Cavitation on hydrofoils with sinusoidal leading edge

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Abstract. Cavitation characteristics of hydrofoils with sinusoidal leading edge were examined experimentally at a Reynolds number of $7.2 \times 10^5$. The hydrofoils had an underlying NACA 63$-$021 profile and an aspect ratio of 4.3. The sinusoidal leading edge geometries included three amplitudes of 2.5%, 5%, and 12% and two wavelengths of 25% and 50% of the mean chord length. Results revealed that cavitation on the leading edge-modified hydrofoils existed in pockets behind the troughs whereas the baseline hydrofoil produced cavitation along its entire span. Moreover, cavitation on the modified hydrofoils appeared at consistently lower angles of attack than on the baseline hydrofoil.

1. Introduction
Despite its large size (12 – 16 m) and rigid body, the humpback whale ($M. novaeangliae$) is quite maneuverable compared to other species. This agility has been attributed to the humpback whales’ use of its unique pectoral flippers [1]. The flippers have several distinct characteristics including a unique planform shape with an aspect ratio of about 6, a span of up to one-third of the body length, and large protuberances along the leading edge. The Reynolds number for the flipper ranges from one-half to one million. Tight turns during bubble netting are unique to the humpback whale, and the protuberances on the pectoral flipper leading edges are thought to be for flow control.

Idealized humpback whale flipper models with and without leading edge protuberances were tested in a wind tunnel by Miklosovic et al. [2]. The effects of a sinusoidal leading edge on the loading of full-span NACA 63$-$021 foils were investigated in a water tunnel by Johari et al [3]. Depending on the geometry of the leading edge, lift on the modified foils was lower in the pre-stall regime and higher in the post-stall regime when compared to a baseline foil without any protuberances. No drag reduction was observed for any of the modified leading edge foils studied. Flow visualization revealed that the flow over the protuberance peaks remains attached well past the stall angle of attack of the baseline foil. Load measurements on wings with various planforms and sinusoidal leading edge have been reported by Custodio et al. [4]. Weber et al. [5] tested ship rudder geometries with and without leading edge protuberances in a water tunnel at Reynolds numbers up to $8.8 \times 10^5$. They indicated that the effects of leading edge modifications vanished at high Reynolds numbers. Yoon et al. [6] carried out numerical simulation of rectangular wings with a sharp tip and a semi-aspect ratio of 1.5 at Reynolds number of $10^6$ for ship rudder applications. The rudder had protuberance amplitude and wavelength of 2.5% and 20% of the chord length, respectively. Lift enhancement was observed only in the post-stall regime, similar to the lower Reynolds number full-span experiments.

The primary objective of this study was to establish the effect of various sinusoidal leading edge geometries on the cavitation characteristics of rectangular planform wings at a Reynolds numbers of $7.2 \times 10^5$ and angles of attack up to $24^\circ$. 
2. Experimental Setup

To examine the cavitation characteristics of hydrofoils with leading edge protuberances, a qualitative flow visualization study was carried at the Naval Undersea Warfare Center closed-loop water tunnel facility in Newport, RI, USA. The water tunnel has a 0.30-m square test section, and the freestream velocity was set at 7.2 m/s. The freestream turbulent intensity on the tunnel centerline was 0.6%. The freestream velocity in the water tunnel was monitored at a point 0.66 m upstream of the models using a Laser Doppler Velocimeter. Monitoring and adjustment of the freestream velocity was required due to the variations caused by the different models and angles of attack. The angle of attack, $\alpha$, was varied from $12^\circ$ to $24^\circ$ in increments of $3^\circ$. Cavitation was absent at angles of attack below $12^\circ$ at the freestream velocity of 7.2 m/s. Images were taken with a Nikon D200 Digital SLR camera and 200 $\mu$s strobe lighting to illuminate areas of cavitation; further details are available in [7]. The incipient cavitation criterion was the first visual cues of presence of vaporeous cavitation near the leading edge.

Seven rectangular planform hydrofoils with mean chord length $c = 102$ mm and span of 219 mm were designed and CNC-fabricated from aluminum and are hydrodynamically smooth. To eliminate the sharp, flat edge at the free tip, rounded caps were attached to the free end of these models. Including the rounded cap, all hydrofoils had an aspect ratio of 4.3. All models had an underlying NACA 63-021 profile, which is symmetric with a maximum thickness of $0.21 \, c$ located at $0.4 \, c$. This profile was chosen for its similarity to the humpback whale flipper cross-section. The Reynolds number based on the mean chord length and the freestream velocity was $7.2 \times 10^5$ for all cases.

The leading edge of the modified hydrofoils was defined by a sinusoidal pattern with specified amplitude and wavelength; the leading edge amplitude and wavelength were constant fractions of the mean chord length. Three amplitudes of $0.025 \, c$, $0.05 \, c$, and $0.12 \, c$ along with two wavelengths of $0.25 \, c$ and $0.50 \, c$ were considered. These values were chosen as they are representative of those found on the humpback whale flippers. Each hydrofoil was designated by the wavelength (4 for $0.50 \, c$ and 8 for $0.25 \, c$) and amplitude (S for $0.025 \, c$, M for $0.05 \, c$, and L for $0.12 \, c$) of the leading edge. The hydrofoils were designed so that the top and bottom surfaces were not wavy.

