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SYMPOSIUM

The Tubercles on Humpback Whales' Flippers: Application of Bio-Inspired Technology

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Synopsis The humpback whale (*Megaptera novaeangliae*) is exceptional among the large baleen whales in its ability to undertake aquabatic maneuvers to catch prey. Humpback whales utilize extremely mobile, wing-like flippers for banking and turning. Large rounded tubercles along the leading edge of the flipper are morphological structures that are unique in nature. The tubercles on the leading edge act as passive-flow control devices that improve performance and maneuverability of the flipper. Experimental analysis of finite wing models has demonstrated that the presence of tubercles produces a delay in the angle of attack until stall, thereby increasing maximum lift and decreasing drag. Possible fluid-dynamic mechanisms for improved performance include delay of stall through generation of a vortex and modification of the boundary layer, and increase in effective span by reduction of both spanwise flow and strength of the tip vortex. The tubercles provide a bio-inspired design that has commercial viability for wing-like structures. Control of passive flow has the advantages of eliminating complex, costly, high-maintenance, and heavy control mechanisms, while improving performance for lifting bodies in air and water. The tubercles on the leading edge can be applied to the design of watercraft, aircraft, ventilation fans, and windmills.

Introduction

The fields of biomechanics and functional morphology, as they developed, have largely relied on an understanding of engineering principles to describe the relationships between anatomical structures and their functions. Before the mechanics of the flight of birds and bumblebees could be comprehended, knowledge of steady and unsteady aerodynamics was required. Similarly, skeletal mechanics involved an understanding of architecture, material science and beam theory, while swimming in fish involved application of hydrodynamics. The application of physics through engineering and the development of technology led the way to a broader knowledge of biological form and function. Indeed, the development of technology was considered a means for humans to escape the vagaries of nature (Burke 1978). Technology was a means of dominating nature and inventions were products of our imaginations.

Today, the relationship between engineering and biology is being reversed. Nature is now being considered as the template for improving mechanical devices and operations, and developing whole new technologies (Benyus 1997; Vogel 1998; Forbes 2005; Bar-Cohen 2006; Muller 2008; Allen 2010). As novel morphologies and physiological operations are investigated by biologists, they are serving as the inspiration used by engineers for advances in technological development. Bio-inspiration and biomimetics attempts to produce engineered systems that possess characteristics that resemble living systems or

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function like them (Vogel 1998). The goal of this approach is to engineer systems that emulate the performance of living systems or their constructs, particularly in instances in which an organism's performance exceeds current human-engineered technologies (Taubes 2000; Fish 2006, 2009; Mohseni et al. 2006). In this way, biology becomes a heuristic tool.

The inherent problem in combining biology and engineering in the development of products through biomimicry is that organisms operate with a different set of principles than those of technology (Forbes 2005). Engineered systems are designed and fabricated by conscious decision-making, whereas organisms are the result of the evolutionary Darwinian process of "natural selection." Natural technologies rely upon materials that are wet and flexible, whereas engineered technologies are defined by dry, rigid structures (Vogel 1998; Forbes 2005). An enormous difference remains in the scale of structure and operation that each of these technologies uses. Engineered systems are large in size and fast in speed compared to biological systems, which are small and relatively slow. Jet aircraft carry greater payloads and fly faster at higher altitudes than do small birds; race cars move faster over land than cheetahs, gazelles, or race horses; despite the capability to leap entirely out of the water, dolphins can only maintain the high speed of submarines and surface ships by riding the bow wave (Fish and Hui 1991; Williams et al. 1992). Such discrepancies of scale limit the effective transition of natural designs to engineered technologies. For example, the stresses associated with high-speed flight by jet aircraft preclude copying the complex kinematics and structures of the joints in the wings of birds to produce agile turning maneuvers (Dudley 2002; Warrick et al. 2002).

The problem of scale for use in biomimicry may be reduced by finding areas of overlap in size and performance between a biological structure and an engineered application. One such example are the tubercles on the leading edge of the humpback whale flipper, which will be the focus of this article. The tubercles and flipper function at a size and in a Reynolds regime that coincides with a large array of engineered applications. Conventional airfoils and hydrofoils with straight leading edges generate flow fields that place limitations on the performance associated with co-varying parameters of lift, drag, and stall. Action of the tubercles as passive, leading-edge control structures through modification of the flow over lifting surfaces (i.e., wings) presents a new phenomenon in fluid dynamics (Fish and Lauder 2006; Fox et al. 2009).

