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An experimental study on flow separation control of hydrofoils with leading-edge tubercles at low Reynolds number

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ABSTRACT

Hydrodynamic characteristics of hydrofoils with leading-edge tubercles were experimentally investigated in a water tunnel at a Reynolds number of $Re = 1.4 \times 10^4$. Particle image velocimetry measurements and particle-streak visualizations reveal that the tubercles improve flow separation behaviour. In particular, hydrofoils with larger wave amplitudes and smaller wavelengths tend to perform significantly better in flow separation control. Cross-stream flow measurements indicate that streamwise counter-rotating vortex pairs are generated over the tubercles and mitigate flow separation. Analysis confirms that the tubercles function as vortex generators, due to their comparable heights relative to the boundary layer thickness. The vortex pairs meander and interact with adjacent flows, causing the flow separation behaviour to be occasionally unstable, thus leading to variable flow separation region sizes. This suggests that measures may have to be taken to ensure the stability of the counter-rotating vortex pairs for more persistent and predictable improvements.

1. Introduction

1.1. Research background

In the past decades, drawing inspirations from nature for solutions to engineering problems have seen increased interests from a number of new research areas. Lately, a novel passive flow control technique derived from the morphology of humpback whales has attracted increasing attention of scientists from different areas (Fish et al., 2011; Bolzon et al., 2015). The humpback whale is capable of performing complex underwater manoeuvres to catch prey, including sharp, high-speed, banked turns, as well as loops and rolls. This has been attributed to their pectoral flippers, where several tubercles are distributed along the leading-edge (Fish and Battle, 1995; Fish and Lauder, 2006). Since whales use pectoral flippers as hydrodynamic control surfaces (with a Reynolds number of about $Re = 10^6$), questions are being raised as to whether these leading-edge tubercles could be applied on marine engineering devices. In fact, potential marine applications of leading-edge tubercles have been reviewed by Fish et al. (2011). Some of these applications include rudders (Weber et al., 2010), dive planes, stabilizers, surfboard skegs and propellers. Another potential application of these tubercles is on unmanned underwater vehicle (UUV) control surfaces. These vehicles often cruise at low speeds and tend to have lower Reynolds number flows associated with their control surfaces. Lower Reynolds number flows have thicker boundary layers and more prone to flow separations, thus often leading to poor performance.

1.2. Literature review

The idealized humpback whale flipper model with leading-edge tubercles was tested by Miklosovic et al. (2004) in a wind tunnel at $Re = 5 \times 10^5$. They found that the wing with leading-edge tubercles increases the maximum lift by 6% and delays the stall angle-of-attack by about 40%, as compared to one without tubercles. Murray et al. (2005) showed that the three-dimensional flipper models could increase maximum lift values by 9% and 4% for sweep angles of 15° and 30° respectively, as compared to one without leading-edge tubercles. Johari et al. (2007) investigated the effects of tubercle wavelength and amplitude on the flow separation behaviour of full-span NACA634-021 models in a water tunnel at $Re = 1.83 \times 10^5$. It was found that wings with tubercles reduce the maximum lift coefficient. However, the wings stall more gently and the lift coefficient could be raised by as much as 50% in the post-stall regime.

Flow visualizations using surface tufts and dye showed that the flow behind tubercle peaks remains attached to part of the wing surface in the post-stall regime of the baseline hydrofoil (Johari et al., 2007; Custodio, 2007). Similar trends for the lift and drag of a full-span NACA 0020 aerofoil with leading-edge tubercles were also observed by Miklosovic and Murray (2007) at $Re = 2.74 \times 10^5$.

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In addition, using dye visualization technique, Custodio (2007) showed that each tubercle behaves like the leading-edge of a small delta wing and a counter-rotating vortex pair is created behind each tubercle. The analogy of a tubercle as a small delta wing was later confirmed by Stanway (2008). This study also measured the lift and drag of the whale flipper model with and without tubercles at $Re = 4.4 \times 10^4$ to 1.2×10^5, where it was found that there is no significant improvement on the maximum lift except for the highest Reynolds number. In addition, the flow field around the flipper model with tubercles was measured by particle image velocimetry (PIV) technique in that study, where delays in flow separation and formations of streamwise vortices were shown. Furthermore, force characteristics of the whale flipper were tested under dynamic conditions (i.e., as flapping foils).

Later, Ozen and Rockwell (2010) applied leading-edge tubercles onto a flapping wing and PIV results showed that the tubercles could attenuate the positive and negative spanwise flows along the wing surface, as well as demonstrating the onset and developments of the large-scale concentrations of positive and negative streamwise vortices at inboard locations. Goruney and Rockwell (2008) have also implemented them on a delta wing in an attempt to look into their flow effects on the flow structures and topology along the wing surface. Hansen et al. (2011) investigated the influence of leading-edge tubercles on the aerodynamic characteristics of two NACA aerofoils. They suggested that the tubercles behave in a manner similar to conventional vortex generators and that the optimum tubercle amplitude and wavelength bear strong resemblances to the optimum vortex generator spacing and height. Zhang et al. (2014) investigated the effects of leading-edge tubercles on the aerodynamic performance of a full-span NACA634-021 aerofoil in a wind tunnel for a wide range of angles-of-attack. Particle image velocimetry results confirmed the formation of streamwise counter-rotating vortex pairs, though it should be highlighted that only one measurement location was considered. Furthermore, Delgado et al. (2014) tested a unity aspect-ratio wing with a sinusoidal leading-edge at $Re = 1.4 \times 10^5$ using stereoscopic PIV to aid their numerical modelling.

