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Thesis abstract

The flow around a fish-inspired heaving and pitching hydrofoil

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An extensive investigation into the flow around a fish-inspired heaving and pitching hydrofoil was performed using a combination of two dimensional digital particle image velocimetry (PIV), direct strain gauge force and moment measurements, dye visualisation and hydrogen bubble visualisation. The intention of this investigation was to study the effect of the foil dynamics on the foil wake structure and hydrodynamic forces, with the ultimate goal of determining if the oscillating foil, and by implication, fish, employ unsteady flow mechanisms to generate optimal thrust.

The experiments were performed by systematically varying the foil non-dimensional heave-amplitude-to-chord ratio, h_0/c=0.25-0.75, the foil pitch amplitude, θ_0=0-45°, and the free-stream velocity, U_∞. The phase difference between the pitching and heaving motion was fixed at ψ=90° (heave lagging pitch). Experiments consisted of 113 different flow cases for dye visualisation, 38 flow cases for hydrogen bubble visualisation and 108 flow cases for simultaneous PIV and force measurements. The resultant Strouhal numbers, based on the heave amplitude, fall into the range $0.1 \leq St_h \leq 1$ while the Reynolds numbers, based on the foil chord length, were approximately Re=500-12,500.

The experimentally measured time-averaged thrust coefficient, C_t, obtained independently using PIV and direct strain gauge measurements, shows excellent agreement, and indicates that very large values of C_t>10 can be generated by the foil, particularly when the non-dimensional heave amplitude is large relative to the pitch amplitude, and St_h is large. The results also indicate that in all investigated cases, there is no sign of a sudden loss in lift that is associated with the "stall" phenomenon usually seen in steady foils, even when the unsteady foil achieves very large instantaneous angles of attack (α_{max}>60°).

To obtain a context for comparison, a quasi-steady model (Q-S model) of the oscillating hydrofoil was developed, based on the assumption that the flow around the unsteady foil at any given instant is equivalent to the flow around an identical steady foil with the same angle of attack. For most foil dynamic parameters and flow conditions, the value of C_t predicted by the Q-S model shows excellent agreement with the results obtained experimentally. However, when h_0/c is large compared to θ_0, the experimentally measured values of C_t far exceed the theoretical predictions. This suggests that the oscillating foil employs unsteady flow mechanisms to augment thrust production when h_0/c is large relative to θ_0.

Flow visualisation of the foil wake indicates that different wake patterns are produced, depending on the flow conditions. The observed wake patterns are interpreted as a combination of "primary" vorticity, which is associated with the production of lift (and hence thrust) by the foil, and "secondary" vorticity, which is associated with the drag produced by the foil. During each foil half-cycle, secondary vorticity manifests itself as multiple vortical roll-ups ("S" vortices), whereas the primary vorticity sheds as a single, typically large vortex, which combines with adjacent "S" vortices to form one "P" vortex. When h_0/c is large compared to θ_0, these "P" vortices are observed as very large leading edge vortices with strong spanwise flow (towards the foil centreline). These leading edge vortical structures are further evidence that the foil employs unsteady flow mechanisms to generate large thrust coefficients.

Based on the positions of these "P" and "S" vortices in the wake, we define three distinct wake regimes, a) "Drag regime", occurring at $St_h \leq 0.15$, b) "Transitional regime", occurring at $0.15 < St_h \leq 0.3$ and c) "Thrust regime", occurring at $St_h > 0.3$, whereby each regime produces subtly different wake patterns.

The wake behind the foil was also analysed quantitatively by measuring the first moment of circulation of the foil wake, which is defined as the product of the total circulation generated by the foil (of any given sign) per cycle and the wake width based on the centroids of the shed vorticity. In an important finding, it is shown that the data for C_t vs. the first moment of circulation collapse onto a single curve, regardless of flow conditions and foil dynamic parameters. For most (≈95%) of the cases measured, it is shown that C_t is approximately linearly proportional to the moment of circulation, indicating that the thrust produced by the foil can be increased by generating large vortical structures and/or increasing the wake width.

Based on these results, we therefore conclude that the foil employs unsteady flow mechanisms only when h_0/c is large relative to θ_0. Under these conditions, large thrust coefficients are generated by the foil due to the generation of leading edge vortical structures with large circulation, which are positioned far away from the foil time-averaged centreline.

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