Morphology of the flipper

The humpback whale, *Megaptera novaeangliae*, is a relatively short, stout whale compared to the other rorquals in the family Balaenopteridae (Winn and Reichley 1985). This whale feeds on a variety of foods, including Antarctic krill and schooling fish, such as sardine, mackerel, anchovy and capelin (Bonner 1989).

The flippers of the humpback whale are the longest of any cetacean (Fish and Battle 1995). Length varies from 0.25 to 0.33 of total body length (Tomilin 1957; Winn and Winn 1985; Edel and Winn 1978; Fish and Battle 1995). The flippers are highly mobile at the shoulder and exhibit some flexibility along their length (Edel and Winn 1978), especially when compared with other species of whale. The flippers display a high-aspect-ratio planform that curves gently at the distal end, and its cross-section closely resembles the 21%-thick, low drag, NACA 63_4-021 airfoil (Fish and Battle 1995).

The species name *Megaptera novaeangliae* means "great wing of New England." However, another name that had been used was *Megaptera nodosa*. In this case, the species epithet referred to the knobby swellings or bumps that adorn the head and leading edge of the flippers (Bonner 1989). The bumps are arranged sinusoidally as rounded tubercles (Fig. 1), which give the flippers a scalloped appearance (Winn and Reichley 1985; Bushnell and Moore 1991; Fish and Battle 1995). The position of the tubercles is associated with the multiple joints and terminal phalanges from the hyperphalangy of the manus (Cooper et al. 2007). Hyperphalangy is an increased number of phalanges per digit beyond the normal (2/3/3/3/3) condition for mammals. The humpback whale has only four digits in the manus with the absence of digit I (Cooper et al. 2007). The number of tubercles typically ranges from 9 to 11. The first tubercle is positioned at the joint between the radius and metacarpal of digit II and the fourth tubercle is located at the terminus of digit II. Tubercle development occurs early as they occur in young fetuses (Fig. 2).

Analysis of measurements, relative to the span of the flipper (i.e., linear distance from base to tip), was made from photographs of 77 individual humpback whales. Mean aspect ratio was 4.9 ± 0.8 ($\pm$SD) with maximum and minimum aspect ratios of 7.7 and 3.6, respectively. The largest tubercles are the first and fourth from the shoulder of the whale (Fig. 3).

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Fig. 1 Photographs of humpback whales' flippers showing the scalloped leading edge formed by tubercles.

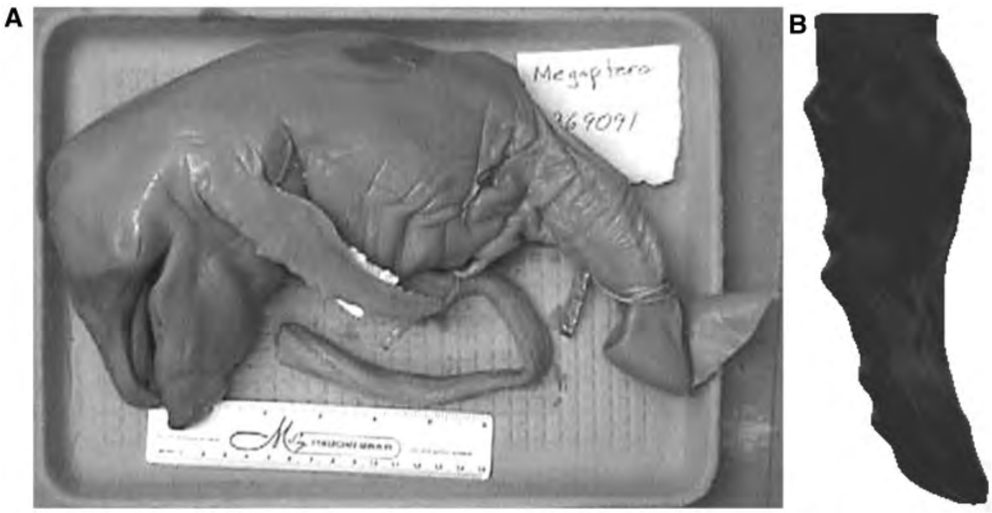

Fig. 2 (**A**) Fetal humpback whale showing elongate flipper and tubercles. (**B**) Reconstruction of fetal flipper from CT scans.

