2000mm×2600mm. Boundary layer turbulent flow was used as experimental wind. Fig.1(a) shows mean wind speed and turbulent intensity profiles of experimental wind. The experiment wind was made for suburban and forest. The power law exponent α is 0.2. Turbulent intensity at the height of nacelle is approximately 13%. Fig.1(b) shows power spectrum density. The power spectrum density form of experimental wind are seem to be very close to the *Karman* type spectrum.

Experimental models and cases

Configurations of wind turbine nacelles are classified into 4 types i.e. rectangular type, cylinder type, globe type and disk type, generally. In this paper, rectangular type which is major configuration of wind turbine nacelle is subject. Experiment models are shown in Fig.2.



(a)Vertical Profile (b)Power Spectrum

Fig.1 Experimental Wind

Geometric scale of model is 1/50. The Experiment models of height H to depth D ratio of 1.0 and of length L to width D ratio of 2.0, 2.5 and 3.0 were tested. Aspect ratios of models were decided according to results of survey on actual wind turbine configurations. Nacelle models and load-cell were connected by support rod. In order to measure the just wind force act on nacelle, support rod was covered by tower model in case of wind force measurements. The tower model was separated from nacelle model, support rod and load-cell completely. Fig.3 shows wind force measurement set up. Definitions of wind forces are shown in Fig.4. The nacelle models also set up on wind tunnel floor in order to investigate ground effects and

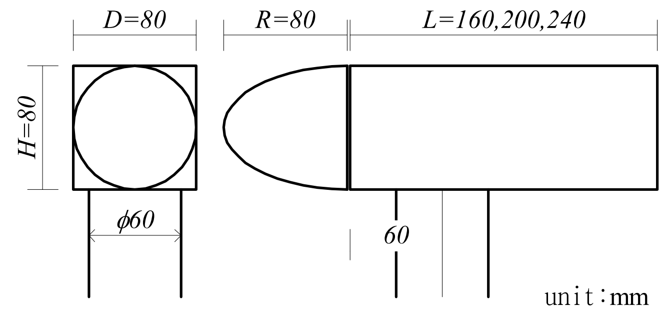


Fig.2 Experimental Model of Nacelle

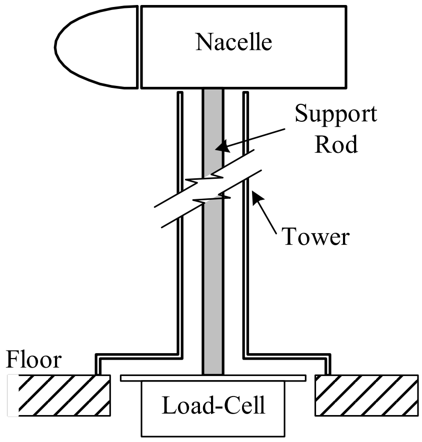


Fig.3 Setup of Model in Wind Force Measurements

Table.1 Experimental Cases of Wind Force Measurements

Case No.	Nacelle Position	Hub	Length Ratio
Case 1	On the Ground	w/o	L/D=2.5
Case 2	Top of Tower		
Case 3		w/	L/D=2.0
Case 4			L/D=2.5
Case 5			L/D=3.0

