Abstract—Experimental and numerical study on the effect of wavy leading edge (WLE) on pitching rectangle wings were conducted using NACA 0018 airfoil. The shape of WLE is sinusoidal function. URANS simulations were employed using SST k-ω turbulence model. The WLE wing has preferable forces at the post-stall region compared to baseline wing. The lift force improvement at upstroke motion was higher than downstroke motion, whereas the drag increase was found to be less than the lift increase. The numerical simulation clarified that stall is suppressed during pitching motion of the WLE wing.

Index Terms—stall, wavy leading edge, rectangle wing, pitching motion.

I. INTRODUCTION

Humpback whales have the ingenious ability of catching their prey. Their flippers are characterized by the presence of tubercles on their leading edge. Research on the humpback whale flipper was first conducted by Fish et al. [1]. They showed that tubercles on the flipper may improve its hydrodynamic performance. The shape of the flipper plays an important role in improving the hydrodynamic performance. The tubercles on the flipper are thought to increase the lift and reduce the drag coefficient. From the viewpoint of bio-engineering applications, the humpback whale fin is being considered for fluid machinery, such as wind turbines, rudders, or ship stabilizers. In general, these machineries operate in unsteady conditions and often suffer from stall. A stall is caused by changing angle of attack, it may suddenly decrease the lift force because the angle of attack exceeds the critical angle of attack. The suppression of stall in fluid machinery is crucial to ensuring good performance.

Miklosovic et al. [2] showed that a scalloped flipper is able to delay stall and increase the lift force. They also reported [3] that the scalloped flipper showed better performance than a full span model. Johari et al. [4] investigated the shape of WLE on end-plated rectangular wings, the shape of WLE in their research was sinusoidal protuberance which is put in the leading edge of the wing. Pedro et al. [5] performed detached eddy simulation and claimed that the improved aerodynamic performance of the scalloped flipper was due to the presence of streamwise vortices produced by the tubercles. Arai et al. [6] observed that a WLE on a rectangular wing with an aspect ratio of 1.6 was able to restrain flow separation. A numerical investigation conducted by Arai et al. [7] highlighted the generation of streamwise vortices around WLE by the use of helicity density and showed that the streamwise vortices prevented flow separation. Since then, more detailed numerical analysis has been conducted by Hansen et al. [8] and Torro et al. [9] for end-plated rectangular wings, clarifying the structure of a pair of counter-rotating streamwise vortices created by a WLE.

The above studies have clarified the effect of WLEs in the steady state but have not addressed the case of stall during pitching motion. Thus, the present study focuses on the effect of WLE on stall phenomenon during pitching motion. Suppression of the stall could be accomplished using Vortex Generator (VG) or WLE. Bak et al. [10] have observed that VG can effectively suppress stall only at angle of attack below 20°.

In the present study, a pitching motion experiment was conducted to elucidate the effect of WLE on stall. As a comparison, the unsteady experiment of VG was also given in the present study. Numerical investigation was carried out to understand the effect of WLE on the stall phenomenon during pitching motion. The wing shape considered in the present study has been previously analyzed under steady conditions by Arai et al. [6, 7].

II. METHODS

A. Experimental Methods

The base wing is a rectangular wing NACA0018 section with an Aspect Ratio (AR) of 1.6. An AR 1.6 referred to the previous study [6], [7] used to apply to ship rudder. The plane views of the models are shown in Figs. 1 and 2. Unsteady experiments were performed by pitching wing in a circular water channel at Hiroshima University, Japan.
The measuring section of the circular water channel had a width of 1400 mm, height of 900 mm, and a length of 3300 mm. A schematic diagram of the experimental apparatus is shown in Fig. 3. The coordinate system of the wing is given in Figure 4. The pivot point of the pitching motion was located at the quarter-chord from the leading edge. A Cartesian coordinate system \( O-xyz \) is employed and the origin is located on the leading edge at the center of the wing span. The \( x \)-axis was taken as parallel to the direction of the uniform flow, and the \( y \)-axis was taken as parallel to the span direction. The details of the experiments are listed in Table 1. Figure 5 shows the shape and dimensions of VG used on the VG wing. It has counter-rotating vanes of height 0.016 \( c \) and length 0.048 \( c \), where \( c \) is the chord length. The angles of VG are relative to the chord-wise direction are \( \pm 20^\circ \).