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The first and fourth tubercles are 14.9% and 19.4% of the local chord, respectively, and each is about 4% of flipper span. The other tubercles are smaller with decreasing size toward the tip of the flipper. The intertubercular distances decrease distally along the flipper, although intertubercular distances remain relatively constant at ~7–9% of span from 0.53 ± 0.05 to 0.87 ± 0.04 of the span of the flipper (Fig. 3).

The occurrences of biological leading-edge structures with possible hydrodynamic effects, like the tubercles, although rare, are not unique. Paleozoic fishes of the order Inioperygia had an array of large fish-hook-shaped denticles along the leading edge of the elongate pectoral fins (Zangerl and Case 1973). These cartilaginous fishes were envisioned to use the fin as their principle locomotor organ by employing vertical oscillations. The genus *Protosphyraena* was a group of swordfish-like, predatory marine fishes from the Upper Cretaceous period. These fishes possessed high-aspect-ratio pectoral fins with serrated leading edges (Fig. 4). The cephalofoil of the hammerhead sharks (e.g., *Sphyrna lewini*) has a scalloped leading edge (Bushnell and Moore 1991; Kajiura et al. 2003), which may improve hydrodynamic performance related to pitching (Nakaya 1995). Small tubercles ($\geq$1.1 mm) are found along the leading edge of the dorsal fin of porpoises (Ginter et al. 2011). It was argued that these tubercles could act as passive flow-regulating structures to reduce disturbances at the water's surface. The mystacial vibrissae of phocid seals have a sinusoidal profile that reduces vortex-induced vibrations to improve sensing by underwater movements of prey fish (Fish et al. 2008; Ginter et al. 2010; Hanke et al. 2010).

Use of the flipper by humpback whales

The elongate flippers and leading-edge tubercles are associated with the feeding methods of the humpback whale. The humpback whale is the only baleen whale that relies on maneuverability to capture prey (Fish and Battle 1995). Other balaenopterids (e.g., blue, fin, minke) swim rapidly forward and engulf prey-laden water (Pivorunas 1979; Ridgway and Harrison 1985) and balaenids (e.g., right, bowhead) swim slowly through patches of prey (e.g., krill, copepods, schools of fish) (Burns et al. 1993; Woodward et al. 2006; Cooper et al. 2008). For both families, the typical feeding behavior is to swim rectilinearly with little maneuvering.

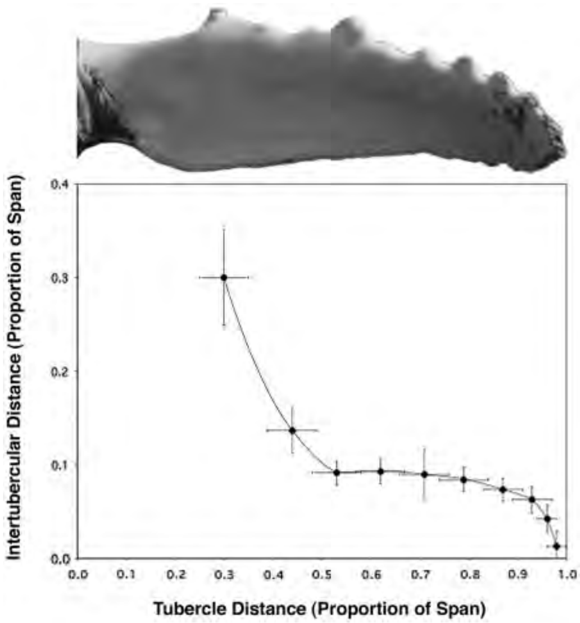

Fig. 3 Plot of the intertubercular distance as a function of distance of each tubercle from the shoulder of the whale. Measurements are shown as a proportion of span of the flipper. The error bars are ±1SD. The flipper planform above the graph illustrates the distribution of tubercles along the leading edge.

