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<tr>
<th>Title</th>
<th>APPLICATION OF CFD TO OPTIMIZATION OF HYDRODYNAMIC PERFORMANCES OF NON BALLAST SHIPS</th>
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APPLICATION OF CFD TO OPTIMIZATION OF HYDRODYNAMIC PERFORMANCES OF NON BALLAST SHIPS

NGO VAN HE

July, 2013

Doctoral Thesis at Osaka Prefecture University
Content of thesis

Abstract.......................................................... 5
Acknowledgements.................................................. 7
List of figure.......................................................... 9
List of table.......................................................... 15
Chapter 1: Introduction............................................. 17

Chapter 2:
Validation of the CFD.............................................
2.1 Model ships using for validation.......................... 21
2.2 Boundary condition and meshing of fluid domain for calculation................................................. 23
2.3 Assessment of CFD results in calm water................. 24
2.4 Assessment of CFD results in regular waves............. 26
2.5 Conclusions of the chapter 2.................................. 28

Chapter 3:
Optimization of bow shape for non ballast water ships
3.1. Design parameters of optimum bulbous bow shape... 29
3.1.1 Volume of bulbous bow...................................... 29
3.1.2 Height of volume center and angle of bow bottom... 32
3.1.3 Length of bow................................................. 34
3.2. Assessment of Effect of Bulbous bow.................. 38
3.2.1 Assessment of effect of bulbous bow on resistance acting on ship in calm water......................... 38
3.2.2 Assessment of effect of bulbous bow on added resistance acting on ship in waves......................... 42
3.2.2.1 Pressure distribution and wave pattern........... 42
3.2.2.2 Added resistance acting on new ships in waves... 47
3.3 Measurement of resistance at towing tank................ 48
3.3.1 Experimental results of resistance in calm water.... 49
3.3.2 Experimental results of resistance in regular head wave with moderate wave

3.4 Conclusions of the chapter 3

Chapter 4:
Resistance acting on a hull of ship in high waves

4.1 Models and fluid domain for computation

4.2. Dynamic pressure and wave pattern
   4.2.1 Wave pattern at free surface
   4.2.2 Dynamic pressure distribution over hull surface of the ships

4.3. Velocity distribution in boundary layer

4.4. Measurement of resistance in high waves

4.5 Conclusions of the chapter 4

Chapter 5:
CFD calculation of air resistance

5.1. Air resistance acting on accommodations of ships
   5.1.1 Box shape accommodation
   5.1.2 Modified box shape accommodation
   5.1.3 Streamlined accommodation
   5.1.4 Optimum shape for accommodation of ship

5.2. Interaction effects between hull and accommodation of ships
   5.2.1 Interaction effects of location of accommodation on deck
   5.2.2 Interaction effects between hull and accommodation

5.3. Conclusions of the chapter 5

Chapter 6: Conclusion of thesis

List of Publications

Bibliography

Nomenclature
Abstract

In this thesis, the author studies on application of CFD to optimized hydrodynamic performance of ships. Both hydrodynamic performances of ships in water and in air are studied in the thesis.

At first, accuracy of the commercial CFD code “Fluent” version 14 which is developed by ANSYS group in the present study is validated by comparing the CFD results with the experimental results at Towing tank of Osaka Prefecture University.

Then, development of new bow shapes for ships with minimum resistance acting on the hulls is discussed in the next chapter of the thesis. The targets of this chapter are to investigate the applicability of the CFD to optimizations of bow shapes of ships in calm water and in head waves. A new series of bow shapes with lower resistance is developed, and the optimum shape is determined by using the CFD. The causes of reducing resistance acting on ships are also clarified by using pressure distribution and wave pattern calculated by the CFD.

In next chapter, added resistances due to high waves are successfully calculated. Resistances acting on three kinds of bow shapes with and without bulbous bows are investigated in high waves by the CFD, and an optimum bow shape is determined. Pressure and wave pattern generated by the ships running in high waves are compared to find the causes of reducing resistance due to bow shapes.

In the last chapter of the thesis, interaction effects between a hull and an accommodation of a ship on its air resistance are investigated by the CFD. Air resistances acting on the whole ship, on the hull part and on the accommodation part are computed to obtain the air resistance acting on each part and the interaction effects. The results of this chapter demonstrate that the interaction effects between the hull and its accommodation house significantly depend on shape and location of accommodation houses. It is also shown how to reduce the total air resistance by using an accommodation house.
Acknowledgements

This thesis would have been impossible without the supports, the guidance and the encouragement of my supervisor Prof. Yoshiho Ikeda. At the 5th Asia-Pacific Workshop on Marine Hydrodynamics – APHydro2010 at Osaka Prefecture University in Japan, I have met him. It is so lucky to me and I could not believe that I could become his PhD student. That is a great time in my life, so I have never forgot it.

First and foremost I would like to sincerely thank my supervisor Prof. Yoshiho Ikeda. That of all I must be talking, that is my great honor to be his student.

And then, I would like to warmly thank Assistant Professor Yasunori Nihei for his kind help and advice during my PhD research at Osaka Prefecture University. Also, I would like to thank you so much to Assistant Satowa Ibata and her students who helped me in my experiment at Towing tank of Osaka Prefecture University.

My gratitude goes to Professors of Department of Marine System Engineering, Officers at Ikeda Laboratory, at Marine System Engineering, International student office of Osaka Prefecture University who helped me during my PhD course.

My special gratitude goes to my fellow lab mates, at Ikeda Laboratory and my friend in Osaka Prefecture University.

I would like to thank you very much to Prof. Toichi Fukasawa and Prof. Nobuhiro Baba who kindly review my thesis and give me valuable comments.

The most important in my life is my family who is always on my side to help and encourage me. It is not enough to say thank you also in my deep gratitude, I warmly thank you so much my parents, my wife and my family I love them so much.

And finally, I would like to thank a lot to all other people in Osaka Prefecture University and outside, ship building companies who helped me in my life, supported to me, touch me Japanese and Japanese culture during my PhD course in Osaka Prefecture University.
## List of Figure

<table>
<thead>
<tr>
<th>Fig.</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Body plan of the simple hull form, named as NBS -original, without bulbous bow</td>
<td>22</td>
</tr>
<tr>
<td>2</td>
<td>Body plan of improved hull form, NBK-N6 with developed bulbous bow to reduce the wave resistance in calm water</td>
<td>22</td>
</tr>
<tr>
<td>3</td>
<td>Fluid domain and meshing</td>
<td>23</td>
</tr>
<tr>
<td>4</td>
<td>Frictional resistance calculated by Schoenherr’s formula and CFD</td>
<td>24</td>
</tr>
<tr>
<td>5</td>
<td>Comparison of total resistance between CFD and experimental results</td>
<td>25</td>
</tr>
<tr>
<td>6</td>
<td>Velocity distribution in boundary layer at centerline of $x/L_{pp}=-0.325$, $F_n=0.163$ in calm water</td>
<td>25</td>
</tr>
<tr>
<td>7</td>
<td>Velocity distribution in boundary layer at centerline of AP; $x/L_{pp}=-0.5$ at $F_n=0.163$ in calm water</td>
<td>26</td>
</tr>
<tr>
<td>8</td>
<td>Fig. 7 Ratio of added resistances due to waves of two ships in wave, $H_w=0.02m$ at $F_n=0.163$</td>
<td>27</td>
</tr>
<tr>
<td>9</td>
<td>Fig. 8 Total coefficient resistance of two ships in waves, $H_w=0.02m$ at $F_n=0.163$</td>
<td>27</td>
</tr>
<tr>
<td>10</td>
<td>Body plans of new ships with developed bulbous bow shapes; NBK-N1~3</td>
<td>30</td>
</tr>
<tr>
<td>11</td>
<td>Calculated total resistance of new ship in calm water</td>
<td>31</td>
</tr>
<tr>
<td>12</td>
<td>Calculated results of total resistance in wave at $F_n=0.163; H_w=0.02m$</td>
<td>32</td>
</tr>
<tr>
<td>13</td>
<td>Side profiles of newly developed ships with different height of volume center and angle of bow bottom line</td>
<td>32</td>
</tr>
<tr>
<td>14</td>
<td>Calculated total resistances of new ships in calm water</td>
<td>33</td>
</tr>
<tr>
<td>15</td>
<td>Calculated results of total resistances in wave at $F_n=0.163; H_w=0.02m$</td>
<td>33</td>
</tr>
<tr>
<td>16</td>
<td>Profiles of bow developed ships; NBK-N5M1~M5</td>
<td>34</td>
</tr>
<tr>
<td>17</td>
<td>Body plans of developed ships; NBK-N5M1~M3 and NBK-N5</td>
<td>35</td>
</tr>
<tr>
<td>18</td>
<td>Body plans of developed ships; NBK-N5M4and NBK-N5M5</td>
<td>36</td>
</tr>
<tr>
<td>19</td>
<td>Calculated total resistances of new ships in calm water; NBK-N5M1, NBK-N5M2</td>
<td>37</td>
</tr>
<tr>
<td>20</td>
<td>Calculated total resistances of new ships in calm water; NBK-N5M3, NBK-N5M4 and NBK-N5M5</td>
<td>37</td>
</tr>
</tbody>
</table>
Fig. 21: Calculated results of total resistances in waves at $F_n=0.163$; $H_w=0.02m$; NBS-original, NBK-N5M1, NBK-N5M2 and NBK-N5.

Fig. 22: Calculated results of total resistances in waves at $F_n=0.163$; $H_w=0.02m$; NBK-N5, NBK-N5M3~M5.

Fig. 23: Ratio of pressure resistances coefficients for NBK-N6 and NBS-original in calm water.

Fig. 24: Dynamic pressure distributions over half-front hulls surface of the ships at $F_n = 0.163$ in calm water.

Fig. 25: Calculated wave patterns at free surface of ships at $F_n=0.163$ in calm water.

Fig. 26: Experiment of wave patterns near bow of ships at $F_n=0.163$ in calm water.

Fig. 27: Profiles of wave generated by ships at $y/L_{pp}=0$; $F_n=0.163$ in calm water.

Fig. 28: Profiles of wave generated by ships at $y/L_{pp}=0.09$; $F_n=0.163$ in calm water.

Fig. 29: Dynamic pressure distributions on half-front hulls surface the ships.

Fig. 30: Waves patterns on free surface in regular head waves, $H_w=0.02m$, $\lambda/L_{pp}=0.3$ at $F_n=0.163$.

Fig. 31: Wave profiles at free surface near bow at $y/B = 0$, in regular head waves, $H_w=0.02m$, $\lambda/L_{pp}=0.3$ at $F_n=0.163$.

Fig. 32: Wave profiles at free surface near bow at $y/B=0.5$ in waves, $H_w=0.02m$, $\lambda/L_{pp}=0.3$ at $F_n=0.163$.

Fig. 33: Calculated results of added resistances in regular head waves with $H_w = 0.02m$, $\lambda/L_{pp}<0.6$ at $F_n=0.163$.

Fig. 34: Experimental models of the ships.

Fig. 35: Comparison between experimental results and CFD results of total resistances acting on hull of NBK-N5 in calm water.

Fig. 36: Comparison in total resistances acting on hulls between NBK-N5 and NBS-original in calm water.

Fig. 37: Comparison in total resistances acting on hull of NBK-N5 between CFD results and experimental one, in regular head waves.

Fig. 38: Comparison in added resistances acting on hulls of NBK-N5 and
NBS-original between CFD and experimental results in waves

Fig. 39  Comparison in total resistances acting on hulls of NBK-N5 and NBS-original between CFD results and experimental one, in regular head waves

Fig. 40  Profiles of bow shapes of the ships, NBS-original, NBK-6 and NBK-N5

Fig. 41  Bow shapes of the ships, NBS-original, NBK-N6 and NBK-N5

Fig. 42  Wave patterns at free surfaces at the moment time 0 in waves, $H_w=0.04m, \lambda/L_{pp}=0.3, F_n=0.163$

Fig. 43  Wave patterns at free surfaces at the moment time 0.25$t_w$ in waves, $H_w=0.04m, \lambda/L_{pp}=0.3, F_n=0.163$

Fig. 44  Wave patterns at free surfaces at the moment time 0.5$t_w$ in waves, $H_w=0.04m, \lambda/L_{pp}=0.3, F_n=0.163$

Fig. 45  Wave patterns at free surfaces at the moment time 0.75$t_w$ in waves, $H_w=0.04m, \lambda/L_{pp}=0.3, F_n=0.163$

Fig. 46  Wave patterns at free surfaces at the moment time $\tau_w$ in waves, $H_w=0.04m, \lambda/L_{pp}=0.3, F_n=0.163$

Fig. 47  Wave patterns at free surfaces at the moment time 0 in waves, $H_w=0.04m, \lambda/L_{pp}=0.6, F_n=0.163$

Fig. 48  Wave patterns at free surfaces at the moment time 0.25$t_w$ in waves, $H_w=0.04m, \lambda/L_{pp}=0.6, F_n=0.163$

Fig. 49  Wave patterns at free surfaces at the moment time 0.5$t_w$ in waves, $H_w=0.04m, \lambda/L_{pp}=0.6, F_n=0.163$

Fig. 50  Wave patterns at free surfaces at the moment time 0.75$t_w$ in waves, $H_w=0.04m, \lambda/L_{pp}=0.6, F_n=0.163$

Fig. 51  Wave patterns at free surfaces at the moment time $\tau_w$ in waves, $H_w=0.04m, \lambda/L_{pp}=0.6, F_n=0.163$

