Thrust and lift generation in ‘ground effect’ for heaving and pitching high aspect ratio foils.

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***Abstract*— We present the results of preliminary experimental studies on force production by heaving and pitching oscillating foils operating in 'ground effect' near a flat bottom. Wing-in-ground effect is a well understood phenomenon for the case of steady flight near a solid boundary. However, the overall effect of swimming close to the bottom using biologically inspired oscillatory propulsion mechanisms is still poorly characterized. We experimentally demonstrate that the mean lift for a typical set of thrust generating foil kinematics when operating within two chord lengths of the bottom is increased by an amount consistent with approximately a 1 degree positive (away from wall) bias in the foil pitch angle. In addition to the mean lift effect, flapping a foil near a solid boundary generates significant (18%) variation in peak magnitude of downstroke vs upstroke instantaneous lift. This intra-cycle variation in the magnitudes of the lift peaks provides a detectable signal within a single flapping period (i.e. it does not required an excessive amount of sampling time.) This signal has the added benefit that it does not require comparison to some previously measured baseline in open water to be operationally useful.**

By swimming near the bottom, underwater vehicles can improve navigation and reduce wave and current forcing. Characterization of changes in the instantaneous force profiles on fins as a function of altitude provides an additional sensing modality for vehicles swimming near the bottom. Next generation fin propelled vehicles will be able to use real time fin force data to estimate, and hence control, altitude while near the bottom.

I. Introduction

The limitations of conventional propeller driven unmanned underwater vehicles (UUVs) in dynamic, cluttered, and obstacle laden environments has spurred a large body of research into the capabilities afforded UUVs by alternative propulsion approaches. A wide variety of marine animal species have demonstrated that oscillating foils are an effective means of generating thrust for both long distance swimming and maneuvering near obstacles. In the present effort, we focus on the effects that the presence of a flat rigid boundary has on the forces generated when using oscillating wing propulsion. Wing-in-ground effect is a well understood phenomenon for the case of steady flight near a solid boundary. However, the overall effect of swimming close to the bottom using biologically inspired oscillatory propulsion mechanisms is still poorly characterized.

The presence of a ground effect for oscillating foils has two implications for near bottom swimming UUV designs. First, it is important to understand how swimming near the bottom affects mean thrust generation. Decisions about both UUV design and optimal operation must take ground effect into account to achieve the desired range and swimming speeds. Second, the strength of the ground effect will affect stability in near bottom swimming from a dynamic standpoint (i.e. is the effect stabilizing or destabilizing in pitch and altitude regulation?) and from a sensing standpoint (i.e can changes in actuator demand be used to detect altitude in the near field where traditional acoustic sensing approaches break down?)

II. Methodology

A. Oscillating Foil Kinematics

A 6-axis dynamometer in the 3m x 0.89m x 0.75m glass-lined towing tank at the University of Rhode Island was used to measure forces and moments on a straight NACA-0012 foil of chord $c = 0.07$m and span $s = 0.45$m. The foil was actuated in heave, h, and pitch, θ, while attached to a carriage moving at speed $U = 0.3$m/s. The foil was suspended such that the foil pierced the water to a depth of 0.35m. A schematic indicating the degrees of freedom of the foil and carriage motion is shown in Figure 1. A side view of the tank and carriage apparatus is shown in Figure 2.

All foil motions were performed under the kinematic constraints that the pitch angle $\theta(t)$ be sinusoidal, and that the angle of attack $\alpha(t)$ of the foil with respect to the water (defined following [1] as $\alpha(t) = \theta(t) - arctan\frac{\dot{h}}{U}$) also be sinusoidal, i.e. that:

$$\theta(t) = \theta_0 sin(2\pi ft) \quad (1)$$

$$\alpha(t) = \alpha_0 cos(2\pi ft) + \theta_{bias} \quad (2)$$

For a set foil size and towing speed, the following non-dimensional parameters define the foil motion with respect to the water and the tank completely:

- The Reynolds number, defined as: $Re = \frac{Uc}{\nu}$.
- The Strouhal number, defined as: $St = \frac{h_0 f}{U}$
- The ratio of the heave amplitude to the chord length :$\frac{h_0}{c}$.
- The ratio of the mean heave distance from the wall to the chord length ($\frac{\bar{h}}{c}$).
- The maximum nominal angle of attack of the unbiased motion with respect to the water, α_0.