Observations of swimming performance by humpback whales show them to be highly maneuverable and aquabatic, using the extremely mobile flippers for banking and turning (Tomilin 1957; Nishiwaki 1972; Edel and Winn 1978; Madsen and Herman 1980; Fish et al. 2008). Humpback whales use their flippers as biological hydroplanes to achieve tight turns in conjunction with feeding behaviors (Hain et al. 1982). During the "inside loop" behavior, the whale swims away rapidly from the prey aggregate with its flippers abducted and protracted (Edel and Winn 1978), then rolls 180° making a sharp U-turn ("inside loop"), and lunges toward the prey (Hain et al. 1982). In "bubbling" behaviors, underwater exhalations from the paired blowholes produce clouds or columns of bubbles, which concentrate the prey (Winn and Reichley 1985; Sharpe and Dill 1997; Leighton et al. 2007; Reidenberg and Laitman 2007). Bubble nets are produced as the whale swims toward the surface in a circular pattern from depth. At completion of the bubble net, the whale pivots with its flippers and then banks to the inside as it turns sharply into and through the center of the net (Ingebrigtsen 1929; Hain et al. 1982).

The sharp, high-speed banking turns executed by the humpback whale are favored by the high lift/drag characteristics of the combination of the tubercles and the high aspect ratio of the flippers. In a banking turn, the body rolls or tilts toward the inside of the turn. The lift force developed by the flippers has a horizontal component that supplies the centripetal force necessary to maintain the turn (Weihs 1981, 1993; Fish and Battle 1995). Lift and the angle of bank are inversely related to the radius of turn (Alexander 1983; Norberg 1990). In addition, increased angle of attack up to the stalling point increases the lift to aid in making tighter turns. The tubercles provide an advantage in maneuverability and in capture of prey by acting as leading-edge

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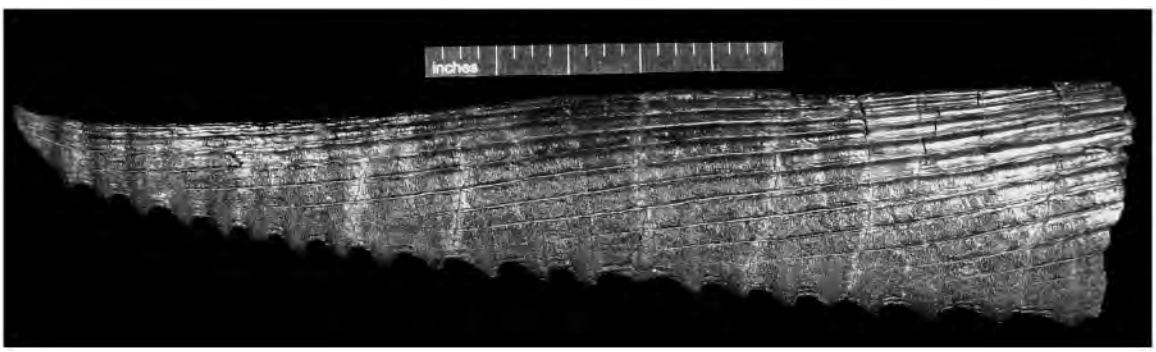

Fig. 4 Distal segment of the pectoral fin from *Protosphyraena* showing protrusions on the leading edge. Photograph courtesy of W. Buckley.

control devices to maintain lift and avoid stall at high angles of attack (Fish and Battle 1995; Fish et al., 2008). Hydroplanes used in turning must operate at high angles of attack while maintaining lift (von Mises 1945; Weihs 1993). If the flippers of the whale were canted at too high an angle of attack during a turn, the flippers would stall and the whale would have a reduced centripetal force. In effect, it would be like driving a car along a curved road and slipping on a patch of ice. The reduced friction between the ice and the tires would cause the car to drive off the road tangential to the curve, rather than following the original curved trajectory. For the whale, the ability to turn tightly would be lost and the prey could escape.

Hydrodynamics of tubercles

Experimental hydrodynamics

The position and number of tubercles on the flipper suggest analogues with specialized leading-edge control devices associated with improvements in hydrodynamic performance. The occurrence of "morphological complexities" on a hydroplane could reduce, or use, variation in pressure at the tip to decrease drag and improve lift to prevent tip stall. Bushnell and Moore (1991) suggested that humpbacks' tubercles might reduce drag due to lift on the flipper. Alternatively, various biological wings utilize leading-edge control devices to maintain lift and avoid stall at high angles of attack at low speeds.