Fig. 52  Profiles of wave around bow when wave crest is at the bow ($t=0.25\tau_w$), $H_w=0.04m, \lambda/L_{pp}=0.3, F_n=0.163$

Fig. 53  Profiles of wave around bow at time 0.75$t_w$, $H_w=0.04m, \lambda/L_{pp}=0.3, F_n=0.163$

Fig. 54  Profiles of wave around bow when wave crest is at the bow
Fig. 55 Profiles of wave around bow when wave trough is at the bow (t=0.25τ_w), H_w=0.04m, λ/L_pp=0.4, F_n=0.163
Fig. 56 Profiles of wave around bow when wave crest is at the bow (t=0.75τ_w), H_w=0.04m, λ/L_pp=0.4, F_n=0.163
Fig. 57 Profiles of wave around bow when wave trough is at the bow (t=0.25τ_w), H_w=0.04m, λ/L_pp=0.6, F_n=0.163
Fig. 58 Dynamic pressure distributions at the moment time 0 in waves, H_w=0.04m, λ/L_pp=0.3, F_n=0.163
Fig. 59 Dynamic pressure distributions at the moment time 0.25τ_w in waves, H_w=0.04m, λ/L_pp=0.3, F_n=0.163
Fig. 60 Dynamic pressure distributions at the moment time 0.5τ_w in waves, H_w=0.04m, λ/L_pp=0.3, F_n=0.163
Fig. 61 Dynamic pressure distributions at the moment time 0.75τ_w in waves, H_w=0.04m, λ/L_pp=0.3, F_n=0.163
Fig. 62 Dynamic pressure distributions at the moment time τ_w in waves, H_w=0.04m, λ/L_pp=0.3, F_n=0.163
Fig. 63 Dynamic pressure distributions at the moment time 0 in waves, H_w=0.04m, λ/L_pp=0.6, F_n=0.163
Fig. 64 Dynamic pressure distributions at the moment time 0.25τ_w in waves, H_w=0.04m, λ/L_pp=0.6, F_n=0.163
Fig. 65 Dynamic pressure distributions at the moment time 0.5τ_w in waves, H_w=0.04m, λ/L_pp=0.6, F_n=0.163
Fig. 66 Dynamic pressure distributions at the moment time 0.75τ_w in waves, H_w=0.04m, λ/L_pp=0.6, F_n=0.163
Fig. 67 Dynamic pressure distributions at the moment time τ_w in waves, H_w=0.04m, λ/L_pp=0.6, F_n=0.163
Fig. 68 Contours of dynamic pressure at the center planes of fluid domain, at the moment time 0 in waves, H_w=0.04m, λ/L_pp=0.3, F_n=0.163
Fig. 69 Contours of dynamic pressure at the center planes of fluid domain, at the moment time 0.25τ_w in waves, H_w=0.04m, λ/L_pp=0.3, F_n=0.163
Fig. 70 Contours of dynamic pressure at the center planes of fluid domain, at the moment time 0.5τ_w in waves, H_w=0.04m, λ/L_pp=0.3, F_n=0.163
the moment time $0.5\tau_w$ in waves, $H_w=0.04m$, $\lambda/L_{pp}=0.3$, $F_n=0.163$

Fig. 71  Contours of dynamic pressure at the center planes of fluid domain, at
the moment time $0.75\tau_w$ in waves, $H_w=0.04m$, $\lambda/L_{pp}=0.3$, $F_n=0.163$

Fig. 72  Contours of dynamic pressure at the center planes of fluid domain, at
the moment time $\tau_w$ in waves, $H_w=0.04m$, $\lambda/L_{pp}=0.3$, $F_n=0.163$

Fig. 73  Contours of dynamic pressure at the center planes of fluid domain, at
the moment time $0$ in waves, $H_w=0.04m$, $\lambda/L_{pp}=0.6$, $F_n=0.163$

Fig. 74  Contours of dynamic pressure at the center planes of fluid domain, at
the moment time $0.25\tau_w$ in waves, $H_w=0.04m$, $\lambda/L_{pp}=0.6$, $F_n=0.163$

Fig. 75  Contours of dynamic pressure at the center planes of fluid domain, at
the moment time $0.5\tau_w$ in waves, $H_w=0.04m$, $\lambda/L_{pp}=0.6$, $F_n=0.163$

Fig. 76  Contours of dynamic pressure at the center planes of fluid domain, at
the moment time $0.75\tau_w$ in waves, $H_w=0.04m$, $\lambda/L_{pp}=0.6$, $F_n=0.163$

Fig. 77  Contours of dynamic pressure at the center planes of fluid domain, at
the moment time $\tau_w$ in waves, $H_w=0.04m$, $\lambda/L_{pp}=0.6$, $F_n=0.163$

Fig. 78  Velocity distributions in boundary layer at centerline of AP of the
ships in calm water at $F_n=0.163$

Fig. 79  Velocity distributions in boundary layer at centerline of AP in one
circle wave of NBS-original running in regular head wave at
$F_n=0.163$, $H_w=0.04m$, $\lambda/L_{pp}=0.6$

Fig. 80  Velocity distributions in boundary layer at centerline of AP in one
circle wave of NBK-N6 running in regular head wave at $F_n=0.163$, $H_w=0.04m$, $\lambda/L_{pp}=0.6$

Fig. 81  Velocity distributions in boundary layer at centerline of AP in one
circle wave of NBK-N5 running in regular head wave at $F_n=0.163$, $H_w=0.04m$, $\lambda/L_{pp}=0.6$

Fig. 82  Computation and measurement of added wave resistances coefficient
acting on the ships in high waves, $\lambda/L_{pp}=0.6$ at Froude number 0.163

Fig. 83  Computation and measurement of added wave resistances coefficient
acting on the ships in high waves, $\lambda/L_{pp}=0.6$ at Froude number 0.163

Fig. 84  Computation and measurement of total resistances coefficient acting
on the ships in high waves, $\lambda/L_{pp}=0.6$ at Froude number 0.163
Fig. 85  Computation and measurement of ratio of total resistances coefficient in waves by total resistance coefficient in calm water of the ships, \( \lambda/L_{pp}=0.6 \) at \( F_n=0.163 \)

Fig. 86  Box shapes accommodations, N1~7

Fig. 87  Contour of dynamic pressure at center plane of N1

Fig. 88  Streamlined accommodation NS

Fig. 89  Contour of dynamic pressure at center plane of streamlined accommodation

Fig. 90  Modified box shape accommodation from N7

Fig. 91  Accommodation with horizontal step in the front

Fig. 92  Modification of rear part of accommodation

Fig. 93  Contour of dynamic pressure at center plane of N7-3

Fig. 94  Dynamic pressure distribution around N7-3.4.1.1.1

Fig. 95  Locations of an accommodation on deck

Fig. 96  Contour of dynamic pressure at center plane of the ship, P1~2

Fig. 97  Contour of dynamic pressure at center plane of the ship, P3~5

Fig. 98  Contour of dynamic pressure at center plane of the ship, P6~6

Fig. 99  Contour of dynamic pressure at center plane of the ship, P9~11

Fig. 100  Contour of velocity around hull of ship at center plane of domain

Fig. 101  Hull and accommodation model N7-3

Fig. 102  Hull and accommodation model N7-3.4.1.1.1

Fig. 103  Hull and streamline accommodation NS.

Fig. 104  Contour of dynamic pressure at center plane and at vertical plane \( z=0.125 \)m of ship with accommodation N7-3

Fig. 105  Contour of dynamic pressure at center plane and at vertical plane \( z=0.125 \)m of ship with accommodation N7-3.4.1.1.1 and NS

Fig. 106  Contour of velocity around hull of ship at center plane and at vertical plane \( z=0.125 \)m of ship with accommodation N7-3

Fig. 107  Contour of velocity around hull of ship at center plane and at vertical plane \( z=0.125 \)m of ship with accommodation N7-3.4.1.1.1

Fig. 106  Contour of velocity around hull of ship at center plane and at vertical plane \( z=0.125 \)m of ship with streamlined accommodation NS
List of Table

Table 1  Principal particular of two models  21
Table 2  Principal particulars of models  31
Table 3  Principal particulars of models  33
Table 4  Principal particulars of models  36
Table 5  Principal particulars of the experimental models of ships  49
Table 6  Dimensions of box shape accommodation, N1  101
Table 7  A comparison of air resistance between CFD result and experimental one  102
Table 8  Dimensions of modified box shape accommodation  103
Table 9  Dimensions of modified box shape accommodation  103
Table 10  Calculated air resistances acting on new accommodations, N2~N7  103
Table 11  Dimensions of streamlined accommodation, NS  104
Table 12  Calculated air resistances acting on accommodations, N1 and NS  105
Table 13  Dimension of new box shapes accommodations  106
Table 14  Calculated air resistance acting on accommodation  106
Table 15  Dimensions of accommodations, N7-3.1~3.5  107
Table 16  Calculated air resistance  107
Table 17  Dimensions of new box shapes accommodations  108
Table 18  Calculated air resistance acting on accommodation  108
Table 19  Dimensions of models with different rear parts  109
Table 20  Calculated air resistance acting on accommodation  109
Table 21  Dimensions of models with different rear parts  109
Table 22  Calculated air resistance acting on accommodation  109
Table 23  Effect of location of accommodation on air resistance acting on ships  111
Table 24  Interaction effects between accommodation and hull on air resistance  112
Table 25  Calculated air resistance  118
Table 26  Interaction effects between hull and accommodation  118
CHAPTER 1:

INTRODUCTION

For long time, model experiments in towing tanks have been playing important roles in developing innovative ship shapes. Because ship hydrodynamics are very complex due to waves generated on free surface between water and air, viscosity of water, vortex shedding flow and so on, very sophisticated experimental methods to grasp hydrodynamic performance of a ship have been established. The methods of model experiences, however, are not suitable to optimize ship shapes because a lot of models and huge numbers of tests are needed. To overcome the problem, for these thirty years, many researchers in Naval Architecture field have worked on developing theoretical methods, called as Computation of Fluid Dynamic (CFD), to solve the Navier Stokes Equation for a ship. In CFD, ship shapes can be easily changed and the hydrodynamic forces acting on many ship shapes can be calculated. Then optimization of ship shapes can be carried out faster and cheaper than model experiments which are expensive and consume a lot of time. Now a day, CFD becomes a popular and powerful tool for developing and designing ships. Many commercial codes of CFD are distributed, and some of them can be applied to calculate hydrodynamic forces acting on ships.

Previous works on application of CFD to hydrodynamic performance of ships in these several years are as follows: Y. Ahmed et al, 2009 presented results of the incompressible free surface flow around the VLCC hull form at Froude number 0.1285 by used CFD code “ANSYS-CFX” and the potential flow code Kelvin. The authors concluded that predicted results of wave pattern and resistance between two codes are good agreement for the VLCC hull. De-cheng Wan et al, 2010 proposed a numerical simulation of viscous flows around surface ship by a level set method. In the paper, numerical simulations of viscous flows around a Wigley hull by coupling the 3D incompressible Reynolds Averaged Navier Stokes Simulation (RANS) equations with a level set method had simulated, the authors used turbulent viscous model k-ω with the Shear Stress Transport formulation (SST) and
concluded that the simulated results of viscous flows around a Wigley hull are in good agreement with experimental results. Y.M. Ahmed, 2011, presented results of incompressible turbulent free surface around the hull form of the DTMB 5415 at two speeds by using CFD code “ANSYS-CFX” with RANS method, and used Volume of Fluid (VOF) turbulent viscous model k-ε. The author concluded that turbulent free surface flow around DTMB 5415 at two Froude number are in agreement with experimental data. C. Ciortan et al, 2012, developed a free surface, turbulent flow code by using the slightly compressible flow formulation, and tested flow around the hull of Wigley ship. The authors concluded that simulated results are in good agreement with experimental one. Zhi-rong Zhang et al, 2006, applied CFD code with RANS formulations for simulated viscous free surface flow along the hull of Series 60 (C_b=0.6) at several Froude number and wake flow of a complex surface hull with various appendages. The authors concluded that CFD results of series 60 are good agreement with experimental results. Bing-jie Guo et al, 2011, evaluated added resistance of KVLCC2 in short and head waves by CFD. Shukui Liu et al, 2011, used a established frequency domain 3D panel method and a new hybrid time domain Rankine source Green function method to predict the added resistance of the ship and tested on the hulls of Wigley ship, Series 60 (C_b=0.6) and S-175 container ship. Haixuan Ye et al, 2012, presented results of the numerical prediction of added resistance and vertical ship motions of the hull of S-175 container ship in regular head wave by used RANS formulation. Bing-jie Guo et al, 2012, predicted the added resistance of KVLCC2 hull in regular head waves by using CFD with RANS. And, H.S. Hosseini et al, 2013, applied CFD to predict added resistance, ship motion and wake flow of the KVLCC2 hull in regular waves. Almost all of the papers concluded that CFD could predict the performance of the ships (Wigley, KVLCC2, DTMB 5415 and Series 60) with high accuracy. It was also concluded that pressure resistance dominates in the ship resistance in waves, and the frictional resistance due to waves is small.

In the present study, a commercial CFD code “Fluent” is applied to calculations of hydrodynamic performance of ships in calm water, in head waves and in head winds. Model experiments are indispensable to validate the computed results by CFD. In CFD simulations the simulated results must be regularly tested by the corresponding experiments because CFD sometimes gives wrong results under inappropriate calculation conditions. Therefore some experiments to measure resistances acting on ships in calm
water and in waves are carried out to validate the CFD results. The Practical Guideline for Ship CFD Applications updated in 2011 by the 26th International Towing Tank Conference (ITTC) was also referred for the tunings of the calculating conditions.

