Validation of dimensionless method using height average wind velocity for wind forces

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Summary

The wind forces acting on a ship are normalized using the air density, the projected area of the ship and the representative wind velocity. In this regard, the authors have presented that the use of height average wind velocities (HAWV) can reduce the effect of differences in wind profiles on wind force coefficients. In this study, the results of wind forces calculations carried out by several companies and institutes using flow solvers available for each participant on two types of ships were compared, and show the effectiveness of HAWV. The CFD calculations were performed with different wind profiles depending on the participants of the calculation. Although the difference of calculation conditions of each simulation causes the difference of profiles of inflow velocity and the wind forces acting on the ship, the HAWV have been proposed as an appropriate, representative wind velocities for the normalization which can reduce the influence of the difference of the wind profiles by considering the concept of kinetic energy. The normalization with the HAWV provides flexibility in CFD calculation settings and in the same in modeling wind profile demanded for estimation of the wind forces. This approach also expands the possibilities of available CFD tools. In addition, the calculation results with various configurations, such as differences in boundary conditions set in computational domain, mesh types and considerations of flow unsteadiness, were non-dimensionalized by HAWV method with enough accuracy for practical use. It indicates that the above variations might be the options for the computation set up.

1. Introduction

Wind force measurement tests of ships conducted in wind tunnels are mostly performed using smaller scale models than actual ships. The wind forces obtained in this way are normalized and converted back to be used for estimation of the wind forces of actual ships. To the non-dimensionalization, it is necessary to be normalized by the characteristic values such as the air density, the projected area of the ship and the representative wind velocities. Of these parameters, the representative wind velocity is determined according to the procedures or practices of each institution and the non-dimensionalization results in different coefficients of wind forces.

Further, even if it is clear which representative wind velocity is used for the normalization, there is a problem that the wind force coefficients cannot be used as long as the different wind profiles are assumed among the tests or computations. The velocities at the same specific position do not characterize the wind profiles acting on the ship.

In order to solve such problems, the authors tried to calculate the representative wind velocities by integrating the wind profile in a vertical direction with reference to the past literatures1)~4), and have shown its effectiveness5). In this paper, the representative wind velocity determined in this way is called "height average wind velocity" (HAWV).

Here, in order to validate the effectiveness of the height average wind velocity again, the calculations for the wind force estimation were performed by CFD (Computational Fluid Dynamics) using two types of ships, and the wind forces were non-dimensionalized by two kinds of representative wind velocities. The calculations were implemented by several participants using different CFD solvers and different wind profiles. All of the CFD solvers employ a method to solve the Navier-Stokes equation. The CFD results were non-dimensionalized using the wind velocity at a specific position or the height average wind velocity, and the wind force coefficients were compared, respectively.

The height average wind velocity includes the concept of kinetic energy in its derivation process, and it has been shown to be able to reduce the effect on wind force coefficients due to differences in wind profile1)~5). The objective of this paper is to confirm its validity again by the results of CFD calculations.

2. Ship Models

The wind force calculations by CFD were carried out with two types of ships shown in Table 1, where LOA is length overall, LPP is length between perpendiculars and B is breadth. Each ship is a kind of bulk carrier, which is so-called a cape size (JBC: Japan Bulk Carrier) and a handy size (HSBC: Handy Size Bulk Carrier), and has realistic ship shape. Figs. 1 and 2 show the views of front and side projection of the ships. For the JBC model, the modeling of detailed shapes such as handrails or outfittings is omitted, but for the HSBC model, more detailed shapes are reproduced. The

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projected areas shown in these figures are used for non-dimensionalization for wind forces. The CFD calculation results are compared not only between the calculation results but also with the wind tunnel test results, and the wind tunnel test was performed on a model having the same shape as shown in these figures. The wind tunnel used for the measurements was at National Maritime Research Institute, Japan for JBC model, and at Ship Design and Research Centre in Poland for HSBC model.

