ENERGY EXTRACTION THROUGH FLAPPING FOILS

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ABSTRACT

We demonstrate experimentally that flapping foils within an oncoming stream can efficiently extract energy from the flow, thus offering an attractive, alternative way for energy production. The greatest promise for flapping foils is to use them in unsteady and turbulent flow, where their own unsteady motion can be controlled to maximize energy extraction. The foils in this study perform a sinusoidal linear motion (sway, or heave) in combination with a sinusoidal angular motion (yaw or pitch); the effect of three principal parameters is studied systematically, yaw amplitude, the Strouhal number, and the phase angle between sway and yaw. The foils are made of aluminum, in the shape of NACA 0012 airfoils, using three different aspect ratios, 4.1, 5.9, and 7.9; they were tested at Reynolds numbers around 14,000. Efficiencies of up to 52 $\pm$ 3% are achieved with simple sinusoidal motions, thus demonstrating that foils can efficiently extract energy from unsteady flows.

INTRODUCTION

The purpose of this work is to use biomimetically designed devices, based on the performance of live fish, for ocean energy extraction; Prof. Newman has worked on related issues, modeling fish hydrodynamics (Newman 1973, 1979) and on wave energy extraction (1983ab).

As the price of oil and gas climbs to unprecedented heights, while hydrocarbon reserves are finite with a predictable expiration date, there is a pressing need for alternative energy sources, now more than ever. Renewable, climate- and planet-friendly energy sources are especially attractive, so it is natural to turn to ocean currents and waves as potential sources for our energy needs. There is potentially abundant and consistent ocean power, especially in tidal and persistent currents, but also in water waves: An average wave power density of 2-3 kW/m^2, as measured below the ocean surface and perpendicular to the wave front is quoted (Falnes 2007), sufficient to provide a portion of the world's energy demands.

Ocean energy extraction studies have included ocean thermal energy (Vega 2002; Pelc 2002), ocean wave energy (McCormick and Kraemer 2002; Muetze and Vining 2006; Falnes 2007), and ocean current energy (Bryden et al. 2005; Ullman 2002). To review previously studied systems for wave energy conversion, these may rely upon devices such as oscillating water columns, or surging, pitching, and heaving devices; or windmill-like devices, turbines with a horizontal or vertical axis, oscillating vanes, and venturi constrictions (Bryden et al. 2005).

We focus on ocean wave and current energy systems, which are based on unsteadily moving (flapping) foils. The reason for turning to flapping foils is that studies involving live fish and flapping foils have demonstrated the capability for energy extraction in unsteady and vortical flows. Given that waves and currents are characterized by unsteadiness and often turbulence, it becomes an important consideration to have energy extraction systems that can efficiently adapt to the flow conditions.

An additional reason for turning to flapping foils is biomimetic inspiration, the fact that live fish and cetaceans employ their tails and fins for energy control; in certain cases fish are known to extract energy from the flow to minimize their expended energy (Liao et al 2003, Beal et al 2006). Wu (1972) and Wu & Chwang (1974) showed theoretically that a heaving and pitching foil within an oscillatory stream, is capable of producing thrust and extracting energy passively; Isshiki & Murakami

(1984) verified this experimentally in the case of harmonic waves. Dolphins can surf in the bow waves of ships (Fejer 1960), and whales gain significant thrust benefits from swimming near surface waves, owing to the oscillating flow over the tail fluke (Bose & Lien 1990). It has been estimated that a whale could extract up to 25% of its required propulsive power in head seas and 33% of propulsive in following seas (Bose & Lien 1990). Liao et al. (2003) demonstrated that rainbow trout placed within a flow channel containing a vertically mounted cylinder synchronize their swimming frequency; an electromyographic study of their axial muscle exhibited substantial reduction in muscular activity. Kato (2000, 2003), Hover (2004), Schouveiler (2005), and Triantafyllou (2000), Colgate and Lynch (2004) have studied fish propulsion using flapping foils. The mechanics of optimal thrust production in flapping foils have been associated with the formation of vortical patterns in their wake in the form of a reverse Karman street (Triantafyllou et al. 1991).

In this experimental work we seek to determine ways to optimize direct energy extraction using a flapping foil. Of primary interest are the influence of the Strouhal number and the angle of attack; other parameters are the phase angle between the sway and yaw motions, the aspect ratio of the foil, and the ratio of the oscillation amplitude over the chord length.