More recent experimental studies include that by Custodio et al. (2015). They conducted a systematic testing of the hydrodynamic forces on finite-span wings with leading-edge tubercles at Reynolds numbers up to $Re = 4.5 \times 10^5$, as well as making use of three different planforms and a wide range of tubercle geometries. Besides the above experimental works, Van Nierop et al. (2008) developed a mathematical model based on lifting-line theory to investigate the stall characteristics of semi-span wings with tubercles. The control mechanism has been attributed to modifications to the pressure gradient on the suction side of the wing. Pedro and Kobayashi (2008) used detached-eddy simulation (DES) to simulate the flow field over a flipper model at $Re = 5.0 \times 10^5$ and they noticed that the tubercles could reduce the flow separation near the tip of the flipper. Similar simulation work was also conducted by Weber et al. (2011) at Reynolds number between 5.05×10^5 and 5.2×10^5. Câmara and Sousa (2013) used DES technique and evaluated the aerodynamic characteristics of wings with leading-edge tubercles at $Re = 1.6 \times 10^5$, while the case with Reynolds number up to 3×10^6 was also considered by Dropkin et al. (2012).

These above CFD simulations demonstrate that they can provide information on the surface pressure distributions and 3D flow structures which are not readily available from experimental and theoretical investigations. Numerical simulations were conducted by Rostamzadeh et al. (2014) to investigate the formation mechanism of streamwise vortices and surface pressure distributions were also captured in wind tunnel testing. They found that a skew-induced mechanism accounts for the generation of streamwise vortices and the development of these vortices is accompanied by flow separation in delta-shaped regions close to the trailing-edge. More interestingly, they made use of critical-point theory to depict and explain the flow topology above the wing surface. Skillen et al. (2015) used large-eddy simulation (LES) and studied infinite-span wings with leading-edge undulations at $Re = 1.2 \times 10^5$ and the results showed that a secondary flow toward the regions behind the troughs are driven by the spanwise pressure gradient. The stall delay properties behind the peak were explained by the entrainment of higher-momentum fluid and the re-energization of the boundary layer.

1.3. Current research motivation

It should be noted that although much work has been done on the implementation of leading-edge tubercles on wings, the flow separation behaviour still has not been entirely clarified. Furthermore, most of the previous studies on either aerodynamic or hydrodynamic applications were performed at relatively high Reynolds numbers. It should be mentioned that in an earlier study by the authors (New et al., 2014b), a full-span NACA634-021 wing with leading-edge tubercles has been investigated in a water tunnel at $Re = 1.4 \times 10^4$, where PIV and particle-streak visualization techniques were applied to reveal some preliminary understanding on the flow separation behaviour. In this work however, the hydrodynamic characteristics of the hydrofoils with leading-edge tubercles are considered at a similar Reynolds number but with a wider variety of tubercle amplitudes and wavelengths. The aim is to reveal the fundamental flow behaviour of tubercles and to relate them to the resulting flow separation behaviour. It should also be kept in mind that the flow-fields associated with these tubercles will be highly three-dimensional. Hence, to avoid the limitation of two-dimensional PIV and particle-streak photography techniques, three laser sheet positions along the tubercle trough, peak and a location mid-way between them were included during the streamwise experiments. For cross-stream experiments, the laser sheet planes were aligned at four different chordwise locations downstream of the leading-edge to elucidate the nature of the streamwise counter-rotating vortex pairs.

Table 1
Configurations and experimental conditions for hydrofoils with leading-edge tubercles.

Hydrofoil label	A (mm)	λ (mm)	A/λ	U_0 (m/s)	Re	α	Measurement planes	
							Streamwise	Cross-stream
NACA634-021 baseline	–	–	–	0.19	1.4×10^4	0°, 10° 15°, 20°	Mid-span	–
$A9\lambda18.75$	9	18.75	0.48	0.19	1.4×10^4	0°, 10° 15°, 20°	Trough ($z/s = 0.50$) Mid ($z/s = 0.48$) Peak ($z/s = 0.46$)	$x/c = 0.12, 0.25, 0.38, 0.52$
$A9\lambda37.5$	9	37.5	0.24	0.19	1.4×10^4	0°, 10° 15°, 20°	Trough ($z/s = 0.50$) Mid ($z/s = 0.46$) Peak ($z/s = 0.44$)	–
$A1.875\lambda18.75$	1.875	18.75	0.1	0.19	1.4×10^4	0°, 10° 15°, 20°	Trough ($z/s = 0.50$) Mid ($z/s = 0.48$) Peak ($z/s = 0.46$)	–
$A1.875\lambda37.5$	1.875	37.5	0.05	0.19	1.4×10^4	0°, 10° 15°, 20°	Trough ($z/s = 0.50$) Mid ($z/s = 0.46$) Peak ($z/s = 0.44$)	–