Fluid dynamic effects of small projections based on dorsal ridge tubercles of the finless porpoise

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Abstract

The finless porpoise has characteristic tubercles on its dorsal ridge. These tubercles are supposed to have biological and mechanical functions. In the former, specific nerve endings and fibers exist in the tubercles indicating its function as a sensory organ. In the latter, tubercles provide fluid dynamic functions such as underwater drag reduction or inhibition of wave or spray drag while breathing at the sea surface. This research focuses on the latter function aiming at the application to the drag reduction in moving vehicles. Small projection models, or tubercle models were fabricated with resin and tested in the wind tunnel to investigate the effect on the lift and the drag characteristics of an airplane model with the tubercle models attached on the wing-fuselage connection. In consequence, it was shown that the tubercles effectively delayed the wing stall at high angles of attack without largely degrading the wing performance. The oil flow experiments also clarified that this delay of wing stall was caused by the inhibition of flow separation on the wing surface. The tubercles then had a positive influence on the flow around the wing or fuselage effectively inhibiting the flow separation and thus may be a useful device to reduce drag, noise, or vibration of moving vehicles.

Key words: Tubercle, Finless porpoise, Drag reduction, Flow separation, Wing stall

1. Introduction

The finless porpoise (Neophocaena asiaeorientalis) is a small odontocete (toothed whale) belonging to the Phocoenidae. Two species are now recognized within genus Neophocaena; N. phocaenoides, and N. asiaeorientalis (Jefferson & Wang, 2011). The maximum body size is about 2.0 m (Kasuya, 2011), and maximum weight is about 72kg, but these are geographically variable (Kasuya, 1999). It lives in the coastal area south of Japan, South-east Asia, India, and Arabia (Jefferson and Hung, 2004). The most notable feature of this species is the lack of a dorsal fin as shown in Fig. 1(a). Instead, it has a dorsal ridge covered with a lot of tubercles as shown in Fig. 1(b). The function of these tubercles were discussed from a biological and a mechanical point of view. From the biological point of view, the function as a sensory organ was pointed out because there were specific nerve endings or nerve fibers in the tubercles (Liu, 1985). In contrast, from the mechanical point of view, the hydrodynamic function was pointed out. Many phocoenid porpoises such as the harbor porpoise (Phocoena phocoena) have tubercles on the leading edge of the dorsal fin. They are supposed to act as a flow regulator that minimizes the disturbances of flow at the water surface while
breathing, thus decreasing the wave and spray drag (Ginter et al., 2011). It is also known that the humpback whale (*Megaptera novaeangliae*) has large tubercles on the leading edge of flippers and that they may improve the performance of flippers by modifying the water flow around them (Miklosovic et al., 2004). These kinds of hydrodynamic advantages by the tubercles are also found in artificial moving vehicles such as airplanes, ships, or cars. So-called roughness or vortex generators are used on the wing and fuselage of airplanes, on the hull of ships, or on the body of cars (Reneaux, 2004; Brandner and Walker, 2001; Koike et al. 2004). They are usually small plates or 3D structures standing on the wing or body surface and generally have a function to transfer the laminar boundary layer flow on the surface to the turbulent one. The turbulent flow can supply energy to the lower layer of the boundary flow to increase flow speed and thus inhibits flow separation. This separation inhibition effectively contributes to the reduction of pressure drag, noise, or vibration of vehicles caused by the flow disturbance.

Because the function of the dorsal ridge tubercles of the finless porpoise was not yet investigated thoroughly, this study focuses on their hydrodynamic functions referring to instances in other species of porpoises or whales or to the examples in moving vehicles just stated above. Small projection models, hereafter denoted as tubercle models, were fabricated based on the original tubercles of the finless porpoise, and wind tunnel experiments were conducted to investigate the fluid dynamic characteristics of tubercles.

Fig. 1 Pictures of the adult finless porpoises at Toba Aquarium in Japan (a) and its dorsal ridge tubercles (b) taken by the authors. The finless porpoise lacks a dorsal fin, and instead it has a dorsal ridge running antero-posteriorly from middle of the body to the tail. The ridge is generally made up of soft elastic tissue, and there are many tubercles on the ridge, covering it from top to bottom on both sides

2. Method
2.1 Tubercle measurement

Shape, size, and density of tubercles of finless porpoise was measured using a plaster model of dorsal ridge as shown in Fig. 2. This model was made from a mold taken from a young finless porpoise the body size of which was 120cm or 60% of the maximum size of finless porpoises. The ridge began at the quarter position of the body and extended to the tail. The longitudinal section shape varies antero-posteriorly, gently-sloping in front and steeply-sloping at rear as shown in Fig. 2. The shape of the tubercle was like a cone with an extended base and a rounded top as shown in Fig. 3. The diameter of the base was 1-2mm and the height was about 1mm. The density of the tubercles was about 16/cm² and this was almost constant along the ridge. The distance between tubercles was 2-3mm.

