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# Effect of mass ratio on thrust production of an elastic panel pitching or heaving near resonance

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ABSTRACT

Flapping wings of aerial insects and undulating fins of fish typically experience significant elastic chordwise deformations, and such deformations have been shown in previous studies to be beneficial on force production and/or power efficiency for both types of animal locomotion. However, it is still not conclusive whether the resonant vibration plays a common role in these problems. For fish fins, passive deformations are predominantly due to the hydrodynamic force of the surrounding fluid, while for insect wings, the wing inertia becomes also important in driving the surface deformation in addition to the aerodynamic force. In the current study, we use a two-dimensional elastic panel pitching or heaving in a free stream as a model to represent the animal wings or fins. Bending rigidity of the panel and the flapping frequency are varied so that the panel flaps near or away from resonance of the coupled fluid–structure system. The results show that at low mass ratios where the fluid force is dominant over the panel inertia, or at intermediate mass ratios where the fluid force is comparable with the panel inertia, the system resonance significantly improves or maximizes the thrust force and also efficiency; in addition, thrust performance is improved around resonance for a wide range of flapping frequencies or Strouhal numbers. On the other hand, at high mass ratios where the panel inertia is dominant, the system resonance makes thrust production increasingly difficult and propulsion much less efficient. In conclusion, the role of resonant vibration in thrust production of flapping wings and fins depends on participation of the fluid inertia in the process.



## 1. Introduction

Fluid–structure interaction of flexible wings of aerial insects and flexible fins of fish is essential for understanding the force production in flying or swimming locomotion of those animals. In both types of locomotion, significant chordwise bending along the line from the leading edge to the trailing edge is experienced by the elastic structure of the wings or fins. Such deformation is usually passive for insect wings (Combes and Daniel, 2003), while active modulation can also be involved for fish fins through muscle activities to modify the curvature of the fin ray and control the shape of the fin surface (Standen and Lauder, 2005). In the past, quite a few studies have shown that the passive chordwise deformation is generally beneficial for propulsion by enhancing force production and/or increasing power efficiency (Heathcote and Gursul, 2007; Zhu, 2007; Vanella et al., 2009; Eldredge et al., 2010; Yin and Luo, 2010; Dai et al., 2012), and that such benefit can be achieved both in air, where the structural inertia is significant (Yin and Luo, 2010), and in water, where the structural inertia is small or negligible (Heathcote and Gursul, 2007; Zhu, 2007; Dai et al., 2012). One question to ask in these fluid–structure interaction problems

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of elastic propulsors concerns the role that the resonant vibration plays in the propulsion. Several previous studies have specifically focused on the effect of resonant vibration in the context of fish swimming. For example, using an inviscid flow model of a flexible heaving panel, Michelin and Llewellyn Smith (2009) have shown that both thrust and power could peak at the system resonance, and that meanwhile the thrust efficiency is largely improved although the maximum efficiency does not necessarily happen at resonant vibration. Studying an oscillating flexible thin foil swimming freely in water, Alben et al. (2012) observed resonant-like peaks in the swimming speed that depends on the foil length and rigidity, and they found that the foil deformation agreed with the prediction of their inviscid flow model. Moored et al. (2012) performed a linear stability analysis of the time-averaged wake behind an actively flexible fin. They found that when the driving frequency of the fin matches the most unstable eigenmode of the wake, i.e., the hydrodynamic resonant frequency, the optimal propulsive efficiency is achieved. A similar result was obtained through a numerical study of Zhu et al. (2014a). In a water channel experiment, Dewey et al. (2013) found that a passively flexible panel had peak performance near the system resonance in terms of both thrust and efficiency and that thrust, power, and efficiency all scale reasonably well when normalized using the elastic force.