EXPERIMENTAL SETUP AND METHODS

Experiments were conducted in a small tank, 2.8m long, 1m wide and 1m in height, filled with water up to the 0.6m mark. Two tracks were mounted on the sides of the tank, to tow an aluminum carriage housing the foil apparatus, load cell, and motors. The foil apparatus consisted of the foil, the yaw motor, the load cell, and a cantilevered arm, as pictured in Figure 1. The load cell was mounted to the cantilevered arm and the yaw motor was mounted between the foil and this load cell. The cantilevered arm was connected to a motor that moved in the transverse direction with maximum sway amplitude of 0.085m. Finally, a third motor controlled the tow speed of the carriage down the track. The foils used were aluminum NACA 0012 profiles. A constant chord length of 0.069m was used and the spans for the three foils were 0.283m, 0.406m, and 0.581m.

We investigated the effect of (a) the Strouhal number, which is a dimensionless number relating the dynamics of the wake with the kinematics of the foil (b) the maximum angle of attack, and (c) the aspect ratio of the foil. Strouhal numbers were varied from 0.2 to 0.6 in increments of 0.1; the maximum angle of attack was varied from 11 to 57 degrees; the aspect ratios tested were 4.1, 5.9, and 7.9. The phase difference between the sway and yaw motion was fixed at 90 degrees. Additionally the sway amplitude to chord length ratio was fixed for all experiments at 1.23. For each set of parameters, two repeat runs were conducted and the results were compared for consistency. Noise from the yaw motor was removed using an acrylic plate mounted between the force sensor and the yaw motor to dampen vibrations.

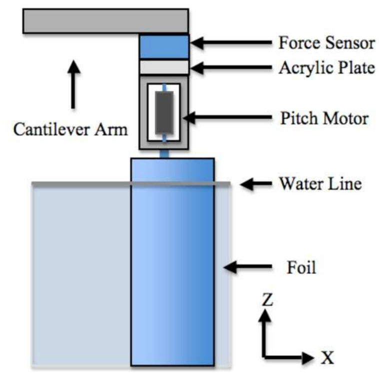

Figure 1 - Apparatus Setup: Cantilevered arm with six-axis load cell mounted. Acrylic plate placed between yaw motor and force sensor for noise and vibration dampening.

Force and moment measurements were obtained using a JR3 model 20E12A-125 six-axis load transducer, capable of measuring up to 110 N in each force axis and 5 N-m in each moment axis. The forces consist of the drag force, the lift force, their respective moments, and the twist moment of the foil. Force calibrations had an average error of 0.35% and moment calibrations had an average error of 1.8%.

FOIL KINEMATICS AND PERFORMANCE MEASURES

The motion of the foil consists of three components: yaw, sway, and surge. The yaw and sway motions were chosen to be sinusoidal with a fixed relative phase angle of 90 degrees. Equation 1 describes the sway motion as a function of time, *t*, where h_0 is the sway amplitude in meters, ω is the frequency in rad/s. Equation 2 describes the yaw motion as a function of time where θ_0 is the yaw amplitude in meters and ψ is the phase angle between yaw and sway in radians. Equation 3 describes the inline motion where *U* is the inline (tow) speed; in this set of experiments we did not oscillate the foil in the surge direction, although the apparatus allows this degree of freedom.

$$h(t) = h_0 \sin(\omega t) \qquad (1)$$

$$\theta(t) = \theta_0 \sin(\omega t + \psi) \qquad (2)$$

$$U(t) = U \tag{3}$$

Using these three equations it is possible to determine the nominal angle of attack (Read 2000), expressed as:

$$\alpha(t) = \left\{ \arctan\left(\frac{h_0 \omega \cos(\omega t)}{U} \right) - \theta_0 \sin(\omega t + \psi) \right\} \tag{4}$$

It should be noted that here we study energy extraction, which is associated with generation of drag; as a result, the angle of attack is negative, unlike the case of thrust-producing foils.