The tubercles of the humpback whale flipper were hypothesized to be analogous to strakes used on aircraft (Fish and Battle 1995). Strakes are generators of large vortices that change the stall characteristics of a wing (Hoerner 1965; Shevell 1986). Stall is postponed because the vortices exchange momentum within the boundary layer to keep it attached over the surface of the wing. Lift is maintained at higher angles of attack with strakes compared to wings without strakes, although maximum lift is not increased by strakes.

Flow-visualization experiments on wavy bluff bodies showed periodic variation in the width of the wake across the span (Owen et al. 2000). A wide wake occurred where the body protruded downstream and a narrow wake occurred where the body protruded upstream. Reduction of drag by at least 30% was achieved on a bluff body with a spanwise sinusoidal form compared to equivalent straight bodies (Bearman and Owen 1998). Flow experiments conducted on a model wing section with leading edge tubercles at low speeds showed flow separation from the troughs between adjacent tubercles, but attached flow on the tubercles (Johari et al. 2007).

Wind-tunnel experiments showed that the leading-edge tubercles on an idealized humpback whale flipper delay stall and increase total lift without significantly increasing drag (Miklosovic et al. 2004). The one-fourth-scale flipper models were based on a NACA 0020 section with (scalloped) and without tubercles (baseline). The sinusoidal pattern on the scalloped flipper had an intertubercular spacing and size that decreased with increasing distal location. The static tests were run over a range of angles of attack (α) at a Reynolds number (Re) = 500,000 ($Re = UC/\nu$, where U is the fluid velocity, C is the foil chord length, and ν is the kinematic viscosity of water), which corresponds to approximately one-half of the value of the whale at lunge-feeding speed (2.6 m/s).

The lift coefficient (C_L) increased monotonically with angle of attack for both scalloped and baseline flippers (Miklosovic et al. 2004) up to the onset of stall. The maximum lift increased by 6% over baseline for the scalloped flipper. The baseline flipper stalled (i.e., loss of lift) abruptly at an angle of attack of 11°. The stall angle was increased by 40% for the scalloped flipper with leading-edge tubercles compared to the baseline flipper with straight leading-edges. When the scalloped flipper did stall, the stall was gradual. The drag coefficient (C_D) of the scalloped flipper was less than that of the baseline geometry in the range $12° < \alpha < 17°$ and is only slightly greater in the range $10° < \alpha < 12°$. Below 10°, C_D is indistinguishable between the flippers, indicating no drag penalty for having the tubercles. The lift to drag (L/D) ratio, which quantifies the drag-cost of producing lift or aerodynamic efficiency, displayed a greater peak L/D for the scalloped geometry (Fig. 5; Miklosovic et al. 2004, 2007; Hansen et al. 2009).

Similar trends were shown for models with tubercles and sweep angles of 15° and 30°. Higher α was required by the sweep models to achieve stall and the scalloped models showed superior drag performance over most of the range of α compared to models without tubercles (Murray et al. 2005). Flow tests on delta wings with a sweep of 50° showed that at high angles of attack large-scale, three-dimensional separation occurred for the wing with a straight leading edge (Goruney and Rockwell 2009). However, when tubercles are added, the flow is radially transformed. Tubercles with amplitude of 4% of wing chord can completely eradicate the negative effect of the separation and fosters re-attachment.

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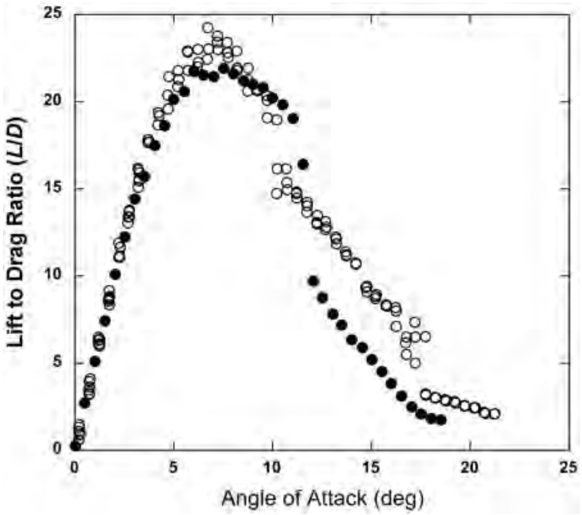

Fig. 5 Lift to drag ratio (*L*/*D*) as a function of angle of attack (α) based on data from Miklosovic et al. (2004). Open circles are for a wing with leading-edge tubercles and closed circles are for a comparable baseline wing without tubercles.

