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Effect of bio-inspired sinusoidal leading-edges on wings

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ABSTRACT

Observations of maneuvering humpback whales have revealed unique hydrodynamic performance hypothesized to be a result of tubercles on the leading-edge of the whales' pectoral flippers. Inspired by this biological observation, it is shown sinusoidal leading-edge wings prevent the dramatic loss of lift caused by stall and instead generate a gradual decrease in lift with as much as 25% higher lift in the poststall regime. Six different wing geometries, smooth and sinusoidal leading-edge models, swept and unswept configurations, were tested at angles of attack of −2 to 24 degrees at Reynolds numbers between 100,000 and 500,000. Oil surface flow visualization and CFD results reveal variations in flow phenomena between the smooth and sinusoidal leading-edge configurations.

1. Introduction

HE humpback whale uses pectoral flippers while swimming. These flippers have leading-edge tubercles, whose existence has been suggested as hydrodynamically significant as a sort of passive flow control devices [1]. Humpback whales are highly maneuverable, completing tight turns and rolls during "bubble net" feeding [1]. Fig. 1 is a photograph of a humpback whale where the leading-edge tubercles are visible on the pectoral fin.

Over the past 10–20 years, many studies all over the world have been conducted varying the leading-edge of airfoils and wings based principally on the inspiration of humpback whale tubercles. These studies have attempted to demonstrate the feasibility of sinusoidal leading-edges as passive flow control devices and have tried to quantify their effects. These studies have been both experimental [2–15] and computational [16–23] in nature. Other studies [24–27] have focused on using the leading-edge sinusoidal modifications to reduce acoustical signatures of wings or fan blades.

The whale pectoral can be approximated to have a symmetric profile with a rounded leading-edge and semi-sharp trailing-edge, with the point of maximum thickness varying from 0.20*c* at the midspan to 0.40*c* near the tip [1]. Studies have investigated various 2-D [4–8,11] and 3-D [2,5] NACA airfoil and wing models such as NACA 0012, 0020 [2,5], 0021 [8], 4415, 63_4-021 [4,6], 630921, 65-021 [8], and LS1-0417 [11]. Researchers [4,8,11] have varied leading-edge parameters such as the amplitude of the sinusoidal leading-edge, *A*, and the spanwise wavelength of the sinusoidal leading-edge, λ. In most cases, there was an effect on the aerodynamic coefficients and performance.

Fig. 1. Humpback whale with leading-edge tubercles. From "Stellwagen Bank Sanctuary Site History and Resources," *National Marine Sanctuaries* [online], [retrieved 23 September 2015], http://sanctuaries.noaa.gov/science/condition/sbnms/history.html.

An average whale flipper size can be 5 meters (∼16.5 feet) in span and 0.50 m (∼1.6 feet) [1] in chord, giving a rather large aspect ratio (≈10). Typical swim speeds of humpback whales are 3–9 mph (∼4.4–13 ft/s or 1.3–4 m/s) with burst speeds up to 16 mph (23.5 ft/s or 7.2 m/s). Using the typical flipper chord, the average normal swim speed, and a viscosity of seawater of 1.35×10^{-6} m^2/s yields a Reynolds number of 960,000. Previous research in the literature have investigated maximum Reynolds numbers around 500,000 [2], with others at 275,000 [5], ∼183,000 [4,6,7], 120,000 [8], and even lower [11].

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Nomenclature

A	amplitude of sinusoidal leading-edge	Re	Reynolds number
A_x	axial force	q	dynamic pressure
B	bias uncertainty	S	planform area
C_D	coefficient of drag	S_{CL}	standard deviation in coefficient of lift
C_L	coefficient of lift	s	half-span
C_{Lmax}	maximum coefficient of lift	t	student's t-value
c	chord	V_∞	freestream velocity
h_{eff}	effective height	y^+	non-dimensional distance
L	lift	α	angle of attack
L/D	lift-to-drag ratio	δ	boundary layer thickness
M	Mach number	γ	ratio of specific heats
N	normal force	λ	wavelength of sinusoidal leading-edge
P_o	total pressure	ρ	density

Miklosovic et al. [2] were one of the first teams to investigate the aerodynamic effects of leading-edge tubercles on a humpback whale flipper. When comparing two scale models of humpback whale flippers, one with and one without leading-edge tubercles, the addition of leading-edge tubercles increased the stall angle by as much as 40% [2]. At higher angles of attack, beyond stall, the drag even decreased. The study was conducted in a low-speed wind tunnel at Mach 0.2, intentionally incompressible, with a Reynolds number between 505,000 and 520,000 and an angle of attack, α, sweep from -2 degrees to 20 degrees [2]. Findings from this study showed that the tubercles had a significant impact on lift, drag, moment, and stall characteristics. In addition to the delayed stall angle, the maximum lift coefficient, C_{Lmax}, increased by 6% and drag coefficient, C_D, decreased by as much as 32% [2]. The effect of the tubercles was superior post-stall performance, namely to delay stall by increasing lift at high angles of attack and ameliorating stall characteristics in the post-stall region by maintaining higher post-stall lift while reducing drag [2].