The CFD code is applied to optimization of bow shapes to reduce resistances acting on the ships in calm water and in regular head waves, and optimization of accommodation shapes to reduce air resistance and interaction effects between hulls and accommodations on air resistance acting on the ship. Results of the study are presented in five chapters in this thesis including this chapter as follows.

In the chapter 2, validations of the CFD results of the flow around ship hulls and resistance acting on them in calm water and in regular head waves are carried out by comparing the results with experimental results. As well known, CFD results depend on calculation domain, number and shape of meshes and turbulent models. A lot of calculations of the CFD for various calculating conditions are carried out, and the results are carefully compared with the experimental results. As the results, appropriate conditions in CFD are determined. The conclusions of this chapter are that accuracy of the CFD code is fairly good for the present purposes and that the CFD code could give us much information about pressure distributions, wave patterns and flow field in boundary layer as well as the total resistance acting on ship hulls.

In the chapter 3, the CFD is applied to optimization of the bow shape in terms of the resistances in calm water and in regular head waves. In these applications Non Ballast Water Ships which was developed at Laboratory of Prof. Ikeda in Osaka Prefecture University is selected as an object ship. In the chapter, some series of bow shapes for the non-ballast water ship is systematically developed. Resistance acting on each hull is calculated and compared among hulls of the series to find a minimum resistance hull form.

Computed results given by the CFD like resistance, pressure and wave pattern making by ship movement both of in calm water and in waves are used for developing hull shapes in the optimization processes. An optimal bow shape for the ship could be found by comparing the results each other in series of bow shapes. In the computation in waves, the ship is in fully captured condition because shorter waves in \( \lambda/L_{pp} < 0.6 \) are assumed here.

From results of comparison among the CFD results of pressure distribution over hull
surface, wave patterns making by the ships running in calm water and in regular head waves, and added resistance acting on the ships, the assessments of effect of bulbous bow on resistance acting on the ships in calm water and in regular head waves are carried out. The calculated resistances acting on the hull with the optimum bulbous bow are compared with the experimental results to show that the optimization method used by the commercial CFD code in this thesis is valid.

In the chapter 4, the CFD is used to reveal the characteristics of the added resistance due to high waves. The effect of wave height on the added resistance due to waves is clarified. Three kinds of bow shapes of the ship which were developed at previous chapter, NBS-original without bulbous bow, improved bulbous bow shape NBK-N6 and optimum bow shape NBK-N5, added resistances acting on them are computed in higher regular head waves. The range of waves height is in 0.02~0.07m for the 2m model, and the ratio of wave length to ship length is smaller than 0.6 ($\lambda/L_{pp} < 0.6$). By comparing the computed results of pressure, wave pattern and resistance acting on hull among three ships, the best bow shape for ships in high waves is found. Measurements of resistance acting on the three ships in high waves are carried out and the experimental results are compared with those of CFD results.

In the chapter 5, air resistance acting on ships is computed by the CFD to find the optimum shape above water surface with minimum air resistance. At first, air resistances acting on some kinds of accommodations shapes of ships are investigated. By comparison among the calculated results of pressure distribution and air resistances acting on the accommodations, an optimum accommodation shape is found. And then, air resistance acting on a hull with an accommodation on its deck is computed. From the calculated results of air resistances acting on the hull, the accommodation and the hull with the accommodation on the deck, the interaction effects between hulls and accommodations are clarified. By comparison among the calculated results of air resistance each other, the best location of an accommodation on the deck and the best shape of accommodations with the smallest air resistance are found. The computed results suggest that interaction effects between the hull and the accommodation of a ship on its air resistance are important.

In the chapter 6, the conclusions obtained in the present study are summarized.
CHAPTER 2:
VALIDATION OF THE CFD

2.1 Model ships using for validation

In this chapter, accuracy of CFD results is validated by comparing the calculated results with experimental results at towing tank of Osaka Prefecture University. Resistance acting on a hull of a ship in calm water as well as in regular head waves, and velocity distribution in boundary layer of ship are validated.

Figs. 1 and 2 show the models of Non Ballast Water ships using for validating the CFD code. One is a simple bow shape without bulbous bow named as “NBS original”, and another one is the improved one, named as “NBK-N6”, with large bulbous bow to reduce the wave resistance in calm water. NBS means Non Ballast-water Ship and NBK means Non Ballast Tankers and Bulkers which was developed at Ikeda’s Lab. These ships have the same stern shape but different bow shapes. Table 1 shows the principal particulars of them.

Table 1 Principal particular of two models

<table>
<thead>
<tr>
<th>No</th>
<th>NBS-original</th>
<th>NBK-N6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length, L_{pp} (m)</td>
<td>2.000</td>
<td>2.000</td>
</tr>
<tr>
<td>Breadth, B (m)</td>
<td>0.359</td>
<td>0.355</td>
</tr>
<tr>
<td>Draft (m)</td>
<td>0.131</td>
<td>0.131</td>
</tr>
<tr>
<td>Displacement, Dispt (ton)</td>
<td>0.06504</td>
<td>0.06388</td>
</tr>
<tr>
<td>Wetted surface area, WSA (m²)</td>
<td>0.921</td>
<td>0.925</td>
</tr>
</tbody>
</table>
Fig. 1 Body plan of the simple hull form, named as NBS -original, without bulbous bow

Fig. 2 Body plan of improved hull form, NBK-N6 with developed bulbous bow to reduce the wave resistance in calm water
2.2 Boundary condition and meshing of fluid domain for calculation

For the CFD calculations, a larger domain of fluid is better but causes longer computing time. Therefore, an appropriate domain of fluid should be selected for matching the ability of processor. The practical guideline for ship CFD applications updated in 2011 by the 26th International Towing Tank Conference (ITTC) is referred for the tunings of calculating conditions. Since the experiments for the comparisons in this thesis were carried out for 2m models, the domain of fluid is determined in 10m of length, 2.6m of breadth and 1.5m of depth. Meshing of this domain is done in structure mesh with 1.6 million Hex-Grid, the value of $y+$ is about 50~250 and the smallest quality of mesh is about 0.4. Meshing and fluid domain are shown in Fig. 3.

In computations, a commercial CFD code “Fluent” is used. The Volume of Fluid model (VOF) k-ω for unsteady flow is used. For VOF problem in calm water condition, the conditional boundary is setup with the pressure inlet at the inlet, the pressure outlet at the outlet. In computing condition with regular head waves, at the inlet is setup with velocity inlet, and opening channel condition with regular head wave is setup at free surface of calculating fluid domain. The problem is simulated in unsteady flow, and two phases of air and water are set. The target of residual convergence is set at $10^5$ for this problem.

Fig. 3 Fluid domain and meshing
2.3 Assessment of CFD results in calm water

Accuracy of the CFD results of resistances is validated by comparing the results with the experimental results in Towing tank of Osaka Prefecture University.

In Fig. 4 the frictional resistances acting on the hulls of these ships obtained by Schoenherr`s formula and the CFD code are compared. Slight difference between them can be seen.

Fig. 5 shows the comparison between the calculated and the experimental results of total resistances acting on the ships in calm water. The agreement between the calculated and experimental results is fairly good.

The computed and measured velocity distributions in boundary layers at stern part are compared in Fig. 6. The agreement between them is fairly good, and we can say that viscous forces are obtained in good accuracy by the CFD code.

In Fig. 7, the velocity distributions in boundary layer at AP obtained by the experiments and the CFD computations are compared. The agreement between them becomes a little worse compared with that in Fig. 6. It should be noted that the AP of the ships is located at the end of ships.

![Fig. 4 Frictional resistance calculated by Schoenherr`s formula and CFD](image-url)
Fig. 5 Comparison of total resistance between CFD and experimental results

Fig. 6 Velocity distribution in boundary layer at centerline of $x/L_{pp} = -0.325$, $F_n = 0.163$ in calm water
2.4 Assessment of CFD results in regular waves

In this section, accuracy of the calculated results by the CFD code in regular head waves will be assessed by comparing the calculated results for the two models with experimental results measured by the author. The incident waves are shorter and regular head ones ($\lambda/L_{pp}<0.6$) and the wave height is $H_w=0.02m$ for 2m models of them. Froude number is 0.163.

In Figs 8 and 9, the calculated and experimental results of resistances are shown in terms of a ratio of resistance coefficients of NBK-N6 to that of NBS-original model. The results show that agreement between CFD results and experimental results of total resistance of ship in regular head waves is fairly good. Added resistance acting on the ship in regular waves could reduce about by 25% by the developed bulbous bow of NBK-N6.
Fig. 8 Ratio of added resistances due to waves of two ships in wave, 
$H_w = 0.02m$ at $F_n = 0.163$

Fig. 9 Total coefficient resistance of two ships in waves, $H_w = 0.02m$ at $F_n = 0.163$
2.5 Conclusions of the chapter 2

- It is confirmed that a commercial CFD code “Fluent” gives us fairly good results of the resistance acting on a ship hull both in calm water and in regular head waves, viscous flow in boundary layer around it in calm water.

- The frictional resistances computed by the CFD code and Schoenherr’s formula are slightly different.

- The calculated results of the ratio of added resistance due to wave of two ships are in good agreement with the experimental results.

- The improved bulbous bow shape of NBK-N6 could reduce by 10% of total resistance in calm water and by 17% of total resistance in regular head waves with the wave height $H_w=0.02m$ and relative wave length $\lambda/L_{pp}<0.6$, in compared with that of NBS-original. The results are close with the calculated results given by the CFD code.
CHAPTER 3:

OPTIMIZATION OF BOW SHAPE
FOR NON BALLAST WATER SHIPS

3.1. Design parameters of optimum bulbous bow shape

In this chapter, at first the commercial CFD ‘Fluent’ is applied to optimization of the bulbous-bow shape of the Non Ballast Water ship. And then, assessment of effects of bulbous bow shape on reduction of resistances acting on a ship is discussed. Lastly, predicted results given by the CFD are validated by comparing them with experimental results.

For this section, the resistance acting on the ship in calm water and in regular head waves is defined as the object function in the optimization process. Following features of bulbous bow shapes are considered as design parameters that are volume of bulbous bow, height of volume center, angle of bow bottom and length of bulbous bow.

3.1.1 Volume of bulbous bow

In this optimizing process, the original ship with a blunt simple bow, NBS-original, which was developed in the research project to develop a non-ballast water ships at Ikeda’s Lab of Osaka prefecture University is selected as the initial model. NBS-original was experimentally confirmed to have some wave resistance in low Froude number, 0.15, and a bulbous bow is needed to reduce the wave resistance. An optimum bulbous bow shape for the ship is developed in the optimizing process by using the CFD. The stern of the ship is the same as that of NBS-original for all ships. The length, breadth and draft of the ships keep to be the same. The volume of the ships is slightly changed from NBS-original.
Fig. 10 Body plans of new ships with developed bulbous bow shapes; NBK-N1, NBK-N2 and NBK-N3
Table 2 Principal particulars of models

<table>
<thead>
<tr>
<th>No</th>
<th>L_{pp} (m)</th>
<th>B (m)</th>
<th>draft (m)</th>
<th>Dispt (ton)</th>
<th>WSA (m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NBK-N1</td>
<td>1.998</td>
<td>0.355</td>
<td>0.129</td>
<td>0.06445</td>
<td>0.9626</td>
</tr>
<tr>
<td>NBK-N2</td>
<td>1.998</td>
<td>0.355</td>
<td>0.130</td>
<td>0.06443</td>
<td>0.9539</td>
</tr>
<tr>
<td>NBK-N3</td>
<td>1.999</td>
<td>0.355</td>
<td>0.131</td>
<td>0.06469</td>
<td>0.9539</td>
</tr>
</tbody>
</table>

Fig. 10 shows the body plans of newly developed ships. The principal particulars of them are shown in Table 2. The resistances acting on them are calculated by using the CFD code. Total resistances acting on them running in calm water and in regular head waves are shown in Figs. 11 and 12. In the calculation in waves, the ship is assumed to run in constant speed in fully captured condition, or without any ship motions in waves because the wave length is assumed to be short compared with the ship length.

The results shown in Fig. 11 demonstrate that the bulbous bow of NBK-N1 is too large to decrease the wave resistance and NBK-N3 has minimum resistance in calm water.

The results in waves shown in Fig. 12 demonstrate that NBK-N3 has the minimum resistance in shorter waves, $\lambda/L_{pp}=0.3$ and 0.4, but NBK-N2 has smaller resistance than NBK-N3 in $\lambda/L_{pp}=0.5$ and 0.6. The results suggest that the optimum bulbous bow depends on wave length of encounter waves.

![Fig. 11 Calculated total resistance of new ship in calm water](image-url)
3.1.2 Height of volume center and angle of bow bottom

In next step, the height of volume center of the bulbous bow and angle of bow bottom line of the ships are changed from low to high as shown in Fig. 13. The NBK-N3 is the best one in case of optimum volume of bow shape in calm water as shown in previous section. Table 3 shows their principal particulars.

