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Hydrodynamic advantages of a low aspect-ratio flapping foil

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ABSTRACT

A high aspect-ratio foil is known to be advantageous in terms of both thrust and efficiency in flapping propulsion. However, many species of fish have evolved a low aspect-ratio hydrofoil, which naturally leads one to search for its physical advantages in locomotion. Here we study the flow physics of a hydrofoil in angular reciprocating motion with negligible free-stream velocity to reveal the effects of an aspect ratio on hydrodynamic performance. By establishing a scaling law for the thrust of a foil of general shapes and corroborating it experimentally, we find that the thrust of an angularly reciprocating foil is maximized at a low aspect ratio of 0.7 while hydromechanical efficiency continuously increases with an aspect ratio. This result suggests that a low aspect-ratio foil can improve thrust produced by the foil when they start from rest, but at the expense of efficiency.

1. Introduction

Most of swimming and flying animals flap their fins or wings to propel through a surrounding fluid. The topics of flapping locomotion that have been addressed thus far include measuring the precise kinematics of animals (Fish and Lauder, 2006; Shelton et al., 2006), analyzing the flow structure and forces of a flapping foil (von Ellenrieder et al., 2003; Dong et al., 2006; Buchholz and Smits, 2008; Green and Smits, 2008; Kim and Gharib, 2013) and examining the role of an aspect ratio and flexibility of fish-like locomotion (Dewey et al., 2013; Raspa et al., 2014; Feilch and Lauder, 2015; Quinn et al., 2015; Yeh and Alexeev, 2016). One of the important issues in the mechanics of flapping propulsion is the effect of an aspect ratio of the foil. Early studies have proposed that a high aspect-ratio foil is advantageous in terms of both thrust coefficient and hydromechanical efficiency (Chopra, 1974; Chopra and Kambe, 1977; Cheng and Murillo, 1984; Karpouzian et al., 1990; Dong et al., 2006; Buchholz and Smits, 2008; Green and Smits, 2008; Dewey et al., 2013).

However, many biological studies revealed clear distinction of the caudal fin aspect ratio between migratory and non-migratory fish (Nursall, 1958; Webb, 1984; Domenici and Blake, 1997; Flammang and Lauder, 2009; Domenici and Kapoor, 2010). The data on the aspect ratio are summarized in Fig. 1. The highly migratory fish, which are expected to give priority to efficiency improvement in cruising, have a high aspect-ratio caudal fin as shown in Fig. 1a. On the other hand, non-migratory fish generally have a smaller aspect ratio than migratory fish. The comparison in normalized coordinates in Fig. 1c,d clearly shows the stark difference of the caudal fin shape between migratory and non-migratory fish. We further compared the distribution of the caudal fin aspect ratio of highly migratory and non-migratory marine fish in Fig. 1e (refer

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Table 1
Experimental parameters.

h	Height	1.5–22.5 cm
w	Width	1.2–20 cm
Λ	Sweepback angle	0–53 deg
l_s	Side length	0–20 cm
$2\theta_m$	Stroke angle	35 deg
f	Frequency	0.1–2.5 Hz
R	Radius of rotation	13.2–32 cm
S	Surface area	24–96 cm^2

to Supplementary Material for the definition of an aspect ratio and the data of the aspect ratio of aquatic animals). In general, the former group has a caudal fin of a high aspect ratio, whereas the latter has a caudal fin of a much smaller aspect ratio.

The comparative studies on the fish caudal fins of diverse species found that a high aspect ratio is advantageous for efficiency improvement in cruising while a low aspect ratio is advantageous for thrust maximization in sprinting (Nursall, 1958; Webb, 1984; Domenici and Blake, 1997; Flammang and Lauder, 2009; Domenici and Kapoor, 2010), which is inconsistent with the conventional hydrodynamic argument that a high aspect ratio is advantageous in terms of both thrust and efficiency (Chopra, 1974; Chopra and Kambe, 1977; Cheng and Murillo, 1984; Karpouzian et al., 1990; Dong et al., 2006; Buchholz and Smits, 2008; Green and Smits, 2008; Dewey et al., 2013). Such controversy has not been treated or resolved by fluid-dynamic theory thus far. In this study, we investigate physical mechanisms underlying the advantages of a low aspect-ratio foil and resolve the inconsistent views on the role of an aspect ratio on thrust and efficiency.