The effect of leading-edge tubercles was investigated on the performance of two-dimensional foils based on NACA 0021, 63_4-021 and 65-021 sections (Johari et al. 2007; Hansen et al. 2009, 2011; Custodio et al. 2010). Foils with tubercles on the leading edge did not stall like foils with a straight leading edge. The best performance was observed for tubercles of small amplitude (Johari et al., 2007; Hansen et al. 2009, 2011). Stall was delayed to higher α with C_L over 50% higher for foils with tubercles compared to the baseline foil, but with greater C_D in the prestall regime (Johari et al. 2007).

The results on two-dimensional foil sections point out limitations for the use of tubercles under conditions in which the ends of a hydrofoil are bounded by walls or the hydrofoil is considered to be of an infinite span (Miklosovic et al. 2004; Johari et al. 2007; van Nierop et al. 2008). Tubercles have a largely three-dimensional benefit (Miklosovic et al. 2004, 2007). Foil sections with no wing tip that emulate infinite wings do not demonstrate reduced drag and increased lift, although stall is still delayed. Effects of the tip occur as a consequence of generation of lift when a fully three-dimensional wing is canted at an angle of attack to an incident flow. Induced drag is produced in generation of lift from kinetic energy imparted to the fluid from differences in pressure between the two surfaces of the wing as there is leakage of fluid from high pressure to low pressure around the distal tip of a lifting surface, resulting in spanwise flow and the formation of vortices at the tip (Vogel 1981). The flow pattern set up by the tubercles is considered to maintain a chordwise flow and reduce the induced drag due to tip vortices.

Experiments were performed on flapping wings with tubercles. Tubercles were observed to affect the spanwise flow, which is a key feature along flapping wings with a straight leading edge (Ozen and Rockwell 2010). Spanwise flow reduces the efficiency of a wing. A flapping wing with tubercles, however, does not produce a pronounced region of spanwise flow. Ozen and Rockwell (2010) also found that the structure of the tip vortex was relatively uninfluenced by the geometry of the leading edge. The pressure field induced by the flapping motion may have overwhelmed any effect of the tubercles in elevating formation of the tip vortex. Measurements of force on foils with tubercles that were oscillated in roll and pitch demonstrated that the tubercles did not improve hydrodynamic performance. Stanway (2008) considered that degraded performance in flapping was from the redirection of energy to tubercle-generated vortices from the vortices of the wake, which are necessary for production of thrust during flapping. Alternatively, the limitation of the tubercles in flapping may be due to the period of oscillations being too rapid to allow the full development of the vortices over a wing as has been observed from tests on static wings. It is necessary to have a relatively steady flow to maintain the pattern of the vortices and to incur the hydrodynamic advantages (Stanway 2008).

Computational fluid dynamics

The use of computational methods has been beneficial in understanding the fluid mechanics and modifying complex geometries associated with the humpback whale's tubercles (van Nierop et al. 2008; Pedro and Kobayashi 2008; Saadat et al. 2010). While the complexity of the structure, design and kinematics of real flippers cannot be adequately analyzed through numerical simulations, simplified geometries of basic foil sections and wing-like geometries can be modified with tubercles and computationally examined under static flow.

A panel-method simulation was used to evaluate the forces acting on a uniform section of the humpback whale's flipper (Watts and Fish 2001). Wing sections with tubercles at 10° angle of attack showed a 4.8% increase in lift, a 10.9% reduction in induced drag, and a 17.6% increase in lift/drag when compared to a section without tubercles. However, due to the limitations of the panel method, neither viscous drag nor stall behavior could be studied.

