Engineering Analysis with Boundary Elements 95 (2018) 69–84

Contents lists available at ScienceDirect

Engineering Analysis with Boundary Elements

journal homepage: www.elsevier.com/locate/enganabound

A vortex-based method for improved flexible flapping-foil thruster performance

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ARTICLE INFO

Keywords:
Flapping-foil
Biomimetic thruster
Flexibility effects
Vortex-based method

ABSTRACT

A vortex-based method is presented for the hydroelastic analysis of a hydrofoil in flapping motion, operating as a biomimetic thruster. The system performs combined heaving and pitching motion with appropriate phase difference. As a first approximation, the foil is assumed to be very thin permitting to neglect thickness effects as higher-order contributions to the hydrodynamics. Moreover, the flapping thruster is considered to be flexible, free to deform under inertia and reactive forces caused by its forced motion and hydrodynamic pressure, respectively. The proposed method is validated through a series of comparisons with other models, as well as experimental results, for the case where the foil is clamped at its leading edge, while its trailing edge acts as a free end. It is illustrated that chordwise flexibility can significantly improve the propulsive efficiency. For demonstration purposes, a realistic propulsion problem concerning an autonomous underwater vehicle (AUV) is studied, indicating an efficiency increase almost 10% in comparison with the rigid case. The present method can serve as a useful tool for the preliminary design, as well as for the assessment and dynamic control of such biomimetic systems for marine propulsion and energy recovery.

1. Introduction

Biomimetic flapping-foil thrusters are able to operate efficiently while offering the desirable levels of thrust forces for a marine vehicle or a small vessel, see, e.g., Triantafyllou et al. [40], Rozhdestvensky & Ryzhov [35], Taylor et al. [38]. Extended review of hydrodynamic scaling laws in aquatic locomotion and fishlike swimming is available in Triantafyllou et al. [39]. Flapping-foil configurations have been investigated both as main propulsion devices and for augmenting ship propulsion in waves; see, e.g., Belibassakis & Politis [6], Filippas & Belibassakis [14], Belibassakis & Filippas [8], Xu et al. [44] and the references cited there. Apart from propulsion applications, flapping foil systems have also been examined for the development of marine renewable energy devices; see, e.g., Xiao & Zhu [43], Jeanmonod & Olivier [18], Filippas et al. [15].

An important additional component of fish-swimming mechanisms is the flexural ability of their tails. Various methods have been developed for the treatment of the coupled hydroelastic problem of a flexible foil in unsteady flow. In this direction, the analysis of a foil with prescribed chordwise deformation has been presented by Wu [42]. Katz & Weihs [21] studied the coupled hydroelastic problem for slender unsteady propulsors for large motion amplitudes with small angles of attack, in the context of inviscid flow. Their results suggested that the propulsor's efficiency is increased with increasing flexibility, although the thrust coefficient is decreased. Yamaguchi & Bose [46] applied a vortex lattice method with nonlinear corrections to account for viscous and 3D effects for a flexible flapping foil. The open water efficiency of rigid flapping wing propulsor was found up to 25% higher than that of a conventional screw propeller, however, in operating conditions at the stern of the ship, it becomes similar to the screw propeller. Adding flexibility to the flapping foil thruster, its efficiency in the ship wake could become 5% greater than the conventional propeller.

The efforts to tackle the coupled hydroelastic problem have substantially increased in recent years. Alben [2] proposed a hydrodynamic model coupled with a linear elastic sheet formulation for a foil pitching about its pivot axis located at the leading edge. Peaks in thrust and efficiency were reported, corresponding to specific rigidity parameters. Moreover, De Sousa & Allen [12] used a coupled fluid–structure solver for an elastic membrane in pitching motion, and concluded that flexibility increases the efficiency of a pitching wing. Also, they found that increasing the foil's structural mass further improves the efficiency. Barranyk et al. [5] performed experiments with flat plates in flapping motion of varying stiffness and reported that increasing flexibility increased both thrust and efficiency in the parameter range tested. Furthermore, [30] performed experiments with chordwise flexible flapping foils in towing tanks. Propulsive efficiencies as high as 87%, up to 36% higher than those of rigid foils were recorded. Kancharala & Philen [19] explored chordwise varying stiffness profiles, motivated by fish tails, and

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https://doi.org/10.1016/j.enganabound.2018.06.016
Received 26 February 2018; Received in revised form 6 June 2018; Accepted 27 June 2018

found that when stiffness is decreased towards the trailing edge the resulting force vector is better aligned with the motion direction, leading to higher thrust production. Moreover, Paraz et al. [28] studied the flexibility of heaving flat plates both experimentally and theoretically. They reported that thrust displays peaks in motion frequency values coinciding with the resonance frequencies of the system, comprising of the foil and the surrounding fluid.