NBK-N3:

NBK-N4:

NBK-N5:

NBK-N6:

Fig. 13 Side profile of newly developed ships with different height of volume center and angle of bow bottom line
Table 3 Principal particulars of models

<table>
<thead>
<tr>
<th>No</th>
<th>$L_{pp}$ (m)</th>
<th>$B$ (m)</th>
<th>draft (m)</th>
<th>Dispt (ton)</th>
<th>WSA ($m^2$)</th>
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<tr>
<td>NBK-N4</td>
<td>1.999</td>
<td>0.355</td>
<td>0.131</td>
<td>0.06376</td>
<td>0.9383</td>
</tr>
<tr>
<td>NBK-N5</td>
<td>2.000</td>
<td>0.355</td>
<td>0.134</td>
<td>0.06455</td>
<td>0.9317</td>
</tr>
<tr>
<td>NBK-N6</td>
<td>2.000</td>
<td>0.355</td>
<td>0.131</td>
<td>0.06388</td>
<td>0.9250</td>
</tr>
</tbody>
</table>

Fig. 14 Calculated total resistance of new ship in calm water

Fig. 15 Calculated results of total resistance in wave at $F_n = 0.163; H_w = 0.02m$
Figs. 14 and 15 show the calculated results of resistance acting on them in calm water and in regular head waves. The calculated results of resistance in calm water shown in Fig. 14 show that NBK-N6 is the best one at Froude number of 0.14 but that NBK-N5 is the best one at Froude number of 0.16 and 0.18. The optimum bow shape in waves depends on Froude number as well as in calm water.

In regular head waves, NBK-N5 has the minimum resistance in wave height, $H_w$, of 0.02m and in the wave length region of $\lambda/L_{pp} < 0.6$ as shown in Fig. 15.

### 3.1.3 Length of bow

In next step, length of bow of NBK-N5, which has the minimum resistance hull form in previous optimum process, is changed. The volume of each newly developed ship keeps the same as that of NBK-N5. Figs 16–18 show the profiles on centerline of bows and body plans of them. Their principal particulars are shown in Table 4.

Figs 19–22 show the calculated results of resistance acting on newly developed ships in calm water and in regular head waves. The calculated results show that model named as NBK-N5 is the minimum resistance hull form in calm water and in regular head waves in this series.

---

Fig. 16 Profiles of bows developed ships; NBK-N5M1–M5
Fig. 17 Body plans of developed ships; NBK-N5M1~M3 and NBK-N5
NBK-N5M4:

NBK-N5M5:

Fig. 18 Body plans of developed ships; NBK-N5M4 and NBK-N5M5

Table 4 Principal particulars of models

<table>
<thead>
<tr>
<th>No</th>
<th>L&lt;sub&gt;pp&lt;/sub&gt; (m)</th>
<th>B (m)</th>
<th>draft (m)</th>
<th>Dispt (t)</th>
<th>WSA (m&lt;sup&gt;2&lt;/sup&gt;)</th>
</tr>
</thead>
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<tr>
<td>NBK-N5M5</td>
<td>2.083</td>
<td>0.371</td>
<td>0.128</td>
<td>0.06504</td>
<td>0.9445</td>
</tr>
<tr>
<td>NBK-N5M4</td>
<td>2.080</td>
<td>0.370</td>
<td>0.128</td>
<td>0.06504</td>
<td>0.9497</td>
</tr>
<tr>
<td>NBK-N5M3</td>
<td>2.078</td>
<td>0.369</td>
<td>0.128</td>
<td>0.06504</td>
<td>0.9535</td>
</tr>
<tr>
<td>NBK-N5M2</td>
<td>2.075</td>
<td>0.369</td>
<td>0.127</td>
<td>0.06504</td>
<td>0.9616</td>
</tr>
<tr>
<td>NBK-N5M1</td>
<td>2.073</td>
<td>0.368</td>
<td>0.127</td>
<td>0.06504</td>
<td>0.9686</td>
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</tbody>
</table>
Fig. 19 Calculated total resistances of new ships in calm water; NBK-N5M1, NBK-N5M2

Fig. 20 Calculated total resistances of new ships in calm water; NBK-N5M3, NBK-N5M4 and NBK-N5M5

Fig. 21 Calculated results of total resistances in waves at $F_n = 0.163$; $H_w = 0.02m$; NBS-original, NBK-N5M1, NBK-N5M2 and NBK-N5
3.2. Assessment of Effect of Bulbous bow

As well known, a bulbous bow which is appropriately designed can reduce the wave resistance by using interference effect of waves generated by the bulbous bow and the main hull. This section discusses about assessment of effect of bulbous bow to understand that causes of reducing the resistances by an appropriately designed bulbous bow.

3.2.1 Assessment of effect of bulbous bow on resistance acting on ship in calm water

The computed results of the two ships, NBS-original without bulbous bow and NBK-N6 with a developed bulbous bow are compared in this section.

Fig. 23 shows reduction of the pressure resistance of NBK-N6 from that of the NBS-original. In the pressure resistance, wave and viscous pressure resistances are included. We can see that the pressure resistance decreases due to the bulbous bow of NBK-N6 with increasing advanced speed and is smaller by 70% than that of NBS-original at Froude number of 0.15. In the figure the experimental results of residual resistance component are also shown. The agreement between them is in fairly good.

The computed results of dynamic pressures at just outside of boundary layer and wave pattern around the hulls of the two ships running in calm water at Froude number of 0.163 are shown in Figs. 24 and 25. These results give us some important information for understanding the reasons why the bow shape reduces resistances acting on a ship in calm water and waves.
The calculated dynamic pressure distribution over the half front hull surface of each ship is shown in Fig. 24. The results at Froude number of 0.163 are shown in the figures. Wide and low dynamic pressure area (blue area) over the front-edge of bow of NBS-original disappears on the bow of NBK-N6 with the bulbous bow. Since low dynamic pressure causes high pressure over the hull surface, the resistance acting on the hull must increase if the area of low dynamic pressure area is wide. On the contrary lower dynamic pressure (Red or yellow area in the figures) reduces the resistance. From these dynamic pressure distributions, we can imagine how the bulbous bows change the flow around the hulls and the pressure over the hull surface.

Fig. 23 Ratio of pressure resistance coefficients for NBK-N6 and NBS-original in calm water

NBS-original:

Fig. 24a Dynamic pressure distribution over half-front hull surface of the ship at \( F_n = 0.163 \) in calm water
NBK-N6:

Fig. 24b Dynamic pressure distribution over half-front hull surface of the ship at $F_n = 0.163$ in calm water.

NBS-original:                         NBK-N6:

Fig. 25 Calculated wave patterns at free surfaces of ships at $F_n = 0.163$ in calm water

NBS-original:                         NBK-N6:

Fig. 26 Experiments of wave patterns near bow of ships at $F_n = 0.163$ in calm water
Fig. 25 shows the calculated free-surface levels around the bows of NBK-N6 and NBS-original. The results demonstrate higher and wider waves are created in front of the bow of NBS-original than that of NBK-N6. It can be seen that the waves near shoulder are also different in them. In Fig. 26 photographs of bow waves of NBK-N6 and NBS-original which are taken in a circulating water channel are shown. Similar wave patterns to the calculated results obtained by the CFD can be seen in the experimental photographs.

In Figs. 27 and 28 calculated wave profiles in front of the bows of NBK-N6 and NBS-original are shown. In the figures, x denotes longitudinal axis, the origin of which is at the mid-ship. The results demonstrate that generated waves in calm water are significantly reduced by the newly developed bulbous bow of NBK-N6.

![Fig. 27 Profiles of wave generated by ships at y/B=0; F_n =0.163 in calm water](image)

![Fig. 28 Profiles of wave generated by ships at y/B=0.5; F_n =0.163 in calm water](image)
3.2.2 Assessment of effect of bulbous bow on added resistance acting on ship in waves

In this section, assessment of effect of bulbous bow on added resistance acting on a hull in regular head waves is discussed to find reasons why the added resistance due to waves depends on bow shapes. Pressure distribution over hull surface of ships and wave pattern at free surface generated by ships moving in waves are computed by the CFD. From the comparison among the computed results of pressure and wave pattern of ships in waves may be found the reasons of reduction of added resistance by bow shape of ships.

3.2.2.1 Pressure distribution and wave pattern

Fig. 29 shows the computed dynamic pressure distribution over half-front surface of hulls running in regular head waves which are $H_w = 0.02m$ and $\lambda/L_{pp} = 0.3$, at $F_n = 0.163$.

Fig. 29a Dynamic pressure distributions on half-front hull surface the ships
Fig. 29b Dynamic pressure distributions on half-front hull surface of developed ships in regular head waves, $H_w = 0.02m$, $\lambda/L_{pp} = 0.3$ at $F_n = 0.163$

Figs. 29a and b clearly show different pressure distributions over half-front surface of the hulls with newly developed bow shapes in regular head waves. The area where is in lower dynamic pressure (blue area in the figure) is in higher static pressure acting on the hull surface. This means that smaller high pressure area induces higher added resistance.
The results demonstrate that the newly developed bow shapes may reduce the resistance in waves.

Figs. 30 and 31 show the computed wave pattern at free surface of ships moving in regular head waves with height wave; $H_w=0.02m$ and wave length; $\lambda/L_{pp}=0.3$, at Froude number of 0.163.

NBS-original:

NBK-N1:

NBK-N2:

NBK-N3:

Fig. 30a Waves patterns on free surfaces in regular head waves, $H_w=0.02m$, $\lambda/L_{pp}=0.3$ at $F_n=0.163$
Fig. 30b Waves patterns on free surfaces in regular head waves, $H_w=0.02m$, $\lambda/L_{pp}=0.3$ at $F_n=0.163$

Fig. 31a Wave profiles at free surfaces near bow at $y/B = 0$, in regular head waves, $H_w=0.02m$, $\lambda/L_{pp}=0.3$ at $F_n=0.163$
Fig. 31b Wave profiles at free surfaces near bow at $y/B = 0$, in regular head waves, $H_w = 0.02\,\text{m}$, $\lambda/L_{pp} = 0.3$ at $F_n = 0.163$.

Fig. 32 Wave profiles at free surfaces near bow at $y/B = 0.5$ in waves, $H_w = 0.02\,\text{m}$, $\lambda/L_{pp} = 0.3$ at $F_n = 0.163$.
Figs. 31 and 32 show the calculated profiles of waves at free surface near the bow of the ships. x is longitudinal axis, the origin of which is located at the mid-ship and y is transverse axis, the origin of which is located in the centerline of the ship.

Figs. 30~32 clearly show that generated waves by the ships in waves on free surface depend on the developed bow shapes and decrease with bulbous bow compared with those of the original model. The results may suggest that wave resistance of newly developed hull forms decrease in regular head waves.

### 3.2.2.2 Added resistance acting on new ships in waves

In this section, added resistances acting on the new ships in waves are computed. The results are compared with each other to find the minimum added resistance hull form.

Fig. 33 shows the computed added resistance of the ships in waves with wave height; \(H_w=0.02\text{m}\) and at \(F_n=0.163\). The added resistance coefficient is defined as follows:

\[
C_W = C_{T(W)} - C_{T(O)}
\]

where \(C_{T(W)}\) and \(C_{T(O)}\) are the coefficients of total resistance acting on ship in waves and in calm water, respectively.

Fig. 33a Calculated results of added resistance in regular head waves with \(H_w=0.02\text{m}\), \(\lambda/L_{pp}<0.6\) at \(F_n=0.163\)
These results show that the ships with developed bulbous bows have smaller added resistance than that of NBS-original. The results also demonstrate that the added resistances acting on ships depend on wave length. At $\lambda/L_{pp}<0.4$ NBK-N1 with a larger bulbous bow has the minimum added resistance, but at $\lambda/L_{pp}>0.4$ NBK-N5 has the minimum added resistance.

In the computed results, we can see different characteristics of the added resistance in waves. The added resistances due to waves acting on NBK-N1 and NBK-N3 with larger bulbous bow and on NBS-original with a blunt bow increase with wave length. On the contrary, the added resistances acting on hulls with smaller bows like NBK-N4, NBK-N5 and NBK-N6 decrease with wave length, as shown in Figs. 33a and b.

### 3.3 Measurement of resistance at towing tank

In this section, experiments of the optimum hull shape are carried at the towing tank of Osaka Prefecture University. The scale model is in 2m of length, and is fixed to the towing carriage in calm water and in regular head waves at Froude number 0.163. The wave height ($H_w$) is 0.02m and relative wave length ($\lambda/L_{pp}$) is lower than 0.6.

Fig. 34 shows photographs of the scale models of NBS-original and NBK-N5 used for measurement of resistance acting on hulls. Table 5 shows principal particulars of the experimental models of them.
NBS-original:

NBK-N5:

Fig. 34 Experimental models of the ships

Table 5 Principal particulars of the experimental models of ships

<table>
<thead>
<tr>
<th>No</th>
<th>$L_{pp}$ (m)</th>
<th>B (m)</th>
<th>draft (m)</th>
<th>Dispt (t)</th>
<th>WSA (m$^2$)</th>
</tr>
</thead>
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<td>NBS-original</td>
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<td>0.0667</td>
<td>0.8980</td>
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<td>NBK-N5</td>
<td>2.077</td>
<td>0.360</td>
<td>0.131</td>
<td>0.0668</td>
<td>0.9701</td>
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</tbody>
</table>

3.3.1 Experimental results of resistance in calm water

Fig. 35 shows the comparison between the experimental results and the CFD results of total resistance coefficient of NBK-N5 in calm water. The results show that the agreement between them is fairly good. Fig. 36 shows the comparison in the total resistance between NBS-original and NBK-N5 in calm water. The resistances acting on the ships are closed each other in low Froude number region. It is difficult from the experimental results to find differences between the two models, but slight difference between them can be clearly seen in the CFD results. It may demonstrate that CFD is an appropriate tool to identify such small differences of resistances.
3.3.2 Experimental results of resistances in regular head waves with moderate wave height at towing tank

Experiments of the ship in regular head waves with moderate wave height are carried at the towing tank of Osaka Prefecture University. The scale model is fixed to the towing carriage in regular head short waves at Froude number of 0.163. Incident waves are much shorter than ship length, \( \lambda/L_{pp} < 0.6 \), because the non-ballast water ships are planned to be huge.
Fig. 37 shows the comparison of the total resistance coefficient of NBK-N5 between calculated by the CFD and experimental results. Fairly good agreement between them can be seen in the figure.

