Effect of Wavy Leading Edge with Various Aspect Ratios on a Rectangular Wing

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Abstract. Learning from nature, the humpback whale can swim faster than other baleen whales. The humpback whale has the flipper with wavy leading edges (WLE), which has an improvement of hydrodynamic performance. The WLEs have the function to generate vortices to maintain lift and to prevent stall at high angles of attack. This research aim is to find out the WLE effect on hydrodynamic performance in different wing aspect ratios (AR), whose profile is the rectangular wing of NACA 0018 as a baseline wing. The WLE profile was designed by a sinusoidal function. We focused on steady flow conditions in both the experiments and numerical simulations. The experimental work was conducted in the circular water channel at Hiroshima University, Japan. Meanwhile, the numerical work was employed using RANS simulation with SST k-ω turbulence model. Based on the results, we clarified that the increase of AR could possess a higher lift coefficient (Cl), and then physically interpreted the WLE effect on various aspect ratios. This knowledge could be expanded into the application of eco-friendly energy-saving devices such as fin stabilizers of ships and wind turbines to improve hydrodynamic performance.

1. Introduction

Numerous applications such as fin stabilizers or wind turbines could be accomplished by learning from nature such as the wavy leading edge (WLE) in the flipper of the humpback whale. Their flipper morphology believed to increase the hydrodynamic performance by increasing the lift coefficient and reducing the drag coefficient. The pioneer research has been conducted by Fish et al [1] about the morphology of the humpback whale flipper. They reported that the tubercles of their flipper have an essential role to generate vortices to maintain lift and prevent a stall. The shape of their flipper is blunt and round in the leading-edge area. To obtain the benefit of this flipper shape, features of the WLE may be adapted to the applications which operate in a steady motion. Its applications could be worked with frequently facing the stall condition. Therefore, improvement should be necessary to avoid the stall condition within WLEs.

Miklosovic et al [2] investigated NACA 0020 profile as a baseline wing and a scallop flipper in quasi 2D and 3D wings using wind tunnel experiments. The lift of the scallop model has a higher lift at higher incidence angles and delays the stall of approximately 40%. They showed that the scallop flipper has better performance in the post-stall region in 3D case. Pedro et al [3] employed research on about stall delay on humpback whale flipper where the scallop flipper possesses much more momentum than the smooth flipper, and the scallop flipper can delay the separation. Hansen et al [4]
experimentally examined the tubercles effect of NACA 0021 profile at low Reynolds numbers. They claimed that the effectiveness of tubercles is more dependent on the Reynolds number than on 3D effects. Another research has been recently conducted by Arai et al [5] about the hydrodynamic performance of the WLE wing with the aspect ratio (AR) of 1.6. They observed that the WLE on the rectangular wing was able to restrain the flow separation. Similar research has been conducted by Torro et al [6]. They clarified that the structure of counter-rotating streamwise vortices generated around the WLE. The streamwise vortices around the WLE prevented the separation. Separated flow control around the leading-edge bumps has been investigated by Favier et al [7] using NACA 0020 profile. They claimed that the tubercles have an influence on delaying the stall angle. Beside that the streamwise structures were generated by the leading-edge bumps.

The previous our research [8] showed that the WLE wing with the aspect ratio 1.6 has superior forces at the post-stall region compared to the baseline wing in pitching motion. However, the previous studies above mentioned were conducted to explore the wavy leading-edge effect in just only steady case. In this study, to investigate the WLE effect based on variety of aspect ratios, steady case experiments were employed in this research. We investigate the effect of WLE regarding various aspect ratio. The numerical methods are carried out to clarify the flow mechanism on the wing with the WLE. Four aspect ratios are examined in the present study to find out advantages in practical applications such as fin stabilizers or wind turbines.

2. Methods
2.1. Experimental Method
A NACA 0018 profile with four types of aspect ratio (AR) of 1.6, 3.9, 5.1 and 7.9 were chosen in this study. The shape of the WLE and the AR variations were referred from the previous studies [9,10]. The plane view of the wings is shown in Figure 1. The chord length (c) of the wing is 125 mm. The shape of the WLE is corresponding to the wavelength (W/c) of 8%, the amplitude (d/c) of 5%. An Oxyz coordinate system employed in this study is shown in Figure 2. The origin of the coordinate system is located on the leading edge at the centre of the wing-span.