2.2 Tubercle model fabrication

The tubercle model was made of resin referring to the plaster model mentioned above. The heated resin was squeezed from a glue gun on a vinyl tape attached to a flat plate. Moving away the glue gun vertically from the plate shortly after squeezing generates a conical shape of the resin as shown in Fig. 4. The top of the resin model was rounded because of the surface tension and thus having similarity to the tubercle shape in Fig. 3. The size of the base of the model was about 1.5mm and height was about 2mm which were slightly larger than the measured values considering the measured individual was young and 60% of the maximum size of finless porpoises. This fabrication
process was repeated carefully until 360 similar tubercle models were made in total. The tubercle models were then placed at each node of 5mm mesh on a vinyl tape with 50mm width and 200mm length as shown in Fig. 5. This distance was also larger than the measured value because of the same reason as the tubercle size. This tubercle tape was used in the following wind tunnel experiment.

Fig. 2 Plaster model of dorsal ridge of finless porpoise. It was made by pouring plaster into a rubber mold that was taken from a real finless porpoise. The white colored region shows an upper surface of the plaster model that was put on a black table. White lines below the model show the section shape of the dorsal ridge at each arrowed position. The shaded area shows the region where the tubercles existed and the shape, the size, and the density of them were observed in this area.

Fig. 3 An enlarged photo of tubercles at the middle position of the plaster model shown in Fig. 2. They were dispersed over the ridge like this picture with almost constant density.

Fig. 4 Single tubercle model made by resin. The resin squeezed from a glue gun on a vinyl tape cooled down quickly and stuck to the tape without using glues.

Fig. 5 The vinyl tape (50mm×200mm) with 5mm mesh. Resin tubercles are placed on each node of the mesh. Two types of tape with and without tubercles were made. The tape without tubercle was used as a control to confirm the fluid dynamic effect of tubercles. These tapes were attached on the model airplane in the wind tunnel experiment.
2.3 Wind tunnel experiment

The fabricated tape with the tubercle models was attached to an airplane model which was a 1/8.6 scale of Fuji Heavy Industries (FHI) FA-200 light airplane known as “Aero Subaru” as shown in Fig. 6. This model has a simple rectangular wing with 1,100mm wing span and 178mm wing chord length. The aspect ratio of the wing is 6.34 and the airfoil is U-615M. This kind of rectangular wing generally has a wing root stall characteristic because the local lift coefficient at the wing root is larger than the other part of the wing and then the wing stall starts first at the wing root at high angle of attack. The flow at the wing-fuselage connection also tends to be disturbed because so-called “horseshoe vortex” is generated along the wing root (Gand et al., 2010, Fu et al., 2007, Ölçmen and Simpson, 2006). The adverse pressure gradient around the flow stagnation point at the leading edge of the wing root generates vortex which flows downstream on each side of the wing forming a horseshoe shaped vortex as shown in Fig. 7. This vortex disturbs the flow at the wing-fuselage connection and induces flow separation. The tubercle tape, then, was attached along the wing-fuselage connection as shown in Fig. 8 to confirm whether the tubercles have a positive flow control such as separation-prevention on this region or not. Besides this tubercle tape, tape of the same size without any tubercles was used as a control. By comparing the result with the tubercle tape and that with the tape only, the influence of the tubercles could be evaluated.

The airplane model was set at the wind tunnel of Tokai University that has a nozzle size of 1000mm height and 1500mm width. The wind speed $V$ was 20m/s and 30m/s that were calculated from the observed range of Reynolds number from $8.9 \times 10^5$ to $3.6 \times 10^6$ in the swimming of phocoenid porpoise in nature.

The angle of attack $\alpha$ was changed from -10 to 28 degrees at 2 degrees interval while the side slip angle $\beta$ was kept zero.

![Fig. 6 The airplane model used in the wind tunnel experiment. This was a 1/8.6 scale of Fuji Heavy Industries (FHI) FA-200. The original airplane has a propeller at the nose but it was excluded in the model for easy handling.](image)

![Fig. 7 Schematic diagram of the horseshoe vortex formed at the wing-fuselage connection](image)

![Fig. 8 Tubercle tape attached on the wing-fuselage connection. In order to fit the tape to a curved shape of the wing surface, a fuselage side half of the tape was cut at several places.](image)
2.4 Oil flow experiment

If any difference is found between the results with the tubercle tape and with the tape only, an oil flow experiment is conducted to observe the flow on the wing and the fuselage surface. Colored oil is used for this experiment, e.g. white colored oil for a black colored model or vice versa, to clearly visualize the flow on the surface. In this study, white colored oil was used which was made of liquid paraffin and titanium dioxide with oleic acid as a mediator. The oil is initially painted on the surface of the model with a brush so that the brush mark orients perpendicularly to the flow direction, and then the air is blown. The oil drifts due to the friction of the air flow when the flow is not separated from the surface and the initial brush mark disappears, but it does not drift when the flow is separated and thus the initial brush mark remains. The characteristic pattern of oil is then made on the surface showing the region where the flow is separated or not.

