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CORRESPONDENCE

Cambered profile of a California sea lion's body

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More than 100 research articles have referred to an experimental study by Feldkamp (1987) on the California sea lion, which mentions that its body resembles a symmetric airfoil NACA 66018. We believe that perhaps an over simplification has been made in this paper. This conclusion may be arrived at by shifting the leading and trailing edges of the contour of the sea lion in order to move the chord line in the upward direction, such that the maximum thickness of the selected airfoil is close to that of a sea lion's body. It is pertinent to highlight that most of the research articles on different species of sea lions (Cheneval, 2005; Suzuki et al., 2014; Fish, 1998; Stelle et al., 2000) are related to its hydrodynamic drag and lift generated by its flippers. However, the effect of assuming resemblance to a symmetric airfoil reduces the additional hydrodynamic lift and the induced drag generated by the body.

If one closely observes the sketch used by Feldkamp (1987), it is obvious that a sea lion's upper and lower contours are different (Fig. 1A); this feature is unique to any cambered airfoil. In order to elaborate it further; this sketch was used as a baseline sketch and graphically digitized for unit length (L) by defining the maximum thickness (d) equal to 18% of unit length (Fig. 1B). The upper and lower contour lines were generated by using a 4th order polynomial fit and the camber line is also plotted to show the difference between a symmetric and a cambered airfoil. Feldkamp (1987) did not specifically mention the maximum diameter (d) of the body. The only known information is the lateral view of the body resembling a NACA 66-018 airfoil. Hence the maximum thicknesses of 18% of the chord length and fineness ratio equal to 5.5, Fig. 1A are used in the present work for defining a suitable cambered airfoil.

In order to select a cambered airfoil that best fits the shape of the sea lion at its nose, upper and lower contours and meet the requirements of maximum thickness and its location, RONCZ 1082 and FX S 03-182 were randomly chosen. These are two standard cambered airfoils which have maximum thickness of 18% at 40% chord and 18.2% at 40.2% chord, respectively (Airfoil Tools, 2014). Once the profile of these airfoils were plotted on the sketch used by Feldkamp (1987), it was observed that the lateral view of the California sea lion's body cannot fully resemble any engineering application airfoil (Fig. 1C). Although its body is streamlined, the lower contour of its body is somewhat bulkier, whereas the upper is elongated.

Unfortunately, complete geometric details of the sea lion required to compare with different airfoils are still missing in the open literature. However because of the difference between the upper and lower contour in lateral view, the body of the sea lion partially resembles a cambered or un-symmetric airfoil. The same also holds true for a sea lion lying on the ground, as observed at Zoo Negara, Kuala Lumpur, Malaysia (Fig. 1D). Also, it is well known that most of the terrestrial vertebrates have a vaulted dorsum which makes the body appear in the lateral view as a cambered airfoil. Based on the discussion above, it may be concluded that the sea lion's body resembles a cambered airfoil.

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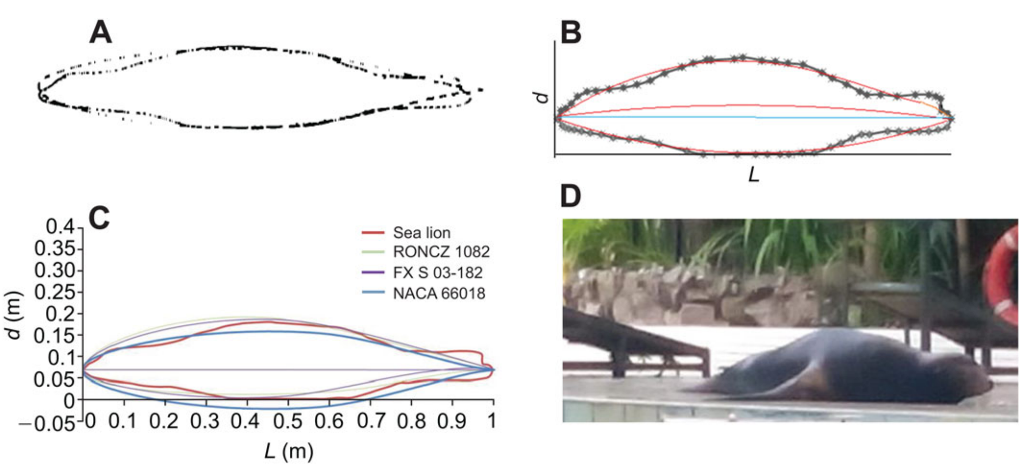

Fig. 1. Sketches and images of the California sea lion body shape compared with airfoil cross-sections. (A) Sketch used by Feldkamp (1987) in which the dotted line shows the profile of airfoil NACA 66018. (B) Sketch drawn to show the camber in lateral view of the sea lion (black data points and plotted black line). Red and blue lines indicate………., respectively. (C) Geometric comparison of sea lion outline sketch (red) with NACA 66018 and cambered airfoils. (D) Pictorial view of California sea lion, taken in Zoo Negara, Kuala Lumpur.