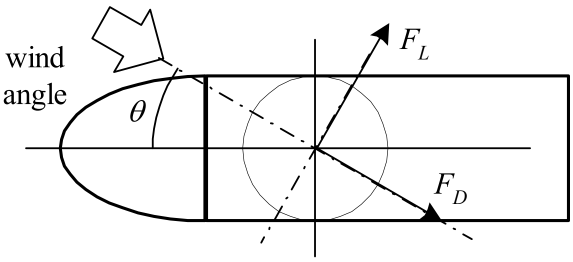
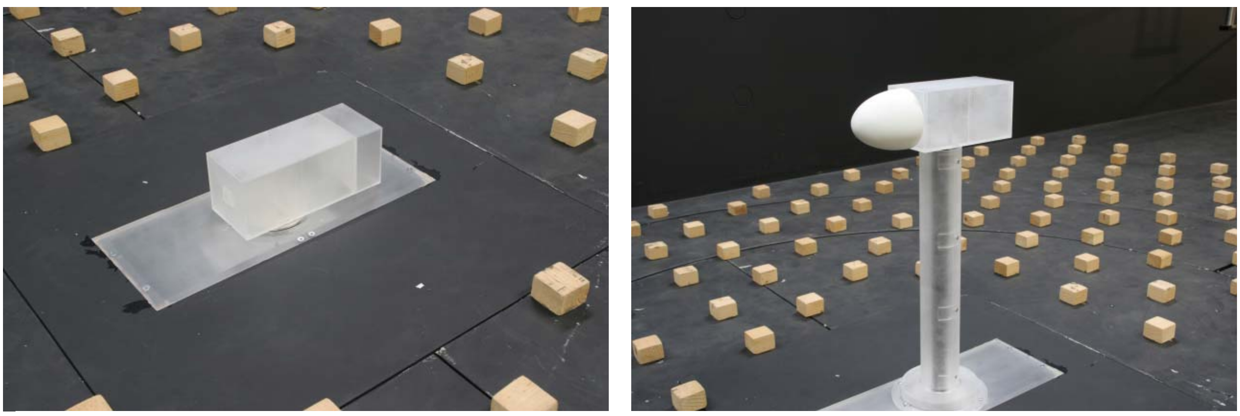


Fig.4 Difinitions of Force and Wind Angle



(a) Case1(L/D=2.5 on the ground) (b) Case4(L/D=2.5,at the top of tower)

Fig.5 Set up Examples of Wind Force Measurement compare with other wind force coefficients that were proposed for design of structure built on ground in some building code or standard. Measurement cases of wind forces were done for five cases summarized in Table 1. The set up examples are shown in Fig5. In order to assure large quantity of turbulent intensity, the tower height set to 400mm that is lower than real proportion of wind turbine tower, but it is enough to avoid the ground effects for wind force on nacelle. There are some Influences of blades to wind forces on nacelle, but that effects were not considered in measurements. In wind forces measurements, wind speed at the height of nacelles was 8m/s, sampling ratio(Δt) was 10ms, number of was 6000 for a sample, 5 sampling were carried out and averaged 5 samples to calculate mean wind force coefficients. Wind angles are from 0^o to 180^o, as pitch is 5^o.

Experimental model used in surface pressure measurement is only one that height to length ratio is 2.5 (Case4 in wind forces measurement). Arrangements of pressure orifices are shown in Fig.5. All pressure orifices were placed on one side of the model. Total number of pressure orifices was 187.

In surface pressure measurements, wind speed at the height of nacelles was 14m/s, sampling ratio (Δt) was 2.5ms, number of data was 8192 for a sample, 10 samples were carried out.

Evaluation of peak pressure coefficient

Sampling period of one sample in full scale was about 300sec based on design wind speed(50m/s). Sampling period of peak pressure coefficients for using design of wind load must be longer than 600sec. in Japan. Peak pressure coefficients, therefore, were evaluate as follows,

1) A positive and a negative peak values were picked up from one sample. Moving average method was conducted to each sample. Averaging time was decided by TVL method [3].
2) Larger peak value was adopted from 2 samples, that evaluating period regard as 600sec.
3) Above procedures were carried out about at all wind angle, and largest coefficient among all wind angle was defined as peak pressure coefficient.

Averaging time was calculated using TVL method as a time interval of peak pressure