For flying insects and their wing–air interaction, some previous studies also shed light into optimal rigidity and benefits of chordwise deformation. For example, Vanella et al. (2009) used a two-link model in hovering motion to show that the wing has the best lift and lift-to-drag ratio when the flapping frequency is one third of the natural frequency of the wing determined in vacuum. A similar result was obtained by Yin and Luo (2010) using a continuum wing model in hovering configuration, and furthermore, in that study the authors found that the mass ratio (i.e., the ratio of the structural inertia to the fluid inertia) of the wing may have a significant effect on the lift efficiency. The overall conclusions in these modeling studies are qualitatively consistent with an experimental study of a self-propelled flapping wing apparatus designed by Ramananarivo et al. (2011), where the optimal flapping frequency in air is much lower than the natural frequency. These studies suggest that resonant deformation of the wing surface may not be the best choice for the insects. A similar conclusion was obtained by Zhu et al. (2014b), where the authors studied efficiency of an elastic plunging foil self-propelling in a fluid. By further examining the wake structure, the same authors (Zhu et al., 2014b, c) found that moderate flexibility that leads to efficient propulsion also helps preserve the wake symmetry, while excessive flexibility close to structural resonance can trigger symmetry-breaking. Related discussions on the effects of the mass ratio and structural resonance can also be found in a few other studies (Olivier and Dumas, 2016a, b).

Having discussed these relevant studies, we point out that it is still not clear how the role of resonant deformation may change when the inertia of the structure is systematically varied with respect to the fluid inertia. An interpretation by combining aforementioned previous studies is difficult since the parameter regimes in these studies are quite different; in addition, both the resonant frequency of the structure–fluid system and natural frequency of the structure alone have been used to describe resonance, which makes a direct comparison not straightforward.

In this paper, we will use a two-dimensional elastic panel with a variable mass ratio to model the wing/fin structure. Both pitching and heaving motions of the panel in a free stream will be considered to represent characteristic kinematics in both swimming and flying. We systematically vary the driving frequency of the panel so that it will cover the first resonant vibration mode of the structure–fluid system. The effect of the system resonance on thrust production, power consumption, and thrust efficiency will be investigated along with the panel deformation and flow field.

## 2. Problem formulation

As shown in Fig. 1, we consider an elastic thin panel that either rotates around its leading edge or whose leading edge heaves harmonically in a uniform free stream of velocity $U$. The time-dependent pitch angle is described as $\alpha(t) = \alpha_m \sin(2\pi f_0 t)$, where $f_0$ is the oscillating frequency and $\alpha_m$ is the pitch amplitude. For heaving motion, the transverse position of the leading edge is described as $y(t) = y_m \cos(2\pi f_0 t)$, where $y_m$ is the heaving amplitude. The homogeneous and isotropic panel has length $L$, density $\rho_s$, thickness $h$, Young's modulus $E$, and Poisson's ratio $\nu_s$. The panel is assumed to be nearly inextensible but may bend elastically under the fluid force and/or its own inertia. The mechanics of the panel is governed by a nonlinear equation described previously (Yin and Luo, 2010; Tian et al., 2013). In the equation, the bending moment is linearly related to the curvature of the panel, but the geometric nonlinearity is incorporated to account for large displacement of the panel.

The fluid density and viscosity are $\rho$ and $\nu$, respectively, and the flow is governed by the viscous incompressible Navier–Stokes equation and the continuity equation. The nondimensional parameters governing the problems are the pitching or heaving amplitude, $\alpha_m$ or $y_m/L$, the reduced frequency, $\omega = 2\pi f_0 L/U$ or $f = \omega/(2\pi)$, the Reynolds number, $Re = UL/\nu$, the mass ratio, $m^* = \rho_s h/(\rho L)$, and the reduced stiffness, $K = EI/(\rho U^2 L^3)$, where $I = h^3/12$ is the area moment of inertia of the cross section. To evaluate the performance of propulsion, we define the thrust coefficient $C_T$ and power coefficient $C_P$ as

$$C_T = -\frac{F_x}{\frac{1}{2}\rho U^2 L}, \qquad C_P = \frac{P}{\frac{1}{2}\rho U^3 L}, \tag{1}$$

where $F_x$ is the total hydrodynamic force on the panel in the $x$-direction, and $P$ is the total power output to the fluid and is calculated with $P = -\int \mathbf{f} \cdot \mathbf{v} \mathrm{d}S$, where $\mathbf{f}$ is the hydrodynamic traction and $\mathbf{v}$ is the velocity of a point on the panel. The