3. Results and discussion
3.1 Wind tunnel experiment

The lift and the drag coefficients calculated from the wind tunnel experiment are shown in Figs. 9(a)-9(d) for different wind speeds and with or without tubercles, i.e. with the tubercle tape or with the tape only, respectively. For the drag coefficient $C_D$, the model with tubercles had a slightly larger value than the model without tubercles between $\alpha=6^\circ$ and $12^\circ$ at both wind speeds of $V=20$m/s and $V=30$m/s. For the lift coefficient $C_L$, significant difference was not observed at $V=20$m/s, but some difference was observed at high angles of attack with $\alpha=18^\circ$ or $20^\circ$ at $V=30$m/s. The lift coefficient for both with and without tubercles decreased suddenly around this angle of attack indicating an occurrence of wing stall. In the case without tubercles, this wing stall occurred at $\alpha=18^\circ$, but in the case with tubercles it did not occur prior to $\alpha=20^\circ$, indicating that the tubercles delayed the wing stall.

![Fig. 9 The drag coefficient $C_D$ (a) and (b)) and the lift coefficient $C_L$ ((c) and (d)) vs. angle of attack $\alpha$ of the airplane model with and without tubercles. The wind speed $V$ for (a) and (c) was 20m/s and for (b) and (d) was 30m/s. In the legend, “Without tubercles” denotes with the tape only and “With tubercles” denotes with the tubercle tape.](image-url)
3.2 Oil flow experiment

In order to confirm the difference of flow causing this discrepancy of $C_L$ between with and without tubercles, an oil flow experiment was conducted. The tubercle tape was attached to the wing-fuselage connection on the right side of the model and only the tape was attached at the same place on the left side of the model to observe the oil pattern at the same time.

The white colored oil was applied to both sides of the wing and 30m/s wind was blown until clear oil patterns appeared. This experiment was conducted at the angles of attack around the wing stall angle of attack, i.e. $\alpha=18^\circ$, $20^\circ$, and $22^\circ$, to see the flow difference between the right and the left side of the wing for these angles.

These results are shown in Figs. 10(a)-10(c). Fig. 10(a) shows the result at $\alpha=18^\circ$. The oil patterns on the right and the left side of the wing were almost the same, showing large yellow colored region on both sides. This means the flow was not separated largely on both sides and that the right and the left wings both generated almost the same lift. This situation of flow corresponds to the $C_L$ at $\alpha=18^\circ$ in Fig. 9(d) where the wing was not stalled for either model with and without tubercles.

Fig. 10(b) shows the result at $\alpha=20^\circ$. At this angle of attack, the oil patterns differed significantly. A large yellow colored region spread on the right side of the wing, indicating the flow separation was limited to a small region on this side. However, there was not any yellow colored region on the left side of the wing, indicating the flow was fully separated on this side. This difference of flow between the right and the left sides of the wing also explains the difference of $C_L$ between the model with and without tubercles at $\alpha=20^\circ$ in Fig. 9(d) where the $C_L$ with the tubercles did not decrease suddenly showing the wing did not stall at $\alpha=20^\circ$, whereas the $C_L$ without tubercles decreased suddenly showing the wing stalled at this angle of attack.

Fig. 10 The results of oil flow experiments. The experimental condition was based on the wing stall observed in Fig. 9(d), i.e. the flow speed was $V=30$m/s and the angle of attack was $\alpha=18^\circ$, $20^\circ$, $22^\circ$, to investigate the flow around the wing stall angle of attack. The tubercle tape was attached on the wing-fuselage connection of the right side of the model and only the tape was attached on the same position of the left side of the model. The yellow color was added afterward on the image to show the region where the oil was drifted and the original brush mark disappeared and thus the flow was not separated in order to be distinguished easily from the flow separated region.
Fig. 10(c) shows the result at $\alpha=22^\circ$. The oil patterns on both sides again showed a similar result where the yellow colored region obliquely spread outward from the front root of the wing. Although the left wing had a somewhat larger yellow colored region than the right one, the flow was separated in a large area of both wings. This also correlates to the similarity of $C_L$ at $\alpha=22^\circ$ in Fig. 9(d) where $C_L$ with and without tubercles was almost the same and the wing stalled in both cases.