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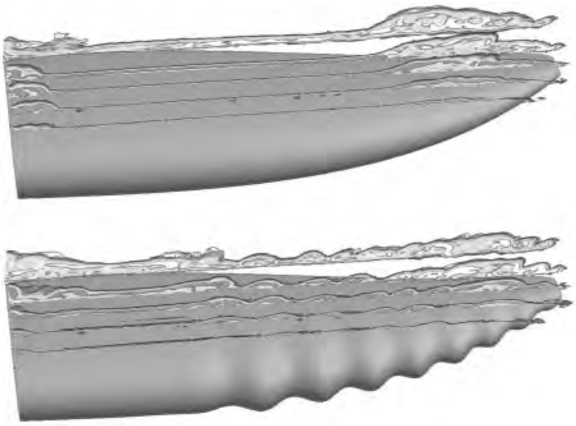

Fig. 6 Depiction from a computational hydrodynamic model of the instantaneous vorticity magnitude of a smooth flipper (above) and a flipper with tubercles (below) at $\alpha = 15^\circ$. Geometries of flippers were based on designs from Miklosovic et al. (2004). The flipper with tubercles shows large streamwise vortices that are aligned with the tubercles and re-energize the boundary layer (Pedro and Kobayashi 2008). Illustration courtesy of HTC Petro.

Unsteady Reynolds-Averaged Navier-Strokes (RANS) simulation (Paterson et al. 2003) on a NACA 63-021 baseline foil with and without equally spaced tubercles showed flow-separation patterns and surface pressure to be dramatically altered by the tubercles (Fig. 6). For regions downstream of the tubercle crest, separation was delayed almost to the trailing edge. This appears to be due to an increase in pressure on the suction side, which locally reduces the adverse pressure gradient. The tubercles generate separated, chordwise vortices in the troughs. Flow strikes the surface of the trough obliquely and is sheared to the trough's center to generate the vortices. These vortices are convected along the chord (Fig 6). The spanwise arrangement of the vortices is in a pair on each side of the tubercle's crest with opposite spins (Hansen et al. 2010). The flow directly over the tubercle is accelerated posteriorly due to the interaction with the vortex pair. These effects prevent the local boundary layer from separating and push the stall line further posterior on the flipper. When integrated over the entire structure, the flipper with tubercles will not stall at a higher α than a flipper without tubercles.

When a computational model (Detached Eddy Simulation) used the geometry previously tested in a wind tunnel (Miklosovic et al. 2004), the results were in good agreement (Pedro and Kobayashi 2008). The vortices produced from the tubercles were considered to re-energize the boundary layer by carrying high-momentum flow close to the flipper's surface (Fig. 6; Pedro and Kobayashi 2008; Hansen et al 2010). In addition, the aerodynamics is improved by confining separation to the tip region. A separate computational model (Unsteady RANS using the k–ω and Spalart–Allmaras turbulence models) which also replicated geometry previously tested in a wind tunnel (Miklosovic et al. 2004) found that tubercles delay stall by causing a greater portion of the flow to remain attached on a flipper with tubercles as compared to a flipper without tubercles, and also found that the attached flow was localized behind the crests of the tubercle (Weber et al. 2011).

Applications of tubercle technology

Few other passive means of altering fluid flow around a wing-like structure can delay stall and both increase lift and reduce drag at the same time. As a result, the application of leading-edge tubercles for passive control of flow has potential in the design of control surfaces, wings, propellers, fans, and wind turbines.

Like the humpback whale, the use of tubercles on control surfaces (e.g., rudders, dive planes, sailboat keels, fins, skegs) has implications for increased maneuverability. Weber et al. (2010) investigated the hydrodynamic performance of tubercles on a low-aspect-ratio rudder with an unswept leading edge. A rudder with leading-edge tubercles was found to generate more lift at angles of attack above 22° compared to a smooth rudder at a Reynolds number of 200,000. At higher Reynolds numbers for the rudder and tubercle geometry of the study (Weber et al. 2010), this effect diminishes and the tubercles accelerate the onset of cavitation. The maintenance of lift at high angles of attack means enhanced control during turning. A human-powered submarine, Umpty Squash, utilized tubercled dive planes and rudders. In 2005, the submarine competed in the International Submarine Races held at the David Taylor Model Basin in Bethesda, Maryland. Commercially, the company Fluid Earth markets a surfboard skeg with tubercles on the leading edge (Fig. 7; Anders 2009).

The passive nature of leading-edge tubercles may be particularly appropriate for application to wings involved with the aerodynamics of high angle of attack. Such aerodynamics occurs on an airplane with a highly swept wing at a physically large angle of attack with leading-edge vortex separation or from a heavily load wing operating at a lower-than-optimum aerodynamic efficiency (Erickson 1995). Such situations occur in general aviation aircraft and in helicopter rotorblades (Erickson 1995,

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Fig. 7 Surfboard skeg based on leading-edge tubercles of the humpback whale's flipper. Photograph courtesy of H. Swales and Fluid Earth.