| Table 1 Dimensions of subject ships in model scale. |
|---------------------------------------------|
| Ship ID | Type            | $L_{om}$ [m] | $L_{pp}$ [m] | $B$ [m] |
|---------|-----------------|--------------|--------------|---------|
| JBC     | Cape size bulker | 1.2484       | 1.2000       | 0.1929  |
| HSBC    | Handy size bulker | 0.9051       | 0.8674       | 0.1501  |

Table 2 Grid parameters for JBC.

| Participant Code | Shape and Dimensions of Computational Domain | Type of Elements | Total Number of Elements |
|------------------|---------------------------------------------|------------------|--------------------------|
| J-1              | Cuboid, $L_{pp} = 6.25 L_{pp}$              | Structured       | 9.6E+06                 |
| J-2              | $L_{pp} = 1.25 L_{pp}$                       | Hexahedral       | 2.1E+06                 |
| J-3.2            | $L_{pp} = 1.67 L_{pp}$                       | Hexahedral       | 1.0E+06 - 1.7E+06       |
| J-3.3            | (Same as the wind tunnel)                   | Polyhedral       | 1.1E+06                 |
| J-5              |                                            | Polyhedral       | 1.5E+06 - 2.0E+06       |
| J-6.2            | Cylindrical                                 | Hexahedral       | 4.1E+06                 |

Table 3 Grid parameters for HSBC.

| Participant Code | Shape and Dimensions of Computational Domain |
|------------------|---------------------------------------------|
| H-1              | Cylindrical, $height = 1.729 L_{pp}$, radius = 5.764 L_{pp} | Prismatic and Tetrahedral | 17.4E+06 |
| H-2.1            | Cuboid, Length and Width $= 5 L_{pp}$, Height $= 2 L_{pp}$ | Tetrahedral | 9.6E+06 |
| H-2.2            | Cuboid, Length and Width $= 5 L_{pp}$, Height $= 2 L_{pp}$ | Prismatic and Tetrahedral | 19.9E+06 |
| H-3              | Cuboid, Length $= 8.647 L_{pp}$, Width $= 1.729 L_{pp}$, Height $= 2.306 L_{pp}$ | Structured | 42.3E+06 |
| H-4              | Cuboid, Length and Width $= 2 L_{pp}$, Height $= 1 L_{pp}$ | Polyhedral | 1.50E+06 |

3. Calculation Conditions

3.1 Grid Parameters

Tables 2 and 3 show the shape of the computational domain, the types and the total number of cells, the dimensionless distance $y'$ of the first layer from the object surface, which were set by each participant.

The names of the organizations or institutions are symbolized as “participant code”, because the CFD results were provided on an anonymous basis. The symbol is the integer or decimal notation that includes the ship identifier J- or H-, where the integer part represents the participants and the decimal part distinguishes the calculation cases by the same participant. The proper nouns of CFD solvers which the participants used are not shown because they may link the calculation results to the participants.

Only one participant chose the structured grid on both ships. The use of the high Reynolds number model using the wall function and the low Reynolds number model that solves the flow near the wall were almost evenly divided. The choice of both models affects the grid resolution near the object, which causes the total number of cells to be different. However, in this comparative calculation, there was no correlation between the choice of the models and the total number of cells. Regarding the shape and size of the computational domain, most participants on JBC model used cuboids of the same size because it was specified to the same shape with the channel of the wind tunnel, but in the case of HSBC, the shape was not specified and each cuboid is different in size.

3.2 Computational Conditions

Tables 4 and 5 list the computational conditions selected by the participants. It describes the boundary conditions of the computational domain and the frictional condition of the floor, the type of turbulence model and the steady or unsteady calculation.

