ESTIMATION AND REFINEMENT OF WIND-FORCE COEFFICIENT ACTING ON A PHOTOVOLTAIC ARRAY ON THE GROUND

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Wind loads, known to be an essential factors in the design of structures for photovoltaic arrays, are the products of kinetic pressure, wind-force coefficient $C_W$ and array area, under JIS C 8955. However, the use of $C_W$ is limited to an array angle-of-attack $\theta$ between 15° and 45°, and is not applicable where angle-of-attack is low at approximately 10°. However, such low $\theta$ have been used increasingly in recent years. In addition, the impact of the difference in the distance from the ground to array has not been investigated. When objects having a wing-form shape are moving close to the ground, a ground-effect may arise, resulting in an increase in lift power, and a similar increase is expected for arrays that have shapes similar to wings. If these wind loads can be evaluated properly, it is expected that the safety and economical performance of arrays can be further improved. In this research, the authors conducted a wind tunnel test using a 1/20 single-unit scale array model to estimate and refine wind-force coefficient $C_W$ taking into account the array’s angle-of-attack and its structure height.

Key Words: photovoltaic arrays, wind-force coefficient, wind-resistance design, ground effect

1. INTRODUCTION

Photovoltaic power generation facilities are under the spotlight as sources of alternative energy to fossil fuels that may help us mitigate global warming. Especially since the enactment of the electricity purchasing scheme in July 2012, construction of large-scale photovoltaic power stations has been rapidly growing in number. Photovoltaic power stations need no fuel cost for operation and have relatively low maintenance cost; thus their project profitability depends on the initial construction cost.

Early studies on wind loads applied on photovoltaic arrays (hereafter referred to as arrays) installed on ground surface include studies by Shirai-shi, Matsumoto, et al. with presumption of construction of Saijo Power Station¹,²), design of the frame of arrays by Ukita, et al.³), a study on Japanese Industrial Standard (JIS) C 8955 to specify the design methods on array support structures⁴) (hereafter referred to as JIS) and technological development by New Energy and Industrial Development Organization (NEDO), which was used as the basis for arrays. ⁵)

Wind loads that are especially important in the design of photovoltaic array support structures are expressed as the product of kinetic pressure, wind-force coefficient, $C_W$ and array area under JIS. However, the use of $C_W$ is limited to an array angle-of-attack $\theta$ between 15 and 45°, and is not applicable where angle-of-attack is low at approximately 10°, which has been adopted more popularly in recent
years. In addition, the impact of the difference in the distance from the ground to the array bottom edge (hereafter referred to as support height $H$) has not been investigated.

When objects having a wing-form shape are moving close to the ground, a ground effect may arise, resulting in an increase in lift power, and a similar increase is expected for arrays that have shapes similar to wings. If these wind loads can be evaluated properly, it is expected that the safety and economical performance of arrays can be further improved. Therefore in this research, the authors conducted a wind tunnel test using a 1/20 single-unit array model to check the variation tendencies of wind-force coefficient $C_W$ by varying the support height $H$ (four types) and angle-of-attack $\theta$ (eight types) under fair wind or head wind, and tried to refine $C_W$ with considering support height $H$ and low angle-of-attack $\theta$ and establish an estimation formula. We have also evaluated the data in comparison to the existing research outcomes to confirm its reliability.

Furthermore, the results of this research will also be used as the basic data for the research ultimately determine the array position and reduction area for the “central section” where reduction can be expected. It is said that “the arrays in the central section can be 1/2 of the value at the edges where wind applies directly if there are multiple frames” in the use of $C_W$ under JIS. According to the research results of the authors so far, with regard to the relationship between wind-force coefficient $C_W$ for a single-unit array (which can be used as the reference value for wind-resistant design) and wind-force coefficient $C_W$ for the first column of arrays (which represents the edges where wind applies directly and which is used as the reference in the collection of arrays), we were beginning to understand that $C_W$ for the first column of arrays became smaller than that of a single-unit array if there was a column of arrays downstream to the single unit array. It is also known that $C_W$ for the second column of arrays and later in the collection of arrays decreases further than the first column, although the reduction rate varies depending on the angle-of-attack $\theta^{(1, 6)}$. While the reduction rate for these has not been quantified at present, the $C_W$ for a collection of arrays is known to decrease in 2 steps from that of a single-unit array. Thus, refinement of $C_W$ and establishment of an estimation formula in this article will play an important role in the examination of array collections.

2. OUTLINE OF WIND TUNNEL EXPERIMENT

(1) Experiment system

The wind tunnel used in the experiment was a suction-type boundary layer wind tunnel owned by the Department of Civil and Architectural Engineering, Kyushu Institute of Technology with the dimensions of measurement block being 2.4 m width x 1.8 m height x 20 m length. A schematic drawing of the wind tunnel experiment is shown in Fig. 1. The array model was installed on a ground plate with the ground set at the position 0.75 m in height from the floor of the wind tunnel measurement block and 3.34 m from the upstream edge, so that the width direction of the array would be orthogonal to the main stream. The ground plate was installed for the full width of the measurement block in 6.15 m length in main stream direction in the wind tunnel measurement block.

While the air stream used in experiment was uniform, a boundary layer turbulent flow was generated while it flows down above the ground plate as described later. At the position approximately 60, mm which would be the array center height $H_c$, wind
velocity $U$ was set to three different values ($U = 6$, 7 or 8 m/s) with the intensity of disturbance approximately 16%. The Reynolds number $Re$ becomes approximately $Re = 1 \times 10^5$ (representative length: depth of single-unit array model $L = 0.18$ m). According to literature\(^2\), the Reynolds number $Re$ for this experiment was located within the subcritical region close to the critical Reynolds number $Re = 2.8 \times 10^5$ when compared to a flow around a smooth column, indicating that the flow was nearly completely turbulent.