In the present work a vortex-based method is developed for the hydroelastic analysis of a thin foil in flapping motion operating as a biomimetic thruster. The system is subjected to combined oscillatory heaving and pitching motions with appropriate phase difference. As a first approximation the foil-thickness effects are neglected as higher-order contributions to the hydrodynamic part of the problem. The flapping thruster is considered to be flexible, in whole or in part, and is free to deform under inertia and reactive forces caused by its forced motion and hydrodynamic pressure. A numerical model based on vortex singularities representing the lifting surface, in conjunction with Kirchhoff plate theory, is applied to the solution of the lifting flow problem including the effects of elastic deformation. The foil is considered clamped at its leading edge, while its trailing edge acts as a free end. Numerical results are shown and compared against other models and experimental data, validating the present method and illustrating that chordwise flexibility can significantly improve the propulsive efficiency of the biomimetic thruster.

The structure of the paper is as follows: In Section 2 the formulation of the hydrodynamic problem is presented and subsequently, details concerning the developed discrete vortex-based method are provided in Section 3. The extension of the model to incorporate the effects of hydroelasticity is discussed in Section 4, including the effects of nonlinearity, inertial forces and damping. Numerical results and validation of the method are presented in Section 5, first concerning the calculated performance of the system as a rigid flapping–foil propulsor against available experimental data. Subsequently, results for the same system with flexibility effects are shown and comparisons with other methods and measured data are displayed. The effects of material parameters on the biomimetic thruster performance are illustrated in Section 6, indicating that the performance of the system can be significantly improved. Moreover, a realistic propulsion problem of an autonomous underwater vehicle (AUV) is investigated. Finally, conclusions and directions for future research are provided.

2. Formulation of the hydrodynamic problem

The rigid body kinematics of a flapping foil are described by the following equations:

$$h(t) = h_0 \sin(\omega t),\ \ \theta(t) = \theta_0 \sin(\omega t + \psi), \tag{1}$$

where h_0, θ_0 are the heaving and pitching motion amplitudes, respectively. The phase difference ψ is customarily equal to 90^o, although it has been demonstrated both experimentally and numerically that other values lead to enhanced propulsive characteristics. As a general rule, the phase difference lies in the $(75^o, 105^o)$ range; see, e.g., Anderson et al. [3], Schouveiler et al. [36]. This combination leads to a "smooth" foil motion, where the leading edge faces upwards during the upstroke and downwards during the downstroke. The result is a lifting force vector that has a component aligned with the forward motion direction, hence producing thrust.

The following non-dimensional parameters are the most-important for describing the flapping hydrodynamics (see, e.g., [3,45]): (i) the Strouhal number $St = fA/U$, where f is the flapping motion frequency, A is the nominal trailing edge amplitude (taken as $A = 2h_0$) and U is the free-stream velocity, (ii) the non-dimensional heaving amplitude h_0/c where c is the foil's chord length, (iii) the pitching motion amplitude θ_0 or, alternatively, the effective angle of attack $\alpha_{eff} = tan^{-1}(\pi St) - \theta_0$, as derived from simple geometric arguments, (iv) the chordwise position of the pivot point x_R (expressed in terms of the chordlength) around which the foil performs its pitching motion. The hydrofoil is considered to be clamped to the motor-axis driving its rotation at the pivot point. In this work we consider $x_R = 0$, corresponding to the foil clamped at the leading edge, in order to present comparisons with experimental data available in the literature, as e.g., Barranyk et al. [5], Paraz et al. [27], Fernandez-Prats [13]. However the present method can be easily extended to treat an arbitrary position of the pivot point.