4. Wind Velocity Profiles

The height average wind velocities are calculated using the vertical wind profile obtained at the center of rotation when there is no model ship. Therefore, all participants were required to provide not only the wind force calculation results of the model.
Table 4 Computational parameters for JBC.

| Participant Code | Boundary Condition | Turbulence Model | Time Step [s] |
|------------------|--------------------|------------------|---------------|
| J-1              | Inlet: Velocity inflow Top, Sides: Symmetry Bottom: No-slip | EASM | Steady State |
| J-2              | Inlet: Velocity inflow Top, Sides: Symmetry Bottom: No-slip | \(k-\omega\) SST | Steady State |
| J-3.2            | Inlet: Uniform inflow Top, Sides: Symmetry Bottom: No-slip | \(k-\varepsilon\) realizable, Wall function | Unsteady, 0.01 |
| J-3.3            | Inlet: Uniform inflow Top, Sides: Symmetry Bottom: No-slip | \(k-\omega\) SST, Wall function | Unsteady, 0.0002 |
| J-3.4            | Inlet: Velocity inflow Top, Sides, Bottom: Freeslip | RSM QPS, Wall function | Steady State |
| J-5              | Inlet: Velocity inflow Top, Sides, Bottom: Freeslip | \(k-\omega\) SST, Wall function | Unsteady, 0.0002 |
| J-6.1            | Inlet: Velocity inflow Top, Sides, Bottom: Freeslip | RSM | Steady State |
| J-6.2            | Top: Freeslip Sides: Velocity Bottom: No-slip | \(k-\omega\) SST | Steady State |

Table 5 Computational parameters for HSBC.

| Participant Code | Boundary Condition | Turbulence Model | Time Step [s] |
|------------------|--------------------|------------------|---------------|
| H-1              | Inlet: Velocity inflow Top, Sides, Bottom: Freeslip | \(k-\varepsilon\) SST, Wall function | Unsteady, 0.0002 |
| H-2.1            | Inlet: Velocity inflow Top, Sides, Bottom: Freeslip | \(k-\varepsilon\) realizable, Wall function | Steady State |
| H-2.2            | Inlet: Velocity inflow Top, Sides, Bottom: Freeslip | \(k-\omega\) SST, Wall function | Steady State |
| H-3              | Inlet: Velocity inflow Top, Sides: Symmetry Bottom: No-Slip | EASM | Steady State |
| H-4              | Inlet: Velocity inflow Top, Sides, Bottom: Freeslip | RSM, Wall function | Steady State |

The height average wind velocities is described in a Reference 5, it is shown again in Eqs. (1) and (2). Where, \(H_{BR}\) is the height from the sea surface to the navigation bridge, and \(H_L\) is the average height obtained by dividing the side projected area of the ship model above the water surface by the overall length. \(U_{A1}\) and \(U_{A2}\) are calculated by integrating the profile of the square value of the wind velocity in the range from the bottom corresponding to the sea surface to the representative height, \(H_{BR}\) or \(H_L\), as shown in a conceptual diagram in Fig. 5. The calculated height average wind velocities \(U_{A1}\) and \(U_{A2}\) are summarized in Tables 6 and 7 together with the reference velocity \(U_{ref}\) at the inflow boundary of the calculation area (corresponding to the upstream of the wind tunnel).

\[
U_{A1}^2 = \frac{1}{H_{BR}} \int_0^{H_{BR}} U(z)^2 dz
\]

\[
U_{A2}^2 = \frac{1}{H_L} \int_0^{H_L} U(z)^2 dz
\]

Table 6 Height average wind velocities for JBC.

| Participant Code | \(H_{BR}\) [mm] | \(H_L\) [mm] | \(U_{ref}\) [m/s] | \(U_{A1}\) [m/s] | \(U_{A2}\) [m/s] |
|------------------|-----------------|--------------|-------------------|-----------------|-----------------|
| Exp.             | 121.8           | 49.6         | 25.0              | 23.32           | 20.98           |
| J-1              | 22.71           | 20.14        |                   |                 |                 |
| J-2              | 22.85           | 20.16        |                   |                 |                 |
| J-3.2            | 23.01           | 20.20        |                   |                 |                 |
| J-3.3            | 23.05           | 20.17        |                   |                 |                 |
| J-3.4            | 22.91           | 20.13        |                   |                 |                 |
| J-5              | 25.05           | 25.05        |                   |                 |                 |
| J-6.1            | 24.38           | 23.68        |                   |                 |                 |
| J-6.2            | 23.74           | 22.51        |                   |                 |                 |