The Strouhal number is given as follows, where *f* is the frequency in Hz:

$$St = \frac{2h_0 f}{U} \tag{5}$$

The maximum angle of attack is found numerically and is is a function of the Strouhal number and the yaw amplitude. An example of the foil's path and yaw motion is depicted in Figure 2 for an energy extraction case which also produces drag. It is possible to see the orientation of the foil, which points downwards relative to the oncoming flow for the entire cycle. The corresponding angle of attack plot for this motion can also be seen in Figure 2. Note that the resulting angle of attack plot is not purely sinusoidal. Hover et al (2004) have shown that introducing high harmonics in the motion such that the angle of attack becomes purely harmonic improves efficiency; this is currently under investigation.

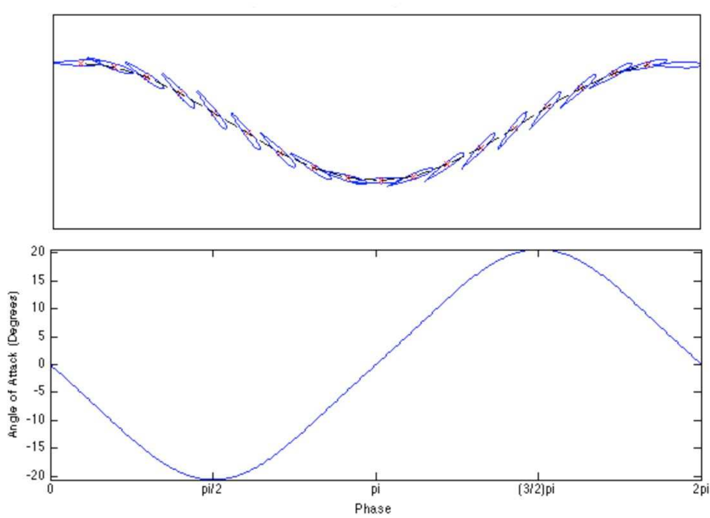

Figure 2 - Example foil movement and AOA plot (St 0.3, Max AOA -20.6 deg)

The power extracted from the flow, P_e, can be calculated from the kinematics and the measured forces. The largest component of extracted energy comes from the lift force of the foil, while a very small component is contributed by the moment. This provides a very effective way to control foils for optimal energy extraction since the yaw motion requires very little energy while it affects the angle of attack, and hence the lift force substantially.

The extracted power is defined as the average energy over a cycle, calculated as the integral of the lift force times the sway velocity plus the moment times the angular velocity. To evaluate the efficiency of the system we have to define the flow power input. The power available from a flow is:

$$P = \frac{1}{2} \rho U^3 A \tag{6}$$

where ρ is the density of the fluid, U is the free stream velocity, and A is the area swept by the foil normal to the oncoming flow, $A = 2cs$ (13), where c is the chord length and s is the span length. We can now write the efficiency as the ratio of power output to power input as

$$h = P_e/P \tag{7}$$

Finally, we determine the drag coefficient:

$$C_D = \frac{F_H}{\frac{1}{2} \rho U^2 cs} \tag{8}$$

RESULTS

Three different aspect ratios were investigated, 4.1, 5.9 and 7.1. In flapping foils it is well known that the induced velocities from the tip vortices are significantly lower than in steadily moving foils, because as the shed vortices alternate, the tip vortices (which form part of shed vortex rings, or rather loops) alternate in sign as well. As a result, the effect of the aspect ratio is much milder in flapping foils.

From figures 3, 4, and 5 we find that the maximum measured efficiency is 52 ± 3%, obtained with a foil of aspect ratio 7.9 at a Strouhal number of 0.5 and a maximum angle of attack of -25.2 degrees. For aspect ratios of 5.9 and 4.1, maximum efficiencies of 48 ± 3% and 43 ± 3% were measured, respectively; both occurred at Strouhal numbers of 0.5 and maximum angles of attack of -29.8 degrees. It is significant to note that the areas of large efficiency are quite large, establishing the robustness of energy extraction even in the presence of unsteadiness in the flow.

The highest efficiencies were observed at angles of attack between -20 and -30 degrees, and for high Strouhal numbers, for all aspect ratios tested. Efficiencies were mostly positive (energy extraction) over the parametric range tested; very high Strouhal numbers combined with high angles of attack often result in negative efficiency (energy from the foil to the flow). Efficiency does depend on the aspect ratio, but much more mildly than on other parameters, as also explained previously. A three-dimensional plot of the efficiency as function of the three parameters used in the experiments is provided in figure 6, where it is clearly seen that efficiency is gradually improving as the aspect ratio increases.

