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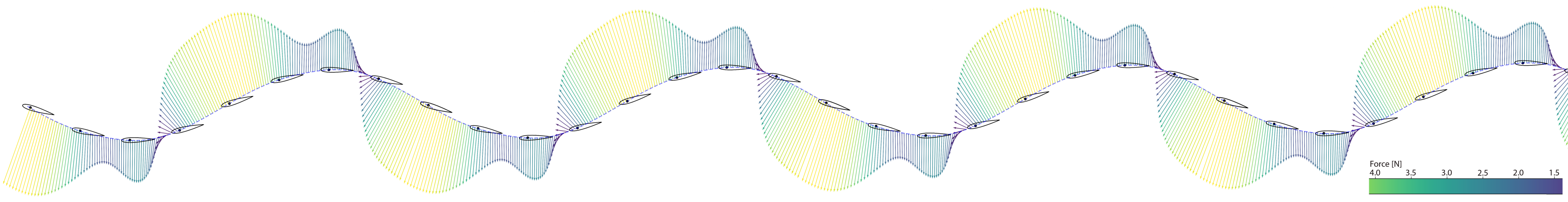

Figure 7: Resulting forces generated through combined yaw and sway oscillation. The foil is translated or "swimming" to the left.

Thrust optimisation of an oscillating hydrofoil

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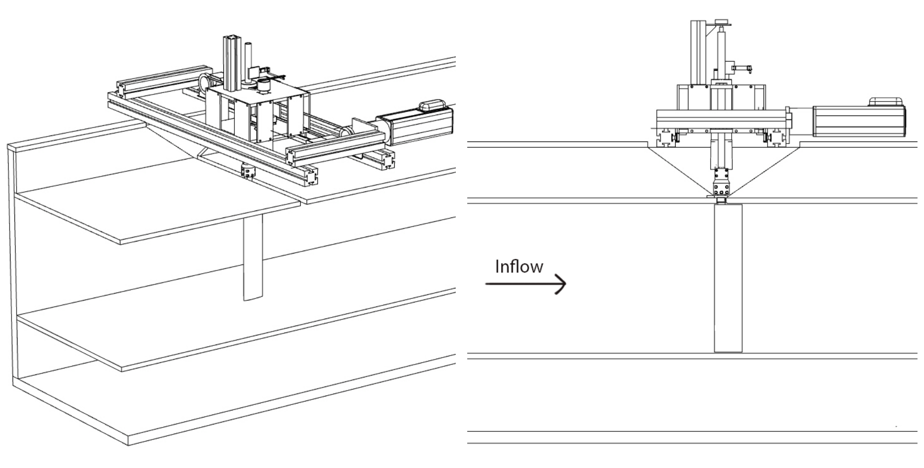


(a) Isometric view with side-wall removed (b) Side-view

Figure 2: CAD-sketches of the foil oscillator rig mounted inside the circulating water tunnel. Two electrical motors are used to create a sway and yaw motion via a belt-pulley system. Force and energy measurements are done with several strain gauges, accelerometers, and position sensors. Courtesy to John Martin Kleven Godø.

Abstract

Past research has shown that oscillating hydrofoils can enhance the propulsion efficiency significantly compared to traditional propellers. Dynamic stall plays an important role in the thrust generated by an oscillating hydrofoil, combining this with non-sinusoidal motion makes this an complicated phenomenon to investigate. A Genetic Algorithm is therefore employed to optimize the foil motion for maximum thrust efficiency in a circulating water tunnel (CWT). Two different flow conditions are considered: one at low Reynolds number with a wide range of Strouhal number (S_t); and another with higher Reynolds number, and a turbulent boundary layer through turbulence stimulation. Efficiencies above $\eta > 60\%$ are observed for a wide range of thrust coefficients (C_T).