Figs. 38 and 39 show clearly reduction of resistance acting on NBK-N5 in comparison with those of NBS-original.

The results show that the CFD results are in good agreement with the experimental results. The experimental results demonstrate that the resistance acting on NBK-N5 is smaller than that on NBS-original at region of $\lambda/L_{pp}<0.6$. It can be said that the bow of NBK-N5 could reduce added resistance due to waves by 60% and total resistance in waves by 15% from those of NBS-original.
3.4 Conclusions of the chapter 3

In this chapter, by using a commercial CFD code “Fluent” an optimum bulbous bow for a Non Ballast Water ship in calm water and in regular head waves is developed, and following conclusions are obtained:

- Series of bow shapes to reduce the resistance in waves as well as in calm water are developed and the resistances of the series of hulls are calculated by the CFD code to find an optimum bow shape. The optimum bow shapes among the developed hulls are determined by comparing the calculated resistances for the hulls.

- The CFD results show that the optimum hull shape in calm water depends on Froude number although this is already common in the ship hydrodynamic field.

- The CFD code gives us a lot of important information like pressure distributions on the hull surface, wave patterns at free surface, and so on. The information plays an important role for understanding the phenomenon which causes the added resistance due to waves.

- The calculated results are in good agreement with the experimental one. The optimum hull shape NBK-N5 can decrease the added resistance in regular head waves by 60% and total resistance by 15% in moderate short head waves ($H_w=0.02m$ and $\lambda/L_{pp}<0.6$) at Froude number of 0.163.
4.1 Models and fluid domain for computation

In this chapter, added resistances acting on a ship in high waves are theoretically and experimentally investigated. In previous chapters, incident waves are assumed to be moderate. For a 2m model for experiments and calculations, the wave height is 0.02m. This means that the wave height is 15% of draft of the ship in full load condition. In this chapter, added resistances in high waves up to 0.07m for a 2m model or 53% of the full load draft are investigated. In such high waves linear wave theories which have been using in design stage of a ship for a long time may not work well anymore, and experiments are only tool to predict the added resistance in high waves.

Some newest CFD codes have an ability to calculate the nonlinear hydrodynamic forces. Only serious problem for calculations of hydrodynamic forces may be numbers of memories of the computers and long computing times because huge numbers of meshes must be arranged near free surfaces oscillating in large amplitudes. In calculations of added resistance in high waves, only half symmetry domain is used. Then double numbers of meshes can be used and small meshes can be distributed near free surfaces.

Three ship models are selected as the object ones, NBS-original, NBK-N5 and NBK-N6. NBS-original was the original hull shape developed in the research project of non-ballast water ships, and NBK-N6 has the improved bulbous bow, NBK-N5 is the optimum hull in moderate regular head waves developed in Chapter 3. Figs. 40 and 41 show the bow shapes of them. Their stern shapes are same.
4.2. Dynamic pressure and wave pattern

4.2.1 Wave pattern at free surface

In this section, calculated waves by the CFD in the conditions; \( H_w=0.04 \text{m}, \lambda/L_{pp}=0.3, 0.6 \) and \( F_n=0.163 \), are shown. The computed wave patterns in a wave cycle for \( \lambda/L_{pp}=0.3 \) and 0.6 are shown in birds-eye view in Figs. 42~51. We can see that incident waves are disturbed at the bows of the ships, and waves rise in front of the bows and fall at the side shoulders. The rise of the front waves of NBS-original is higher than those of NBK-N6 and NBK-N5. It should be noted that incident waves shown in these figures look like not to be in a steady oscillating condition because the scales of expressions of free-surface elevation are too rough.

Wave profiles on a center plane (\( y/B=0 \)) and a side plane (\( y/B=0.5 \)) near the bows (the bow is located at \( x/L_{pp}=0.5 \)) are shown in Figs. 52~57. In the calculations, relative wave lengths (\( \lambda/L_{pp} \)) are 0.3, 0.4 and 0.6, and corresponding wave periods (\( \tau_w \)) are 0.4sec, 0.45sec and 0.6sec, respectively. Wave height (\( H_w \)) is 0.04m. Wave profiles shown in these figures are those at the moments when wave crest locates near the bow (\( t=0.25\tau_w \)) and when wave trough locates near the bow (\( t=0.75\tau_w \)).

The results of \( \lambda/L_{pp}=0.3 \) shown in upper figures of Fig. 52 show that when the wave crest locates near the bow edge, wave runs up on the bow of NBS-original up to about 2.5 times of the wave amplitude of the incident waves and that those of NBK-N6 and NBK-N5 run up to about 1.5 times. We can also see that large sinusoidal oscillations of incident waves disappear on the center plane in front of the bows and only small amplitude oscillations remain in front of the bows. The results of Fig. 53 at the moment when the wave trough locates near the bows show that higher water level above the calm water surface is kept in front of the bows in a wave length.

Similar tendency of the wave profiles can be seen in the calculated results for longer waves, \( \lambda/L_{pp}= 0.4 \) and 0.6, as shown in the upper figures in Figs. 54～57.
Fig. 40 Profiles of bow shapes of the ships

Fig. 41 Bow shapes of the ships, NBS-original, NBK-N6 and NBK-N5
Fig. 42 Wave patterns at free surface at the moment time 0 in waves, \( H_w=0.04 \text{m}, \lambda/L_{pp}=0.3, F_n=0.163 \)
Fig. 43 Wave patterns at free surface at the moment time $0.25\tau_w$ in waves, $H_w=0.04\text{m}$, $\lambda/L_{pp}=0.3$, $F_n=0.163$
Fig. 44 Wave patterns at free surface at the moment time $0.5\tau_w$ in waves, 
$H_w=0.04\text{m}$, $\lambda/L_{pp}=0.3$, $F_r=0.163$
Fig. 45 Wave patterns at free surface at the moment time $0.75\tau_w$ in waves,
$H_w=0.04\text{m}$, $\lambda/L_{pp}=0.3$, $F_n=0.163$
Fig. 46 Wave patterns at free surface at the moment time $\tau_w$ in waves,
$H_w=0.04\text{m}$, $\lambda/L_{pp}=0.3$, $F_n=0.163$
Fig. 47 Wave patterns at free surface at the moment time 0 in waves, $H_w=0.04m$, $\lambda/L_{pp}=0.6$, $F_n=0.163$
Fig. 48 Wave patterns at free surface at the moment time $0.25\tau_w$ in waves, $H_w=0.04\text{m}$, $\lambda/L_{pp}=0.6$, $F_n=0.163$
Fig. 49 Wave patterns at free surface at the moment time $0.5\tau_w$ in waves, $H_w=0.04$m, $\lambda/L_{pp}=0.6$, $F_n=0.163$
Fig. 50 Wave patterns at free surface at the moment time $0.75\tau_w$ in waves, $H_w=0.04m, \lambda/L_{pp}=0.6, F_n=0.163$
Fig. 51 Wave patterns at free surface at the moment time $\tau_w$ in waves,
$H_w=0.04\text{m}$, $\lambda/L_{pp}=0.6$, $F_n=0.163$
Fig. 52 Profiles of wave around bow when wave crest is at the bow (t = 0.25τw),
Hw=0.04m, λ/Lpp=0.3, Fn=0.163
Fig. 53 Profiles of wave around bow at time $0.75\tau_w$, $H_w=0.04\text{m}$, $\lambda/L_{pp}=0.3$, $F_n=0.163$
Fig. 54 Profiles of wave around bow when wave crest is at the bow ($t = 0.25 \tau_w$), $H_w = 0.04m$, $\lambda/L_{pp} = 0.4$, $F_n = 0.163$
Fig. 55 Profiles of wave around bow when wave trough is at the bow ($t = 0.75 \tau_w$), $H_w = 0.04 m$, $\lambda/L_{pp} = 0.4$, $F_n = 0.163$
Fig. 56 Profiles of wave around bow when wave crest is at the bow \((t=0.25\tau_w)\),
\(^{H_w}=0.04m, \lambda/L_{pp}=0.6, F_n=0.163\)
Fig. 57 Profiles of wave around bow when wave trough is at the bow \((t = 0.75 \tau_w)\), \(H_w = 0.04\text{m}, \lambda/L_{pp} = 0.6, \text{F}_n = 0.163\)
4.2.2 Dynamic pressure distribution over hull surface of the ships

Calculated dynamic pressure distributions over hull surface of the ships running in high waves are shown in Figs. 58～67. The dynamic pressures just outside of boundary layers are shown in these figures. In the figures, lower dynamic pressure area is shown in blue area, where higher static pressure acts on the hull surface. Upper figures show pressure distributions on half front hull surfaces of the three ships, middle ones show those on half aft hull surfaces and bottom ones show those on side surfaces.

The pressure distributions for $\lambda/L_{pp}=0.3$ in a wave cycle are shown in Figs. 58～62 demonstrate that low dynamic pressure widely spread on the bow of NBS-original and these pressure may cause larger added resistance due to head waves. We can see some disturbed pressure distributions on the bow of NBS-original due to spray. The pressure distributions on the half aft surface are slightly different among the three ships. This may suggest that viscous resistances are different among them.

The results for $\lambda/L_{pp}=0.6$ are shown in Figs. 63～67. Larger differences of dynamic pressure distributions among them can be seen.

In Figs. 68～77 dynamic pressure distribution on the center plane of the calculating fluid domain in a circle wave are shown for $\lambda/L_{pp}=0.3$ and 0.6. We can see the change of dynamic pressure distribution around the three ships in a wave cycle and differences of wave profiles in front of the bows and behind the sterns in a wave cycle. In the upper figures in Fig. 68 water on deck due to waves can be seen.

The added resistance acting on the hull must increase if the area of low dynamic pressure on the half front hull surfaces is wide. On the contrary, higher dynamic pressure (red or yellow area) on the surface reduces the resistance. From the results of dynamic pressure distributions, we can know how the bow shapes change the flow around the hulls and pressure over the hulls surfaces.

The results shown in this section suggest that the bulbous bow of NBK-N5 reduces area of low dynamic pressure and increases high dynamic pressure area on the half front hull surface at the moment when the crest and the trough of incident waves hit the bow.
Haft front hull surface of the ships:

NBS-original:    NBK-N6:    NBK-N5:

Haft aft hull surface of the ships:

NBS-original:    NBK-N6:    NBK-N5:

Fig. 58 Dynamic pressure distributions at the moment time 0 in waves,
$H_w=0.04\text{m}$, $\lambda/L_{pp}=0.3$, $F_n=0.163$
Fig. 59 Dynamic pressure distributions at the moment time $0.25\tau_w$ in waves, $H_w=0.04m$, $\lambda/L_{pp}=0.3$, $F_n=0.163$
Haft front hull surface of the ships:

NBS-original:    NBK-N6:  NBK-N5:

Haft aft hull surface of the ships:

NBS-original:    NBK-N6:  NBK-N5:

Fig. 60 Dynamic pressure distributions at the moment time $0.5\tau_w$ in waves, 
$H_w=0.04m$, $\lambda/L_{pp}=0.3$, $F_n=0.163$
Fig. 61 Dynamic pressure distributions at the moment time $0.75\tau_w$ in waves,
$H_w=0.04m$, $\lambda/L_{pp}=0.3$, $F_n=0.163$
Haft front hull surface of the ships:

NBS-original:  NBK-N6:  NBK-N5:

Haft aft hull surface of the ships:

NBS-original:  NBK-N6:  NBK-N5:

Fig. 62 Dynamic pressure distributions at the moment time $\tau_w$ in waves, $H_w=0.04m$, $\lambda/L_{pp}=0.3$, $F_n=0.163$
Haft front hull surface of the ships:

NBS-original:  NBK-N6:  NBK-N5:

Haft aft hull surface of the ships:

NBS-original:  NBK-N6:  NBK-N5:

Fig. 63 Dynamic pressure distributions at the moment time 0 in waves, $H_w=0.04\text{m}$, $\lambda/L_{pp}=0.6$, $F_n=0.163$
Haft front hull surface of the ships:

NBS-original:  NBK-N6:  NBK-N5:

Haft aft hull surface of the ships:

NBS-original:  NBK-N6:  NBK-N5:

Fig. 64 Dynamic pressure distributions at the moment time $0.25\tau_w$ in waves, $H_w=0.04m$, $\lambda/L_p=0.6$, $F_n=0.163$
Haft front hull surface of the ships:

NBS-original:  
NBK-N6:  
NBK-N5:

Haft aft hull surface of the ships:

NBS-original:  
NBK-N6:  
NBK-N5:

Fig. 65 Dynamic pressure distributions at the moment time $0.5\tau_w$ in waves, $H_w=0.04m$, $\lambda/L_{pp}=0.6$, $F_n=0.163$
Haft front hull surface of the ships:

NBS-original:          NBK-N6:          NBK-N5:

Haft aft hull surface of the ships:

NBS-original:          NBK-N6:          NBK-N5:

Fig. 66 Dynamic pressure distributions at the moment time $0.75\tau_w$ in waves,
$H_w=0.04\text{m}$, $\lambda/L_{pp}=0.6$, $F_n=0.163$
Fig. 67 Dynamic pressure distributions at the moment time $\tau_w$ in waves, $H_w=0.04\text{m}$, $\lambda/L_{pp}=0.6$, $F_n=0.163$
Fig. 68 Contours of dynamic pressure at the center planes of fluid domain, at the moment time 0 in waves, $H_w=0.04\text{m}$, $\lambda/L_{pp}=0.3$, $F_n=0.163$
Fig. 69 Contours of dynamic pressure at the center planes of fluid domain, at the moment time $0.25\tau_w$ in waves, $H_w=0.04\text{m}$, $\lambda/L_pp=0.3$, $F_n=0.163$
Fig. 70 Contours of dynamic pressure at the center planes of fluid domain, at the moment time $0.5\tau_w$ in waves, $H_w=0.04m$, $\lambda/L_{pp}=0.3$, $F_n=0.163$
Fig. 71 Contours of dynamic pressure at the center planes of fluid domain, at the moment time $0.75\tau_w$ in waves, $H_w=0.04m$, $\lambda/L_{pp}=0.3$, $F_n=0.163$
Fig. 72 Contours of dynamic pressure at the center planes of fluid domain, at the moment time $\tau_w$ in waves, $H_w=0.04m$, $\lambda/L_{pp}=0.3$, $F_n=0.163$
Fig. 73 Contours of dynamic pressure at the center planes of fluid domain, at the moment time 0 in waves, $H_w=0.04m$, $\lambda/L_{pp}=0.6$, $F_n=0.163$
Fig. 74 Contours of dynamic pressure at the center planes of fluid domain, at the moment time $0.25\tau_w$ in waves, $H_w=0.04m$, $\lambda/L_{pp}=0.6$, $F_n=0.163$
Fig. 75 Contours of dynamic pressure at the center planes of fluid domain, at the moment time $0.5\tau_w$ in waves, $H_w=0.04m$, $\lambda/L_{pp}=0.6$, $F_n=0.163$
Fig. 76 Contours of dynamic pressure at the center planes of fluid domain, at the moment time $0.75\tau_w$ in waves, $H_w=0.04\text{m}$, $\lambda/L_{pp}=0.6$, $F_n=0.163$
Fig. 77 Contours of dynamic pressure at the center planes of fluid domain, at the moment time $\tau_w$ in waves, $H_w=0.04m$, $\lambda/L_{pp}=0.6$, $F_n=0.163$
4.3. Velocity distribution in boundary layer

In this section velocity distribution in boundary layer at centerline of aft perpendicular (AP) of the ships running in high waves and in calm water are investigated by the CFD. It should be noted that AP is located at the end of stern. Incident wave is head wave, its wave height ($H_w$) is 0.04m, and its ratio of wave length to ship length ($\lambda/L_{pp}$) is 0.3.

In Fig. 78 the calculate velocity distributions of the three ships in calm water are shown. Slight differences between NBS-original and other two ships with bulbous bow can be seen. It can be said that wakes at the stern end of NBK-N6 and NBK-N5 are slightly weaker than that of NBS-original.

In Figs. 79～81 the calculated velocity distributions of them in high waves are shown in a wave cycle. The results show that velocities in boundary layers in waves are faster than those in calm water. This fact means that wakes of ships weaken due to head waves and suggest that propulsive efficiency of a ship is declined by head waves.

![Fig. 78 Velocity distributions in boundary layer at centerline of AP of the ships in calm water at $F_n=0.163$](image-url)
Fig. 79 Velocity distributions in boundary layer at centerline of AP in one circle wave of NBS-original running in regular head wave at $F_n=0.163$, $H_w=0.04m$, $\lambda/L_{pp}=0.3$

Fig. 80 Velocity distributions in boundary layer at centerline of AP in one circle wave of NBK-N6 running in regular head wave at $F_n=0.163$, $H_w=0.04m$, $\lambda/L_{pp}=0.3$
4.4. Resistances in high waves

Resistances acting on the three ships in high waves are calculated and measured at towing tank of Osaka Prefecture University. The calculated results given by the CFD are compared with the experimental results to validate CFD results. The wave used for the computations and the experiments is regular head and high one, ratio of wave length to ship length is kept to be $\lambda/L_{pp}=0.6$, and wave height is changed from 0.02m to 0.05m. The length of the ship is 2m in the CFD and in the experiments.

The calculated and measured results of resistances acting on the ships are shown in differently defined coefficients in Figs. 82~85. As shown in the figures, agreements between the CFD results and the experimental ones are good.

The results of added resistance in terms of a common resistance coefficient shown in Fig. 82 demonstrate that the bulbous bow of NBK-N5 significantly decreases added resistance in high waves and that NBK-N5 is the best hull form to reduce total resistance acting on hull in shorter waves.
Fig. 83 shows the results of added resistances due to waves in terms of another coefficient defined as follows.

\[ C_a = \frac{R_w}{(\rho g H_w^2 B^2 / L_{pp})} \] (2)

Both calculated and experimental results clearly show that the coefficients decrease with increasing wave height. This means that added resistances acting on the ships are not proportional to the square of wave height.

Fig. 84 shows the total resistance coefficients of them in waves, and Fig. 85 show the increasing rate of the total resistances due to head waves. The calculated results demonstrate that the resistance in waves of NBS-original increases by double of it in calm water at 0.045m of wave height, but that the resistance of NBK-N5 reaches double at 0.07m of wave height for 2m models.

Fig. 82 Computation and measurement of added wave resistances coefficient acting on the ships in high waves, \( \frac{\lambda}{L_{pp}} = 0.6 \) at Froude number 0.163
Fig. 83 Computation and measurement of added wave resistances coefficient acting on the ships in high waves, \( \lambda/L_{pp} = 0.6 \) at Froude number 0.163

Fig. 84 Computation and measurement of total resistances coefficient acting on the ships in high waves, \( \lambda/L_{pp} = 0.6 \) at Froude number 0.163
4.5 Conclusions of the chapter 4

In the chapter, the performance of three kinds of non-ballast-water ships with and without bulbous bow in regular head waves is theoretically and experimentally investigated. The following conclusions are obtained.

- The CFD code “Fluent” gives us fairly good results of the resistances acting on hulls of the ships in regular head waves, with high waves; $H_w>0.02m$. The computed results like pressure distribution, waves and profile of wave patterns are useful to understand the causes of reduction of added resistance.

- Using the CFD code, the best bow form for the non-ballast water ships in head waves with shorter wave length can be determined. It is experimentally confirmed that the form has the minimum resistance in head waves.

- The model NBK-N5 is confirmed to be the best one in this research. It could significantly reduce total resistance in shorter head waves.
Reduction of the total resistance of NBK-N5 in head waves is kept even high wave.

It was theoretically and experimentally confirmed that added resistance due to waves is not proportional to the square of wave height. The CFD can correctly show the dependency of the added resistance on wave height.
CHAPTER 5:

CFD CALCULATION
OF AIR RESISTANCE

5.1. Air resistance acting on accommodations of ships

5.1.1 Box shape accommodation

Air resistance acting on a box shape as shown in Fig. 86 is computed. The accommodation is named as N1, and used as reference shape in the present chapter. The dimensions of the accommodation are shown in Table 6.

Fig. 86 Box shapes accommodations, N1~7
Table 6 Dimensions of box shape accommodation, N1

<table>
<thead>
<tr>
<th>Name</th>
<th>b/l</th>
<th>h/l</th>
<th>Frontal projected area S_{FPA}, m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>1</td>
<td>1</td>
<td>0.016</td>
</tr>
</tbody>
</table>

Table 7 A comparison of air resistance between CFD result and experimental one

<table>
<thead>
<tr>
<th>Name</th>
<th>Coefficient of air resistance C_d - CFD</th>
<th>Experimental result C_d - Exp</th>
<th>Difference %</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>1.07</td>
<td>1.09</td>
<td>-2%</td>
</tr>
</tbody>
</table>

Fig. 87 Contour of dynamic pressure at center plane of N1

Fig. 87 shows the computed result of dynamic pressure distribution at center plane of the model. Table 7 shows the calculated result of air resistance acting on the accommodation and experimental result measured in the towing tank at Osaka Prefecture University.

The calculated result of the drag coefficient C_d for the accommodation N1 is almost 1 and is in good agreement with the experimental results.

5.1.2 Modified box shape accommodation

In this section, the accommodation N1 is modified by changing the ratio b/l keeping in constant value of bxl. This means the same floor area, and different aspect ratio of floor shape. The height of the modified accommodation of Model N2 to N4 is the same as that of N1. Model N5–N7 have lower height than that of N1. Table 8 and Table 9 show dimensions of the modified accommodations, N2 – N7.
Table 10 shows the calculated results of air resistances acting on the accommodations, N2~N7, and the difference of air resistances of them from that of N1.

The calculated results show that the drag coefficients of air resistances acting on all models are close as shown in Table 10. However, the air resistance acting on the modified box shape N5 is the smallest. This is because Model N5 has the smallest frontal projected area as shown in Table 9.

Table 8 Dimensions of modified boxes shapes accommodations

<table>
<thead>
<tr>
<th>Name</th>
<th>(b/l)</th>
<th>(h/l)</th>
<th>Fontal projected area (S_{FPA}, \text{m}^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2</td>
<td>0.44</td>
<td>0.67</td>
<td>0.0105</td>
</tr>
<tr>
<td>N3</td>
<td>2.20</td>
<td>1.49</td>
<td>0.0234</td>
</tr>
</tbody>
</table>

Table 9 Dimensions of modified boxes shapes accommodations

<table>
<thead>
<tr>
<th>Name</th>
<th>(b/l)</th>
<th>(h/l)</th>
<th>Fontal projected area (S_{FPA}, \text{m}^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N4</td>
<td>1.08</td>
<td>0.88</td>
<td>0.016</td>
</tr>
<tr>
<td>N5</td>
<td>0.44</td>
<td>0.57</td>
<td>0.010</td>
</tr>
<tr>
<td>N6</td>
<td>2.27</td>
<td>1.28</td>
<td>0.023</td>
</tr>
<tr>
<td>N7</td>
<td>0.64</td>
<td>0.72</td>
<td>0.011</td>
</tr>
</tbody>
</table>

Table 10 Calculated air resistances acting on new accommodations, N2~N7

<table>
<thead>
<tr>
<th>Name</th>
<th>Air resistance (N)</th>
<th>Coefficient of air resistance, (C_d)</th>
<th>Difference of air resistance from N1, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>2.178</td>
<td>1.07</td>
<td>0%</td>
</tr>
<tr>
<td>N2</td>
<td>1.210</td>
<td>0.90</td>
<td>-44%</td>
</tr>
<tr>
<td>N3</td>
<td>3.365</td>
<td>1.12</td>
<td>+54%</td>
</tr>
<tr>
<td>N4</td>
<td>2.117</td>
<td>1.05</td>
<td>-3%</td>
</tr>
<tr>
<td>N5</td>
<td>1.128</td>
<td>0.88</td>
<td>-48%</td>
</tr>
<tr>
<td>N6</td>
<td>3.167</td>
<td>1.09</td>
<td>+45%</td>
</tr>
<tr>
<td>N7</td>
<td>1.468</td>
<td>1.01</td>
<td>-33%</td>
</tr>
</tbody>
</table>
5.1.3 Streamlined accommodation

As well known, a streamlined shape has the smallest drag coefficient. In this chapter, a streamlined accommodation is developed and the air resistance acting on it is calculated by using the CFD. Table 12 shows dimensions of the streamlined accommodation.

![Streamlined accommodation NS](image)

**Fig. 88 Streamlined accommodation NS**

<table>
<thead>
<tr>
<th>Name</th>
<th>$b/l$</th>
<th>$h/l$</th>
<th>Fonal projected area $S_{FPA}$, $m^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS</td>
<td>0.92</td>
<td>0.72</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Table 11 Dimensions of streamlined accommodation, NS

Fig. 89 shows contours of dynamic pressure at center plane of the streamlined accommodation. Calculated air resistance acting on the streamlined accommodation NS and comparison with that of the box shape accommodation N1 is shown in Table 12.

The result shown in Table 12 demonstrates that the streamlined accommodation drastically reduces air resistance.
Fig. 89 Contour of dynamic pressure at center plane of streamlined accommodation

Table 12 Calculated air resistances acting on accommodations, N1 and NS

<table>
<thead>
<tr>
<th>Name</th>
<th>Air resistance (N)</th>
<th>Coefficient of air resistance, C_d</th>
<th>Difference of air resistance from N1, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>2.178</td>
<td>1.07</td>
<td>0%</td>
</tr>
<tr>
<td>NS</td>
<td>0.603</td>
<td>0.31</td>
<td>-72%</td>
</tr>
</tbody>
</table>

5.1.4 Optimum shape for accommodation of ship

A streamlined accommodation is an optimum one. In this section an accommodation whose air resistance is close to a streamlined one but which could be built easily is developed. Fig. 90 shows a shape modified from the box shape N7 by systematically changing the front shapes. The dimensions of them are the same as those of N7. Table 14 shows dimensions of them.