Fig. 8 Model of commercial jet airliner with leading-edge tubercles on the wings and stabilizers. Addition of tubercles on wings could potentially improve safety and reduce weight and fuel costs by the removal of control surfaces needed to change the stall characteristics of the wings.

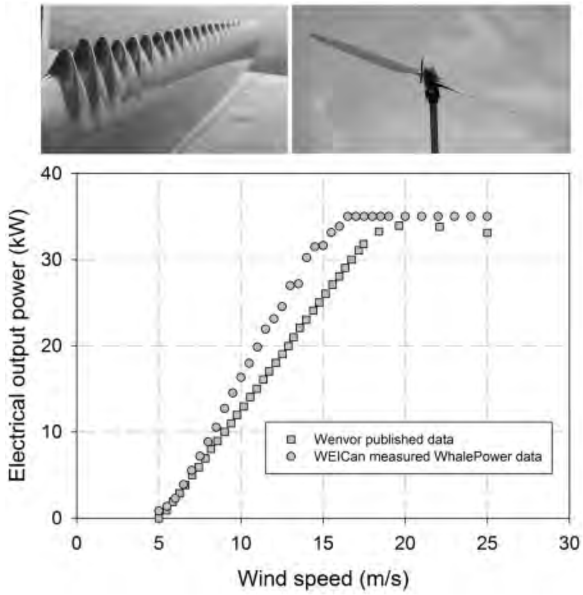

Fig. 9 Windmill blade designed by L. Howle (above left) and wind turbine (above right) utilizing leading-edge tubercles with their comparative performance data (below). The WhalePower windmill blade with tubercles was based on a standard Wenvor blade. At moderate wind speeds in an open field test performed by the Wind Energy Institute of Canada (WEICan), the WhalePower turbine (circles) out-performed the standard Wenvor blade (squares). Courtesy of WhalePower Corporation.

Conlisk 1997). As tubercles delay stall at high angles of attack, their use on conventional aircraft may allow for the replacement of boundary-layer control structures, such as flaps and slots (Fig. 8). These structures are necessary to prevent stall, particularly at periods of high angles of attack (i.e., takeoff and landing). The elimination of flaps and slots with their associated machinery could reduce the weight of the aircraft and increase fuel economy.

Energy efficiency is enhanced by addition of tubercles on fan blades. Envira-North Systems Ltd. produces industrial ceiling fans for large buildings (e.g., factories, warehouses, arenas, dairy barns) with the tubercle modification. A high-volume, low-speed (HVLS) model with a 24-foot diameter of five blades is reported to be 25% more efficient and consumes 20% less electricity to operate than a 10-blade configuration (Ontario Power Authority 2010). In addition, the HVLS fan is 20% quieter. Suppression of tonal noise by the addition of tubercles to an airfoil in a low-speed wind tunnel was observed (Hansen et al. 2010). Tonal noise is most effectively reduced by tubercles of large amplitude and smaller wavelength.

Leading-edge tubercles placed on turbine blades can increase generation of energy (Muller 2008). Field trails run on a 35 kW, variable-pitch wind turbine with retrofitted blades with tubercles (WhalePower Corp.) demonstrated increased electrical generation at moderate wind speeds compared to unmodified blades (Fig. 9; Howle 2009, Wind Energy

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Institute of Canada 2008). Blades with tubercles were also found to be effective in generation of power by a marine tidal turbine at low flow speeds (Murray et al. 2010). Compared to blades with smooth leading edges, blades with leading-edge tubercles demonstrated enhanced performance.

The utility of tubercles in improving the performance of engineered systems comes directly from examination of an animal that at one time was slaughtered in large numbers. The novel morphology of the humpback whale's flipper provides a new direction in the construction of devices that can help conserve energy as well as generate energy cleanly and sustainably. It is therefore ironic that an animal, which was exploited close to extinction by humans, should provide us with the inspiration to better our own future. The lesson from such cases as the humpback whale is that a diversity of organisms needs to be maintained as a potential source of innovation as the application of biomimetic technology becomes ever more integrated into our lives.

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