While this will be described later, a value somewhat smaller than the wind-force coefficient obtained in this experiment was delivered in a similar study implemented at approximately 1/10 to 1/2 of the Reynolds number in this experiment, thus there is a experiment; thus it could be a laminar area. In design of actual sites, when wind velocity is estimated as $U = $ approximately 40 m/s and representative length $L = 4$ m, the Reynolds number $Re$ becomes approximately $1.0 \times 10^5$, which is nearly 100 times larger than that of this experiment and therefore the stream is surely turbulent. Thus, it falls in the same area as this experiment and the calculation of loads by Newtonian approximation as shown in Equations (1) and (2).

Figure 2 shows the vertical distribution of standard wind velocity after standardizing the wind velocity $U$ at each height near the array position. Wind velocity $U$ is set at 6 or 8 m/s at the array center with height $H_C$ (approximately 60 mm) as the reference wind velocity. Since the value remains the same when the height reaches approximately 250 mm or higher under this condition, it indicates that the boundary layer occurs at heights lower than 250 mm from the ground plate.

Since the wind velocity varies within the boundary layer depending on the height from the ground, correction against the effect of boundary layer was made. The environmental coefficient was calculated by the average velocity in height direction and gust response factor based on the reference wind velocity for design at 10 m above ground, with consideration of the ground surface coarseness type and average height of the array surface from the ground. In this experiment using array center height $H_C$ as the reference height, wind-force coefficient $C_W$ for both uniform flow and gradient flow were compared. A height sufficiently distant from the ground was the reference height and wind velocity $U = 6$ m/s based on simulation results by LES conducted by the Central Research Institute of Electric Power Industry was used in this experiment. While the $C_W$ for the gradient stream was naturally smaller than that of the uniform stream as a consequence, it was reported that the wind-force coefficient $C_W$ was nearly equivalent between the uniform stream and gradient stream. In the calculation, the array center height $H_C = $ approximately 60 mm proposed by Shiraishi, et al.\(^3\) was used as the representative flow rate.

A six-component force meter (LMC-6336 by Nissei-Electric-Works) was used for measuring the aerodynamic force, and two components of aerodynamic force, namely, drag $F_D$ and lift $F_L$, which were necessary for calculation, were measured using the wind-force coefficient $C_W$ characteristics as the typical value of aerodynamic force.

Please see literature\(^6\) for details of the experiment method.

(2) Experiment model

The array model used to measure the aerodynamic force was an aluminum plate with a single-unit array using a module with 9 kW power output as 1 unit in a reduced scale of 1/20, with the following dimensions: width $W = 900$ mm × depth $L = 180$ mm × thickness $T = 2.5$ mm, and aspect ratio $A_S$ (ratio of array width $W$ compared to array depth $L$) = 5. The support height $H_S$, which is the distance between the ground plate and the bottom edge of the array model, was varied by adjusting the installation height for the six-component force meter depending on each experiment case. Furthermore, as shown in Figs.1 and 3, the array model was supported by the six-component force meter via the two arms, and only the aerodynamic force applied on the rectangular flat plate array was used as the measurement value. Aerodynamic force applied on the supporting structure and the effect of the supporting structure were not taken into consideration.

(3) Definition of wind-force coefficient $C_W$

Drag coefficient $C_D$ and lift coefficient $C_L$ were calculated by using Equations (1) and (2), respectively, with the application of least squares method supposing them as the aerodynamic force against
each wind velocity $U^2$ and gradient passing through the origin similar to existing researches\(^1\), \(^6\). They were found to be independent of wind velocity in the wind-velocity range of this report.

Wind-force coefficient $C_W$ was calculated as a component working in the direction of normal array using Equation (3) based on the definitions shown in \textbf{Fig.4}. Drag coefficient $C_D$, lift coefficient $C_L$ and wind-force coefficient $C_W$ are collectively called the aerodynamic coefficients.

$$
C_D = F_D / \left(0.5 \times \rho \times U^2 \times L \times W\right) \quad (1)
$$
$$
C_L = F_L / \left(0.5 \times \rho \times U^2 \times L \times W\right) \quad (2)
$$
$$
C_W = C_D \times \sin \theta + C_L \times \cos \theta \quad (3)
$$

Where,

$C_D$: Drag coefficient, $C_L$: Lift coefficient, $C_W$: Wind-force coefficient, $F_D$: Drag [N], $F_L$: Lift [N], $\rho$: Density of air [kg/m\(^3\)], $U$: Wind velocity [m/s], $L$: Array depth [m], $W$: Array width [m]

\textbf{(4) Experiment case}  

As shown in \textbf{Fig.3}, the experiment case was set so that the wind direction in which the array was pressed was considered as the fair wind, and the direction in which the array was blown up was the head wind. Since the practical site construction height was 300 to 600 mm, support height $H$ was set to 15 to 30 mm with 5 mm increments considering that the scale reduction was 1/20. Angle-of-attack $\theta$ was set between $5^\circ$ and $40^\circ$ with $5^\circ$ increments considering the low angle-of-attack that has become popularly adopted in recent years. In addition, $75^\circ$ and $90^\circ$ were also used for angle-of-attack $\theta$ for comparison with existing literature.

\section{3. EXPERIMENT RESULTS AND ANALYSIS OF TENDENCY IN AERODYNAMIC COEFFICIENTS}

In this chapter, we analyze the tendencies of aerodynamic coefficients $C_D$, $C_L$, and $C_W$ to vary depending on the size of support height $H$ and angle-of-attack $\theta$ under fair wind and head wind conditions.

\textbf{(1) Tendency in aerodynamic coefficients under fair wind and head wind} 

Aerodynamic coefficients tend to vary depending on angle-of-attack $\theta$, which coincides with the experimental results of existing studies\(^1\), \(^6\) with the value for head wind being larger as a whole when the values under fair wind and head wind in \textbf{Figs.5} and \textbf{6} are compared.