The shape of WLE is given by a sinusoidal function determined as follows:

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

(1)

where \( x_{\text{LE}} \) indicates the \( x \)-coordinate at the leading edge of basic wing shape. The width \( W \) and depth \( d \) correspond to the wavelength and amplitude, are equal to 0.08 \( c \) and 0.05 \( c \), respectively. The angle of attack (\( \alpha \)) is given by the following equation:

\[
\alpha(T) = \alpha_c + \alpha_a \cos (kT)
\]

(2)

where \( \alpha_c \) and \( \alpha_a \) are mean angle of attack and amplitude of pitching motion, respectively. Additionally, \( k \) and \( T \) are reduced frequency and dimensionless time defined as:

\[
k = \frac{2\pi fc}{U_0}
\]

(3)

\[
T = \frac{tU_0}{c}
\]

(4)

where \( f \) is frequency (Hz), \( t \) is the times, \( c \) is the chord length (m), and \( U_0 \) is the free-stream velocity (m/s). Three reduced frequencies were selected \( k = 0.09, k = 0.12, \) and \( k = 0.25 \) by considering the ship stabilizers of a RORO ship. The mean angles were chosen \( 20^\circ \) and \( 30^\circ \) and the amplitude of pitching motion was \( 5^\circ \) due to the limitations of actuator drive. The average angles and amplitude of pitching were set to be around the steady-state stall angle and the deep stall angle.

Table 1 Details of experiment

| Details of experiment | Value |
|-----------------------|-------|
| Wing section          | NACA 0018 |
| Aspect Ratio          | 1.6 |
| Reynolds Number, \( Re \) | \( 1.4 \times 10^5 \) |
| Reduced Frequency, \( k \) | \( 0.09, 0.12, \) and \( 0.25 \) |
| Mean angle of pitch motion, \( \alpha_c \) | \( 20^\circ \) and \( 30^\circ \) |
| Amplitude of pitch motion, \( \alpha_a \) | \( 5^\circ \) |
| Chord length, \( c \) | 0.25 m |
**B. Numerical Methods**

Simulations were carried out by the use of the simulator Autodesk CFD® to solve the unsteady Reynolds-averaged Navier–Stokes (URANS) equations. The SST k-\omega, which is capable to capture the flow dynamics of stall [11], is employed for the turbulence model. The simulated domain configurations and their boundary conditions are given in Fig. 6. To simulate the pitching motion of the wing, the sliding mesh method was applied. The diameter of the pitching region is four times of the chord length. The unstructured meshing was applied in the simulations shown in Fig. 7.

**III. RESULTS AND DISCUSSION**

**A. Experimental Results**

The experiments were conducted in steady and unsteady cases for the baseline, VG, and WLE wings. In unsteady case, pitching motion experiments were carried out at reduced frequencies of \( k = 0.09, 0.12, \) and 0.25. Figs. 8 to 10 show the 100-cycle phase-average of measured \( Cl \) and \( Cd \) of Baseline and WLE wing. The measurement results in the steady case are given for comparison. The standard deviation of the measured \( Cl \) and \( Cd \) are 0.027 and 0.0060, respectively. These values are less than 4% of the maximum value of each coefficient. In the figure, “upstroke” and “downstroke” correspond to the periods during angle of attack increasing and decreasing, respectively. The hydrodynamic force acting on the wing was obtained by subtracting the inertial force measured by pitching in air.

In steady case results, the maximum lift occurs at the angle of attack \( 22^\circ < \alpha < 23^\circ \). So it can be defined that pre-stall region at angles \( \alpha \leq 22^\circ \) and post-stall region at angles \( \alpha \geq 23^\circ \). The \( Cl \) value of WLE wing was lower than the baseline wing in the steady case at the pre-stall region (\( \alpha \leq 22^\circ \)). Although the stall angle of WLE wing was lower than baseline wing, WLE was able to acquire higher \( Cl \) than that of baseline at the post-stall region (\( \alpha \geq 23^\circ \)). For the unsteady case, the WLE wing showed the same behavior as the WLE wing during the upstroke motion in the pre-stall region (\( \alpha \leq 22^\circ \)), but had a better \( Cl \) value than baseline wing at the post-stall region (\( \alpha \geq 23^\circ \)). Regarding the \( Cd \) value, increase in drag was found to be less than increase in lift. Thus, in the post-stall region (\( \alpha \geq 23^\circ \)), WLE is effective to suppress the stall.
A similar trend was observed at the three reduced frequencies. In more detail, high frequency pitching WLE wing can increase the maximum lift compared to the lower frequency motion. The simulated absolute value may not be accurate with that experiment. However, the calculated results express the experimental trends qualitatively. Therefore, the ratio of the lift of the WLE wing and that of the baseline wing was calculated, and the trend of the change was compared between the experiment and the calculated results.