Miklosovic et al. [2] hypothesized an imbalance in lift on the flippers (positive lift on one, negative lift on the other) served to enhance the whale's ability to roll. Maximum lift on both flippers in the same orientation creates a pitching moment about the center of mass, enabling a quick dive or climb. These enhanced maneuvering capabilities were thought to include tighter turns, which could help with the whales' "bubble net" feeding.

Since the work of Miklosovic et al. [2], many researchers have been intrigued by the aerodynamic potential of leading-edge modifications to lifting surfaces. Some of the findings of those works are presented and summarized here. Using a 63_4-021 2-D airfoil in a water tunnel at a Reynolds number of 183,000, Levshin et al. [4] and Johari et al. [6] found that for angles of attack less than the baseline stall angle, leading-edge modifications caused a reduction in lift and an increase in drag. But above the stall angle of attack, lift increased by 50% with little to no drag penalty, thus, leading to an increased lift-to-drag ratio in the poststall regime.

Levshin et al. [4] and Johari et al. [6] varied the amplitude and the spanwise wavelengths of the sinusoidal leading-edge within ranges to mimic the variance of whale morphology found in nature. The amplitude, A, was varied from 2.5% to 12% of the mean chord length, while the spanwise wavelengths, λ, varied from 25% to 50% of the mean chord length. Results showed that a variance in amplitude did have an effect, but wavelength did not exhibit much of an effect. The larger the amplitude the flatter the lift and drag curves. Additionally, tuft flow visualization indicated separated flow in the troughs and attached flow on the peaks at angles above the stall angle of attack.

Miklosovic et al. [5] conducted a second investigation comparing models with and without leading-edge tubercles. Again, a low-speed wind tunnel was used but with a Reynolds number of approximately 275,000. This study focused on determining whether the superior stall characteristics result from 2-D effects such as a sectional enhancement, 3-D effects such as spanwise stall progression, or from some other Reynolds number effects on a tapered planform. Miklosovic et al. [5] observed vastly different results for 2-D and 3-D configurations, with the 3-D configuration showing the most benefit. However, the Reynolds number for the 3-D case was nearly twice that of the 2-D case, which could also be a Reynolds number effect.

Instead of only leading-edge protuberances, Zverkov [7] investigated extending the peaks and troughs geometry the entire chord on a TsAGI R-3a-12 2-D airfoil. Looking closely at the separation bubble that occurs at low Reynolds numbers, such as 170,000, substantial differences of the transition location were observed for the peaks and troughs.

Hansen et al. [8] compared NACA 0021 and NACA 65-021 airfoils at Reynolds numbers of 120,000 with and without leading-edge modifications. The NACA 0021 cross-section most closely resembles the whale morphology found in nature [2] and had a maximum thickness at 0.30c, whereas the NACA 65-021 has a maximum thickness further aft at 0.50c. When compared with its baseline unmodified equivalent, the NACA 65-021 airfoil showed more beneficial results than the NACA 0021, suggesting location of maximum thickness may be a parameter to optimize. The effect of the sinusoidal leading-edge was similar in all cases tested: a smoother stall characteristic. For these airfoils, stall was progressive and began behind the troughs at lower angle of attack. As the angle of attack increased beyond the unmodified airfoil stall angle of attack, drag was lower.

Hansen et al. [8] also found that reducing the tubercle amplitude, A, resulted in a higher maximum lift coefficient, C_{Lmax}, and larger stall angle than higher tubercle amplitudes. Yet, the maximum lift coefficient was still higher for the unmodified airfoils. Reducing the wavelength to a limit, increased the lift performance, but beyond the limit the performance was reduced. Hansen et al. [8] suggested there exists an optimal amplitude-to-wavelength ratio, and when coupled with the highest performing amplitude, the best airfoil performance could be achieved. For the study the optimal configuration had an amplitude of 0.03c and a wavelength of 0.11c [8]. The well-documented effectiveness of small vortex generators with h_{eff}/δ ratios of 0.2–0.5 could suggest that a further reduction in amplitude could lead to improved tubercle performance.

Guerreiro and Sousa [11] investigated an LS1-0417 airfoil with and without sinusoidal leading-edges at a Reynolds number range of 70,000–140,000 for application to the design of micro air vehicles. The study was limited to high aspect ratio ($\sim$1 and 1.5)

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