![Figure 1](image-url)  
**Figure 1.** Plane view of the wings: (a) Baseline; (b) WLE.
Figure 2. Coordinate system of the wing.

The coordinate system of the WLE shape is sinusoidal function represented by the following equation:

$$x_{WLE(y)} = x_{LE} - \left[ \frac{d}{2} \sin \left( \frac{2\pi}{W} \left( y - \frac{W}{4} \right) \right) + \frac{d}{2} \right]$$ (1)

, where $x_{LE}$ indicates the x-coordinate at the leading edge of the basic wing shape. The schematic view of the WLE is given in Figure 3. The experiments were conducted in the circular water channel at Hiroshima University. As shown in Figure 4, the measurement of cross-section is width of 1.4 m, the height of 0.9 m, and the length of 3.3 m. The Reynolds number is set to $1.4 \times 10^5$.

Figure 3. Schematic view of the WLE wing (left: side view, right: bird’s eye view).

Figure 4. Experimental set-up in the circular water channel.
2.2. Numerical Method
The numerical study was conducted using CFD® Autodesk with SST k-ω turbulence model. The ADV-5 (Modified Petrov-Galerkin) scheme is chosen in the simulations. The unstructured meshing systems is applied in the simulations. The computational domain and its boundary conditions were described in Figure 5. The inlet boundary condition is set as uniform velocity inlet, the outlet at the down-stream is imposed as a pressure, the other boundary conditions are imposed as the symmetry. The dimensions of the outer boundary in the cases of AR 1.6, 3.9, and 5.1, coincides with the blockage effect of 8%. Meanwhile, the dimension of the outer boundary of AR 7.9 is adjusted, then the blockage effect is identical. The enlarged mesh system around the wing is shown in Figure 6.

![Figure 5. Computational domain (top: upper view, bottom: side view).](image)

![Figure 6. Mesh configuration around the wing.](image)
3. Results

3.1. Experimental Results

The experiments were conducted in the steady cases for AR 1.6, 3.9 and 5.1 with the baseline wing and the WLE wing. The experimental results of AR 1.6 refer to our previous research [9, 10]. The comparison of the experimental result of AR 1.6 is given in Figure 7. Figures 8-9 show the measured the ratio of lift and drag, L/D (hydrodynamic efficiency) for AR 3.9 and 5.1, respectively. The standard deviations of measured lift and drag coefficient are 0.0027 and 0.006, respectively. The experimental results are denoted as “Exp” in Figures 7-9. The ratio of L/D between the baseline and the WLE wing has no significant difference at the angles $\alpha \leq 5^\circ$ but at the angles $\alpha > 5^\circ$ the baseline wing is more efficient compared to the WLE wing until the stall occurs at the angle $\alpha \approx 22^\circ$ for AR 1.6 and $\alpha \approx 17^\circ$ for AR 3.9 and 5.1. In this study, the subsequent angle of attack is defined as the post-stall region after the stall condition. In this region, the ratio of L/D in the WLE wing has a better performance than that in the baseline wing. Since the WLE wing has favourable ratios of L/D in the post-stall region, the research only focused on the post-stall region. It can be seen that the ratio of L/D is increasing with AR in Figures 7-9. The increasing of AR could possess a higher lift coefficient ($C_l$), and then the WLE effect on various aspect ratios can be interpreted. The WLE effect on a variety of AR will be clarified in the next section.

Figure 7. The ratio of L/D in AR 1.6 (experiment).

Figure 8. The ratio of L/D in AR 3.9 (experiment).
3.2 Validation and Numerical Results
To validate the numerical analysis, the grid convergence of numerical results with experimental ones should be firstly required. The convergence check was performed in three different grid numbers with coarse, medium and fine mesh using the WLE wing of AR 1.6 at the angle of attack $\alpha = 25^\circ$. The ratio of L/D was used to validate with the experimental results, and the convergence is indicated by deviation. The computed differences are shown in Table 1. Based on the deviation, the medium mesh has the lowest deviation. Therefore, the medium mesh system was employed in the following results of this study.