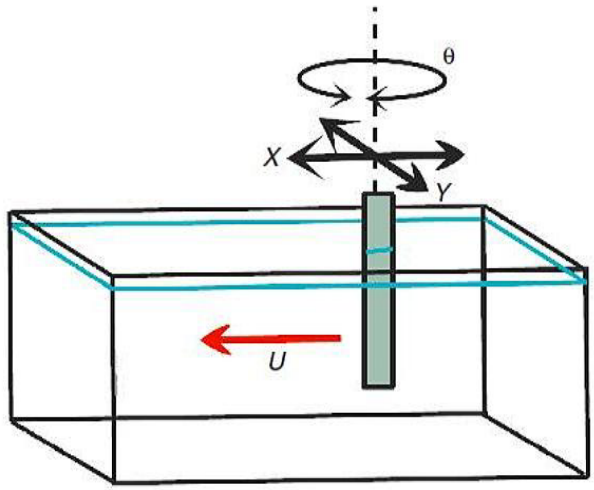

Fig. 1. Diagram defining axes for foil motion with the tank, definitions and schematic adapted from [2]. The foil is attached to a carriage via a dynamometer, and actuated in two degrees of freedom (Y and θ) with respect to the carriage while the carriage translates down the length of the tank a constant speed. $X(t) = 0$ for all experiments presented here, where X is defined as motion of the foil with respect to the carriage in the direction parallel to the carriage motion..

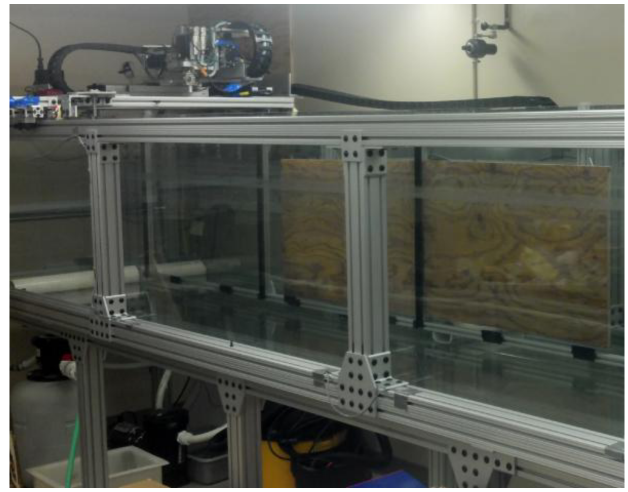

Fig. 2. Tank apparatus showing tow carriage (top left) mounted on rails above glass walled water tank. 3/4" thick plywood of rigid sidewall is visible through tank wall.

- The angular pitch bias θ_{bias}

Refer to [2] for the iterative approach used to calculate the foil heave velocity given these constraints and parameters.

B. Experimental Procedure

We performed a series of experiments with $St = 0.4$, $\alpha_0 = 40^0$, and $\frac{h_0}{c} = 1.0$. A movable side wall acted as the solid boundary, and different distances from this 'ground' were tested by moving the wall and/or changes the mean heave position, $\bar{h}$ of the foil motion. For each wall distance $\frac{\bar{h}}{c}$ = [1.50 1.75 2.00 6.00], the foil kinematics were executed with pitch bias θ_{bias} = [-4 -2 0 1 2 4 6]^0. The wall position within the tank was held constant for $\frac{\bar{h}}{c} < 6.00$. For $\frac{\bar{h}}{c} = 6.00$, we moved the wall to the far extreme of the tank. Images of the foil in the extreme heave position for the case of $\frac{\bar{h}}{c} = 2.00$ and $\frac{\bar{h}}{c} = 1.50$ are presented in Figure 3 and Figure 4 respectively.

