Comparison of Steady-state and Unsteady Hydrodynamic Mechanisms

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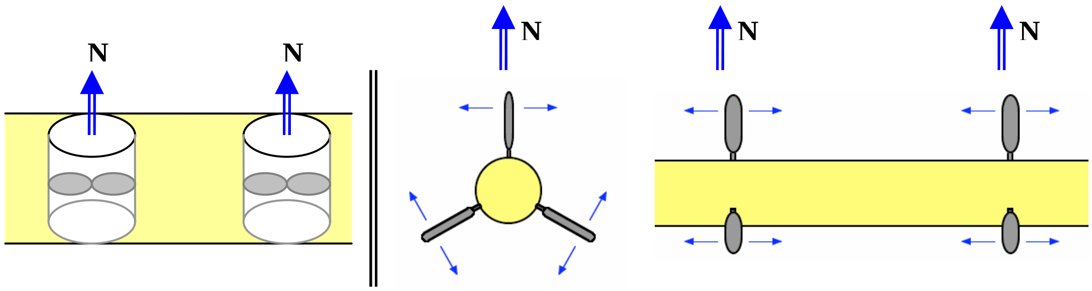
Maneuvering thrusters based on the mechanisms of steady state and unsteady hydrodynamics have been compared in their roles on cylindrically-shaped vehicles. The goal is to determine if, during hovering, unsteady hydrodynamic mechanism consumes less energy than steady state hydrodynamic mechanism. The former is in play in swimming and flying animals while the latter is the foundation of conventional engineering platforms which swim and fly. These tests compare a heaving and pitching high-lift foil as an example of an unsteady hydrodynamic thruster with a conventional cross-tunnel thruster that has fixed blades. It is estimated that the vehicle with unsteady actuators consumes, typically, as much as 60% less hydrodynamic power.

Introduction:

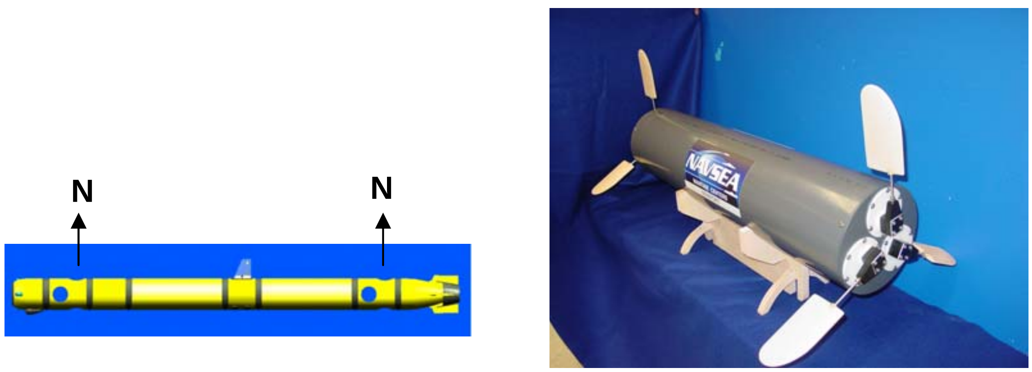
Some of the recent efforts aimed at improving the hydrodynamic performance of underwater vehicles have focused on the understanding and implementation of high-lift principles used by swimming and flying animals, such as dynamic stall and rotational effects. Biological studies show that cost and reliability can be such that they can indeed be used in a systems context. The state of the art is described in Refs. [1] - [3]. The present work is an example where the high-lift principles are implemented and the improvements have been measured against a specific contemporary vehicle taken as a benchmark. In a companion paper, comparison of power is made against the converged trend between manufactured underwater vehicles and red and white muscle based power consumption by swimming animals such as shark and tuna [4]. Such an approach offers precise matrices of improvement.

Figure 1 shows the current solution – a vehicle with cross-tunnel thruster (CTTs) – and the proposed solution – a vehicle with 6 flapping fins – schematically. In the former, two pairs of conventional thrusters (that is, propellers) are configured perpendicular to each other in the fore and aft of the vehicle. In the absence of axial flow, this allows the vehicle to move sideways, upwards, and downwards. When the vehicle is in motion and the thrusters are on, the vehicle drag increases significantly due to suction and blowing of the thruster jet. Additionally, the effectiveness of the maneuvering thrusters decrease as axial speed is increased. On the other hand, the proposed solution allows 6-degrees of motion in both the presence and absence of forward or backward motion of the vehicle. Furthermore, in the proposed solution, the control surfaces over the boat tail of the main cylinder are not needed. Figure 2 shows the NUWC Mid-sized Autonomous Research Vehicle (MARV) with CTTs, and the NUWC Biorobotic Autonomous Underwater Vehicle (BAUV) with actuators as shown in Fig. 1b.