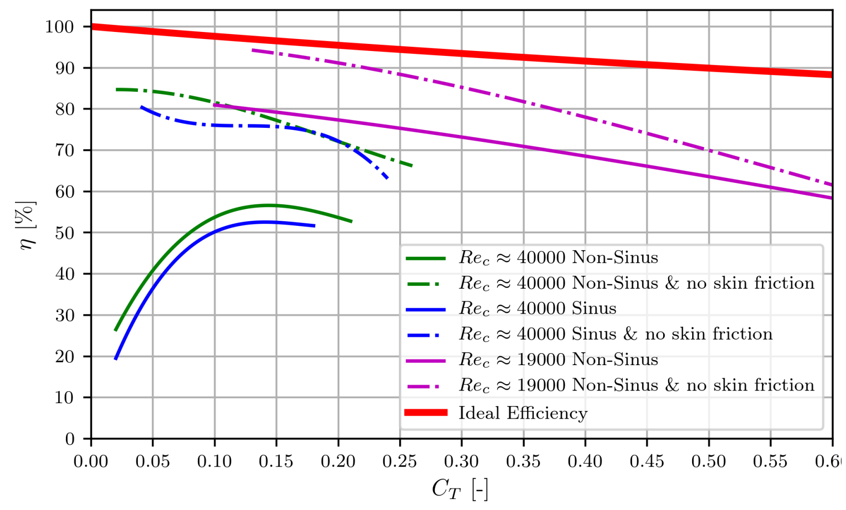


Figure 3: Summary of the highest efficiency achieved at different thrust coefficients. Two lines are represented for each experiment: one with skin friction; and one without. The thrust coefficient is referenced to foil area: span (s) multiplied with chord (c).

Introduction

Oscillating hydrofoils is a renown concept for ship propulsion, and energy extraction from waves, wind and currents. A foil is oscillated in yaw and sway to generate thrust. This concept could achieve higher efficiency than a conventional propeller system since the swept water area can be significantly larger (Yamaguchi & Bose, 1994).

Several research institutes are investigating the effect various motion-parameters have on thrust generation and efficiency. The most cited results are by Anderson, Streitlien, Barrett, and Triantafyllou (1998), they were able to measure a maximum efficiency of 87% by doing a parametric search for sinusoidal sway and yaw motion. In similar experimental research Read, Hover, and Triantafyllou (2003) uncovered that adding higher-harmonics to the sway motion, and thereby modifying the sinusoidal motion increased the efficiency, he recommended that future studies should focus on combining non-sinusoidal motions in both sway and yaw. Then this becomes very complicated because at least 6 parameters will define the motion, to deal with this optimisation techniques will be utilised in this thesis.

The objective is to automate optimisation tests based on real-time experimental measurements. An optimisation algorithm, inspired by biological evolution, is written in the master thesis by Thomas Gjerde and is employed in collaboration with him. The algorithm will select motion-parameters during the experiment, basing those parameters on maximising thrust efficiency.

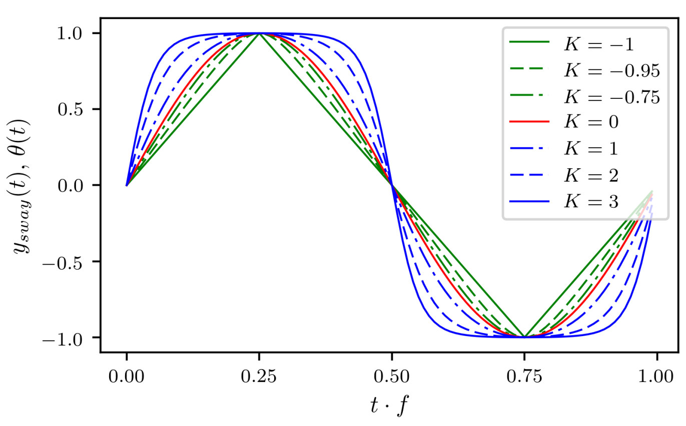


Figure 4: The motion profile function for sway or yaw for one period where K is varied, illustrating how a zigzag, sinusoidal or square motion is represented. Period and amplitude is normalized.

Experimental setup

The experiments are conducted in a circulating water tunnel (CWT), located at NTNU campus Tyholt. Periodic motion in sway and yaw is created with equipment lent from John Martin Kleven Godø(see figure 2). Modifications to the real-time control algorithm in LabView are made to allow for automation of the experiments and non-sinusoidal motions.