Fig. 90 Modified box shape accommodation from N7
Table 13 Dimensions of new boxes shapes accommodations

<table>
<thead>
<tr>
<th>Name</th>
<th>b/l</th>
<th>h/l</th>
<th>x/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>N7-1</td>
<td>0.64</td>
<td>0.72</td>
<td>0.13</td>
</tr>
<tr>
<td>N7-2</td>
<td>0.64</td>
<td>0.72</td>
<td>0.19</td>
</tr>
<tr>
<td>N7-3</td>
<td>0.64</td>
<td>0.72</td>
<td>0.25</td>
</tr>
<tr>
<td>N7-4</td>
<td>0.64</td>
<td>0.72</td>
<td>0.32</td>
</tr>
<tr>
<td>N7-5</td>
<td>0.64</td>
<td>0.72</td>
<td>0.38</td>
</tr>
<tr>
<td>N7-6</td>
<td>0.64</td>
<td>0.72</td>
<td>0.45</td>
</tr>
<tr>
<td>N7-7</td>
<td>0.64</td>
<td>0.72</td>
<td>0.51</td>
</tr>
<tr>
<td>N7-8</td>
<td>0.64</td>
<td>0.72</td>
<td>0.57</td>
</tr>
<tr>
<td>N7-9</td>
<td>0.64</td>
<td>0.72</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Table 14 Calculated air resistances acting on accommodations

<table>
<thead>
<tr>
<th>Name</th>
<th>Air resistance (N)</th>
<th>Coefficient of air resistance, C_d</th>
<th>Difference of air resistance from N1, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>N7-1</td>
<td>0.658</td>
<td>0.453</td>
<td>-70%</td>
</tr>
<tr>
<td>N7-2</td>
<td>0.604</td>
<td>0.420</td>
<td>-72%</td>
</tr>
<tr>
<td>N7-3</td>
<td>0.597</td>
<td>0.411</td>
<td>-73%</td>
</tr>
<tr>
<td>N7-4</td>
<td>0.604</td>
<td>0.415</td>
<td>-72%</td>
</tr>
<tr>
<td>N7-5</td>
<td>0.616</td>
<td>0.424</td>
<td>-72%</td>
</tr>
<tr>
<td>N7-6</td>
<td>0.626</td>
<td>0.430</td>
<td>-71%</td>
</tr>
<tr>
<td>N7-7</td>
<td>0.635</td>
<td>0.437</td>
<td>-71%</td>
</tr>
<tr>
<td>N7-8</td>
<td>0.653</td>
<td>0.449</td>
<td>-70%</td>
</tr>
<tr>
<td>N7-9</td>
<td>0.690</td>
<td>0.474</td>
<td>-68%</td>
</tr>
</tbody>
</table>

Table 14 shows calculated results of air resistances acting on the accommodations. The calculated results show that all models have close air resistance coefficients. Among them, Model N7-3 is the optimum one.

In the next step, on the basis of Model N7-3, horizontal steps at the front are examined as shown in Fig. 91. In the calculations the ratio $h_1/h=0.18$ is kept the same and the ratio $x_1/l$ is systematically changed. Table 15 shows the dimensions of the modified models. The calculated results for the models show that Model N7-3.4 is the minimum air resistance in
this case and its resistance coefficient $C_d$ reaches 0.395 which is larger than that of the streamlined one, 0.31.

On the basis of Model N7-3.4, some models by changing ratio $h_1/h$ are developed as shown in Table 17. Calculated results are shown in Table 18. The calculated results show at $h_1/h=0.09$ the air resistance acting on Model N7-3.4.1 is minimum, and its resistance coefficient reaches 0.39.

![Fig. 91 Accommodation with horizontal step in the front](image)

Table 15 Dimensions of accommodations, N7-3.1～3.5

<table>
<thead>
<tr>
<th>Name</th>
<th>$b/l$</th>
<th>$h/l$</th>
<th>$h_1/h$</th>
<th>$x_1/l$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N7-3.1</td>
<td>0.64</td>
<td>0.72</td>
<td>0.18</td>
<td>0.32</td>
</tr>
<tr>
<td>N7-3.2</td>
<td>0.64</td>
<td>0.72</td>
<td>0.18</td>
<td>0.25</td>
</tr>
<tr>
<td>N7-3.3</td>
<td>0.64</td>
<td>0.72</td>
<td>0.18</td>
<td>0.19</td>
</tr>
<tr>
<td>N7-3.4</td>
<td>0.64</td>
<td>0.72</td>
<td>0.18</td>
<td>0.13</td>
</tr>
<tr>
<td>N7-3.5</td>
<td>0.64</td>
<td>0.72</td>
<td>0.18</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Table 16 Calculated air resistance

<table>
<thead>
<tr>
<th>Name</th>
<th>Air resistance (N)</th>
<th>Coefficient of air resistance, $C_d$</th>
<th>Difference of air resistance from N1, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>N7-3.1</td>
<td>0.585</td>
<td>0.403</td>
<td>-73%</td>
</tr>
<tr>
<td>N7-3.2</td>
<td>0.604</td>
<td>0.416</td>
<td>-72%</td>
</tr>
<tr>
<td>N7-3.3</td>
<td>0.578</td>
<td>0.398</td>
<td>-73%</td>
</tr>
<tr>
<td>N7-3.4</td>
<td>0.575</td>
<td>0.395</td>
<td>-74%</td>
</tr>
<tr>
<td>N7-3.5</td>
<td>0.600</td>
<td>0.413</td>
<td>-72%</td>
</tr>
</tbody>
</table>
Table 17 Dimensions of new box shapes accommodations

<table>
<thead>
<tr>
<th>Name</th>
<th>b/l</th>
<th>h/l</th>
<th>h₁/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>N7-3.4.1</td>
<td>0.64</td>
<td>0.72</td>
<td>0.09</td>
</tr>
<tr>
<td>N7-3.4.2</td>
<td>0.64</td>
<td>0.72</td>
<td>0.27</td>
</tr>
<tr>
<td>N7-3.4.3</td>
<td>0.64</td>
<td>0.72</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Table 18 Calculated air resistance acting on accommodation

<table>
<thead>
<tr>
<th>Name</th>
<th>Air resistance (N)</th>
<th>C_d</th>
<th>Difference of air resistance from N1, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>N7-3.4.1</td>
<td>0.568</td>
<td>0.390</td>
<td>-74%</td>
</tr>
<tr>
<td>N7-3.4.2</td>
<td>0.621</td>
<td>0.427</td>
<td>-71%</td>
</tr>
<tr>
<td>N7-3.4.3</td>
<td>0.654</td>
<td>0.450</td>
<td>-70%</td>
</tr>
</tbody>
</table>

In the last step, the rear part of accommodation is systematically modified. At first the ratio y/b is changed as in Table 19. Calculated results of air resistances are shown in Table 20. The results show that Model N7-3.4.1.1 is the optimum one in this case and its resistance coefficient is 0.354.

Secondly the ratio h₂/h is changed from N7-3.4.1.1 as in Table 21. Calculated results of air resistance acting on the models are shown in Table 22. We can see that N7-3.4.1.1.1 has smallest air resistance coefficient which is 0.346. The value is slightly larger than that of the streamlined accommodation, 0.31. Figs. 93 and 94 show dynamic pressure distribution around the best accommodation, N7-3.4.1.1.1 and N7-3.

![Fig. 92 Modification of rear part of accommodation](image-url)
Table 19 Dimensions of models with different rear parts

<table>
<thead>
<tr>
<th>Name</th>
<th>b/l</th>
<th>h/l</th>
<th>y/b</th>
</tr>
</thead>
<tbody>
<tr>
<td>N7-3.4.1.1.1</td>
<td>0.64</td>
<td>0.72</td>
<td>0.8</td>
</tr>
<tr>
<td>N7-3.4.1.2</td>
<td>0.64</td>
<td>0.72</td>
<td>0.6</td>
</tr>
<tr>
<td>N7-3.4.1.3</td>
<td>0.64</td>
<td>0.72</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 20 Calculated air resistance acting on accommodation

<table>
<thead>
<tr>
<th>Name</th>
<th>Air resistance (N)</th>
<th>C_d</th>
<th>Difference of air resistance from N1, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>N7-3.4.1.1.1</td>
<td>0.515</td>
<td>0.354</td>
<td>-76%</td>
</tr>
<tr>
<td>N7-3.4.1.1.2</td>
<td>0.548</td>
<td>0.377</td>
<td>-75%</td>
</tr>
<tr>
<td>N7-3.4.1.1.3</td>
<td>0.555</td>
<td>0.382</td>
<td>-75%</td>
</tr>
</tbody>
</table>

Table 21 Dimensions of models with different rear parts

<table>
<thead>
<tr>
<th>Name</th>
<th>b/l</th>
<th>h/l</th>
<th>h_2/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>N7-3.4.1.1.1</td>
<td>0.64</td>
<td>0.72</td>
<td>0.09</td>
</tr>
<tr>
<td>N7-3.4.1.1.2</td>
<td>0.64</td>
<td>0.72</td>
<td>0.18</td>
</tr>
<tr>
<td>N7-3.4.1.1.3</td>
<td>0.64</td>
<td>0.72</td>
<td>0.27</td>
</tr>
<tr>
<td>N7-3.4.1.1.4</td>
<td>0.64</td>
<td>0.72</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Table 22 Calculated air resistance acting on accommodation

<table>
<thead>
<tr>
<th>Name</th>
<th>Air resistance (N)</th>
<th>C_d</th>
<th>Difference of air resistance from N1, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>N7-3.4.1.1.1</td>
<td>0.503</td>
<td>0.346</td>
<td>-77%</td>
</tr>
<tr>
<td>N7-3.4.1.1.2</td>
<td>0.509</td>
<td>0.350</td>
<td>-77%</td>
</tr>
<tr>
<td>N7-3.4.1.1.3</td>
<td>0.522</td>
<td>0.359</td>
<td>-76%</td>
</tr>
<tr>
<td>N7-3.4.1.1.3</td>
<td>0.551</td>
<td>0.379</td>
<td>-75%</td>
</tr>
</tbody>
</table>
Fig. 93 Contour of dynamic pressure around N7-3

Fig. 94 Dynamic pressure distribution around N7-3.4.1.1.1
5.2. Interaction effects between hull and accommodation of ships

5.2.1 Interaction effects of location of accommodation on deck

In this section, interaction effects between a hull and an accommodation are investigated by changing location of an accommodation on deck as shown in Fig. 95.

![Fig. 95 Locations of an accommodation on deck](image)

Tables 23&24 show calculated air resistance and interaction effects on air resistance between a hull and a box shape accommodation. The results show that location of an accommodation of a ship on deck has significant effects on air resistance acting on a ship. The results shown in Table 24 demonstrate that accommodation located at the front deck of a ship decreases the interaction effects but accommodation located at the aft deck increases the interaction effects. Figs. 96~100 show computed results of dynamic pressure around hulls at the locations P1~P11.

<table>
<thead>
<tr>
<th>No</th>
<th>Air resistance (N)</th>
<th>Difference from P1, %</th>
<th>C_d</th>
<th>Difference from P1, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>4.794</td>
<td>0%</td>
<td>0.736</td>
<td>0%</td>
</tr>
<tr>
<td>P2</td>
<td>4.372</td>
<td>-9%</td>
<td>0.672</td>
<td>-9%</td>
</tr>
<tr>
<td>P3</td>
<td>4.041</td>
<td>-16%</td>
<td>0.621</td>
<td>-16%</td>
</tr>
<tr>
<td>P4</td>
<td>4.027</td>
<td>-16%</td>
<td>0.619</td>
<td>-16%</td>
</tr>
<tr>
<td>P5</td>
<td>4.043</td>
<td>-16%</td>
<td>0.621</td>
<td>-16%</td>
</tr>
<tr>
<td>P6</td>
<td>4.089</td>
<td>-15%</td>
<td>0.628</td>
<td>-15%</td>
</tr>
<tr>
<td>P7</td>
<td>4.103</td>
<td>-14%</td>
<td>0.630</td>
<td>-14%</td>
</tr>
<tr>
<td>P8</td>
<td>4.034</td>
<td>-16%</td>
<td>0.620</td>
<td>-16%</td>
</tr>
<tr>
<td>P9</td>
<td>3.900</td>
<td>-19%</td>
<td>0.599</td>
<td>-19%</td>
</tr>
<tr>
<td>P10</td>
<td>3.745</td>
<td>-22%</td>
<td>0.575</td>
<td>-22%</td>
</tr>
<tr>
<td>P11</td>
<td>3.664</td>
<td>-24%</td>
<td>0.563</td>
<td>-24%</td>
</tr>
</tbody>
</table>
Table 24 Interaction effects between accommodation and hull on air resistance

<table>
<thead>
<tr>
<th>No</th>
<th>Calculating independence</th>
<th>Ship hull with accommodation</th>
<th>Interaction effect, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hull</td>
<td>Acc</td>
<td>Hull</td>
</tr>
<tr>
<td>P1</td>
<td>1.682</td>
<td>1.968</td>
<td>2.682</td>
</tr>
<tr>
<td>P2</td>
<td>1.682</td>
<td>1.968</td>
<td>2.200</td>
</tr>
<tr>
<td>P3</td>
<td>1.682</td>
<td>1.968</td>
<td>1.887</td>
</tr>
<tr>
<td>P4</td>
<td>1.682</td>
<td>1.968</td>
<td>1.895</td>
</tr>
<tr>
<td>P5</td>
<td>1.682</td>
<td>1.968</td>
<td>1.934</td>
</tr>
<tr>
<td>P6</td>
<td>1.682</td>
<td>1.968</td>
<td>1.983</td>
</tr>
<tr>
<td>P7</td>
<td>1.682</td>
<td>1.968</td>
<td>1.990</td>
</tr>
<tr>
<td>P8</td>
<td>1.682</td>
<td>1.968</td>
<td>1.931</td>
</tr>
<tr>
<td>P9</td>
<td>1.682</td>
<td>1.968</td>
<td>1.785</td>
</tr>
<tr>
<td>P10</td>
<td>1.682</td>
<td>1.968</td>
<td>1.658</td>
</tr>
<tr>
<td>P11</td>
<td>1.682</td>
<td>1.968</td>
<td>1.466</td>
</tr>
</tbody>
</table>

(Acc: Accommodation).