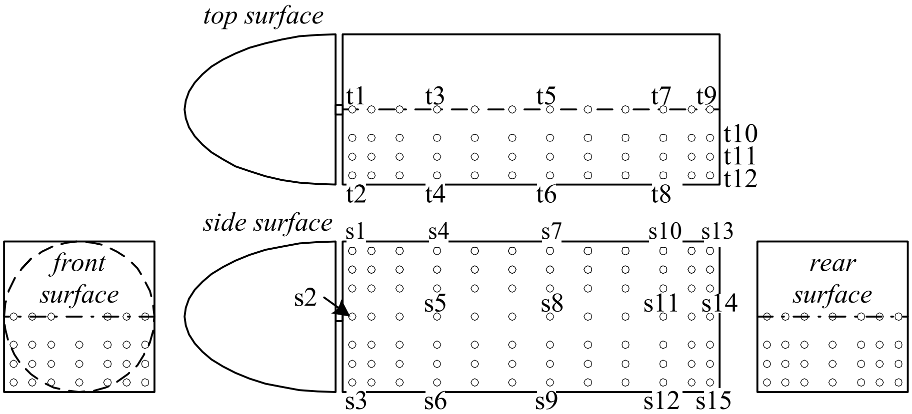


Fig.6 Pressure Measurement Points

coefficients. Averaging time defined by TVL method is given by

$$T_c = k \cdot \frac{l}{U_H} \tag{1}$$

where, T_c: averaging time, l: reference length, U_H: reference wind velocity, k: decay constant

The decay constant k is given by assuming root coherence of 2 points pressure fluctuation to take the form specified by the Davenport type root coherence as

$$\sqrt{coh(n)} = \exp\left(-k\frac{n \cdot dx}{U_H}\right) \tag{2}$$

where, n: frequency, dx: separation distance between 2 points

Root coherence between 2 point pressure fluctuations act on nacelle in this experiment was covered by eq(2) in which setting to k=4. The evidences are described in experimental results of pressure measurements. The reference length l is set to 1m considering the actual nacelle hatch size. Averaging time in full scale of peak pressure acting on 1m extents simultaneously comes to 0.08 sec. assuming that wind speed is 50m/s. Moving average number, therefore, is 2 according to $T_c / \Delta t$.

MEAN WIND FORCES

<u>Influence of ground and hub to mean wind forces coefficients</u>

Drag force coefficients and lift force coefficients defined as follows

$$C_D(\theta) = \frac{F_D(\theta)}{\frac{1}{2}\rho U_H A}, \quad C_L(\theta) = \frac{F_L(\theta)}{\frac{1}{2}\rho U_H A} \tag{3a),(3b}$$

where, F_D: mean drag force, F_L: mean lift force, ρ : air density, θ : wind azimuth, A: reference area(=LH)

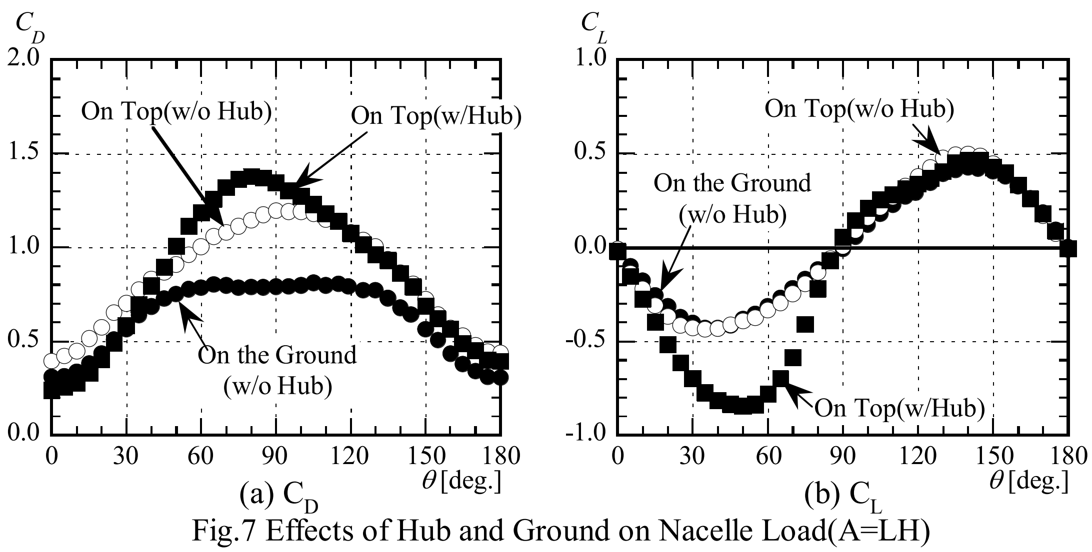


Fig.7 Effects of Hub and Ground on Nacelle Load(A=LH)