The tendency for drag coefficient $C_D$ to vary showed that $C_D$ grew larger as angle-of-attack $\theta$ increased, and this tendency is common between fair wind and head wind (see \textbf{Fig.5 (a)} and \textbf{Fig.6 (a)}). It is surmised that this occurred because the projection area in the right angle direction to the flow increases as angle-of-attack $\theta$ increases. When we focus on the effect of support height $H$, $C_D$ increases as $H$ increases under fair wind conditions, but there is no clear tendency under head wind conditions.

The tendency for lift coefficient $C_L$ to vary showed that $C_L$ value reached a local maximum when angle-of-attack $\theta$ was $30^\circ$, and this tendency was common between the fair wind and head wind conditions (see \textbf{Fig.5 (b)} and \textbf{Fig.6 (b)}). When we focus on the effect of support height $H$, it was indicated that $C_L$ value grew considerably as the support height $H$ increases under fair wind conditions. While it depends little on $H$ under head wind conditions, it is evident that the tendency changes when angle-of-attack is $30^\circ$ with the order of $C_L$ value in concurrence with the increase in support height $H$ reversing at this angle.

The tendency of wind-force coefficient $C_W$ to vary resulted with $C_W$ value tending to be slightly larger than the JIS value in some cases at angle-of-attack $\theta$ being $20^\circ$ or smaller, and to be slightly smaller than the JIS extrapolation value at $\theta$ being $20^\circ$ or smaller.

Under head wind in \textbf{Fig.6 (c)}, $C_W$ value matched the JIS value in the range of angle-of-attack $15^\circ \leq \theta \leq 30^\circ$ although angle-of-attack was around $20^\circ$, and was lower than the JIS extrapolation value when the angle was smaller than $15^\circ$. When we focus on
the effect of support height $H$, the $C_W$ value grows considerably as the support height $H$ increases under fair wind, similarly to $C_D$ and $C_L$ values. However, it depends little on $H$ under the head wind. In addition, the tendency for $C_W$ value to vary is similar to that of $C_L$ being superior based on the characteristic of trigonometric of $C_L$ value. This is due to the effect of lift coefficient function at $\theta < 45^\circ$, as shown in Equation (3).

The effects of support height $H$ on aerodynamic coefficients can be summarized as follows: While $C_D$ value and $C_L$ value under fair wind and $C_D$ value under head wind increase when $H$ is higher, $C_L$ value under head wind increases when angle-of-attack $\theta \geq 30^\circ$, and decreases when $\theta < 30^\circ$. It is therefore assumed that the order of wind-force coefficient $C_W$ grows considerably as the support height $H$ increases under fair wind, similarly to $C_D$ and $C_L$ values. However, it depends little on $H$ under the head wind. In addition, the tendency for $C_W$ value to vary is similar to that of $C_L$ being superior based on the characteristic of trigonometric of $C_L$ value. This is due to the effect of lift coefficient function at $\theta < 45^\circ$, as shown in Equation (3).

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efficient $C_W$ values did not align because the increase or decrease caused by support height $H$ gave it balance when angle-of-attack was in the range of $\theta \leq 30^\circ$.

(2) Effects of angle-of-attack $\theta$ and support height $H$ on aerodynamic coefficients
To elucidate the tendencies of angle-of-attack $\theta$ and support height $H$ to affect aerodynamic coefficients, Fig. 7 (a) organized the data for each support height $H$ using angle-of-attack $\theta$ as the explanatory variable, and Fig. 7 (b) organized the data for each angle-of-attack $\theta$ using support height $H$ as the explanatory variable. In addition, the head wind value at support height $H = 25$ mm and angle-of-attack $\theta = 35^\circ$ was not included as its tendency varied from those of other data.

a) Range of effects support height $H$ on aerodynamic coefficients
Figure 7 (a) shows that the values of aerodynamic coefficients under fair wind and head wind $C_D$ and $C_L$ approach each other when support height $H$ is higher. It is natural that the both values approach each other considering that fair wind and head wind would form a point symmetry flow field against array center if an array is installed in a uniform flow field without the effects of the ground. However, the actual flow field does not have point symmetry due to the effects of the ground, non-uniform flow in the boundary layer and so forth.

Figure 8 shows the results of a simulation conducted by the Central Research Institute of Electric Power Industry by using LES analysis code, and a model with the same shape as the one in this experiment under conditions in which angle-of-attack $\theta = 20^\circ$ and support height $H = 25$ mm. The figure expresses the obtained pressure distribution made dimensionless by $0.5 \times \rho \times U^2$. In this simulation result, they also analyzed the flow field around the three columnar arrays in addition to a single-unit array under fair wind and head wind conditions, and the value of wind-force coefficient $C_W$ was reported to be a favorable match with the experiment results of the authors.

Fig. 9 Tendency of the difference in aerodynamic coefficients under head wind and fair wind to vary depending on support height $H$. 

Fig. 8 Simulation under conditions angle-of-attack $\theta = 20^\circ$ and support height $H = 25$ mm. 

Fig. 7 Changes in aerodynamic coefficients depending on angle-of-attack $\theta$ and support height $H$. 