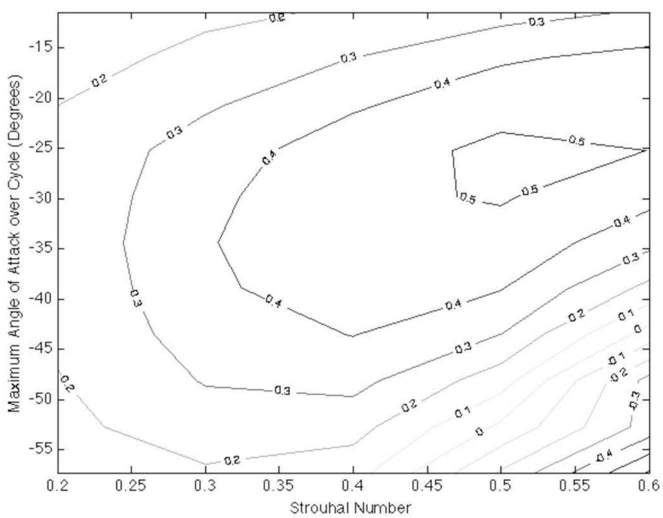

Figure 3 - Efficiency for Aspect Ratio 7.9

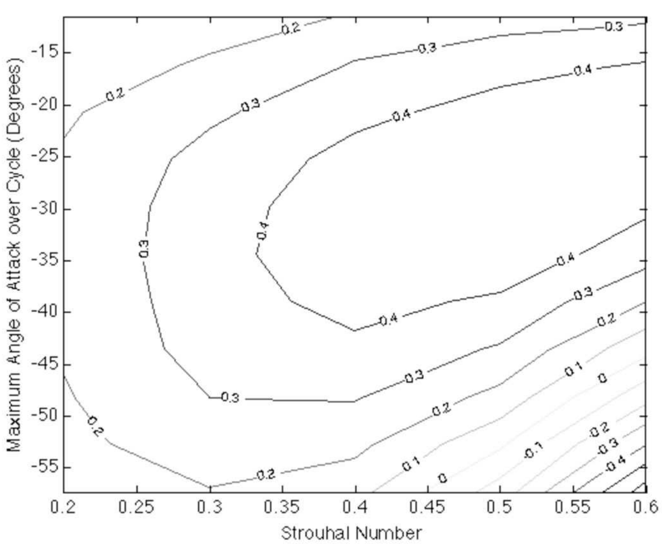

Figure 4 - Efficiency Contours for Aspect Ratio 5.9

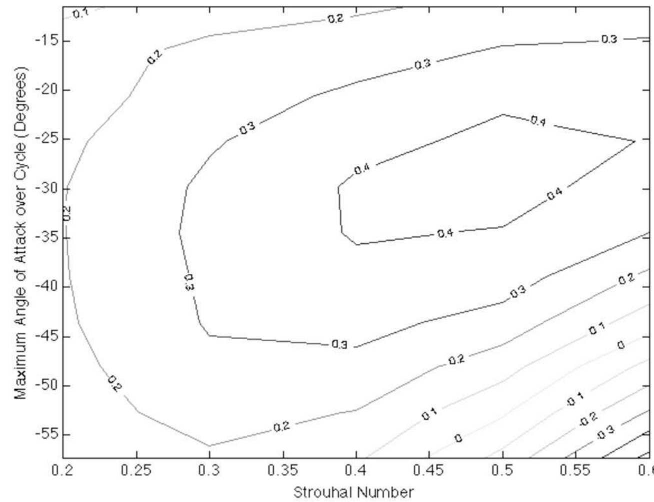

Figure 5 - Efficiency Contours for Aspect Ratio 4.1

Phasing plays an important role in extracting as much power as possible from the flow. As seen in Figure 7, the high efficiency run has similar signs for the transverse velocity and lift force for the majority of an entire cycle indicating that power is extracted. For the low efficiency run in Figure 8 we note opposing signs between the transverse velocity and the lift force and significantly higher harmonics in the lift force for the majority of the cycle indicating that minimal or no power is being extracted by the system. These high Strouhal and angle of attack runs experienced stall which resulted in large lift fluctuations and negatively impacted the power extraction.