Table 7 Height average wind velocities for HSBC.

| Participant Code | \(H_{BR}\) [mm] | \(H_L\) [mm] | \(U_{ref}\) [m/s] | \(U_{A1}\) [m/s] | \(U_{A2}\) [m/s] |
|------------------|-----------------|--------------|-------------------|-----------------|-----------------|
| Exp.             | 112.9           | 71.3         | 20.0              | 19.31           | 16.98           |
| H-3              | 15.94           | 13.94        |                   |                 |                 |
| other than H-3   | 20.00           | 20.00        |                   |                 |                 |

Fig. 3 Wind velocity profiles for JBC.
5. Comparison of Wind Force Coefficients

The wind forces calculated by the participants were non-dimensionalized by $U_{ref}$ and $U_{A1}$, $U_{A2}$, and compared respectively. It is worth noting here that participants had no information about results from the wind tunnel test. The scattering of wind force coefficients, which are dimensionless values of wind forces, are evaluated in each case and discussed the effectiveness of height average wind velocities $U_{A1}$ and $U_{A2}$.

The coordinate system of wind direction and wind forces is shown in Fig. 6, and the equations for calculating the wind force coefficients are shown in Eqs. (3) and (4). Where, $U$ is substituted with $U_{ref}$ or $U_{A1}$, $U_{A2}$; $\rho$ is the air density, $A_T$ and $A_L$ are the front and side projected areas of the model ship, respectively.

$$C_X = \frac{F_X}{\frac{1}{2} \rho U^2 A_T} \quad (3)$$

$$C_Y = \frac{F_Y}{\frac{1}{2} \rho U^2 A_L} \quad (4)$$

5.1 Non-dimensionalization by $U_{ref}$

Figs. 7 ~ 10 show the correlation diagrams between the CFD results and the wind tunnel test results for the wind force coefficients $C_X$ and $C_Y$ of JBC and HSBC models which are non-dimensionalized by $U_{ref}$. The wind tunnel test results are also non-dimensionalized by $U_{ref}$.

In the case of JBC model, only the participant No. 5 (J-5) uses the uniform flow, and as a result, the correlations of $C_X$ and $C_Y$ of the participant No.5 (J-5) are particularly low. This is because the same $U_{ref}$ was used for the non-dimensionalization in all cases, despite the different profiles of wind velocity.
Only participant No.3 (H-3) and wind tunnel test (Exp.) employed the boundary layer flow in the case of HSBC model. The wind forces acting on the models analyzed in different wind profiles are normalized by the same \( U_{ref} \), for the HSBC model as well, and thus the coefficients \( C_x \) and \( C_y \) poorly correlate within each of compared cases. It indicates that \( U_{ref} \) cannot sufficiently reduce the effect of the difference in wind profiles from the wind force coefficients.

5.2 Non-dimensionalization by \( U_{A1} \) and \( U_{A2} \)

Figs. 11 ~ 14 show the correlation diagrams between the CFD results and the wind tunnel test results for the wind force coefficients \( C_x \) and \( C_y \) of JBC and HSBC models which are non-dimensionalized by \( U_{A1} \) and \( U_{A2} \). The wind tunnel test results put down with them are also non-dimensionalized by \( U_{A1} \) and \( U_{A2} \). In the JBC case, only participant No.5 (J-5), and in the HSBC case, only participant No.3 (H-3) and the wind tunnel test (Exp.) estimated the wind forces in the different wind profiles than the others. The correlations of \( C_x \) and \( C_y \) of JBC and HSBC which were non-dimensionalized by height average wind velocities \( U_{A1} \) and \( U_{A2} \) is higher than the case of non-dimensionalization by \( U_{ref} \), and the difference between CFD results and experimental results are roughly within \( \pm 20\% \). This fact means that the height average wind velocities have the effect of reducing the influence of the difference in wind profiles on the wind force coefficients.