(a) Changes in angle-of-attack $\theta$ for each support height $H$
(b) Changes in support height $H$ for each angle-of-attack $\theta$

Fig. 8

(a) Pressure in average flow field (fair wind)
(b) Pressure in average flow field (head wind)
This simulation result shows that suppression occurred from the array’s front end and that a low-pressure area (blue area) expanded from the suppression area as the center on the bottom surface of the array under fair wind and the top surface under head wind. It is evident that a jet stream is generated due to the effect of the ground, especially under fair wind, and that the suppression area is limited. Meanwhile, pressure increased in the area subjected to the flow (red block) as the flow is blocked on both the array top surface under fair wind and the bottom surface under head wind. It shows that a reverse flow occurs near the ground at the front end of the array and that the pressure is reduced especially under the head wind as the flow is further blocked by the effect of the ground. As shown above, the effect of the ground on flow varies between fair wind and head wind, resulting in different effects on the tendency of wind-force coefficient $C_D$ to vary. For flow lines in average flow field and flow velocity distribution in main stream direction, please see literature.

To closely investigate the approach between aerodynamic coefficient values under fair wind and head wind, Fig.9 shows the data with the value obtained by subtracting the fair wind value from the head wind value (average value for each angle-of-attack) for $C_D$ and $C_L$, respectively, as the objective variable, and support height $H$ as the explanatory variable. Based on this result, the difference between head wind value and fair wind value decreased for both lift coefficient $C_L$ and drag coefficient $C_D$ as support height $H$ increased. It is surmised that the height range until this difference is eliminated would be the range where the aerodynamic coefficients are affected by the ground. Therefore, the fair wind and head wind values would become identical for both $C_D$ and $C_L$ when support height $H$ is approximately 50 mm, if it is supposed that the difference in an aerodynamic coefficient between fair wind and back wind values decreases in a linear fashion.

That is, it is expected that the range will be up to this height where there is ground effect. According to the research results by Oka, et al. on lift improvement by ground effect wing reported that the ground effect did not occur if the support height $H$ was only equivalent to depth $L$, and the range of effect in this result, which was examined with the average value of each angle-of-attack, fell within the range of the research results by Oka, et al. However, in this study, the value obtained by subtracting the fair wind value from the head wind value was examined as the average value for each angle-of-attack, and in some cases, the difference between them increased as the support height $H$ increased depending on the conditions, when the values were minutely organized for each angle-of-attack. Thus, it is necessary to examine the range of support height $H$ in detail by expanding it to a size equivalent to the depth when trying to accurately measure the degree of ground effect.

b) Effects of support height $H$ on drag coefficient $C_D$

In Fig.7 (b), the literature values when the array was on air or when it was in contact with the ground under experimental value and angle-of-attack $\theta = 90^\circ$ were simultaneously described. The $C_D$ values in literature were $C_D = 2.0$ and 1.2, respectively. The $C_D$ value in this experiment was placed between air and ground, and did not deviate from the existing findings.

When we focus on drag coefficient $C_D$ in Fig.7 (b), the $C_D$ value increased in stages as angle-of-attack $\theta$ increased either under fair wind or head wind. In addition, if angle-of-attack $\theta$ was constant, the value became larger as support height $H$ increased. This tendency was more apparent as the angle-of-attack $\theta$ was larger. The reason for this is assumed to be the change in velocity gradient in the boundary layer naturally occurring on the ground plate as shown in Fig.2, which caused the $C_D$ value to increase.

c) Effect of angle-of-attack $\theta$ and support height $H$ on lift coefficient $C_L$

When we focus on the lift coefficient $C_L$ in Fig.7 (b), the $C_L$ value under fair wind became larger as support height $H$ increased even when angle-of-attack $\theta$ remained the same. It is assumed that this was because the effect of velocity gradient was prominent similar to drag coefficient $C_D$, as shown in Fig.2.

On the other hand, the $C_L$ value under the head wind varied little if the angle-of-attack $\theta$ remained the same. It is assumed that this happened because the decrease in $C_L$ value caused by decrease in wind velocity $U$ in concurrence with decrease in $H$ and the increase in $C_L$ value caused by the effect of the ground (hereafter referred to as the ground effect) balanced each other out. The ground effect refers to a phenomenon in which the movement of the conical vortex occurring at the end of an array in the width direction is cut off by the ground, making it difficult for the flow to go around to the top surface of the array. This reduces the power to press down on array’s top surface resulting in the increases of the lift.

In addition, close examination of the data shows that the $C_L$ value tends to become smaller as support height $H$ increases, when the angle-of-attack $\theta$ remains the same within the range 0° to 30°, but that it tends to become larger when $\theta$ reaches 30° and grows larger. The phenomenon up to $\theta = 30^\circ$ indicates decrease in the rate of flow on the array bottom surface as it is intercepted by the array. As the flow is further intercepted by the effect of the ground, decrease in flow rate becomes even more prominent. Therefore, it is surmised that the force to
push up the array became smaller with the pressure decrease. It likewise contributed to the decrease in \( C_L \) value as the flow rate at the bottom surface of the array would decrease if array support height \( H \) increased.

On the other hand, the phenomenon where \( \theta \) exceeds 30° is assumed to be the result of composite effects of the pressure at array bottom surface and suppression on array top surface when the local maximum value was exceeded; however, this will need to be examined further in the future. The research results by Shiraishi, et al.\(^1\), where they conducted experiments at support heights \( H \) being 20 mm and 200 mm under the condition of angle-of-attack \( \theta = 33.9° \), also showed that the \( C_L \) value increased when support height \( H \) was larger and thus similar results were obtained. Details will be provided later.

The reason for the existence of a local maximum value for lift coefficient \( C_L \) under both fair wind and head wind is examined in Fig.8, which is a simulation result, as an example. As shown in Fig.8, there are points (blue sections) where pressure deteriorated on the back surface of the array, as in the array bottom surface under fair wind or array top surface under head wind, and these indicate the results of flow suppression\(^3\). Since the flow area expands on the back surface of the array as it goes downstream, adverse pressure gradient occurs, causing reverse flow with flow velocity reaching a negative value in an area with relatively small flow rate in the boundary layer in such a flow field. A boundary layer forms above the reverse flow area, which results in suppression. Increase in angle-of-attack \( \theta \) more rapidly expands the downstream area and therefore the tendency of suppression to occur increases. Since lift \( F_L \) starts decreasing when suppression occurs, a local maximum value appears as angle-of-attack \( \theta \) increases.