In summary, the tubercle models inspired by the dorsal ridge tubercles of the finless porpoise had an apparent fluid dynamic effect on the wing and fuselage surface inhibiting the flow separation. This may be because the drag caused by the tubercles on the wing-fuselage connection weakens the horseshoe vortex generated by the adverse pressure gradient around the leading edge of the wing root as explained in the 2.3 section. The horseshoe vortex causes the flow instability and thus the attenuation of this vortex may contribute to the inhibition of flow separation. The tubercle on the surface of wing root may also act as a surface roughness which promotes the transition of boundary layer flow from laminar to turbulent. As shown in Fig. 10(b) the flow around the leading edge of the right wing root was not separated while that of the left wing was separated. This may be caused by the turbulent transition of boundary layer by the tubercles on the right side of the wing.

The inhibition of flow separation at the wing root inhibited the expansion of the flow separation to outer part of the wing as shown in Fig. 10(b). The rectangular wing has larger lift coefficient at the wing root than in the other part of the wing. The wing stall then tends to initiate at the wing root and expands outer. Therefore the inhibition of flow separation at the wing root could effectively inhibited the expansion of flow separation to the outer part of the wing.

This kind of fluid dynamic effect of the tubercles on the wing-fuselage connection cannot directly be applied to the dorsal ridge of finless porpoise because the 3D shape of the wing root and the dorsal ridge is not same, i.e. the former is concave and the latter is convex. However the flow situation around them may be similar because the wing root is in the horseshoe vortex and the dorsal ridge of finless porpoise may be in the vortex separated from the body because of the body motion while breathing. When the porpoise dives from the water surface after breathing, it initially bends the body downward. In particular, the finless porpoise has flexible articulations around the neck bones and thus bends its body more sharply than other species. In this situation, the water flows across the body from the ventral to the dorsal side and this generally induces the flow separation on the dorsal side, causing the dorsal ridge surrounded with separated vortices indicating the similarity to the wing-fuselage connection. Therefore, the fluid dynamic effects derived from the tubercles in the wing-fuselage connection may be applicable to the dorsal ridge of finless porpoise.

Although the merits of tubercles to inhibit flow separation is significantly confirmed, there is a demerits that the tubercles cause the drag. As shown in Figs. 9(a) and 9(b), the model with tubercles had a slightly larger drag coefficient than the model without tubercles between $\alpha=6^\circ$ and $12^\circ$. This is because the tubercle separates the local flow around it and thus generates pressure drag (Hoerner, 1965). However the increase of drag by the tubercles was small and almost negligible. This may be because the tubercle tape attached to the airplane model had a respectively small area. The area of the tubercle tape was 100 cm$^2$ and which is equivalent to only about 10% of the wing’s surface area and covers less than 5% of total surface of the airplane model. In the wing stall condition, however, it had an apparent effect of separation inhibition although the tubercle tape area was small. This, then, clearly indicates the advantage of tubercles in the flow turbulent condition on the wing or fuselage surface and thus on the dorsal ridge of finless porpoise as well.

For middle or small size dolphins or porpoises like finless porpoises, the merit of separation inhibition or the flow regulation to reduce wave or spray on the sea surface may more than make up for the demerit of drag increase because of the predator avoidance. They are usually preyed on by killer whales (Orcinus Orca) or large sharks and then limiting the surface disturbance may be effective to hide themselves from these predators diminishing the visual or sound cues to detect the porpoises (Ginter et al., 2011).

Further investigation will be necessary to confirm these advantages in the water or at the water surface by conducting an experiment in the water and also the exploration for the availability of tubercles for the positive flow control device on moving vehicles should be considered expecting the drag, noise, or vibration reductions.

4. Conclusion

The fluid dynamic function of the dorsal ridge tubercles of finless porpoise was investigated experimentally. Wind tunnel experiments were conducted using an airplane model with and without tubercles made out of resin referring to the natural dorsal ridge tubercles of the finless porpoise. The vinyl tapes fabricated with resin tubercles were attached
on the wing-fuselage connections of the model where the flow tends to be disturbed. As a result, the lift coefficient showed a significant difference around the wing stall angle of attack at the wind speed of 30m/s, indicating that the wing stall was delayed by the tubercles. The oil flow experiment confirmed the flow separation inhibition on the wing surface by the tubercles, resulting in the suppression of wing stall. In consequence, the separation inhibition effect of tubercles was definitely confirmed and this effect may be beneficial for the finless porpoise to swim actively without disturbing the water surface and also has the potential of a positive flow control device for moving vehicles.

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References

Hoerner, S. F., Fluid Dynamic Drag, Hoerner Fluid Dynamics, P.O. Box 21992, Bakersfield, CA (1965).