The values of these coefficients are shown in Fig.7. It is seen that in Case2 (at the top of tower, without hub), maximum value of mean drag coefficient C_D is 1.2 which occurred at $\theta = 90^{o}$. In Case4 (at the top of tower, with hub), distributions of C_D and C_L are anti-symmetric about the $\theta = 90^{o}$ according to the effects of hub. Maximum C_D in Case4 is occurred at $\theta = 80^{o}$ and the value is 1.4. Increase of C_D caused by influence of hub is almost 23% at $\theta = 75^{o}$. Decreases in C_D caused by hub effects in the wind angle from 0^{o} to 45^{o} were observed. In Case2 (at the top of tower, without hub), C_D were increased 50% than in Case1 (on the ground). The ground effects, therefore, were clearly seen in this study.

As to the value of mean lift coefficients C_L, the values of C_L with hub (Case4) have doubled in comparison with C_L without hub (Case2) in the wind angle from 0^{o} to 90^{o}. The effects of hub are more influential on C_L.

Effect of nacelle length on mean wind forces coefficients

Fig.8 shows C_D and C_L defined by another reference area A^* that face area of hub is comprehended as follow,

$$A^* = A + \frac{\pi HR}{4} \tag{4}$$

Using A^* as reference face area, difference of C_D and C_L caused by nacelle length comes to decrease. On condition using A^* as reference face area, C_D and C_L are represented by proposal equations well, which could be used for design load for tower and base of wind turbine as follow, respectively

$$C_D(\theta) = -0.4\cos(1.95\theta) - 0.06\cos(3.2\theta) + 0.68 \quad ,\left(-180^{o} \le \theta \le 180^{o}\right) \tag{5a}$$

$$C_L(\theta) = \left(-0.9\sin(2\theta) + 0.08\sin(3\theta)\right)\left(0.9 + 0.05\cos(4\theta)\right)\cos(0.43\theta) \quad ,\left(-180^{o} \le \theta \le 180^{o}\right) \tag{5b}$$

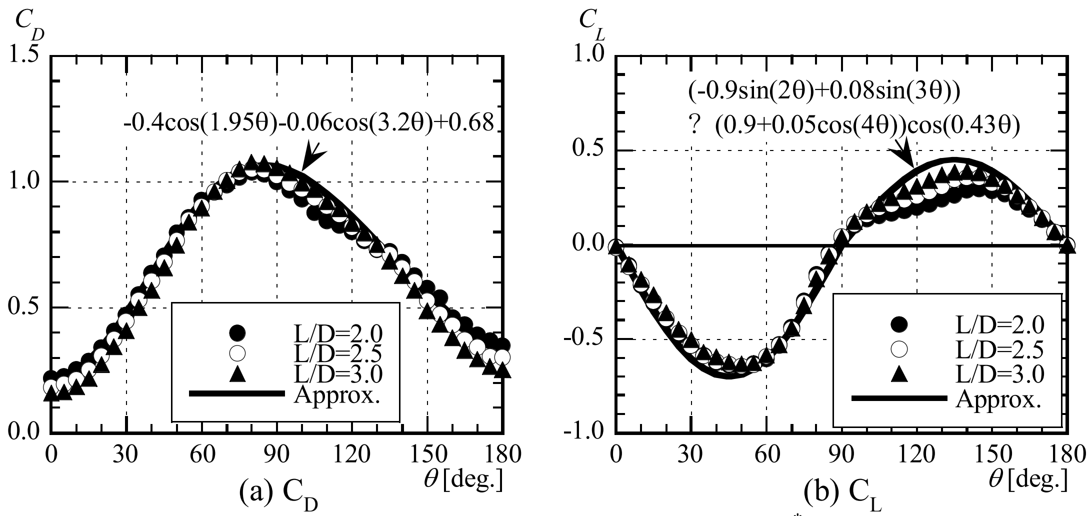


Fig.8 Effects of Hub Length on Nacelle Load(A^* by eq.(2))

In order to compare with C_D or C_L provided in BSLJ or GL2003, We re-define the C_D and C_L using a further another face area A(θ)** as follow,