4. EVALUATION OF THE RELIABILITY OF EXPERIMENT RESULTS

In this chapter, the reliability of the corresponding experiment results is examined using the lift-drag ratio and the existing aerodynamic characteristics experiment results on blades.

(1) Evaluation of validity of aerodynamic coefficients \( C_D \) and \( C_L \) under fair wind and head wind using lift-drag ratio

A method to calculate wind-force coefficient \( C_W \) as a component acting in the normal direction of array using Equation (3), or a method to calculate it using Pythagorean theorem as shown in Equation (4)\(^{13} \) is used. Naturally, the wind-force coefficient \( C_W \) calculated using either method tallies.

However, Pythagorean theorem requires that Equation (5) holds true, and it may not be consistent with practical experimental results.

Experimental values are examined while analyzing this condition.

\[
C_W = \left( C_D^2 + C_L^2 \right)^{0.5} \quad (4)
\]

\[
C_D = C_L + \tan \theta \quad (5)
\]

As described earlier, it is required that the third term on the right side of Equation (6), which is delivered by squaring Equation (3), is always 0 in order for Equations (3) and (4) to be equivalent.

\[
C_W^2 = C_D^2 + C_L^2 - \left( C_D \cos \theta - C_L \sin \theta \right)^2 \quad (6)
\]

That is, \( (C_D \cos \theta - C_L \sin \theta)^2 = 0 \) must hold true, and this condition means that Equation (5) is
satisfied.

Here, $C_L / C_D$, which is a modification of Equation (5), is the lift-drag ratio, and it can be expressed as $1 / \tan \theta$.

Therefore, Fig.10 shows a comparison between experimental lift-drag ratio obtained from the results of this experiment and the lift-drag ratio (hereafter referred to as condition lift-drag ratio) obtained by using Equation (5) and $\theta$, which should naturally match.

This result shows that the experimental lift-drag ratio and condition lift-drag ratio match well at angle-of-attack $\theta$ being $15^\circ$ or larger, but the experimental lift-drag ratio is smaller than the condition lift-drag ratio when angle-of-attack $\theta$ is smaller than 15. This indicates either that the $C_L$ value is relatively too small or that the $C_D$ value is relatively too large. To confirm the sizes of these aerodynamic coefficients, Fig.11 plots the angle-of-attack $\theta$ on the horizontal axis and the angle reverse operated from the experimental values by using Equation (5) on the vertical axis (hereafter referred to as reverse operated angle $\theta'$) for each support height $H$. Based on this result, it is evident that the reverse operated angle $\theta'$ is larger than the set angle-of-attack $\theta$ when angle-of-attack $\theta$ is especially small. It is surmised that the $C_D$ value increased as a result of increase in frictional resistance caused by viscosity of air and increase in form drag by array thickness. That is the feature of the measurements in the low angles-of-attack.

Meanwhile, lift coefficient $C_L$ at a relatively low angle can be calculated by multiplying lift gradient $m$ (indicating the increase in lift coefficient per degree increase in angle-of-attack) with angle-of-attack $\theta$. Lift gradient $m$ takes a certain value which is dependent on the blade profile. Thus, the $C_L$ value varies as a linear function with the angle-of-attack $\theta$ as the variable with no other probable causes of increase or decrease, and $C_D$ value is assumed to have increased as shown in Fig.12.

Based on the above results, it is surmised that the relationship between aerodynamic coefficients $C_D$ and $C_L$ collectively captured the detailed physical phenomena occurring in wind tunnel experiments with high reliability, and that the results of this experiment also have high reliability.

(2) Evaluation of validity of aerodynamic coefficients $C_D$ and $C_L$ under head wind using the aerodynamic characteristic experiments on blades

The values collected in aerodynamic characteristic experiment on blades were the two components drag $F_D$ and lift $F_L$, and the evaluated items were the aerodynamic coefficients. Since the direction of the force applied against the direction of the wind was the same between the head wind conditions of this experiment and aerodynamic characteristic experiment on blades, we evaluated the validity of our aerodynamic coefficients by using the results of aerodynamic characteristic experiment on blades by Okamoto and Jinba at a low Reynolds number region of $Re = 1 \times 10^4$.

In this experiment, the aspect ratio of the array $A_S$ (ratio of array width $W$ to array depth $L$) was set to 5 and the Reynolds number $1 \times 10^7$. In the aerodynamic characteristic experiment on blades, aerodynamic coefficients were calculated for three types of plane blades (triangle, oval, and rectangular) by varying $A_S$ from 0.5 to 6.
Figure 13 shows a comparison of drag coefficient $C_D$ and lift coefficient $C_L$ between the experiment results on rectangular blade and those in this experiment under head wind.

While the drag coefficient $C_D$ in literature\(^{13}\) indicated in Fig. 13\(\text{(a)}\) shows a unique tendency to vary depending on the difference in aspect ratio $A_S$, it can also be interpreted that it becomes closer to $A_S = 6$ value as the aspect ratio $A_S$ becomes larger. Considering that it approaches a two-dimensional blade as aspect ratio $A_S$ is larger owing to the effect of the three-dimensional effects of conical vortex generated on the right and left edges of the array in the width direction\(^{12}\), the result seems to be inevitable. Furthermore, when we compare the results of this experiment at $A_S = 5$ and the literature values at $A_S = 4$ and 6\(^{13}\), which are similar aspect ratios, they are both nearly consistent although the literature value\(^{11}\) is slightly higher at low angle-of-attack range, indicating that the results of this experiment are valid.

