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Experiments with actively pitch-controlled and spring-loaded oscillating foils

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ABSTRACT

Experiments with a horizontal foil undergoing harmonic heave motion while traveling at a steady forward speed were performed. The objective was to study different pitch strategies for maximizing the forward thrust. An oscillating foil can replace the rotating propeller as ship propulsor, or the foil can be mounted to the ship in order to create auxiliary thrust in waves. The latter was the motivation behind the experiments presented in this paper. An actively pitch-controlled foil was tested, where two vanes measured the inflow angle to the foil and a motor pitched the foil based on a specified control algorithm. The effect of varying the parameters in the pitch-control algorithm was tested in practice and is discussed here. A spring-loaded foil was also tested. The pitch motion of the spring-loaded foil is shown to produce higher thrust than that of the actively pitch-controlled foil tested. It was also found that the efficiency with spring-loaded pitch motion was higher than the efficiency with forced harmonic pitch motion leading the heave motion with a 90° phase angle.

1. Introduction

The ongoing climate change requires us to reduce greenhouse gas emissions in all sectors, including shipping. One obvious solution is going back to wind-powered ships, the main means of world trade for centuries, before the industrial revolution. Wind is not the only abundant renewable energy source on the oceans, however. The first boat using wave energy for propulsion – to the authors' knowledge – was Hermann Linden's *Autonaut* [2,5,22]. The *Autonaut* was equipped with a flexible fin at the bow and at the stern and sailed at 3–4 mph. The idea of using flexible fins for propelling a boat in waves, however, was already proposed by Daniel Vrooman in 1858 [26].

Several experimenters later built wave-powered boats employing fins attached to flexible joints [16], or flexible fins [12,17]. Einar Jakobsen's wave powered boats used spring-loaded foils [9,10]. The spring-loaded foil pivots about a point located in front of the center of pressure, so that the foil's angle of attack is reduced in incoming flow. The spring ensures that the angle of attack is not reduced to zero, but ideally to just below the foil's stall limit.

The present paper studies both a foil where the pitch is governed by a spring and an actively pitch-controlled foil, i.e., a foil pitched by a motor in order to maximize the thrust at all times. Naito and Isshiki [13] proposed an actively pitch-controlled foil where the pressure at the bottom surface of the foil was used as input in the control system. The pressure around the foil is composed by a contribution from the circulatory lift force and a contribution from the non-circulatory normal added mass force. By "normal" what is meant is that the force acts normal to the chord line. The pressure contribution from circulatory lift is related to the angle of attack of the foil, whereas the non-circulatory pressure contribution is related to the fluid acceleration normal to the foil. Hence, when using the bottom pressure as an indicator of the foil's angle of attack, the non-circulatory pressure contribution will affect the results.

Based on the above discussion of pressure sensors for detecting the angle of attack, we chose to measure the actively pitch-controlled foil's angle of attack by using two small vanes, see Fig. 3, which passively aligned themselves in the direction of the inflow to the foil. Thus, when knowing the inflow angle and the foil angle, one also knows the foil's angle of attack.

The term "angle of attack" is not precise when used in connection with an oscillating foil. In steady conditions, the term refers to the steady angle between the chord and the flow direction. For an oscillating foil, however, the inflow is influenced by the unsteady wake behind the foil. This effect is often described through an "effective angle of attack". The effective angle of attack is found by dividing the instantaneous lift coefficient – in attached flow conditions – by the lift coefficient slope. This angle of attack has a phase lag and amplitude reduction compared to the angle of attack obtained from the instantaneous motion of the foil relative to surrounding fluid (assuming that the fluid is unaffected by the foil),

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called the quasi-steady angle of attack. Detecting the angle of attack of an oscillating foil hence implies detecting the angle of attack that the foil "feels", i.e., the effective angle of attack.

A wealth of experiments with oscillating foils are reported in the literature. Scherer [19] presents results from testing of a finite-span oscillating foil and notes that the foil must undergo large amplitude oscillations at relatively high frequency in order to achieve practical levels of thrust. DeLaurier and Harris [7] also tested a finite-span oscillating foil, and found a near linear dependence of thrust on reduced frequency.

The Strouhal number, *St*, is a key parameter in oscillating foil propulsion due to its importance for the thrust-producing jet behind the foil, as noted by Triantafyllou et al. [23,24]. For oscillating foils, it is defined as

$$St = \frac{fA}{U}, \tag{1}$$

where f is the frequency of oscillation in Hz, A is the width of the wake, and U is the average forward speed. In oscillating foil propulsion, the distance traveled by the trailing edge is commonly used for the width of the wake. We denote the Strouhal number St if the double heave amplitude is used as the width of the wake and St_{TE} if the trailing edge motion is used. Triantafyllou et al. [23,24] performed experiments on a foil oscillating in a combined heave and pitch motion, with the pitch motion 90° out of phase with the heave motion, and found the efficiency to peak at a Strouhal number of 0.25. They also noted that fish and cetaceans varying in size from shark and dolphins to goldfish oscillate their tails at Strouhal numbers that lie almost invariably in the 0.25–0.35 range. Triantafyllou et al. [25] notes, however, that while "the optimum range of Strouhal number – between 0.25 and 0.35 – is found for certain specific profiles used in Triantafyllou et al. [23]; in other cases, different values may be obtained."