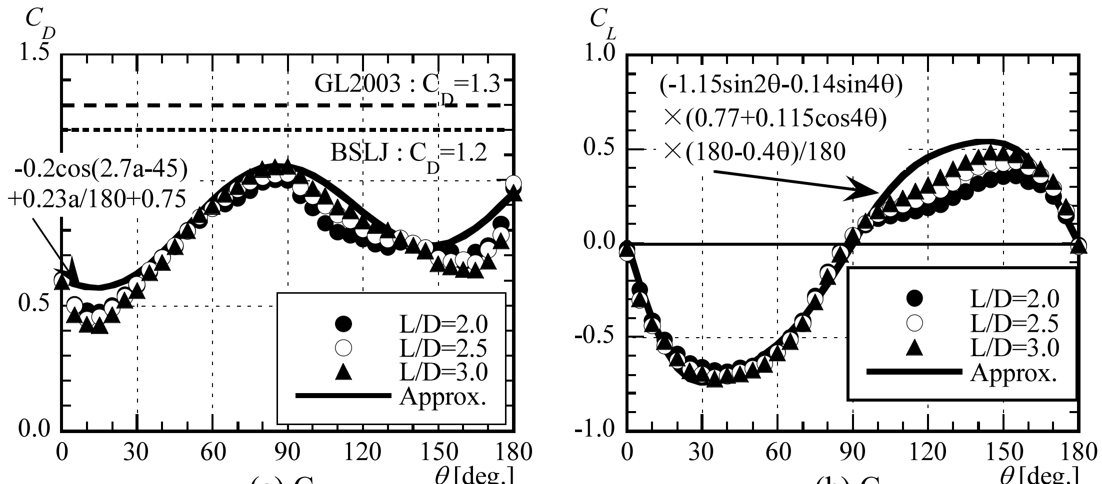
$$A^{**}(\theta) = \left|HR\cos\theta\right| + \left|\left(\frac{\pi R}{4} + L\right)H\sin\theta\right| \tag{6}$$

C_D and C_L defined by A^{**} as reference face area are compared with values provided in BSLJ (C_D =1.2) and GL2003 (C_D =1.3) in Fig.9 together with eq.(5a,5b). It is seen that the values of C_D in BSLJ and GL2003 seem to be conservative rather than proposal values.

PEAK PRESSURE COEFFICIENTS

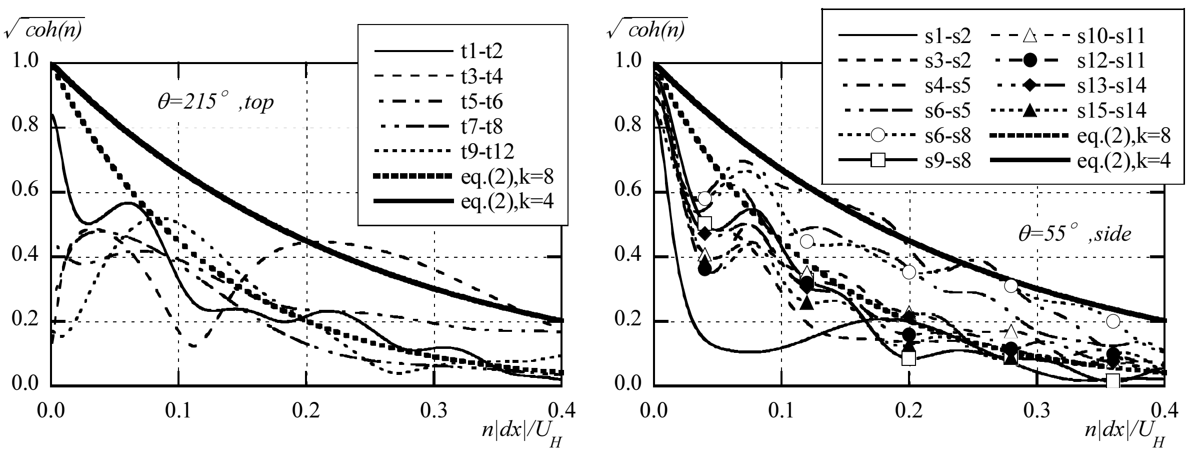
Root Coherences of surface pressures

Examples of root coherence of pressure fluctuation on surface of nacelle are shown in Fig.10 together with eq.(2) with k =8 and k=4. These wind angle are θ=55° and θ=215° in