Force and energy measurements to determine thrust and efficiency are done with several strain gauges, accelerometers, and position sensors. The data is analysed automatically during the experiment in a post-processing script written in Python. The next test parameters are then selected by the optimisation algorithm.

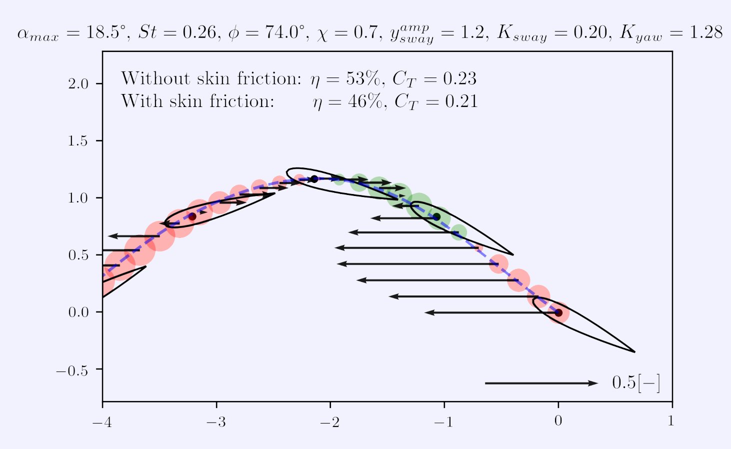
To represent a non-sinusoidal motion an unique K-parameter is used for sway and yaw. This causes the motion through one period to either be; sinusoidal, zigzag, or square, as illustrated in figure 4. The equation is inspired by Lu, Xie, and Zhang (2014).

Test-conditions

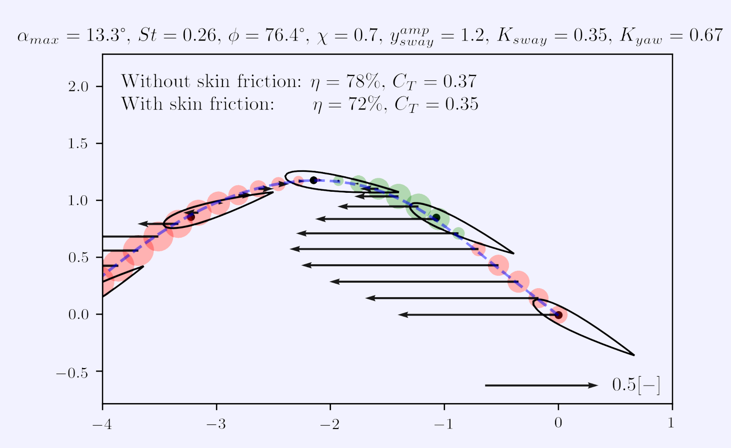
The achievable oscillation frequency is limited by equipment. The Strouhal number is highly dependent on inflow velocity and oscillation frequency. At a too low Reynold number (Re_c) or inflow velocity, scale effects occur due to laminar separation bubbles. Optimisation experiments are therefore conducted at two conditions: at $Re_c \approx 19000$, where the scale effects are severe but high Strouhal number is achieved ($S_t < 0.35$); and at $Re_c \approx 40000$, where the Strouhal number is low ($S_t < 0.18$) and scale effects are minimal. To reduce the scale-effects even further, a boundary layer trip in accordance to Braslow and Knox (1958) is utilized at $Re_c \approx 40000$, the drawback is increased skin friction.

At $Re_c \approx 40000$ two seperate optimisation tests are done: one where a sinusoidal motion is enforced by setting the K-paramater to 0; and the other where a wide range of K is accepted. This will give a direct comparison whether there is a significant performance improvement by using non-sinusoidal sway and yaw motions.

Small changes in motion have a huge impact on performance



(a) Suboptimal



(b) Optimal

Figure 5: Illustration of two similar motions, tested at $Re_c \approx 19000$. The size of the circles denote power consumption at the time incident, when the circle is green, energy is regenerated. The arrow denote the thrust coefficient at the time incident. Notice how a small change in motion can have a huge impact on efficiency and thrust.