3. Results

The cavitation characteristics of modified hydrofoils with wavelengths of $0.50 \, c$ and $0.25 \, c$ are presented in Figs. 1 and 2, respectively. Cavitation can be distinguished by the white color of the vapor in the low pressure regions. Cavitation effects on the baseline hydrofoil can be seen in Figs. 1a, 2a. As with all the hydrofoils examined, cavitation was observed first at $\alpha = 12^\circ$ in the core of the tip vortex. With increased angle of attack, cavitation in the tip vortex grew until $\alpha = 21^\circ$, after which point tip vortex cavitation diminished as a result of stall at the higher angles. Figures 1b and 2b illustrate that the modified hydrofoils with protuberance amplitude of $0.025 \, c$ (4S and 8S) had tip vortex cavitation characteristics similar to the baseline hydrofoil, with an increase in the vortex cavity size until $\alpha = 18^\circ$. At angles of attack greater than $\alpha = 18^\circ$, the size of the cavity generated by the tip vortex decreased gradually. The 4M hydrofoil in Fig. 1c produced a vortex cavity that diminished at an earlier angle than the baseline while the 8M hydrofoil in Fig. 2c revealed a trend similar to that of the baseline. The hydrofoils with the largest amplitude protuberances (4L and 8L) had tip vortex cavities that diminished at an earlier angle than the baseline. At the Reynolds number of the experiments, the baseline hydrofoil produced greater lift than the modified hydrofoils with large protuberances. This created a stronger tip vortex on the baseline hydrofoil, in turn generating a larger tip vortex cavity.

The rapid acceleration of flow near the leading edge of the hydrofoils leads to reduced pressure and cavitation along the leading edge. Similar to the cavitation that occurs in the tip vortex, cavitation at the leading edge was also modified by the presence of protuberances. Sheet cavitation developed on the leading edge of the baseline hydrofoil as angle of attack increased past $\alpha = 15^\circ$, see Fig. 1a. Incipient cavitation occurred on the baseline hydrofoil at an angle of $\alpha = 15^\circ$. At $\alpha = 18^\circ$, sheet cavitation had developed along the majority of the baseline hydrofoil leading edge. As the angle of attack was further increased to $\alpha = 21^\circ$, the cavity associated with sheet cavitation enlarged and remained essentially unchanged as the angle of attack reached $\alpha = 24^\circ$. 


For all modified hydrofoils, incipient cavitation initiated in the troughs of the protuberances. This was due to the larger leading edge radius in the troughs of modified hydrofoils leading to the lowest local pressures. Modified hydrofoils with the largest protuberance amplitude of 0.12\( \text{c} \) showed incipient cavitation at angles as low as \( \alpha = 12^\circ \) whereas all other modified hydrofoils showed the incipient condition at an angle of \( \alpha = 15^\circ \). Hydrofoils with the smallest protuberance amplitude of 0.025\( \text{c} \) in Figs. 1b and 2b, developed sheet cavitation similar to the baseline hydrofoil, with increasing sheet size corresponding to an increase in angle of attack. However, sheet cavitation along the leading edge of the 4S and 8S hydrofoils was limited to a smaller fraction of the chord length.

At high angles of attack, unsteady flow on the surface of the modified hydrofoils led to transient cavitation cells behind the troughs. This was true for all modified hydrofoils at the higher angles of attack but especially true for the hydrofoils with the largest amplitude protuberances. The 4L and 8L modified hydrofoils cavitated only in the troughs and not along the peaks on the leading edge. Hydrofoils with medium (4M and 8M) and large amplitude (4L and 8L) protuberances had similar cavitation characteristics. Protuberance wavelength appeared to play only a minor role in establishing the cavitation patterns observed on the modified hydrofoils in comparison with amplitude. Generally, hydrofoils with the shorter wavelength developed transient cavitation cells at higher angles of attack than the hydrofoils with longer wavelengths.
4. Conclusions
Cavitation characteristics of hydrofoils with various sinusoidal leading edge geometries were examined in a flow visualization experiment at a Reynolds number of $7.2 \times 10^5$. Still images revealed that cavitation on the modified hydrofoils was largely confined to the area directly behind the troughs of protuberances, whereas the baseline hydrofoil exhibited sheet cavitation over the entire span. The incipient cavitation on the baseline hydrofoil always occurred at an angle of attack greater than that for the modified hydrofoils. This implies that for a given local static pressure, leading edge-modified hydrofoils will always cavitate at a lower velocity than their straight leading edge counterpart.

5. References
[1] Fish F E and Battle J M 1995 J. Morphol. 225 51–60
[2] Miklosovic D S, Murray M M, Howle L E and Fish F E 2004 Phys. Fluids 16 L39–42
[3] Johari H, Henoch C, Custodio D and Levshin A 2007 AIAA J. 45 2634–42
[4] Custodio D, Henoch C and Johari H 2015 AIAA J. 53 (doi: 10.2514/1.J053568)
[5] Weber P W, Howle L E and Murray, M M 2010 Marine Technol. 47 27–36
[6] Yoon H S, Hung P A, Jung J H and Kim M C 2011 Comput. Fluids 49 276–89
[7] Custodio D 2012 Ph.D. dissertation, Worcester Polytechnic Institute, Worcester, MA, USA

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