(a) C_D (b) C_L

Fig.9 Effects of Hub Length on Nacelle Load(A^{**} by eq.(4))



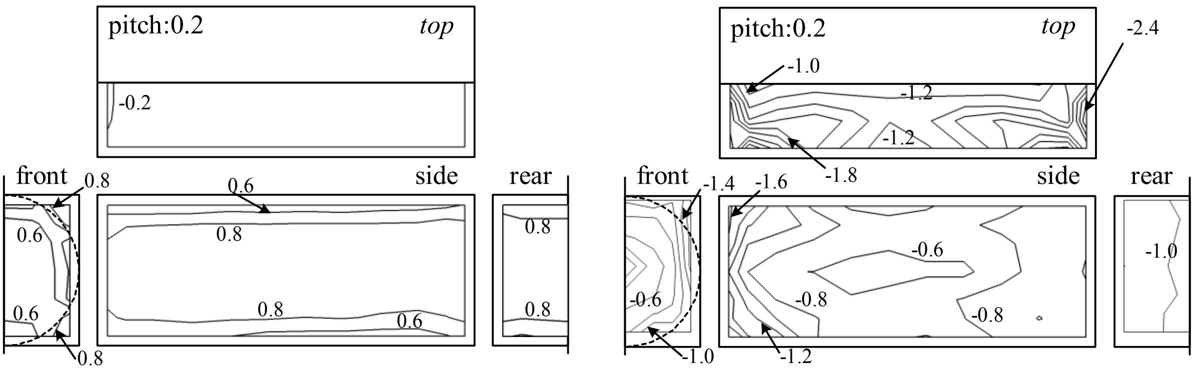
(a) top surface, wind angle:215° (b) side surface, wind angle:55°

Fig.10 Root Coherence of Fluctuating Pressure Coefficients which negative peak pressures were occurred, respectively. The root coherences between 2 points pressure fluctuations have varied from point to point and from wind angles. Eq.(2) with k=8 is center of variations in root coherences. The root coherences of t9-t12 and s1-s2 are smaller than eq. (2) with k=8. The points of s1 and t9 were at the corner of side surface and at the edge of top surface where largest negative peak pressures were occurred, respectively. If the value of k is set to 4, almost root coherences of pressure fluctuation on nacelle are covered by eq.(2). Therefore, value of k is set to 4 in this study and estimate number of moving average of peak pressures.

Distributions of mean and peak wind pressure coefficients

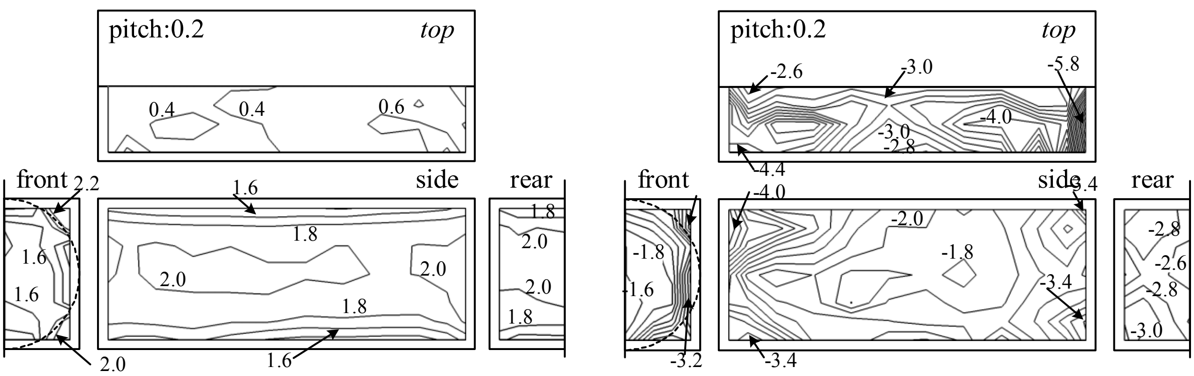
Largest and smallest mean pressure coefficients in all of wind angles are defined as maximum mean pressure coefficients and minimum mean pressure coefficients, respectively. Distributions of maximum mean pressure coefficients and minimum mean pressure coefficients are shown in Fig.11. First, maximum mean pressure coefficients are described. It is seen that, negative values of mean pressure on the top surface of nacelle do not occur. On the side and rear surface, values are 0.8 in almost region, and slightly decrease near upper and lower edge. But these decrease are not seen near vertical edges. On the front surface, values on the region shaded by hub are about 0.6, and about 0.8 on other regions. Distributions of minimum mean pressure on each surface are more complex rather than that of maximum except on rear surface.

