Ocean Engineering 147 (2018) 121–131

Contents lists available at ScienceDirect

Ocean Engineering

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

Developing three dimensional potential solver for investigation of propulsion performance of rigid and flexible oscillating foils

Madjid Abbaspour, Saeed Najafi *

Sharif University of Technology, Mechanical Engineering Department, Iran

ARTICLE INFO

Keywords:
Boundary element method
Unsteady panel method
Time stepping method
Wake sheet generation
Flapping foil

ABSTRACT

Heave and pitch motion of an oscillating airfoil in uniform flow will cause generation of forwarding thrust. Applying a combination of these two motions on flexible foil, one can increase thrust and therefore the efficiency. This is the way that most fishes and other flying animals uses to consume less energy. In this paper, hydrodynamic forces and efficiency of an oscillating airfoil is investigated. A code is developed based on potential flow formulation in combination with Time Stepping Method (TSM) with nonlinear free shear layer dynamic approach to predict the wake behind the lifting bodies. A linear Morino type Kutta condition has been implemented on panels adjacent to trailing edge. In this methodology, there is no need to define the wake shape before starting the simulation and it is an important feature in treating the hydrodynamics of submerged bodies. To validate the presented algorithm, some test cases were investigated. Comparison of propulsion performance of rigid oscillating foil with flexible undulating in different Strouhal number is the novelty of our research. We observe that in a wide range of frequencies, undulation movements is more efficient than rigid oscillations. The numerical results show a good agreement related to analytical and experimental measurements.

1. Introduction

Many scientists and engineers have been interested in flapping wing propulsion by observation of fishes, birds and insects that all use oscillating foil mechanism for generation of thrust. To compare the aero-hydrodynamic performance of biological and man-made propulsive systems to each other, Rozhdestvensky and Ryzhov, 2003) defines two specific parameters: (1) relative speed (ratio of the speed of swimming or flying to the maximum length of an object) and (2) specific power (ratio of full available power to the mass). Using these parameters, he showed that propulsion efficiency of natural systems is drastically better than artificial ones. To improve performance characteristics of man-made mechanisms, he suggested adopting the thrust generation mechanisms used by biological systems for man-made objects. Some special features that distinguish propulsion efficiency of living creatures like Insects, Birds and fishes with those created by human consists: controlled aero-hydro-elasticity, flexible geometry of propulsive surfaces, self-adjustment damping properties of the body, resonant modes of motion, etc.

In the early of 20th century, Knoller and Verein, (1909) and Betz (1912) separately observed that the harmonic oscillations of the foil will induce both longitudinal thrust and vertical lift force components. The first experimental investigation that certified the Knoller-Betz effect has been carried out by Katzmayr (1922) in 1922. Simultaneously, the harmonic oscillation of a wing in incompressible regime has been formulated by Prandtl (1924). Two years later, a linearized version of Prandtl's formulation has been developed by Birnbaum (1924). He regarded the flapping airfoil as a two-dimensional propeller and applied this solution to estimate the generated thrust force.

Von Karman and Burgers, (1935) observed the trailing vortex generation mechanism of flapping foil and explained the dynamic lift and drag based on location and orientation of the vortex street. The observations of Karman and Burgers have been confirmed with flow visualization experiments carried out by Polonskiy, (1948,1950). He also showed the different vortex structures downstream of the lifting bodies.

Young visualizations (Young and Lai, 2004) showed that a momentum shortage occurs in Karman vortex street configuration. This momentum shortage take place in time-averaged velocity profiles of drag dominant wake patterns and leads to an adverse flow jet. On the other hand, the reverse Karman vortex street configurations of thrust dominant wake pattern produce time-averaged velocity profiles where show a momentum excess. This momentum excess results a favorable flow jet.

---

* Corresponding author.
E-mail address: snajafi@mech.sharif.edu (S. Najafi).

https://doi.org/10.1016/j.oceaneng.2017.10.015
Received 18 August 2016; Received in revised form 17 August 2017; Accepted 11 October 2017

With the invention of first generation of computers, numerical methods have been developed gradually. One of the widely applied methods for the investigation of the propulsive characteristics of oscillating airfoil in nonlinear formulation is panel method, because of its computational efficiency as compared to the Navier–Stokes solvers. Formulation of panel method is based on boundary integral equations that lead to the computation of singularity strengths over the body panels.

In the panel method formulation, one can capture the viscous features of the flow by considering the free wake sheet generating from trailing edges downstream of the body. This can be done through satisfying the Kutta condition that correlates the strength of the wake panels with source/doublet strengths of body panels into the equations (Topper, 2011).

Solution of incompressible flow around bodies using panel method has been started by Hess and Smith, (1962). They predict pressure and velocity distribution over 3D arbitrary non-lifting bodies. Ten years later, Hess (1972) developed Panel Method to estimate induced forces generated by a lifting surface. These researches have been supported by Douglas Aircraft Company. In these works, researchers used Prescribed Wake Shape (PWS) model to analyze potential distribution over lifting bodies. Hess (1990) explained a comprehensive historical background of the panel method.

There has been a great deal of research into propellers and hydrofoils using panel methods or boundary element methods. Politis (2004; 2005; 2011; 2016) produced a free wake panel method for a marine propeller using a boundary element formulation. He used a low order panel method coupled with unsteady Morino type Kutta condition to capture the propeller wake Roll-up.