At the location P1:

At the location P2:

Fig. 96 Contours of dynamic pressure at center planes of the ship, P1 and P2
At the location P3:

![Contour of dynamic pressure at P3](image)

At the location P4:

![Contour of dynamic pressure at P4](image)

At the location P5:

![Contour of dynamic pressure at P5](image)

Fig. 97 Contours of dynamic pressure at center planes of the ship, P3−5
At the location P6:

At the location P7:

At the location P8:

Fig. 98 Contours of dynamic pressure at center planes of the ship, P6–8
At the location P9:

At the location P10:

At the location P11:

Fig. 99 Contours of dynamic pressure at center planes of the ship, P9–11
5.2.2 Interaction effects between hull and accommodation

In this section, effects of shape of accommodation on the interaction effects are investigated. Three kinds of accommodations; N7-3, N7-3.4.1.1.1 and the streamlined model NS, are located on deck of a ship as shown in Figs 101~103. Calculated air resistance and interaction effects on it are shown in Table 25 and Table 26. The results demonstrate that the ships with different three accommodations reduce air resistance by 31%~52% compared a conventional ship with a aft and box shape accommodation. As shown in Table 26 the interaction effects play an important role on air resistance.

Computed dynamic pressure distributions and velocity flow at the center planes of calculating domain are shown in Figs. 104~108. The results show clearly differences among three kinds of the accommodations located on the deck of ship. It can be seen that the streamlined accommodation clearly reduces separation behind it.

Fig. 100 Contours of velocity around hull of ship at center planes of calculated domain.
Fig. 101 Hull and accommodation model N7-3

Fig. 102 Hull and accommodation model N7-3.4.1.1.1

Fig. 103 Hull and streamline accommodation NS.
Table 25 Calculated air resistances acting on ships with accommodation on deck

<table>
<thead>
<tr>
<th>No</th>
<th>Air resistance (N)</th>
<th>Difference from P1, %</th>
<th>C&lt;sub&gt;d&lt;/sub&gt;</th>
<th>Difference from P1, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>N7-3</td>
<td>3.041</td>
<td>-37%</td>
<td>0.507</td>
<td>-31%</td>
</tr>
<tr>
<td>N7-3.4.1.1.1</td>
<td>2.720</td>
<td>-43%</td>
<td>0.454</td>
<td>-38%</td>
</tr>
<tr>
<td>NS</td>
<td>2.291</td>
<td>-52%</td>
<td>0.352</td>
<td>-52%</td>
</tr>
</tbody>
</table>

Table 26 Interaction effects between hull and accommodations on its deck

<table>
<thead>
<tr>
<th>No</th>
<th>Calculating independence</th>
<th>Hull with Acc</th>
<th>Interaction effect, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hull</td>
<td>Acc</td>
<td>Hull</td>
</tr>
<tr>
<td>N7-3</td>
<td>1.682</td>
<td>0.597</td>
<td>2.314</td>
</tr>
<tr>
<td>N7-3.4.1.1.1</td>
<td>1.682</td>
<td>0.503</td>
<td>2.047</td>
</tr>
<tr>
<td>NS</td>
<td>1.682</td>
<td>0.603</td>
<td>1.738</td>
</tr>
</tbody>
</table>

(Acc: Accommodation).

Fig. 104 Contours of dynamic pressure at center planes and at vertical plane z=0.125m of ship with accommodation N7-3
Hull with accommodation N7-3.4.1.1.1:

Hull with streamlined accommodation NS:

Fig. 105 Contours of dynamic pressure at center planes and at vertical plane $z=0.125\text{m}$ of ship with accommodation N7-3.4.1.1.1 and streamlined accommodation NS
Fig. 106 Contours of velocity around hull of ship at center plane and at vertical plane $z=0.125m$ of ship with accommodation N7-3

Fig. 107 Contours of velocity around hull of ship at center plane and at vertical plane $z=0.125m$ of ship with accommodation N7-3.4.1.1.1
Fig. 108 Contours of velocity around hull of ship at center planes and at vertical plane $z=0.125\text{m}$ of ship with streamlined accommodation NS

5.3. Conclusions of the chapter 5

The conclusions of this chapter are summarized as follows:

- It is confirmed that air resistance acting on a box shape accommodation can be accurately calculated by CFD code, “Fluent”.

- Air resistance acting on a box shape accommodation decreases with its slenderness because smaller frontal projected area of slender ones when floor area in the accommodation is assumed to be constant.

- The streamlined accommodation developed in this study can drastically reduce the air resistance because of weaker separation of flow.

- Accommodations constructed by only flat plates with almost the same air resistance as that of the streamlined accommodation are developed by using the CFD code.

- It is confirmed that interaction effects between a hull and an accommodation on air
resistance increase the air resistance acting the whole ship by up to 30% compared with that of a ship with a box shape accommodation.

- The hydrodynamic interaction effect depends on location and shape of an accommodation. The accommodation located at bow makes the air resistance smaller. For the box shape accommodation the interaction effect increases the air resistance, but for the streamlined accommodation the effect decreases the air resistance.
CHAPTER 6:
CONCLUSION OF THESIS

The thesis studies on application of a CFD to calculations of resistances acting on ships and optimization of their hydrodynamic performances. Some problems which was introduced in the chapter 1 as well as the validation of the used CFD in the chapter 2, optimization of bulbous bow shape for ships in the chapter 3, resistance acting on a hull of ships in high waves in the chapter 4 and CFD calculation of air resistance acting on ships in the chapter 5, are treated and following conclusions were obtained:

In the chapter 2, validations of a commercial CFD code “Fluent” are carried out. The validations of the CFD results in computation of the velocity in boundary layer and resistance acting on ship both of in calm water and in regular head waves are carried out by comparing the CFD results with the experimental results. The conclusions are that the accuracy of the CFD code is fairly good for the practical purposes and that the CFD code could give us much information about pressure distributions, velocity distribution in boundary layer and wave pattern around ships as well as the resistance acting on their hulls. The obtained conclusions of the chapter 2 are as follows:

- It is confirmed that a commercial CFD code “FLUENT” gives us fairly good results of the resistance acting on a ship hull both in calm water and in regular head wave, viscous flow in boundary layer around it in calm water.

- The frictional resistances computed by the code and Schoenherr’s formula are slightly different.

- The calculated results of the ratio of added resistance due to wave of two ships are in good agreement with the experimental results.

- The improved bulbous bow shape of NBK-N6 could reduce by 10% of total resistance in calm water and by 17% of total resistance in regular head waves with the wave
height $H_w=0.02\text{m}$, $\lambda/L_{pp}<0.6$, compared with that of the NBS-original. The results are close with the calculated results given by the CFD code.

**In the chapter 3**, optimizations of bulbous bow shapes for ships are treated. The series of newly developed bulbous bow shapes with smaller resistance than that of the original ship were developed in the optimizing process. The optimum bow shape for the Non Ballast Water Ships was determined, and it was experimentally confirmed that the bulbous bow shape obtained by the optimization has minimum resistance. The conclusions of the chapter 3 are detailed as follows:

- Series of bow shapes to reduce the resistance in waves as well as in calm water are developed and the resistances of the series of hulls are calculated by the CFD code to find an optimum hull shape. The optimum bow shapes among the developed hulls are determined by comparing the calculated resistances for the series of hulls.

- In the evaluation of the total resistance, the optimum hull shape in calm water depends on Froude number.

- The CFD code gives us a lot of important results like pressure distributions on the hull surface, wave patterns at free surface, and so on. The information plays an important role for understanding the phenomenon which causes the added resistance due to waves and for developing less resistance hull shapes in an optimization process.

- The calculated results are in good agreement with the experimental ones. The optimum hull shape NBK-N5 can decrease the added resistance in regular head waves (wave height $(H_w) = 0.02\text{m}$ and $\lambda/L_{pp}<0.6$) by 60% and total resistance by 15% at Froude number 0.163.

**In the chapter 4**, the characteristics of added resistance in high waves were revealed by using the CFD. The computed results of pressure, profiles of bow waves and wave pattern generated by ships running in high waves, velocity distributions in boundary layer at the aft-end of the ships and resistances acting on hulls of three ships were compared each other to understand the causes of increase of the resistance due to high waves. The conclusions obtained in the chapter 4 are as follows:

- The CFD code “Fluent” gives us fairly good results of the resistances acting on hulls
of the ships in regular head waves, with high waves; $H_s > 0.02\text{m}$. The computed results like pressure distribution, waves and profile of wave patterns are useful to understand the causes of reduction of added resistance.

- Using the CFD code, the best bow form for the non-ballast water ships in head waves with shorter wave length can be determined. It is experimentally confirmed that the form has the minimum resistance in head waves.

- The model NBK-N5 is confirmed to be the best one in this research. It could significantly reduce total resistance in shorter head waves.

- Reduction of the total resistance of NBK-N5 in head waves is kept even high wave.

- It was theoretically and experimentally confirmed that added resistance due to waves is not proportional to the square of wave height. The CFD can correctly show the dependency of the added resistance on wave height.

In the chapter 5, air resistances acting on ships are discussed. The air resistance acting on ship was computed by the CFD to find the shape above water surface with minimum air resistance. Effects of shapes of accommodations and interaction effects between an accommodation and a hull are investigated. Following conclusions are obtained.

- It is confirmed that air resistance acting on a box shape accommodation can be accurately calculated by CFD code, “Fluent”.

- Air resistance acting on a box shape accommodation decreases with its slenderness because of smaller frontal projected area of slender ones when floor area in the accommodation is assumed to be constant.

- The streamlined accommodation can drastically reduce the air resistance because of weaker separation of flow.

- Accommodations constructed by only flat plates with almost the same air resistance as that of the streamlined accommodation are developed by using the CFD code.

- It is confirmed that interaction effects between a hull and an accommodation increase the air resistance acting the ship by up to 30%.
The hydrodynamic interaction effect depends on location and shape of an accommodation on deck of a hull. The accommodation located at bow makes the air resistance smaller. For the box shape accommodation the interaction effect increases the air resistance, but for the streamlined accommodation the effect decreases it.
# List of Publications

<table>
<thead>
<tr>
<th>No</th>
<th>Title of the article</th>
<th>Author(s)</th>
<th>Journal’s Name, Vol., Pages, and Year</th>
<th>Corresponding chapter</th>
</tr>
</thead>
</table>
Chapter 3 |
Chapter 3  
3.1.2 |
| 3  | A study on developing the hull of Non Ballast Tankers with minimum fuel consumption in waves | N.V. He Y. Ikeda | Proceedings of the 5th AUN/SEED-Net RCNRE 2012, pp.253-258. | Chapter 2  
Chapter 2  
Chapter 3  
3.1.1; 3.1.2 |
| 4  | A Study on an Optimum hull form in waves for Non-Ballast Tankers and Bulkers | N.V. He Y. Nihei Y. Ikeda | Proceedings of the 5th PAAMES and AMEC2012, CD, No. NCS-01. (6 pages) | Chapter 3  
Chapter 3  
3.1.1  
3.1.2  
3.2.2 |
3.1.3  
3.2.2 |
| 6  | Development of a Minimum Resistance Hull Form of Non Ballast Tankers and Bulkers in Waves by Using CFD | N.V. He Y. Ikeda | Proceedings of the PRADS2013 on 20th - 25th October, 2013 (Accepted) | Chapter 3  
Chapter 4  
4.1  
4.2 |
| 7  | Optimization of bow shape for Non Ballast Water Ships | N.V. He Y. Ikeda | Journal of Marine Science and Application, 2013 (Accepted) | Chapter 2  
Chapter 3  
2.1; 2.2  
3.1; 3.2 |
5.1~5.3 |


17. ANSYS - Fluent V14.0 User’s Guide.


19. ITTC, 2011, Practical Guideline for Ship CFD Application, No. 7.5-03-01-03.

Nomenclature

$L_{pp}$ Length at the perpendiculars of ship $\text{m}$

$B$ Breadth of ship $\text{m}$

$\text{WSA}$ Wetted surface area $\text{m}^2$

$\text{Dispt}$ Displacement of ship $\text{ton}$

$S_{FPA}$ Frontal projected area $\text{m}^2$

$u$ Velocity at point in flow of fluid $\text{m/s}$

$U$ Free stream velocity $\text{m/s}$

$g$ Gravity acceleration $\text{m/s}^2$

$\varrho$ Density of fluid $\text{Kg/m}^3$

$\nu$ Kinematic viscosity of the fluid $\text{m}^2/\text{s}$

$\lambda$ Length of wave $\text{m}$

$H_w$ Height of wave $\text{m}$

$\tau_w$ Time period of wave $\text{s}$

$R_w$ Added wave resistance $\text{N}$

$C_w$ Coefficient of added wave resistance

$C_{T(0)}$ Coefficient of total resistance in calm water

$C_T$ Coefficient of total resistance in waves

$C_p$ Coefficient of pressure viscous resistance

$C_F$ Coefficient of frictional resistance

$C_d$ Drag coefficient; Coefficient of air resistance

$F_n$ Froude number

$\text{CFD}$ Computation Fluid Dynamic

$\text{Exp}$ Experiment

$\text{NBS}$ Non Ballast-water Ship

$\text{NBK}$ Non Ballast Tankers and Bulkers

$\text{N7-3X}$ Number 7-3X