In the comparison of lift coefficient $C_L$ in Fig. 13\(\text{(b)}\), it is considered that the results mostly match at $A_S = 4$ and 6 except for the range $15^\circ \leq \theta \leq 35^\circ$, where the effect of suppression becomes prominent. A possible reason for inconsistency in this range is that the Reynolds number $Re$ is in a low range in the aerodynamic characteristic experiment on blades. Thus, it is highly likely that the air stream has laminar separation and the $C_L$ value is dropping rapidly when angle-of-attack $\theta$ is larger than $10^\circ$. It can be surmised that the results of aerodynamic characteristic experiment on blades would be closer to the results of this experiment if Reynolds number $Re$ was larger, considering the general theory in aerodynamics that the maximum lift coefficient would be larger as separation would be less likely to occur if $Re$ is larger.

Based on the above, it is surmised that this experiment delivered valid results as the changes in aerodynamic coefficients against the angle-of-attack $\theta$ in both experiments were expected to have the same tendency if aspect ratio $A_S$ and Reynolds number $Re$ are same condition.

5. ESTIMATION OF WIND-FORCE COEFFICIENT

In this chapter, we will describe the specific methods used to estimate aerodynamic coefficients $C_D$ and $C_L$. They involved algebraic approximation of experiment data for those dependent on angle-of-attack $\theta$, and linear approximation for those dependent on support height $H$. The precision of the estimation formula for wind-force coefficient $C_W$, which is obtained by synthesizing the coefficient, was then verified.

(1) Estimation of drag coefficient $C_D$ and lift coefficient $C_L$

a) Estimation formula for each support height $H$

In the estimation of drag coefficient $C_D$ and lift coefficient $C_L$, a polynomial was used that had angle-of-attack $\theta$ (rad) as a variable with $0^\circ \leq \theta \leq 40^\circ$, which included the experiment range as the subject range. Here, the indication unit for angle-of-attack $\theta$ was set to (rad) as the coefficients for the polynomial would be too large if (deg) was used. The degree of polynomial (that is, the degree at which the coefficient of determination with adjusted degree of freedom became maximum for both fair wind and head wind) was calculated to be fourth for lift coefficient $C_L$ and second for drag coefficient $C_D$. The constant term in polynomial was set to 0 at angle-of-attack $\theta = 0^\circ$ as neither drag $F_D$ nor lift $F_L$ was generated. In addition, functions such as exponential were also possible choices for the estimation formula, but application was difficult as the experiment values had a local maximum.

Figures 14 and 15 show the estimation formula for each aerodynamic coefficient and Tables 1 and 2 show the rate of contribution by coefficients of each polynomial ($a$ - $d$) used in the estimation formula.

As evident from these results, the smallest rate of contribution by the estimation formula $R^2$ was high, 0.988 in all cases of lift coefficient $C_L$ and drag coefficient $C_D$ under both fair wind and head wind conditions; thus, the phenomenon is reproduced well.

b) Estimation formula to correspond to the changes in support height $H$

The purpose of this research was to estimate the wind-force coefficient $C_W$ that could deliver results even when angle-of-attack $\theta$ and support height $H$ varied arbitrarily. Therefore, by interpolating the estimation formula for minimum lift coefficient delivered at the minimum support height $H_{\min} = 15$ mm in the experiment case calculated in the previous paragraph (the estimation formula for maximum lift coefficient obtained by estimation value $C_{L_{\max}}$ and maximum support height $H_{\max} = 30$ mm when angle-of-attack $\theta$ was substituted) using support height $H$, an estimation formula for lift coefficient addressing both arbitrary angle-of-attack $\theta$ and support height $H$ was obtained.

More specifically, it was decided that the fluctuation value corresponding to support height $H = 1$ mm should be calculated in advance by dividing the difference between the estimation formula for maximum lift coefficient and the estimation formula for minimum list coefficient $\Delta C_l$ with the support height difference $\Delta H = H_{\max} - H_{\min} = 15$ mm. Likewise that Equation (7) was to add the product of
the difference between support height used for design $H_{dsn}$ and minimum support height $H_{min} = \Delta H'$ and the fluctuation value to $C_{L_{min}}$ value would be used. In addition, lift coefficient $C_L$ in Equation (7) was be replaced with drag coefficient $C_D$.

$$C_{L_{dsn}} = \frac{\Delta C_L}{\Delta C_L / \Delta H \times \Delta H'} + C_{L_{min}}$$

(7)

Where,

$C_{L_{dsn}}$: Lift coefficient estimation formula

Table 1: Coefficients used in polynomial function and their contribution rates (fair wind).

| Drag coefficient | $a$    | $b$    | $c$ | $d$ | $R^2$ |
|------------------|--------|--------|-----|-----|-------|
| $H = 15$         | 0.547  | 0.473  | 0.998 |
| $H = 20$         | 0.601  | 0.493  | 0.997 |
| $H = 25$         | 0.505  | 0.793  | 0.995 |
| $H = 30$         | 0.430  | 0.664  | 0.995 |

| Lift coefficient | $a$    | $b$    | $c$ | $d$ | $R^2$ |
|------------------|--------|--------|-----|-----|-------|
| $H = 15$         | -5.128 | 10.759 | -8.760 | 3.724 | 0.995 |
| $H = 20$         | -18.649| 29.835 | -17.305| 5.133 | 0.996 |
| $H = 25$         | -20.493| 32.018 | -18.620| 5.490 | 0.992 |
| $H = 30$         | -17.871| 28.227 | -17.255| 5.500 | 0.989 |

Table 2: Coefficients used in polynomial function and their contribution rates (head wind).