III. Results

A. Mean Lift in Ground Effect

The mean lift coefficients, $\bar{C_L} = \frac{\bar{L}}{0.5\rho U^2 sc}$ over an entire foil oscillation cycle, as a function of pitch bias, θ_{bias}, are compared for different wall distances $\frac{\bar{h}}{c}$ in Figure 5 . Previous work has shown that maneuvering and altitude control in flapping foil vehicles is simplified by the linear relationship between θ_{bias} and $\bar{C_L}$, allowing a close analogy between fixed wing flight control and flapping wing swimming control [3]. Wing in ground effect for fixed foils is primarily observed as an increase in $\bar{C_L}$ acting on the foil near the ground. As shown in Figure 5, the analogy to fixed wing flight holds for near ground effects. Near ground operation produces a change in $\bar{C_L}$ equivalent to approximately 1^0 of positive θ_{bias} when compared to far field operation.

B. Thrust in Ground Effect

Mean thrust coefficients, $\bar{C_T} = \frac{\bar{T}}{0.5\rho U^2 sc}$ over an entire foil oscillation cycle as a function of pitch bias, θ_{bias}, are compared for different wall distances $\frac{\bar{h}}{c}$ in Figure 6 . $\bar{C_T}$ in the near field case is increased by 8% over the far field control case. Thrust is increased across all values of θ_{bias} tested. The effect of the ground does not significantly change the magnitude of the thrust reduction (vs. the symmetric case) for $|\theta_{bias}| < 5^0$.

C. Ground Induced Intra-cycle Asymmetry in Force Profile

The instantaneous C_L and C_T for the symmetric kinematics ($\theta_{bias} = 0$) for wall distances $\frac{\bar{h}}{c} = 1.50$ and $\frac{\bar{h}}{c} = 6.00$ are compared in Figure 7 in order to show the magnitude and direction of the change in force induced by the presence of the ground throughout the stroke. A direct comparison of instantaneous lift and thrust coefficients, C_L and C_T between upstroke and downstroke (equivalently, between 'toward ground' and 'away from ground' half-cycles) is shown in Figure 8. . The ground induced asymmetry is most easily detected in the the instantaneous C_L than the instantaneous C_T, both in terms of absolute change in maximum force between upstroke and downstroke, and when normalized by the maximum observed force. The magnitude of the change (18%) in peak C_L is promising for the use of instantaneous force measurement to detect and actively control altitude for near bottom flight.

A comparison of force measurement results to those of a foil with identical kinematics and similar test apparatus [2] is shown in Figure 9. Agreement between phase and magnitude of the lift and thrust profiles was used to validate the experimental apparatus and the signal processing techniques..

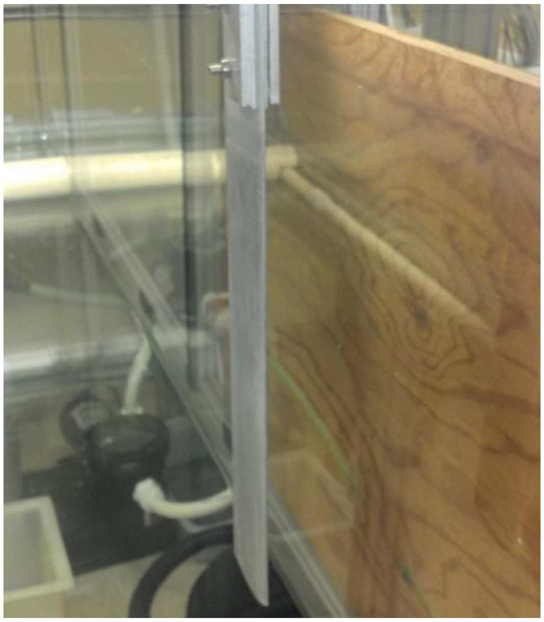

Fig. 3. Foil at closest approach to wall with height to chord ratio $\frac{\bar{h}}{c} = 2$. With heave to chord ratio $\frac{h_0}{c} = 1$, the closest approach is the chord length, c.