In addition to the above, in this work the chordwise flexibility effects on flapping-foil thrusters are studied and exploited for thrust augmentation. We therefore identify two additional important parameters affecting the flapping foil propulsive characteristics; i) the structural mass and ii) the flexural rigidity distribution of the foil from a structural mechanics point of view. The corresponding coefficients will be introduced and included into the set of parameters essentially describing the flapping-foil thruster capabilities and their effects will be systematically studied and assessed. The chordwise flexible flapping foil is treated as an infinite span wing with negligible thickness, thus rendering the 2D thin hydrofoil theory applicable. The foil has a chord length equal to c; see Fig. 1. It travels along the x-axis with constant velocity $-\mathbf{V}_\infty$ (where $-\mathbf{V}_\infty$ is the corresponding parallel stream flow observed from the moving system) and performs an unsteady motion along the y-axis (heaving) and around the z-axis (pitching). Also, due to fluid-structure interactions the foil may deform. The flow is assumed irrotational and incompressible, so a scalar field $\Phi(x, y;\ t)$ can be defined such that the total fluid velocity is given by $\mathbf{u} = \nabla\Phi + \mathbf{V}_\infty$, where the corresponding potential Φ satisfies Laplace's equation

$$\nabla^2\Phi = 0, \tag{2}$$

in the fluid domain D. On the foil's surface ∂D_B the no-entrance Neumann boundary condition holds;

$$\nabla\Phi\cdot = \left(\mathbf{V}_A - \mathbf{V}_\infty - \mathbf{V}_G\right)\cdot\mathbf{n}, \tag{3}$$

where $\mathbf{n}$ is a unit vector normal to the foil's surface, $\mathbf{V}_A$ is the unsteady velocity of points $\mathbf{r}(s;\ t) \in \partial D_B$ due to both the prescribed kinematics and any deformations and $\mathbf{V}_G$ is a background gust velocity. Points on the foil's surface are described using a curvilinear coordinate s. The smallness assumption of foil thickness render it a lifting surface, with a bound vorticity distribution $\gamma_B(s;\ t) = \nabla[\![\Phi]\!]\boldsymbol{\tau}(s;\ t)$ forming around it, where $[\![\Phi]\!] = \Phi_U - \Phi_L$ denotes the potential jump across it and $\boldsymbol{\tau} = \boldsymbol{\tau}(s;\ t)$ is the tangent to the foil's surface unit vector. The instantaneous circulation is given by

$$\oint_{\partial D_B} \mathbf{u}\cdot d\mathbf{l} = \int_{LE}^{TE} (\nabla[\![\Phi]\!]\cdot\boldsymbol{\tau})\cdot\boldsymbol{\tau}\cdot d\mathbf{l} = \int_{LE}^{TE} \gamma_B(s;\ t)ds = \Gamma_B(t), \tag{4}$$

The unsteadiness of the flow results in the formation of a trailing vortex street ∂D_W downstream of the foil. Assuming that the perturbation velocities in the wake vicinity are small compared to the free-stream velocity $U = |\mathbf{V}_\infty|$, a simplified wake model is used [24,29], where the vorticity distribution on the trailing vortex street, $\gamma_W(s;\ t)$, is described by the following advection equation

$$\partial_t\gamma_W + U\partial_x\gamma_W = 0,\ \ \text{and thus,}\ \ \gamma_W(x;\ t) = \gamma_W(x - Ut). \tag{5}$$

In the case of finite heaving and pitching motion amplitudes, the wake vorticity evolution assumes the more complicated form

$$\gamma_W(s;\ t) = \gamma_W\left(s_{TE};\ t - t_{TE}\right), \tag{6}$$

where t_{TE} is the time needed for a material point to travel from the trailing edge where it was emanated with constant velocity U to the arbitrary trailing wake point $\mathbf{r}(s;\ t) \in \partial D_W$. Furthermore, s_{TE} is the curvilinear coordinate for which at a previous time $t - t_{TE}$ it holds that $\mathbf{r}(s_{TE};\ t - t_{TE}) = \partial D_B \bigcap \partial D_W(t - t_{TE})$; that is $\mathbf{r}(s_{TE};\ t - t_{TE})$ coincides with the trailing edge position at $t - t_{TE}$. Eq. (6) is used to describe the trailing wake vorticity, allowing arbitrarily large motion amplitudes (and thus trailing edge positions) to be treated effectively, while retaining the notion that vorticity-carrying material points released from the foil's trailing edge travel downstream with the free-stream velocity U.