Extensive experimental work has been conducted at MIT to study the performance of oscillating foil propulsion [1,8,18,20]. Propulsive efficiencies as high as 87% was measured by Anderson et al. [1]. Czarnowski et al. [6] performed experiments with a model boat equipped with two vertically oriented counter-oscillating foils for propulsion and measured efficiencies of up to 59%.

The main motivation behind the present paper was to compare actively pitch-controlled and spring-loaded foils for wave propulsion of ships. In this case, the heave motion of the foil is governed by the heave and pitch motion of the ship, and the parameter we can control is the pitch angle of the foil. We want to maximize the foil thrust for a given ship motion, but high efficiency of the foil may also imply high foil thrust, since higher foil efficiency implies lower vertical forces and hence less damping of the ship motions.

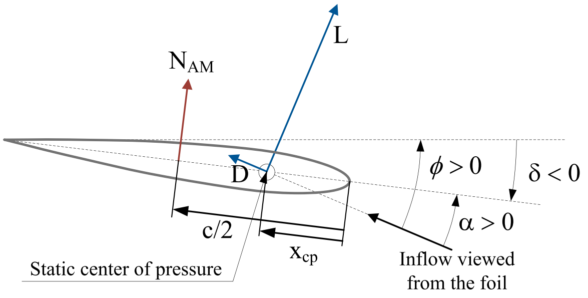

Fig. 1. Foil forces and angles.

2. Controlling the foil pitch

The relevant forces and angles of an oscillating foil is shown in Fig. 1. L is lift, D is drag, and N_{AM} is normal added mass force, which we assume act at half the chord length, c, from the leading edge. In steady conditions, the lift and drag are assumed to act at the center of pressure, which is x_{cp} from the leading edge. ϕ is the inflow angle to the foil, α is the angle of attack, and δ is the foil angle. From Fig. 1 we see that

$$\alpha = \phi + \delta. \tag{2}$$

As in Politis and Politis [15] and Belibassakis and Politis [4], the pitch-controlled angle of attack is taken as a constant times ϕ. We denote this constant the pitch-control parameter, w_{pc}. The inflow angle to the foil, as measured by the small water vanes, is ϕ_E, where ϕ_E is calculated as the average of the two vane angles. A stall criterion can be set so that the angle of attack never exceeds a certain value, α_{max}. The pitch-control algorithm then becomes

$$\delta_{opt} = \begin{cases} -\alpha_{\max} - \phi_E, & w_{pc}\phi_E < -\alpha_{\max} \\ \phi_E(w_{pc} - 1), & -\alpha_{\max} \le w_{pc}\phi_E \le \alpha_{\max} \\ \alpha_{\max} - \phi_E, & w_{pc}\phi_E > \alpha_{\max}. \end{cases} \tag{3}$$

Results for the pitch-controlled foil with different values of w_{pc} and α_{max} are given in Section 3.2.5.

3. Actively pitch-controlled foil

3.1. Experiment setup

A foil of span 1.81 m and max chord length 0.1875 m was tested in a 40 m long, 6.45 m wide, and 1.5 m deep towing tank, at the Marine Technology Center in Trondheim, Norway. The foil sectional form was the NACA 0015 profile. Fig. 2 is a CAD drawing showing the planform and thickness profile of the foil, with dimensions in mm. The foil was previously mounted on a ship model, see [3]. It was thought to have a telescopic design in full scale, where the outermost parts could be retracted into the center part of the foil. This resulted in the unconventional planform, but no telescope mechanism was built in model scale.

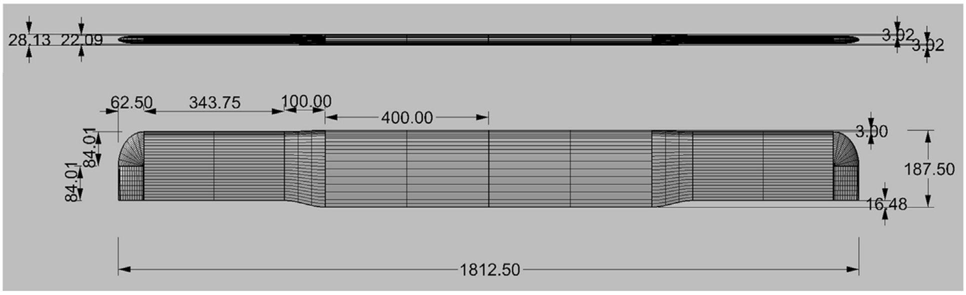

Fig. 2. The planform and thickness profile of the foil used in the experiments, with dimensions in mm.