(a) (b)

Figure 1. Schematic of current solution (a) and proposed solution (b) shown for hovering. Thrusters along horizontal axis are not shown for simplicity. N is the vertical thrust produced at zero forward speed.



(a) (b)

Figure 2. Photographs of the MARV UUV with CTT (a) and the NUWC BAUV (b).

In Fig. 2b, observe that the foil modules follow the CTT arrangement shown in Fig. 2a. A three foil configuration was selected because a two foil module has insufficient degrees of motion and a four foil module has excessive redundancy.

In this paper, the results of low-speed tow tank measurements on an instrumented single foil is used to estimate the power used by the BAUV shown in Fig. 2b. The hydrodynamic power consumption by MARV UUV with CTT has been compared with these estimates for the scaled NUWC BAUV.

Experiments:

Measurements were carried out on a single instrumented foil in the NUWC Low Speed Tow Tank. The entire contraption is suspended from a six component load cell which hangs from the tow tank carriage, as shown in Fig. 3. A pair of motors flaps the foil in two angular directions. A horizontal Plexiglas plate is hung from the carriage just below the water surface to prevent entrainment of air by the foil motion. The foils had a NACA 0012-64 cross-section of 4 inch chord, with truncated trailing edges, and spans of 8 and 12 inches.

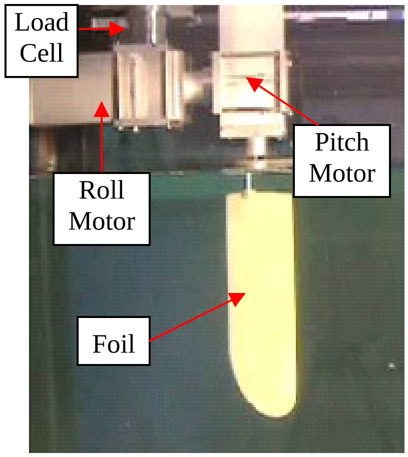


Figure 3. The unsteady foil apparatus is mounted to the tow-tank carriage.

The foil flaps sinusoidally in roll (also called heave) and pitch (as defined in Fig. 3), where the pitch motion is 90 degrees out of phase with roll and can be biased so as to vector the thrust. The foil was tested within a parameter space changing frequency, pitch amplitude, roll amplitude, foil span, and pitch bias, at zero speed. The unsteady loads are measured to give mean thrust and lift, which has an equivalent vectored thrust magnitude and direction. The hydrodynamic power put into the water was calculated through torque sensors attached to each motor along with the instantaneous motor angular velocity. The thrust magnitude was found to scale with frequency squared, which was used to scale up the foil data to match the CTT in force production.

The cross-tunnel thruster data used for comparison was from the manufacturer spinning the propeller at various speeds in an otherwise still pool.

Results:

The estimated hydrodynamic power consumption during hovering by MARV UUV with CTT and NUWC BAUV are compared below. As an example, for upward translation, four foils do the work of two CTTs @110N each, taking into account each fin's orientation of 60 degrees angle from vertical as shown in Fig. 1b.

Lift-based	(12" span):	440W Foils	vs. 1078W CTT
Drag-based	(12" span):	780W Foils	vs. 1078W CTT
Lift-based	(8" span):	540W Foils	vs. 1078W CTT
Drag-based	(8" span):	1,065W Foils	vs. 1078W CTT

The lift-based results are from tests performed with a zero pitch bias, leading to a motion similar to that seen in swimming penguins or flying birds. The drag-based results are from tests done with a 45 degree pitch bias, leading to a vectored thrust in the plane of the roll rotation (lateral to the vehicle body axis), similar to a rowing motion. As can be seen, both the lift-based and drag-based foil motions result in lower power consumption than CTTs, although lift-based foil motion improves over that by drag-based foil motion by a considerable margin. Both are presented because a vehicle utilizing foil maneuvering thrusters in the configuration presented here would be using a drag-based foil motion to generate lateral forces at zero forward speed. Re-orientation of the fin, or an additional degree of freedom allowing the rotation of the entire flapping thruster, would enable lift-based motions to generate vertical forces.

Conclusions:

Low-speed tow tank measurements have been carried out on foils that simultaneously roll (heave) and pitch with a constant phase difference of 90 degrees between them. They indicate that, during hovering, a cylindrical vehicle based on such actuators consumes less power than that based on cross tunnel thrusters.

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