PERFORMANCE AND LEADING-EDGE SEPARATION OF A RIGID FLAPPING FIN AS MANEUVERING THRUSTER

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Many swimming and flying animals use flapping fins for maneuvering, hovering, and cruising. These fins lie along a spectrum from low-aspect ratio highly-flexible fins with exceptional control over the instantaneous fin surface shape, such as the sunfish pectoral fin, to higher aspect ratio rigid fins with constant shape, like those of penguins. This study investigates one extreme of that spectrum: a completely rigid foil with minimal actuation for scientific simplicity. Seen as a canonical form for flapping propulsion, this allows for easier study and understanding of the basic principles and provides a bound for the hydrodynamic performance of swimming animals.

We performed a matrix of experiments with a rigid foil sinusoidally flapping in roll and pitch within an otherwise still fluid (i.e. the only fluid motion was that induced by the flapping fin itself, such as would occur during hovering). Additional tests were performed in a towing tank at constant forward velocity, to represent the creation of maneuvering and propulsive forces both while at rest and during cruise. The foil actuators were mounted to the carriage via a six-axis load cell, and instantaneous torques and velocities from each of the two motors were used to calculate the hydrodynamic power into the system (which is independent of the actuation method used). Regions of separated flow relative to the flapping cycle were measured using thermal anemometers mounted flush with the surface of the fin, illustrating the timing of leading edge separation as an indicator of the instantaneous forces produced by the foil.

The hovering experiments revealed some relatively simple rules to describe the mean maneuvering forces produced. The mean forces were generated almost exclusively in the plane perpendicular to the zero-position of the fin shaft axis. Fluid density, the mean absolute wing velocity, and the swept area collapse the data neatly so that mean thrust, lift, and power are only functions of the pitch amplitude and bias. Additionally, the direction of the thrust jet generated is only a function of pitch bias. Such simplicity eases the creation of an engineering controller.

This elegant simplicity was complicated when a uniform flow was introduced using the tow tank carriage. As speed increases, the flapping frequency and pitch amplitude both must change in order to maintain thrust levels generated during hover. This can be collapsed somewhat using the Strouhal number and maximum angle of attack as described in [1]. However, within the uniform flow mean lift forces are more easily generated and higher efficiencies of thrust development in the downstream direction are possible, reaching a maximum of 55%.

The 3-D instantaneous forces produced by the flapping motion are constrained into a limited range of trajectories, despite the wide range of motion parameters studied. The increased flexibility and articulation seen in the fins of many swimming fishes may serve to increase this range of available instantaneous forces.

References

[1] D.A. Read and F.S. Hover and M.S. Triantafyllou, "Forces on oscillating foils for propulsion and maneuvering," *Journal of Fluids and Structures*, **17**, 163–183, 2003.

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