Table 1. Grid convergence

| Mesh Type  | Total Elements of Mesh | L/D   | % deviation |
|------------|------------------------|-------|-------------|
| Experimental | -                      | 2.08  | -           |
| Coarse     | 3,160,847              | 2.00  | 3.91        |
| Medium     | 11,407,996             | 2.01  | 3.43        |
| Fine       | 20,838,293             | 1.81  | 12.85       |

Figures 10-12 show the experimental and numerical results at the ratio of L/D in AR 1.6, 3.9 and 5.1, respectively, in steady cases. The ratio of L/D in AR 7.9 is compared at the angle of attack $20^\circ$ to $30^\circ$ with no experimental results. The numerical results are in overall agreement with the experimental ones. Especially, the WLE wing show a pretty good agreement between them. On the other hand, there is a little difference with the experimental results for the baseline wing. The similar tendencies of the ratio L/D can be found in Figures 11-13 for other aspect ratios. This may be caused by the wing in the deep-stall region. In this region, the small unsteadiness cold be generated even-though the wing is set to a steady motion. The comparison of the maximum of L/D are shown in Figure 14. The tendencies of the wing results are pretty good with the experimental results. The tendency of numerical results on the baseline wing are a little higher than the experimental results. However, in this study, we are focusing on the improvement of hydrodynamic performance by using the WLE. We can see that the L/D of the WLE is higher than that of the baseline in all aspect ratios. Thus, the WLE could be one of the eco-friendly energy-saving-devices such as fin stabilizers of ships and wind turbines to improve hydrodynamic performance.
Figure 10. The ratio of L/D in AR 1.6.

Figure 11. The ratio of L/D in AR 3.9.

Figure 12. The ratio of L/D in AR 5.1.
Figure 13. The ratio of L/D in AR 7.9.

Figure 14. The ratio of L/D in both wings at $\alpha = 25^\circ$.

Next, the distribution of pressure coefficient ($Cp$) is investigated to clarify the WLEs effect on various aspect ratios. The attack angle of $\alpha = 25^\circ$ is compared to examine the pressure distribution in the stall angle on various aspect ratios. Figure 15 shows the surface distribution of $Cp$ at the all aspect ratios in both wings. The symmetry plane in those figures is denoted as “SP”. The lower pressure region is indicated as blue area in Figure 15. We can find significant differences in the $Cp$ distribution in both wings. The lower pressure is dominant around the WLEs area, and then this lower pressure area indicates that the fluid flow goes smoothly through around the WLE compared with that of the baseline wing at the all aspect ratios. Therefore, the WLEs could control fluid flow and hydrodynamic stall around the leading edge of the upper surface of the wing, and then the lift force could be increased at the larger attack angle, especially after the dynamic stall. The separation flow could be also controlled by the WLE. The WLE could improve the hydrodynamic performance of the wing. In the wing tip area, the wider low-pressure area can be found in the WLE wing at all aspect ratios. Nevertheless, the WLE located near the SP, has no significant effect on the whole flow field and pressure distribution.

Next, further analysis is focused on the WLEs located around the wing tip. The middle section between the second and the third WLEs from the wing tip is focused to investigate the WLE effect on various aspect ratios. Figure 16 shows the velocity distributions around the wing in both the baseline and the WLE. We can see that on the right side, i.e. separation point of the wing is delayed than that of the baseline wing. As mentioned in reference [8], the streamlines are directed toward to the trailing
edge of the baseline wing, while the streamlines are rotating to the wing tip direction for the WLE wing. These streamlines are effected by the flow separation on the wing. As described in the references [6, 10], the vortical flow streamlines around the WLE could contribute flow separation control.

Figure 15. Pressure distribution, $C_p$ on the upper surface of the wings.
Figure 16. Velocity distribution around the wings (left: baseline, right: WLE).

4. Conclusions
The effect of WLE on various aspect ratios has been investigated in steady cases by experimental and numerical works. The conclusion in the present study can be summarized as follows:

- The numerical results of the L/D ratio in both baseline and WLE wings are reasonable compared with the experimental results.
- In the post-stall region, the ratio of L/D in the WLE wing is higher than that in the baseline wing on various aspect ratios.
- The WLE effect could be useful in controlling separation around the wing tip area.

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