| Drag coefficient | $a$    | $b$    | $c$ | $d$ | $R^2$ |
|------------------|--------|--------|-----|-----|-------|
| $H = 15$         | 0.435  | 0.704  | 0.988 |
| $H = 20$         | 0.431  | 0.704  | 0.995 |
| $H = 25$         | 0.427  | 0.782  | 0.991 |
| $H = 30$         | 0.464  | 0.794  | 0.994 |

| Lift coefficient | $a$    | $b$    | $c$ | $d$ | $R^2$ |
|------------------|--------|--------|-----|-----|-------|
| $H = 15$         | -1.678 | 6.342  | -9.743| 5.554 | 0.996 |
| $H = 20$         | -3.440 | 10.092 | -11.849| 5.843 | 0.998 |
| $H = 25$         | -2.201 | 7.420  | -9.984| 5.447 | 0.996 |
| $H = 30$         | 0.295  | 6.364  | -8.145| 5.163 | 0.998 |
(2) Verification on aerodynamic coefficients estimated

a) Verification of accuracy of wind-force coefficient $C_{W}$ calculated using the values of this experiment

In this section, the estimation formula for lift coefficient $C_{L_{dsn}}$ and estimation formula for drag coefficient $C_{D_{dsn}}$ (which were developed in the previous section), as well as the estimation formula for wind-force coefficient $C_{W_{dsn}}$ which was synthesized by using Equation (3), are called estimation formula. Their accuracy are and also verified.

Their accuracy was verified by comparing the experimental values of wind-force coefficient $C_{W}$ described in Figs. 5 and 6 to the estimated $C_{W_{dsn}}$ value calculated using Equation (7). The results of checking at support height $H = 15$ mm to $30$ mm are shown in Fig. 16. The maximum error between estimation formula and experimental values under fair wind was -9% at angle-of-attack $\theta = 10^\circ$ (0.17rad), and -7% under head wind at angle-of-attack $\theta = 5^\circ$ (0.09rad).

Based on these results, the estimation formula was considered applicable for angle-of-attack $5^\circ \leq \theta \leq 40^\circ$ and support height range $15$ mm to $30$ mm, although there are slight errors when angle of attack $\theta$ was small.

b) Check on aerodynamic coefficients by existing array experiments

In a pioneering research on wind resistance of arrays, Shiraishi, et al. (1) conducted experiments on aerostatic force characteristics working on an array with aspect ratio $A_s=7.82$ and surface pressure distribution on array by varying the support height $H$ between $20$ mm and $200$ mm with angle-of-attack $\theta = 33.9^\circ$, which is planned for construction. In this section, the validity of this estimation formula $C_{L_{dsn}}$ is checked by using these results.

Figure 17 shows the literature values (1) and the aerodynamic coefficients estimated for support height $H = 20$ mm within the estimation range of $5^\circ \leq \theta \leq 40^\circ$ under fair wind and head wind, respectively. As a consequence, the drag coefficient $C_{D}$ for support height $H = 20$ mm was similar between the two.

**Fig. 16** Comparison of wind-force coefficient $C_{W}$ estimation formula and experimental values.

**Fig. 17** Comparison with the results of existing array experiments (1).
types of data under both fair wind and head wind conditions, but the literature value\(^1\) was slightly smaller for lift coefficient \(C_L\). It is assumed that this was because the experiment for literature value\(^1\) was conducted at wind velocity \(V = 2\) to 5 m/s and array depth \(L = 184\) mm, and its Reynolds number \(Re\) was very small, nearly a half that of this experiment.

These results in which the literature values\(^1\) and the estimation formula values are similar for drag coefficient \(C_D\), and the literature values\(^1\) are smaller than the estimation formula values for lift coefficient \(C_L\) show a similar tendency as the results of aerodynamic characteristic experiment on blades by Okamoto and Jinba\(^{13}\) discussed in the previous chapter, which was conducted at Reynolds number \(Re\) approximately 1/10 that of this experiment. That is, as shown in Fig.13 (b), suppression starts from a low angle-of-attack \(\theta\) if Reynolds number \(Re\) is relatively small; thus, the lift \(F_L\) also starts decreasing, it is surmised that lift coefficient \(C_L\) would be smaller than the one calculated by the estimation formula if Reynolds number \(Re\) was smaller than that of this experiment. On the other hand, as shown in Fig.13 (a), drag coefficient \(C_D\) does not show considerable decrease even when Reynolds number \(Re\) is small; thus, the value is considered to have remained equivalent to that of the estimation formula.

Here, Fig.18 shows an organization of changes in aerodynamic coefficients by literature values\(^5\) values by Okamoto and Jinba\(^{13}\), and those by the estimation formula at angle-of-attack \(\theta = 33.9^\circ\) depending on \(Re\) value. As a consequence, the aerodynamic coefficients are shown to have varied between the Reynolds number range assumed to have laminar separation \(1.0 \times 10^5 \leq Re \leq 5.0 \times 10^5\) (which is approximately 1/10 to 1/2 of the \(Re\) number in this experiment) and the Reynolds number range for this estimation formula, which is considered to be in the turbulent range.

Furthermore, aerodynamic coefficients \(C_D\) and \(C_L\) at support height \(H = 200\) mm for literature values\(^1\) are larger than those for \(H = 20\) mm in general. As shown in Fig.7 (b), this result matches the tendency for both \(C_D\) and \(C_L\) values to grow as the support height \(H\) increased in this experiment when angle-of-attack \(\theta\) exceeded \(30^\circ\). In addition, the estimation formula was not described for support height \(H = 200\) mm as extrapolation was needed outside the estimation range.

c) **Check on lift coefficient \(C_L\) using the potential theory**

In a research on ground effect on monoplane units, Tomotika, et al.\(^{14}\) used the complex velocity potential theory and calculated the effects of the changes in blade center height \((H_c)\) and angle-of-attack \(\theta\) on lift coefficient \(C_L\) of flat blade. In this section, the validity of this estimation formula \(C_{L,\text{est}}\) is checked by using these results.