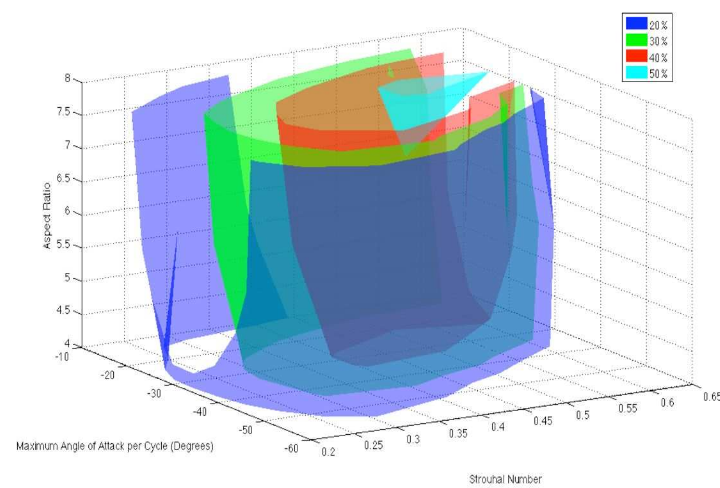

Figure 6 – Efficiency Contours vs. Aspect Ratios. This plot shows a clear decrease in the size of efficiency contours as aspect ratio decreases, most notable in the 50% efficiency region which is only present in the high aspect ratio foil.

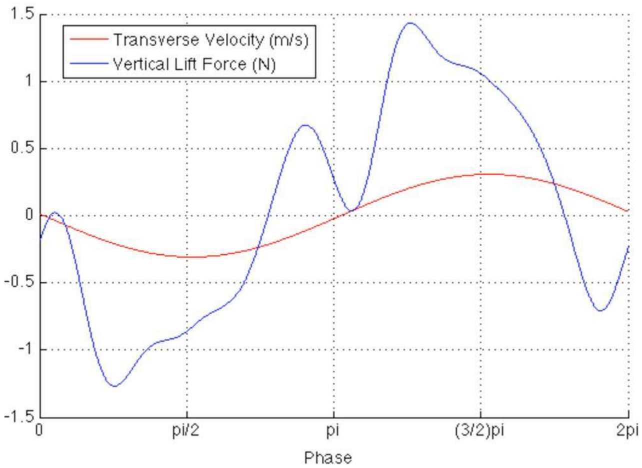

Figure 7 - Phasing of Lift and Transverse Velocity for High Efficiency (St 0.5, Max AOA -25.2 deg)

The power associated with the yaw motion is parameter dependent. In certain cases, for both high Strouhal numbers and high angles of attack, the power required to yaw the foil was large. For smaller angles of attack, however, the yaw power required was minimal relative to the power from the transverse forcing. This is a very important consideration for control, because over the range of useful energy extraction the moment is very small, allowing very effective control of the angle of attack and the forces produced by the foil

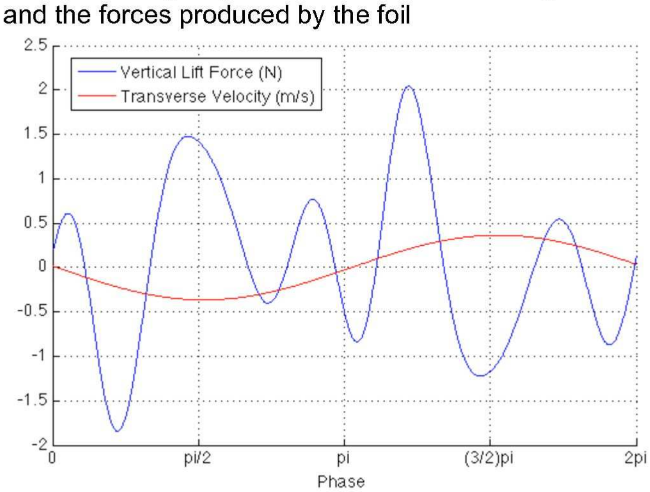

Figure 8 - Phasing of Lift and Transverse Velocity for Low Efficiency (St 0.6, Max AOA -48.1 deg)

For example, the ratio of the maximum yaw power required over one cycle compared to the mean power generated, has a value of around 4.6% for a maximum angle of attack between 11 and 16 degrees; while it reached a value of 19.3% for a maximum angle of attack between 52 and 57 degrees.