5.3 Quantitative Evaluation

In order to quantitatively evaluate the correlation between the CFD results and the experimental results, Root Mean Square Percentage Error (RMSPE) expressed by Eq. (5) is used. Where, \( y_{(CFD)} \) and \( y_{(Exp)} \) are the results of CFD and experiment, respectively and \( n \) is the number of samples for statistical analysis. Since RMSPE is evaluated by the difference between the CFD results and the experimental result, RMSPE will decrease in case that both are normalized with appropriate representative wind velocities.

For each \( U_{ref} \) and \( U_{A1} \), \( U_{A2} \) used as representative wind velocities, the RMSPE for \( C_x \) and \( C_y \) of JBC and HSBC models is calculated and shown in Figs. 15 ~ 18. The application of \( U_{A1} \) and \( U_{A2} \) has reduced the RMSPE of the participant No.5 (J-5) who used the wind profile significantly different from that which occurred in wind tunnel tests of JBC model. Furthermore, in the case of HSBC, although all participants used different wind profiles than the wind tunnel test, the use of height average wind velocities resulted in a decrease in RMSPE of most participants.

These results show quantitatively that especially when the CFD calculation is performed with the wind profile different from the wind tunnel test the effect of the difference in wind profiles can be reduced by using the HAWV.
\[ \text{RMSPE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left( \frac{y_{\text{CFD},i} - y_{\text{Exp},i}}{y_{\text{Exp},i}} \right)^2} \]  \hspace{1cm} (5)

Fig. 11  Correlation diagrams of \( C_T \) of JBC non-dimensionalized by using \( U_{A1} \) between CFD and Experiment.

(a) Following wind side

(b) Head wind side

Fig. 12  Correlation diagram of \( C_T \) of JBC non-dimensionalized by using \( U_{A2} \) between CFD and Experiment.

(a) Following wind side

(b) Head wind side

Fig. 13  Correlation diagrams of \( C_T \) of HSBC non-dimensionalized by using \( U_{A1} \) between CFD and Experiment.

(b) Head wind side

Fig. 14  Correlation diagram of \( C_T \) of HSBC non-dimensionalized by using \( U_{A2} \) between CFD and Experiment.
Discussions

It has been mentioned that the wind forces calculated by the grid parameters and the computational conditions shown in Section 3 improves the correlation with the wind tunnel test results by using HAWV for the non-dimensionalization. In the process, we also obtained useful findings on computational grids and conditions when performing CFD calculations.

First, Tables 2 and 3 show that not only unstructured grids but also structured grids were used. Further, Tables 4 and 5 show that both the low Reynolds number model and the high Reynolds number model using the wall function were used, and that both the steady-state calculation and the unsteady-state calculation were carried out. In all of these CFD results, as long as the height average wind velocities are used, the wind force coefficients are obtained with sufficient accuracy, which suggests that all kinds of the computational grids and conditions described above can be used for practical use.

Conclusions

In order to validate the HAWV effect on reducing the difference in wind forces normalization, the CFD results of wind forces coefficients, implemented by several participants using diverse CFD solvers, were compared. These comparisons were conducted for two kinds of ships with different features of outer shapes. As a result, for both ships, the wind force coefficients calculated from CFD and experimental analyses tend to correlate better when non-dimensionalization is applied with the use of HAWV method, instead of using a reference wind velocity measured at a specific position in a flow channel. Reduction of variance of the wind force coefficients is also confirmed by quantitative evaluation using Root Mean Square Percentage Error, and these facts mean that the usage of the height average wind velocities for the wind force coefficients is validated in the CFD calculations as well. It also indicates that the use of HAWV method allows us to decide more flexible in selection of flow type, uniform or boundary layer, in the wind force estimation process.

Moreover, since the results of CFD for different combinations of calculation conditions such as different boundary conditions, different types of computational grids and differences in the consideration of flow unsteadiness for each participant coincide within an enough accuracy, it can be expressed that there are several options for the above configurations. Those leads to final conclusions that following computational set ups, like:

- a high Reynolds number model with wall function as well as a low Reynolds number model,
- both structured and unstructured grids,
- not only unsteady simulation of flow but also steady flow,

are applicable in hereby presented method.

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