Fig. 4. Foil at closest approach to wall with height to chord ratio $\frac{\bar{h}}{c} = 1.5$. With heave to chord ratio $\frac{h_0}{c} = 1$, the closest approach is one half the chord length, $\frac{c}{2}$.

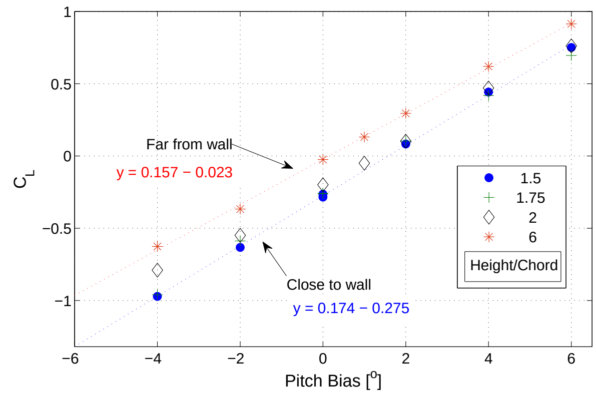

Fig. 5. Mean lift coefficients, $\bar{C_L}$, over an entire foil oscillation cycle as a function of pitch bias, θ_{bias}, compared for different wall distances (i.e. foil 'heights') $\frac{\bar{h}}{c}$.

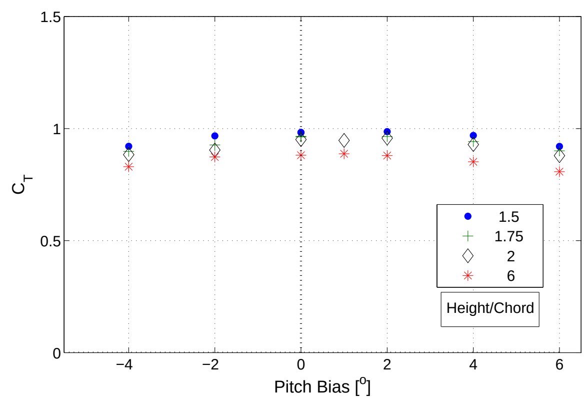

Fig. 6. Mean thrust coefficients, $\bar{C_T}$, over an entire foil oscillation cycle as a function of pitch bias, θ_{bias}, compared for different wall distances (i.e. foil 'heights') $\frac{\bar{h}}{c}$.

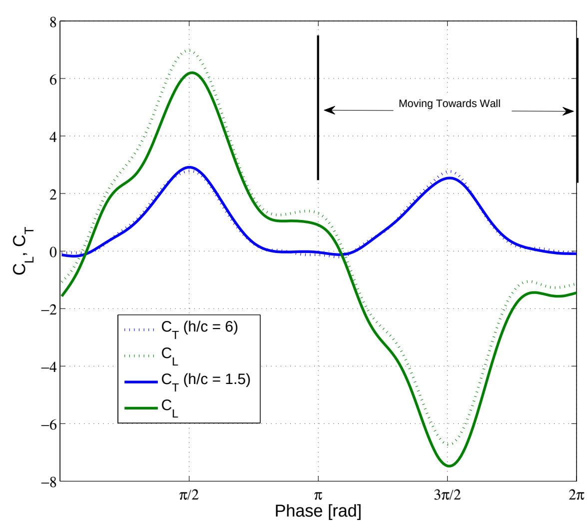

Fig. 7. Instantaneous C_L and C_T for the symmetric kinematics ($\theta_{bias} = 0$) for wall distances $\frac{\bar{h}}{c} = 1.50$ and $\frac{\bar{h}}{c} = 6.00$. The foil is moving towards the wall where $\pi <$ phase $< 2\pi$.