Another important performance parameter considered is the drag force. The foil with aspect ratio 7.9 had a coefficient of drag of 2.5 at the maximum efficiency point; for the foil with aspect ratio 5.9 the coefficient of drag is 2.7; finally, for the smallest aspect ratio foil of 4.1 the coefficient of drag is 2.4. Figure 9 is a nomograph showing the dependence of the efficiency and the drag coefficient for various parametric combinations.

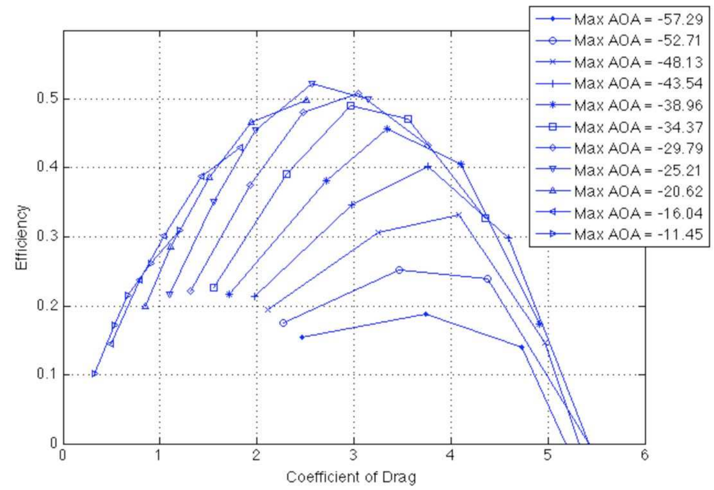

Figure 9 - Relation between Coefficient of Drag and Positive Efficiencies for Aspect Ratio 7.9

From similar graphs for other aspect ratios, we conclude that the coefficient of drag corresponding to the maximum efficiency is almost constant as function of the aspect ratio. It is interesting that relatively small sacrifices in efficiency can result in decreases in the drag coefficient. For example, the coefficient of drag can be reduced from 2.5 to 2.0 while still achieving an efficiency of 47% with the aspect ratio of 7.9.

DISCUSSION OF OPERATION IN UNSTEADY FLOW

Although the tests reported here are for foils tested in steady flow, this is only the beginning of the investigation. In fact, as the evidence from fish and cetaceans shows, animals use energy extraction in unsteady flows very effectively (Bose & Lien 1990, Liao et al 2003). In the case of water waves the theoretical work by Wu (1972) can be used for guidance; for vortical or even turbulent flows there is experimental evidence (Liao et al 2003, Beal et al 2006) that substantial energy extraction is also possible. In both cases it is essential to control the parameters of the foil in response to the unsteady flow; this requires effective flow sensing as well as appropriate control algorithms.

The lateral line of fish is an ideal sensor for flow features that affect foil performance as evidenced by the fish function (Sutterlin et al 1975) and by work at MIT to implement such as sensor consisting of hundreds of MEMS-based mm-size micro pressure transducers (Fernandez et al 2007).

The control action is primarily to adjust the angle of attack through control of the yaw motion. The results herein are important in two aspects: It is established that the power required to effect yaw motion is very small; and the good performance of the foil holds for wide ranges of the parameters involved. As a result, we can conclude that flapping foils are a very promising means for energy extraction from ocean currents and waves.

CONCLUSIONS

Efficient flow energy extraction is demonstrated using flapping foils. The foils used were aluminum NACA 0012 airfoils. Three major parameters, the Strouhal number, the maximum angle of attack, and the aspect ratio were varied, while the phase angle between sway and yaw motion, the flow speed, and the sway amplitude were fixed. Efficiencies up to 52 $\pm$ 3% were noted for a foil with aspect ratio of 7.9, Strouhal number of 0.5, and a maximum angle of attack of -25.2 degrees; with a fixed phase difference of 90 degrees between sway and yaw motions, a flow speed of 0.2 m/s, and a sway amplitude of 0.085m. The maximum efficiency is close to Betz's limit of 57%. Windmills approach this level of performance with very high aspect ratio foils, so it is notable that we measured efficiencies close to this value using significantly smaller aspect ratio foils.

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