In this study, we investigate the hydrodynamics of a flapping foil without steady forward motion as an elementary model of the situation where the caudal fin is used to propel from rest and especially focus on the effects of an aspect ratio on thrust and efficiency. Despite extensive fluid dynamic studies on flapping locomotion, most of them have considered heaving and/or pitching of a foil in steady forward motion or against incoming freestream. The hydrodynamics of a flapping foil without steady forward motion has drawn relatively less scientific interest. The vortex formation around a flapping foil that rotates from rest without forward motion has been investigated recently (Ahlborn et al., 1997; Kim and Gharib, 2011; DeVoria and Ringuette, 2012). The theoretical model for the thrust of an angularly reciprocating rectangular plate has been suggested based on flow visualization (Lee et al., 2013). However, the effect of an aspect ratio on thrust and efficiency in such a motion has not been addressed by the previous studies.

2. Experimental apparatus

An angularly reciprocating foil as an elementary model of a flapping foil at the start of locomotion is shown in Fig. 2. The foil was immersed in a transparent water tank of 75, 55, and 33 cm in the x-, y- and z-directions, respectively. The foil is in a single degree-of-freedom sinusoidal oscillation about the z-axis, and the rotating axis is fixed in space. We employed rectangular, trapezoidal and cropped delta foils of various dimensions; the ranges of design dimensions are height $h = [1.5\ 22.5]$ cm, width $w = [1.2\ 20]$ cm, sweepback angle of quarter-chord line $\Lambda = [0\ 53]$ deg, and side length $l_s = [0\ 20]$ cm. The foil shape used in this study roughly mimics a caudal fin. The foil is attached to a metallic rod of length $l = 12$ cm which oscillates about the z-axis. The radius of rotation of the foil tip is $R = [13.2\ 32]$ cm. While a rotating axis is on the chord of a foil in usual pitching and/or heaving models, in our model, a rotating axis is outside the chord of a foil. The stroke angle of the sinusoidal rotation $2\theta_m$ is fixed to 35°. The flapping frequency f ranges from 0.1 to 2.5 Hz. The experimental parameters are summarized in Table 1. The Reynolds number Re is defined as $Re = Uw/\nu$ where U and ν are characteristic velocity and kinematic viscosity, respectively. In our experiments, the Reynolds number Re, based on the period-averaged speed at 0.7 radius length $U = 4(0.7R)\theta_m f$ (Techet, 2008), ranges from 1.3×10^3 to 1.1×10^5. The other dimensionless parameters are varied such that the aspect ratio $A = h^2/S = [0.075\ 17]$ where S is a surface area, the normalized stroke amplitude $\beta = 2R\theta_m/w = [0.9\ 6.7]$, the height-to-width ratio $\eta = h/w = [0.075\ 17]$, and the taper ratio $\lambda = l_s/w = [0\ 1]$.

The velocity and vorticity fields were obtained from two-dimensional Digital Particle Image Velocimetry (DPIV) using hydrogen bubbles as seeding particles. The hydrogen bubbles are generated by the electrolysis of water using a platinum wire of 50 − m. The electrical power applied to the platinum wire is controlled by a power supply (Kenex HV-401) to maintain the size of hydrogen bubbles similar to the diameter of the platinum wire. To visualize the bubbles, the central plane perpendicular to the flapping tail was illuminated using a 2 W continuous laser with a 532 nm wavelength. The captured images were analyzed using DPIV software to generate velocity fields with an interrogation window size of 32 × 32 pixels with a 50% overlap. The processed velocity vectors were validated using a dynamic mean value operator. The number of error vectors was within 2% of the total number of velocity vectors. The thrust generated by the foil in the y-axis was also measured by a miniature load cell (Kyoto 333FB) at a sampling rate of 2 kHz. The capacity of a load cell is 4.9 N, and the precision is 0.1%, corresponding to the accuracy of about 0.005 N.