論文の要旨

題　目: Study on Wavy Leading Edge Phenomena ~ Effect of Wing Shape and Aspect Ratio ~
（波状前縁翼に関する研究
～翼形状とアスペクト比の影響～）

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Learning from nature-inspired by a humpback whale flipper that is capable of capturing their prey ingeniously. The flipper has WLE-shaped morphology, blunt and rounded around its leading edge. This flipper plays a part in enhancing efficiency on the hydrodynamic. This advantage may be extended to other systems on the ships such as fin stabilizers or wind turbines. A study in the steady and unsteady case was interesting to observe in order to find out the optimum application at Reynolds number 1.4 x 10^5 and NACA 0018 profile. The wing's chord length was 125 mm, and 250 mm, depending on the difference in aspect ratio (AR). The wavelength (W) of the WLE shape is 8% c with the amplitude (d) equal to 5% c. The rectangular wing was selected initially to mimic the form of the flipper. To find out the WLE effect, experimental and numerical methods were employed. The WLE wing has improved performance after stall conditions in steady and unsteady conditions. So, this study focused only on the post-stall condition. The WLE effect was observed with different aspect ratios. This research utilized five aspect ratios (ARs), i.e. 1.6, 3.9, 5.1, 7.9, and 9.6. Aspect ratio 7.9 has the best performance. The rectangular wing was adapted to the form of the taper wing to match the humpback whale flipper. The principal works of research can be summarized as follows:

1. This research employed the numerical approach by using Autodesk® CFD to consider the mechanism of fluid flow on the WLE wing. There are three types of reduced frequencies during unsteady conditions, i.e. k = 0.09, 0.12, and 0.25. The unsteady study was conducted only at aspect ratio 1.6 to find out the WLE effect on the wing. In order to explain the WLE effect during the unsteady condition, variations in the fluid pattern on three forms of reduced frequencies have been observed. At the fastest reduced frequency k = 0.25, variations between baseline wing and WLE wing were seen more clearly. So, the next numerical analysis focused only on the reduced frequency of k = 0.25. The upstroke motion has better performance at aspect ratio 1.6 than it did during downstroke motion. The stronger vortical flow was observed during the upstroke motion with respect to the streamline analysis around the WLE. This vortical flow is thought to contribute suppress the separation.

2. As described above, different aspect ratios on the rectangular wing were performed to get the maximum benefit of the WLE effect. Steady case analysis to determine the best aspect ratio was conducted. Aspect ratio 7.9 has the highest value as compared to all aspect ratios after the stall condition. The position of the WLE effect was also observed in the chord-wise direction on the three parts, i.e. at the symmetry plane, mid-span and area near the tip of the wing. To recognize the phenomenon of flow separation, instantaneous streamline was observed on the suction side of the baseline and WLE wing. In this case the distance from this streamline to the surface of the wing is called as the stream-tube. On the WLE wing, if compared to the baseline wing the stream-tube has a narrower size. This means the flow is capable to attach the WLE wing to the wing surface. In three parts a comparison was performed to find out the WLE effect. The WLE effect has a stronger effect between the mid-span to the direction of the wing tip than the area between the symmetry plane to the mid-span. The WLE effect is seemingly negligible in this field. The WLE effect was used to evaluate further wing form, depending on the position on the wing.

3. A comparison of the aspect ratio 3.9, 5.1, and 7.9 was performed during unsteady analysis to understand the effect of the WLE on the rectangular wing. The range angles only focused on post-stall condition i.e. 25° ≤ α ≤ 35° in these cases. Similar results with aspect ratio 1.6 were

found at aspect ratios 3.9 and 5.1, where the WLE wing shows best performance. The WLE wing has a favorable lift coefficient as compared to the baseline wing during the upstroke motion. But the tendencies on both wings during the down-stroke motion are similar.
The similar lift coefficient for base line and WLE wing was found at aspect ratio 7.9. This trend was inconsistent with steady case analysis in which aspect ratio 7.9 has the best performance in comparison with all aspect ratios. This difference was a fascinating fact to observe the phenomenon of flow with respect to the WLE effect. Hence, the shape of the rectangular wing was assumed to be modified into the form of the taper wing. This idea was inspired by the humpback whale flipper. A taper wing shape is a mere approach to the flipper shape of the humpback whale.

4. The humpback whale flipper has an aspect ratio of around 7.7. An approach to the design of the humpback whale flipper was rendered using three types of taper ratios on the taper ratio, i.e. 0.1, 0.3, and 0.5. Steady analysis was performed on three forms of taper ratios to get the best results. After the stall condition, the range angles were conducted i.e. 20 °, 25 ° and 30 °. Taper wing with ratio of taper 0.3 has the best results. The WLE effect on the taper wing was observed with four parts in chord-wise direction in the area from mid-span to the direction of the wing tip. The results show that three of the area near the tip of the wing have a stronger impact in suppressing the flow separation.

5. A comparison of the best wing on the taper wing and the rectangular wing was observed for finding the optimal wing shape. The rectangular wing with aspect ratio 7.9 and the taper wing with taper ratio 0.3 in this case. This comparison was performed in unsteady analysis at the post-stall region with reduced frequency $k = 0.25$ at range angles $25° \leq \alpha \leq 35°$. Four types of wings were used, i.e. baseline rectangular wing AR 7.9, WLE wing AR 7.9, taper wing baseline TR 0.3, and taper wing WLE wing with TR 0.3. There are no major differences in the same wing shapes between baseline and WLE wing. Differences between WLE wing on rectangular wing and taper wing was seen more clearly. The WLE wing on the taper wing performs better during upstroke and downstroke movements. It means that the shape of a wing affects the phenomenon of flow. The turbulent strength (TI) has been observed for understanding this particular phenomenon. In this case, the distribution of streamlines in turbulent intensity (TI) was used for viewing the separation phenomenon. The streamlines on the rectangular wake region have rotational flow along the wing-span.
   But the straight streamlines were found on the TR 0.3 wing, in the mid-span to the direction of the wing tip. This means that the movement through the taper wing was smoother than the rectangular wing. The wing tip vortex in the taper wing appears to be minimized. We can infer that the separation area in the TR 0.3 wing was controlled by comparison with the rectangular wing.

Further work of this research was to understand the flow phenomenon due to the shape of the wing, it will be interesting to explore the differences between rectangular and TR 0.3 wing with analysis of pressure losses in the wake zone. In addition, the author suggests that its analysis could be applied to another wing profile to determine the best performance in approaching the shape of the humpback whale flipper.