In 2008, Mantia et al., used a new formulation of unsteady Kutta condition to simulate potential flow around a two dimensional oscillating foil (La Mantia and Dabnichki, 2009). They calculate hydrodynamic forces on heave/pitching foil and compared the results with experimental data. Yonghui et al., numerically studied a flapping foil for energy extraction. They showed that power extracted from an oscillating air foil is mainly due to heaving rather than pitching motion (Xie et al., 2014). In 2015, Chien-Chou et al., presented a numerical model to investigate fluid-structure interaction for a 2D flow over a sinusoid-pitching foil. They compared the numerical results with experimental data and showed the numerical model is sufficient to predict the dynamic stall phenomenon (Tseng and Cheng, 2015). Zhang and Ji (2017) studied the vortex shedding and formation behind an isolated cylinder, under the wake generation of an oscillating airfoil. The foil was oscillated with pitch movement and in different frequencies (Zhang and Ji, 2017). In 2017, numerical versus experimental investigation of energy extraction performance of a flapping foil was performed. In this study, pitch and heave motion of the airfoil were adjusting through a crankshaft–like structure. Comparison between numerical and experimental compares good agreement. They also showed that higher efficiency can be achieved with larger pitch amplitude at medium frequency (Xu et al., 2017).

Triantafyllou et al., (1991, 1993, 1996, 2000, 2002, 2004; Triantafyllou and Triantafyllou, 1995) used panel method to model three-dimensional flexible swimmer of arbitrary geometry subject to variable body deflections. Zhu et al. (2006) have also developed a combined hydrofoil and free surface simulation using a boundary element method.

Basically, in simulation of lifting objects using boundary element method, there are some techniques to model the wake sheet. The earliest one is known as Prescribed Wake Shape (PWS). In this method, the wake surface as well as body geometry should be defined using either simple linearized models or experimental observations. In this approach, cause of weak estimation of potential distribution over body panels, calculation of forces and moments were not exact. To overcome the accuracy problem, Wake Relaxation Method (WRM) has been adopted to the solution of steady-state flow problems. In this method, first an initial geometry of wake sheet must be defined and then solver improves the pattern iteratively until the tangential velocity vectors on both sides of sheet converge to each other. Iteratively deformation of panel geometry causes more accurate doublet distribution over body surface and it helps to estimate lift forces and moments more accurately (Katz and Plotkin, 1991).

Another algorithm that used for unsteady simulations is Time Stepping Method (TSM). In this approach, there is no need to define the wake pattern before starting the simulation. We just address the trailing edges as wake sheet generator lines and the free wake would be developed continuously based on mean perturbation velocity of wake nodes. In this study, the implementation of Time Stepping Method for development of vortex sheet downstream the lifting bodies have been shown. To verify and validate our methodology, some test cases including flow over unit sphere, non-lifting and lifting NACA 0012 and harmonic oscillating airfoil has been considered and good agreement between analytical and numerical solutions observed.

2. Method and materials

For solving the governing equation via boundary element method, it is needed to discretize the boundaries in computational domains, including body and boundaries. In the present study, all the test cases are supposed to be in an infinite domain, so that, it just needed to discretize the surface of corresponding object.

Assume an object that moves with linear velocity of $\overrightarrow{V}(t)$ and angular velocity of $\overrightarrow{\Omega}(t)$ in an unbounded flow domain with upstream flow velocity $\overrightarrow{U}_\infty(t)$. As the corresponding object is either solid or flexible, thus each panel has the following instantaneous velocity vector in the inertia reference frame:

$$\overrightarrow{V}_A(t) = \overrightarrow{V}(t) + \overrightarrow{\Omega}(t) \times \overrightarrow{r} \tag{1}$$

Thus, relative velocity for an observer connected to body is:

$$\overrightarrow{q}_A(t) = \overrightarrow{V}_A(t) - \overrightarrow{U}_\infty(t) \tag{2}$$

Considering inviscid, incompressible and irrotational flow, the continuity equation could be written in the form of Laplacian of 3D velocity potential as following (Triantafyllou et al., 2002):

$$\nabla^2\phi = 0 \tag{3}$$

The general solution for this equation would be every linear combination of fundamental potential functions such as sink/source, doublet, vortex and etc. Based on Green's second identity, if ϕ and λ satisfy Laplace's equation, then it is possible to write equation (3) in the form of:

$$2\pi\phi(p) = \int_S \phi \frac{\partial\lambda}{\partial n} dS + \int_S \lambda \frac{\partial\phi}{\partial n} dS \tag{4}$$

For every p located on the body boundaries. In this equation, $\overrightarrow{n}$ is the unit normal vector of panel pointing outward of the body. The kernel function λ could be any fundamental solution of potential flow, like Source, Doublet, Vortex or any combination of them. For simplicity, suppose λ as a point source with unit strength $\left(\lambda = \frac{1}{r}\right)$, then it is possible to find the body perturbation velocity potential $\phi(p, t)$ at any point in terms of surface integrals over the boundaries. Based on Hess (1972), for lifting body problems, to satisfy the Kelvin's theorem, the integral should be expanded over the wake sheet downstream the trailing edges too, as shown in Fig. 1, which S_b and S_w are body and wake panels respectively.

So, the equation (4) could be written in the form of:

$$2\pi\phi(p,t) - \int_S \phi(q,t)\frac{\partial(1/r)}{\partial n} dS = -\int_S \left(\frac{1}{r}\right)\frac{\partial\phi(q,t)}{\partial n} dS \tag{5}$$

where, $S = S_b + S_w$ and $r = |p - q|$ is distance from point $q \, \varepsilon \, S$ to the field point p. It should be noted that, because the both potential ϕ and its normal derivative are continuous across the wake sheet; their