In the post-stall region, the $C_l$ of WLE wing is higher than the baseline wing. The trend of $C_l$ increase differs between the upstroke process and the downstroke process. Table 2 shows the $C_l$ and $C_d$ at $30^\circ$ during the upstroke motion ($30^\circ$↑) and downstroke motion ($30^\circ$↓) for baseline wing and WLE wings. Table 3 gives the ratios of the lift and drag coefficients for the WLE wing to those of the baseline wing, where the subscripts WLE and Baseline indicate coefficients for the WLE and baseline wings, respectively.
Here, we get:

\[
\frac{Cl_{WLE}^{30\degree}}{Cl_{Baseline}^{30\degree}} > \frac{Cd_{WLE}^{30\degree}}{Cd_{Baseline}^{30\degree}} > 1. \]

The inequality is demonstrating that the ratio of \(Cl_{WLE}/Cl_{Baseline}\) is higher during the upstroke motion than the downstroke motion. It can be seen that the lift increase by WLE is more effective in upstroke motion than downstroke motion. Meanwhile, we get the followings for \(Cd_{WLE}/Cd_{Baseline}\) ratio,

\[
\frac{Cl_{WLE}^{30\degree}}{Cl_{Baseline}^{30\degree}} > \frac{Cd_{WLE}^{30\degree}}{Cd_{Baseline}^{30\degree}}, \quad \text{and} \quad \frac{Cl_{WLE}^{45\degree}}{Cl_{Baseline}^{45\degree}} > \frac{Cd_{WLE}^{45\degree}}{Cd_{Baseline}^{45\degree}}.
\]

This quantitatively demonstrates that the drag increase achieved by the WLEs are less than the lift increase. Thus, WLEs is effective to suppress the stall in the post-stall region during pitching motion.

Figure 11 compares the lift and drag coefficients of the VG wing and baseline wing. The VG wing slightly delays the stall angle in the pre-stall region. But the steady case results for the baseline and VG wing are similar in the post-stall region. Table 4 shows a comparison of the ratio of \(Cl_{VG}/Cl_{Baseline}\) and \(Cd_{VG}/Cd_{Baseline}\) at \(30^\circ\) and \(45^\circ\). where \(Cl_{VG}\) denotes \(Cl\) of the VG wing and \(Cd_{VG}\) denotes \(Cd\) of the VG wing.

\[
\frac{Cl_{VG}^{30\degree}}{Cl_{Baseline}^{30\degree}} < \frac{Cl_{WLE}^{30\degree}}{Cl_{Baseline}^{30\degree}}, \quad \text{and} \quad \frac{Cd_{VG}^{30\degree}}{Cd_{Baseline}^{30\degree}} > \frac{Cd_{WLE}^{30\degree}}{Cd_{Baseline}^{30\degree}}.
\]

From Tables 3 and 4, the ratio of \(Cl_{VG}/Cl_{Baseline}\) is less than \(Cl_{WLE}/Cl_{Baseline}\) for both upstroke and downstroke motions, and \(Cd_{VG}/Cd_{Baseline}\) is greater than \(Cd_{WLE}/Cd_{Baseline}\) for both upstroke and downstroke motions. This indicates that the VG wing is not as effective in suppressing stall as WLE wing at the post-stall region. Meanwhile, the VG wing at pre-stall region has greater \(Cl\) compared with Baseline and WLE wing.

**B. Numerical Results**

To establish the accuracy of CFD simulation and maintain a low cost computation, a mesh convergence study was performed by developing three different meshes with coarse, medium, and fine resolution. The number of elements and its ratio compared to coarse type are given in Table 5. In all cases, the mesh spaces adjacent to the wing surface satisfy \(y^+ < 3\). The lift and drag coefficient are shown in Fig. 12. Since the results of WLE wing at post-stall region (\(\alpha > 21^\circ\)) has favorable values than baseline wing, numerical methods only focused on the range angle of attack \(25^\circ \leq \alpha \leq 35^\circ\).

