Abstract

In military technology, and more specifically naval mine hunting, the noise of the screw remains one of the most obvious underwater signatures of the ship. On the other hand, biologists and fluid dynamicists have been impressed by the quiet, smooth and efficient swimming methods of fish. The goal of this thesis is the development of a bio-inspired propeller for ships, and the optimisation of its performance (thrust and efficiency). The noise level of fish is known to be very low, and we assume that all fish-like propulsion systems have similar noise levels. It is not possible to test noise levels using scaled prototypes, and full-scale tests are not possible in the test facilities.

Flapping fin and wing propulsion has been studied widely in the literature, mainly for other applications than ship propulsion. We made a quantitative comparison of the performance of over 1200 individuals found. Of the many different motion patterns, the combination of heaving and pitching proved to be the best performing. Flexible fins are more efficient when the thrust requirements are limited, but when more thrust is desired, stiff fins have higher efficiency. Interestingly, artificial swimmers have higher thrust and efficiency than natural ones, but we attribute this to the fact that thrust and efficiency are human-defined criteria, whereas in nature, there are other and more complex factors that have an impact on the survivability of an organism. The literature review also shows that flapping foil propulsion is possible throughout a wide range of Reynolds numbers.

We developed a simulation methodology for heaving and pitching foils. Since we wanted to conduct a large parametric study, we chose a RANS-modelling of the turbulence, more specifically the kωSST model, because of its relatively good prediction of stall on foils. We also developed a new moving mesh method that maintains high cell quality, while the fin moves with large linear and rotational amplitudes. In this method, the fin is surrounded with an inner cylindrical mesh that moves as one block, and does not deform. Around the inner mesh, there is an outer one that deforms, but only slightly. In between the two, there is a sliding interface.
Since two parameters, the frequency and the heaving amplitude, were already widely covered in the literature, we focused on the other three: phase difference, pitch axis position and pitch amplitude. These are the parameters that need special attention in passive pitching.

An extensive series of simulations proved that a pitch axis close to the leading edge, a limited phase difference, and a large pitch amplitude yield a good compromise between high thrust and efficiency.

The flow field corresponded clearly to the performance of the fin. A strong central jet between large, well-spaced vortices generates high thrust. Moderate, well-spaced vortices lead to high efficiency. Messy wakes with paired, counter-rotating vortices yield negative thrust. The simulations also show that passive pitching is possible when the pitch axis is close to the leading edge.

We constructed a water channel to test fins in flowing water, and built a force sensor to measure the thrust and lateral forces and the pitching moment. The fin was actively heaved by a Scotch yoke mechanism. We designed a new passive pitch mechanism with adaptable rotational stiffness. We tested fins with the pitch axis on the leading edge and on the quarter-chord point, driven by the active heave and the passive pitch mechanisms, with variation of the flapping frequency and the rotational stiffness, in the water channel. The highest thrust was found for the fin with the pitch axis on the leading edge and at the highest frequency. The rotational stiffness had little effect on the thrust. The highest efficiency was found for the same pitch axis position and frequency, and for the smallest stiffness, hence for the highest pitch amplitude.

The passive pitch mechanism flattens out peaks in the pitch motion, because the rotational stiffness increases with the pitch angle. This results in a more sinusoidal variation of the angle of attack. From the literature, this is known to improve the efficiency with respect to sinusoidal heaving and pitching.

Suggestions for even further improvement of the pitch cycle and of the performance are decreasing the inertia of the fin, increasing the flexibility of the pitch joint and increasing the frequency of the heave motion.