Results and discussion

In total 6500 separate oscillation tests are done to optimise the efficiency (η) over a wide range of thrust coefficients (C_T). For each of the 3 optimisation tests a third order function is fitted to the test-individuals with highest efficiency for a given thrust coefficient. The procedure is illustrated in figure 6.

To make it easier to compare results with different flow-conditions and turbulence stimulation, the skin friction is removed from all 3 optimisation-cases. This is achieved by zeroing the drag force at zero angle of attack with a steady foil. The least-square fit functions for all 3 cases are illustrated in figure 3. Tests done at $Re_c \approx 19000$ are able to produce the highest thrust, this is expected due to a higher strouhal number. There is a minor improvement of 5% increased efficiency for $0.01 < C_T < 0.21$ for a non-sinusoidal motion. This is so insignificant that it is expected to be diminished by the complexity of creating a full-scale machinery which can represent other motions than sinus.

In an ideal world without frictional-losses it is expected that it is most efficient to move as little water as possible to produce thrust. The results in figure 3 support this: When friction is subtracted, the efficiency is gradually decreased with C_T; however for the case with turbulence-stimulation and large skin-friction, the highest efficiency is reached at $C_T \approx 0.12$. This could also occur in full-scale, dependent on the magnitude of skin-friction.

Preliminary findings

The current preliminary findings in this master-thesis can be summarized to:

- High efficiencies are measured ($\eta > 60\%$) for a large range of thrust coefficients.
- Skin friction is very important at low thrust coefficients, and can cause a large degradation of efficiency.
- Optimisation techniques can successfully be employed to optimize pysical experiments in real-time.
- Only minor improvement in thrust-efficiency by utilising non-sinusoidal sway and yaw motion.

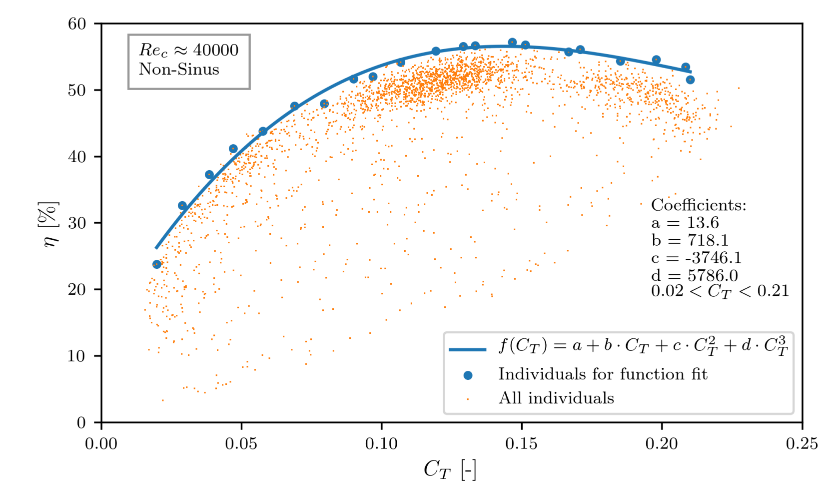


Figure 6: Least square fit to the test-individuals with highest efficiency (η) for different thrust coefficients (C_T). This curve is also represented in figure 3.

Acknowledgement

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Sources

Anderson, J., Streitlien, K., Barrett, D., & Triantafyllou, M. (1998). Oscillating foils of high propulsive efficiency. *Journal of Fluid Mechanics, 360*, 41-72.

Braslow, A. L., & Knox, E. C. (1958). *Simplified method for determination of critical height of distributed roughness particles for boundary-layer transition at mach numbers from 0 to 5.* National Advisory Committee for Aeronautics.

Lu, K., Xie, Y., & Zhang, D. (2014). Numerical investigations into the nonsinusoidal motion effects on aerodynamics of a pitching airfoil. *Energy Procedia, 61*, 2497-2500.

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

Yamaguchi, H., & Bose, N. (1994). Oscillating foils for marine propulsion. *Oscillating Foils for Marine Propulsion, 3*, 539-544.