Because there were no significant differences among the calculation results obtained with each of the three meshes, the medium mesh was used for all subsequent calculations. Figure 13 shows the comparison between calculated unsteady results for baseline wing and WLE wing. Experimental and numerical results are denoted as “Exp” and “CFD”, respectively in Fig. 13. Similar to the facts seen in the experimental results, the calculated results show that at the post-stall region (\(\alpha > 21^\circ\)), \(Cl\) by WLE wing tends to be greater than \(Cl\) of baseline wing. The increase in \(Cl\) by WLE wing tends to be greater in the upstroke process than in the downstroke process. Fig. 14 shows the comparison of the ratio of \(Cl_{WLE}/Cl_{Baseline}\) at \(30^\circ\) upstroke (\(30^\circ\)↑) and \(30^\circ\) downstroke (\(30^\circ\)↓). The same denotation is given for \(Cd_{WLE}/Cd_{Baseline}\). The trends of \(Cl_{WLE}/Cl_{Baseline}\) and \(Cd_{WLE}/Cd_{Baseline}\) observed in the experimental results are shown in the numerical results. The improvement of the lift force in the upstroke motion is remarkable more than that of downstroke motion. The increase in drag due to WLE is not significant and the increase is less than the lift increase.

In order to investigate the difference in trend during upstroke and downstroke motions, distributions of pressure coefficient (\(Cp\)) in the two cases were compared. Here, \(Cp\) is normalized by the uniform flow velocity. Figure 15 shows the \(Cp\) distribution on the suction side of the wing at \(30^\circ\)↑ and \(30^\circ\)↓. The symmetry plane is given as SP. The deep blue color on the left side of Fig. 15 represents the low pressure compared to the surrounding area. At the upstroke motion, the lower pressure area is wider than the downstroke motion. It can be seen that the pressure on the suction side of WLE wing is lower during the upstroke motion than the downstroke motion. Due to the pressure distribution around the leading edge, the \(Cl\) at upstroke motion is higher than the downstroke motion.
Figure 16 shows the velocity distribution on x-z plane at \( y = 0.66c \). In the figure, a streamline is drawn to make clear the flow pattern around the leading edge. The velocity distributions of baseline wing and WLE wing are given on the left and right side, respectively. The separated areas can be compared based on how the streamlines divide. The streamlines of WLE wing are closer to the wing surface than those of the baseline wing. On the WLE wing, the flow is capable of attaching the wing surface. Furthermore, there is a stagnant flow, observable as a deep blue region on the suction side of the wing. For both the baseline and WLE wings, the stagnant flow is greater during the downstroke motion than during the upstroke motion. In the case of WLE wing, the stagnant flow on the suction side of the wing is suppressed in comparison with the baseline wing case.

Figures 17 and 18 show the streamlines flowing in front of the leading edge at the position \( x = 3.632c \). The streamlines are rotating in the direction of the wing tip for the WLE wing, whereas in the case of the baseline wing, the streamlines are directed toward the trailing edge area. For the WLE wing, the streamlines are more twisted during the upstroke motion than they are during the downstroke motion. As described by Arai et al. [7], and Torro et al. [9], the streamwise vortical flow around WLE is thought to contribute to the suppression of separation. In the present unsteady study, a similar streamwise vortical flow was observed around WLE in
the upstroke and downstroke motions. The twisted vortical flow observed during the upstroke motion was stronger than that during the downstroke motion, which is thought to be related to the fact that the higher lift was obtained during the upstroke motion than during the downstroke motion.

Fig. 17 Upstroke Streamlines at α=30°

Fig. 18 Downstroke streamlines at α=30°

IV. CONCLUSION

The effects of WLE (Wavy Leading Edge) on a rectangular pitching wing with reduced frequencies $k = 0.09$, $k = 0.12$, and $k = 0.25$ have been evaluated by experiments and numerical simulations to find out the stall suppression. The conclusion obtained for the wings used in the present study is clarified as follows:

- Improvement of stall by WLE can be accomplished at the post-stall region during pitching motion. In particular, the improvement of the lift force in the upstroke motion is remarkable more than that of downstroke motion.

- The twisted stream-wise vortical flow is observed around WLE in the upstroke and downstroke motion. The vortical flow at the upstroke motion is stronger than the downstroke motion.

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