**Figure 19** plots the value obtained by dividing the lift coefficient \(C_L\) varying by the size of array center height \(H_c\) with the theoretical lift coefficient \(C_{L,0}\) (= lift gradient \(m \times \text{angle-of-attack } \theta\)) when a two-dimensional plane blade is in the air (hereafter referred to as lift coefficient ratio \(C_L / C_{L,0}\)) on the vertical axis and the value obtained by dividing array depth \(L\) with array center height \(H_c\) on the horizontal axis to compare the literature formula\(^{14}\) and our estimation formula.

For the estimation formula \(C_{L,\text{est}}\) in the figure, angle-of-attack \(\theta\) used in literature formula\(^{14}\) was substituted and the value obtained by adding 1/2 of the array height in vertical direction to the support height \(H\) used in this experiment was substituted as the array center height \(H_c\). However, the lift coefficient \(C_L\) in this experiment was obtained for an array with the same shape as a three-dimensional plane blade with aspect ratio \(A_d\) equal to 5. The value was too large to merit applying the two-dimensional plane blade value \(m_\infty = 2\pi\) for lift gradient \(m\) of the theoretical lift coefficient \(C_{L,0}\). We therefore decided...
to use lift gradient $m_s$, which was obtained by correcting lift gradient $m$ to $A_S = 5$ for the conditions of this experiment. Equation (8) was used to calculate the lift gradient for oval blades that show approximation to rectangular blades when aspect ratio $A_S$ is large.

$$m_s = m_e / \left(1 + \left(\frac{m_e}{\pi \times A_s}\right)\right) = 2\pi / \left(1 + \left(\frac{2\pi}{\pi \times 5}\right)\right) = 4.49$$

Where,

$m_e$: Lift gradient $2\pi$ for two-dimensional plane blade

$m_s$: Lift gradient corrected for aspect ratio $A_s = 5$

Literature formula$^{(14)}$ shows that the characteristics of lift coefficient ratio moves close to $C_L / C_{10} = 1$ at array center height $H_C$ which do not affect the aerodynamic force, and then gradually starts varying as the array center height $H_C$ becomes smaller. The lift coefficient ratio in the literature formula$^{(14)}$ tends of to increase when angle-of-attack $\theta$ is $9^\circ$ or smaller, and decrease when $\theta$ is $18^\circ$ or larger. The order of lift coefficient ratio shows smaller values as the angle-of-attack $\theta$ becomes larger.

When our estimation formula $C_{L_{dn}}$ and the literature formula$^{(14)}$ are compared, the lift coefficient ratio by the estimation formula qualitatively shows a tendency to increase when angle-of-attack $\theta$ is $18^\circ$ or smaller, and decrease when $\theta$ is $36^\circ$ or larger. The order of lift coefficient ratio also shows a similar tendency; that is, the value is smaller as angle-of-attack $\theta$ becomes larger.

Furthermore, when the value of lift coefficient ratio is quantitatively examined, the values are similar, although the values for the estimation formula are smaller or larger than those of literature formula$^{(14)}$ at angle-of-attack $\theta = 4.5^\circ$ and $9^\circ$. On the other hand, the estimation formula value was considerably smaller than that of the literature formula$^{(14)}$ at angle-of-attack $\theta \geq 18^\circ$. It is assumed that this occurred as the $m_s$ value was estimated to be too large with the effect of suppression not being considered in the lift gradient $m_s$ used in this calculation. As suppression does not occur under the potential theory, the values are relatively consistent with the experimental values under conditions with low angle-of-attack values where the effect of suppression is small. However, it is said that the values start to vary from the theory as the effect of suppression becomes more prominent, which matches with the results of this experiment.

Figure 20 shows a graph indicating the effect of changes in angle-of-attack $\theta$ on the lift coefficient $C_L$ for the potential theory, and the lift coefficient $C_L$ of this experiment. The lift coefficient $C_L$ of the potential theory indicated the values calculated using lift gradient $m_e = 2\pi$ for two-dimensional blade and lift gradient $m_s = 4.49$, which was corrected for the aspect ratio $A_S = 5$ in this experiment. When lift coefficient $C_L$ obtained from lift gradient $m_s = 4.49$ is compared to the lift coefficient $C_L$ obtained from experiment, they match relatively well until angle-of-attack $\theta = 10^\circ$, where the effect of suppression starts to be considerable. This result supports the results in Fig.19 in which the values of the two were similar at angle-of-attack $\theta \leq 9^\circ$, and it is surmised that the results of this experiment generally reproduce the tendency derived from the complex velocity potential theory.

6. SUMMARY

In this research, we attempted to refine the wind-force coefficient $C_W$ with consideration of support height $H$ and angle-of-attack $\theta$, which were not taken into consideration by JIS under fair wind and head wind condition. We then established an estimation formula to calculate it by conducting a wind tunnel experiment using a single unit array modeled at 1/20 scale. We also evaluated the reliability of the collected data and the estimation formula using values from existing literature.

The outcomes and findings are summarized as follows:

1) The wind-force coefficient $C_W$ obtained under fair wind conditions tended to be larger as the support height $H$ increased, regardless of the angle-of-attack $\theta$. Wind-force coefficient $C_W$ was nearly constant with no dependency on support height $H$ under head wind conditions.

2) We developed an estimation formula for wind-
force coefficient $C_W$ that used support height $H$ and angle-of-attack $\theta$ as the variables with applicable range of angle-of-attack $\theta$ being $5^\circ \leq \theta \leq 40^\circ$ and applicable range of support height being $15 \text{mm} \leq H \leq 30 \text{mm}$.  

3) As a result of checking the devised estimation formula, we found that our results were consistent with existing experiments and the potential theory in general.

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