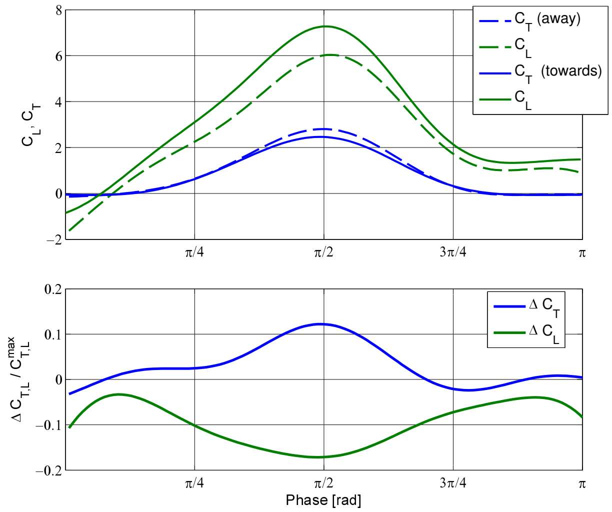

Fig. 8. Direct comparison of instantaneous lift and thrust coefficients, C_L and C_T, between upstroke and downstroke (equivalently, between toward ground and away from ground half-cycles) Symmetric kinematics are used, with ($\theta_{bias} = 0, St = 40, abs\alpha_{max} = 40$ for both upstroke and downstroke. $-C_L$ is plotted for half the cycle, as C_L is an odd function about $\pi/2$ in the ideal far field case. The difference in magnitudes for upstroke and downstroke, normalized by the maximum observed coefficients for this motion, is shown in the lower figure.

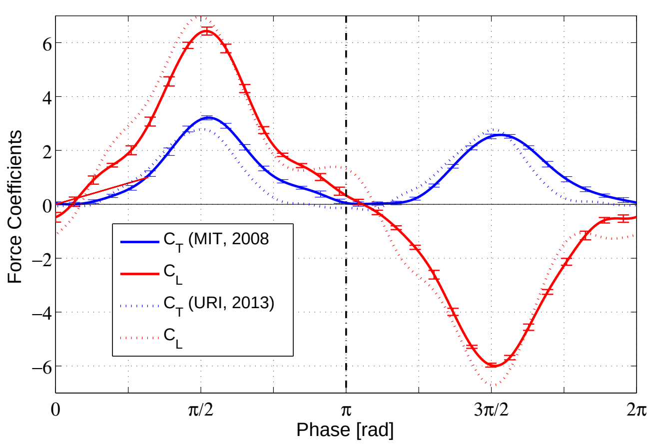

Fig. 9. Comparison of force measurement results to those of a foil with identical kinematics and similar test apparatus (Comparison data from [2]).

IV. Discussion

The results show that there is a signficant change in the lift and thrust generated by an oscillating foil operating very close to bottom when compared to the operation in open water. More importantly, asymmetries in the cycle averaged time histories for lift and thrust suggest a straighforward mechanismc for detecting the presence of ground effect through force monitoring at the foil shaft. The nearly 20% intra-cycle variation in the magnitude of the lift peak between the 'downstroke' and 'upstroke' provides a detectable signal within a single period (i.e. it does not require an excessive amount of sampling time.) This comparison between upstroke and downstroke peak magnitude has the added benefit that it does not require reference to some previously measured baseline in open water.

Future research will focus on varying kinematics (St, $\frac{h_0}{c}$, α_{max}) within the range that is known to be effective for thrust generation, as well as testing a more comprehensive set of foil mean heights ($\frac{\bar{h}}{c}$) in order to determine the distance at which ground effect becomes significant. The tank in which the experiments were performed are suitable for fluid velocity measurement using laser particle image velocimetry (PIV). PIV will be used in future experiments to determine the fluid dynamic mechanisms by which the ground effect is induced.

V. Conclusion

These preliminary results are promising, especially since the ground effect was detectable in the first set of kinematic parameters tested. Future research is needed to determine how strong the ground effect is as a function of the kinematics, By mapping out the strength and signature of the ground effect for different kinematics, we will enable near bottom foil propelled UUVs to select kinematics which appropriately balance altitude detection and stability with efficiency and speed.

By swimming near the bottom, underwater vehicles can improve navigation and reduce wave and current forcing. Characterization of changes in the instantaneous force profiles on fins as a function of altitude provides an additional sensing modality for vehicles swimming near the bottom. Next generation fin propelled vehicles will be able to use real time fin force data to estimate, and hence control, altitude while near the bottom.

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