Positive and negative peak pressure coefficients distributions on nacelle surfaces are shown



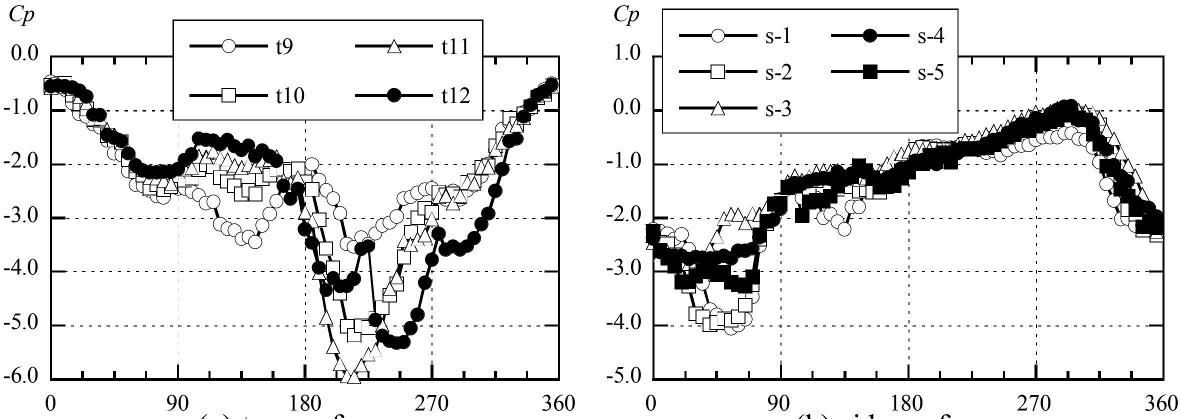
(a) Maximum mean pressure (b) Minimum mean pressure

Fig.11 Maximum and Minimum Mean Pressure Coefficient Distributions



(a) Positive peak pressure (a) Negative peak pressure

Fig.12 Peak Pressure Coefficient Distributions in Fig.12. The values of positive peak pressure coefficients are from 0.4 to 0.6 on top surface, from 1.6 to 2.2 on the other surfaces. It is seen that the locally particularly large values are not appeared on any surfaces. As to the negative peak pressure coefficients local large peak pressures, on the other hand, are occurred near the corner on side surface, on rear surface and on top surface. The values of local peak pressure coefficients are from –3.4 to –4.0 on side surface, –3.0 on rear surface, respectively. The local peak pressure at side surface corner near front are occurred at wind angle 55°(see Fig.13), that at the corner nearby rear are occurred at wind angle 195°,the local peak pressures on side surface occurred in leeward slightly. The local peak pressures are occurred on top surface. Particularly at the edge near rear, where influence of hub is seem to disappear, largest peak pressure appears. The value of local peak pressure at the edge on the top surface is –5.8. It seems that this local peak pressure caused by conical vortices, which appear on upwind edges at diagonal wind angle[4]. In point of fact, it was occurred at wind angle 215°(see Fig.13).