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To understand the complexity of aero- and hydrodynamic effects related to the morphology of animals, the shape of the organism is often simplified. Researchers used engineered foils to approximate the geometry of aquatic animals (Hertel, 1966; Aleyev, 1977; Feldkamp, 1987; Fish and Battle, 1995; Weber et al., 2009). The advantage of this substitution is that the performance (lift, drag, moment) of these idealized shapes was well characterized and documented. Using these quantitative data, the design of different animal body shapes in a flow can be quantitatively assessed. The results of this first-order analysis were used to examine morphological differences, propulsive efficiency and the energetics of locomotion. A potential problem with this approach is how an appropriate engineered foil is selected to mimic the real animal. The choice was based on a catalog of known foils (Abbott and von Doenhoff, 1959; Airfoil Tools, 2014). The appropriate foil to mimic an animal is dependent on similarities of shape parameters including fineness ratio (length/maximum thickness), relative position of maximum thickness, and camber. However, the choice was still subjective as the geometry of the animal and that of the foil section were not an exact match. In effect, it is the equivalent of placing a square peg in a round hole.

Despite its relatively smooth contours, the California sea lion (*Zalophus californianus*) has a complex geometry. Feldkamp (1987) performed the first hydrodynamic analysis of the sea lion. His analysis simplified the shape of the animal by considering it to be equivalent to a streamlined body of revolution with a NACA 66-018 profile. The NACA profile, like the sea lion, had a fineness ratio of 5.5 and maximum diameter of 40% of the body length. Comparison of the sea lion’s shape with the streamlined spindle indicated that the drag for the animal was lower due to differences in flow structure.

Anwar Ul-Haque et al. (2015) call into question Feldkamp’s (1987) use of a symmetrical profile as an equivalent to the shape of the sea lion. For Ul-Haque and his colleagues, the profile of the sea lion is more similar to cambered airfoils. Indeed, the profile of sea lions gliding in water displays an asymmetry in the sagittal plane (Feldkamp, 1987). In general, mammals have asymmetrical profiles due to the distribution of body mass, prominence of the thoracic trunk and curvature of the spine. The asymmetry of the sea lion is even more exaggerated when the animal is lying down on solid ground (Ul-Haque et al., 2015). For these reasons Ul-Haque et al. (2015) argued that the profile of the sea lion in water was better described by cambered airfoils, RONCZ 1082 and FX S 03-182 (Airfoil Tools, 2014). These foils have similar dimensions to the sea lion as described by Feldkamp (1987).

Although Ul-Haque et al. (2015) provided more realistic shapes as a proxy for the geometry of the sea lion, their choice was still as subjective as that of Feldkamp (1987). The cambered foil designs approximated the midsection of the sea lion, but were dissimilar to the anterior and posterior portions of the animal. The pointed rostrum, tapering neck and expanded hind flippers are not emulated in the design of the foil sections. Furthermore, the profiles only describe a two-dimensional shape and do not consider the three-dimension aspects of the animal. It is the very shape of the sea lion that best examines the hydrodynamic implications of that specific morphology. Previously, modeling the exact shape of a biologically complex design with any fidelity was not possible. Airfoil sections that closely resembled an organism therefore were used as acceptable alternatives. More recently, the use of computational geometry, digital photography, computed tomography scanning and three-dimensional scanning allows the reconstruction of the surface geometry of highly complex shapes. This digital reconstruction can be used with computational fluid dynamic programs (e.g. panel code, RANS, LES) to examine the flow structure or to use rapid prototyping, 3D printers to create physical models that can be testing in wind and water tunnels. Such modeling procedures provide more accurate estimates of hydrodynamic parameters. A foil section with a similar geometry to the organism can still be used as a baseline for comparison.

But what is the importance of camber for the body of the sea lion? The major criticism by Ul-Haque and his colleagues was that Feldkamp (1987) did not use a cambered profile to compare with the sea lion. However, the correspondence by Ul-Haque et al. (2015) failed to actually consider the hydrodynamic implications of cambering. Camber on a wing increases the lift generated. For the sea lion, an increase in lift on the body could aid in surfacing when negatively buoyant or decrease the rate of sinking when gliding underwater. However, camber can also change the drag on the body. Feldkamp (1987) found that the symmetrical NACA 66-018 foil had a drag coefficient that was 1.18 times the drag coefficient calculated for a gliding sea lion. The drag coefficients for the camber foils, RONCZ 1082 and FX S 03-182, are 1.89- and 1.79-times greater than for the sea lion, respectively (Airfoil Tools, 2014). The drag coefficients for the cambered profiles were measured at a Reynolds number (1×10^6), which was slightly lower than values for the sea lion (2.03×10^6–2.87×10^6). The implication of the difference in drag coefficients is that there is still an imperfect match between the animal and the engineered shapes.

While it is instructive to match the shape of biological forms to engineered designs as a first-order approximation of performance, tools are now available to more precisely copy and measure the intricacies of biological design. As a result of past limitations in replicating anatomical features, the physics of how biology worked relied on simplified engineered models. Understanding of complexity and performance attributes of morphology can now be more directly addressed. As a result, new engineering concepts are being developed from the integration of biological capabilities and designs with existing technologies (Bar-Cohen, 2012).

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