(a) top surface (b) side surface

Fig.13 Minus Peak Pressure Coefficients

<u>Comparison with standards and recommendations</u>

GL2003 has recommended pressure coefficients for design of nacelle enclosure. These pressure coefficients are mean pressure coefficients based on 3sec. gust wind speed. Pressure coefficients for nacelle enclosure in GL2003 are shown in Fig.14. The values in fig.14 are converted into peak pressure coefficients based on 10 min. mean wind speed using the square of conversion rate (=1.4) between gust wind speed and mean wind speed determined in GL2003. The values of pressure coefficient recommended in GL2003 are 1.6 for positive pressure and –1.2 for negative pressure, which appear to be considerably underestimated compared with results in this study. Positive peak pressure coefficients for cladding on walls provided by BSLJ and AIJ recommendations are 2.3 and 2.0 (height is 60m, category III), respectively. Negative peak pressure coefficients provided in BSLJ and AIJ recommendations are shown in Fig.15. As to the positive peak pressure coefficients, values in BSLJ and in AIJ recommendations are close to results in this experiment results well. Because main cause of positive peak pressure is turbulence in oncoming flow and its almost unrelated to configrations or locations of nacelle. Thought it seems that applying the positive peak pressure coefficients in BSLJ and AIJ for wind resistant design of nacelle enclosure are reasonable. As to the negative peak pressure coefficients, distributions obtained in this experiments are kind of similar to that on roof on which peak pressure comes to large near the corner. Though the values could not be compared directly because those are based on mean hourly wind speed, distributions of pressure coefficients on roof for design provided in ASCE standard[5] are similar to that in this study, in BSLJ and in AIJ recommendations.

On the basis of above results, schematic distributions of positive peak pressure could be drawn with considering above reasons are shown in Fig.16.

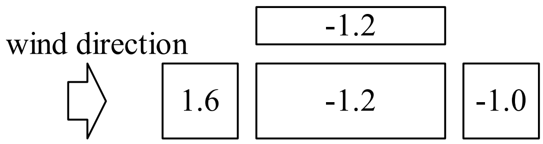


Fig.14 Pressure Coefficients for Nacelles in GL2003

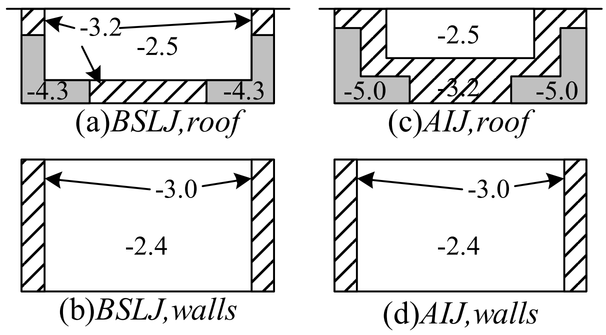


Fig.15 Minimun Peak Pressure Coefficients in BSLJand AIJ Recomendations?

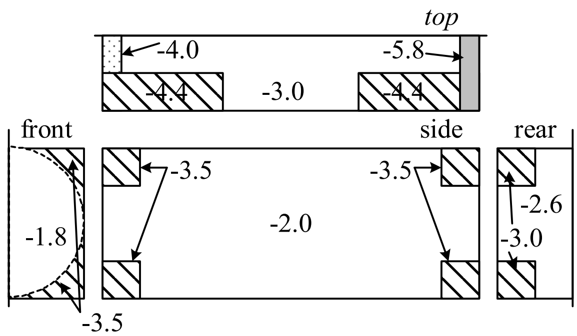


Fig.16 Schematic Distribusions of Minimun Peak Pressure Coefficients for Panel Design Loads of Wind Tubine Nacelles ?

CONCLUDING REMARKS

Total mean wind forces and local peak pressures on nacelles were measured in order to investigate applicable total load on nacelle mounted on tower and distributions of peak pressure coefficients for nacelle enclosure. Mean drag coefficients and mean lift coefficients for estimate total design load and peak pressure coefficients on account of wind resistant design for nacelle enclosure are proposed. The values of mean drag coefficients in Building Standard Low of Japan and GL2003 seem to be conservative rather than proposal values.

However, the values of pressure coefficients recommended in GL2003 appear to be considerably underestimated compared with results in this study, the positive peak pressure coefficients obtained in this study are close to that in BSLJ and in AIJ recommendations. Thought, distributions of negative peak pressure coefficients are kind of similar to that on roof in BSLJ and in AIJ recommendations, the values are larger than that in BSLJ and AIJ recommendations on some regions.

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