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Biomimetic propulsion under random heaving conditions, using active pitch control

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A B S T R A C T

Marine mammals travel long distances by utilizing and transforming wave energy to thrust through proper control of their caudal fin. On the other hand, manmade ships traveling in a wavy sea store large amounts of wave energy in the form of kinetic energy for heaving, pitching, rolling and other ship motions. A natural way to extract this energy and transform it to useful propulsive thrust is by using a biomimetic wing. The aim of this paper is to show how an actively pitched biomimetic wing could achieve this goal when it performs a random heaving motion. More specifically, we consider a biomimetic wing traveling with a given translational velocity in an infinitely extended fluid and performing a random heaving motion with a given energy spectrum which corresponds to a given sea state. A formula is invented by which the instantaneous pitch angle of the wing is determined using the heaving data of the current and past time steps. Simulations are then performed for a biomimetic wing at different heave energy spectra, using an indirect Source-Doublet 3-D–BEM, together with a time stepping algorithm capable to track the random motion of the wing. A nonlinear pressure type Kutta condition is applied at the trailing edge of the wing. With a mollifier-based filtering technique, the 3-D unsteady rollup pattern created by the random motion of the wing is calculated without any simplifying assumptions regarding its geometry. Calculated unsteady forces, moments and useful power, show that the proposed active pitch control always results in thrust producing motions, with significant propulsive power production and considerable beneficial stabilizing action to ship motions. Calculation of the power required to set the pitch angle prove it to be a very small percentage of the useful power and thus making the practical application of the device very tractable.

1. Introduction

Modern research on biomimetic flapping foil propulsion starts in 1936 with Gray's paradox, whose estimations of dolphin resistance resulted in required power about seven times the estimated muscular power of the dolphin. Modern theoretical developments started with the works of Sir James Lighthill (1969) and Wu (1971). A thorough review of those theories can be found in Sparenberg (2002). The evolution of computers allowed direct simulations of the fully 3-D fish propulsion problem using either 3-D–BEM or Navier–Stokes based codes. Bose and Lien (1990) demonstrated numerically that the immature *Balaenoptera physalus* whale's fin, swimming at 2.5 m/s in a fully developed seaway at sea state 5, could

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absorb between 25% and 33% of its required propulsive power. Liu and Bose (1997) presented a 3-D–BEM to study the effect of wing flexibility in the efficiency of a whale's fin. Their model uses a frozen wake assumption and a linear Kutta condition at the trailing edge. Liu and Bose (1999) enriched their 3-D panel code with a 2-D boundary layer inner solution and applied their method to estimate the effects of the shape of a wing's planform to propulsive performance. Zhu et al. (2002) employed a 3-D panel code together with experimental data to establish the 3-D features of the flow around fish-like bodies. He et al. (2006) presented a 3-D panel code to treat tandem oscillating foils. Borazjani and Sotiropoulos (2008) presented calculation of swimming forces and efficiency of a carangiform swimmer using an unsteady 3-D Navier–Stokes equation solver. Ashraf et al. (2011) presented unsteady 2-D Navier–Stokes calculations, using CFD package Fluent, showing the effect of Reynolds number and thickness ratio to the propulsive performance of four digit NACA airfoils in combined heaving/pitching. Benkherouf et al. (2011) presented 2-D Navier–Stokes calculations coupled with Newton's Law for the calculation of translational velocity and efficiency, of a thrust producing flapping airfoil. In parallel to the theoretical and numerical developments, serious efforts have been made by various researchers to investigate experimentally fish propulsion. A detailed presentation of the experimental state of the art can be found in Triantafyllou et al. (2004). Another extensive review of research on biomimetic propulsion can be found in Rozhdestvensky and Ryzhov (2003), along with extensive references to the work of eastern scientists (i.e. Russians and Japanese). A more recent review on the subject can be found in Shyy et al. (2010) and in the book of Taylor et al. (2010). Marine biomimetic propulsors are also discussed in the book of Bose (2008).

The idea of using horizontal wings, located underneath the bow or stern of a ship, as a device for transforming boat kinetic energy (gained from its interaction with the wavy environment) to useful propelling power, is far from new. One of the first attempts was documented in 1895 in the form of a patent for a self-propelled boat. The boat was equipped with a fin located at the bow. Due to the heaving motion of the boat bow, the fin bends upwards and downwards, propelling the boat forward. It was claimed that the boat could reach a velocity of four knots when moving against waves (Anon (1983)). Further successful applications of horizontal wings, located underneath the bow or stern of a ship, as devices capable to transform the bow's (stern's) heaving motion to useful power, are reported in Rozhdestvensky and Ryzhov (2003). A notable example is the full-scale test of a 174 t Russian research fishing vessel which was equipped with a horizontal wing located at the ship bow and demonstrated that a device as such can extract the sea wave energy increasing the propulsive power up to 45–87% and reducing the ship motions by a factor of 2–2.5 (Nikolaev et al. (1995)).

The scope of the current work is first to demonstrate how the active pitch control (to be defined subsequently) of a randomly heaving and translating biomimetic wing can lead to production of significant propelling thrust with simultaneous beneficial effect on ship's motions and second to present quantitative results regarding power production capabilities of this device under certain sea states. There are two main innovations in this work. The first innovation is the use of active control of the wing pitch under random heave motion. By 'active pitch control' we mean the development of a rational, under which a thrust producing selection of the wing's pitch angle at the current time step is possible using the heave velocity estimated from the current and past recordings of the random heave, together with the advance velocity of the boat. The second innovation is the simulation of a biomimetic wing under the previously described random motion, using a novel 3D–BEM time stepping algorithm.

To investigate the applicability of our ideas, hydrodynamic performance simulations are undertaken using an indirect Source-Doublet 3D–BEM, Politis (2004, 2009, 2011), together with a time stepping algorithm capable of tracking the highly nonlinear and random heave motions. A nonlinear pressure type Kutta condition is applied at the trailing edge of the wing at each time step. The main innovation of our numerical algorithm is the step-by-step solution in time, of the corresponding free boundary value problem for the perturbation potential, with a simultaneous calculation of the new position of the free vortex sheet geometry. This is achieved by applying at each time step the free vorticity transport equation which, expressed in terms of the free vortex sheet dipole intensity μ, takes the form $D\mu/Dt=0$ ($D\mu/Dt$ denotes the material derivative). A special mollifier-based filtering technique introduced by Politis (2011) is used to control the inherent instabilities in the self-induced velocities of the free vortex sheets and obtain the 3D unsteady wake rollup pattern of the wing, without any simplifying assumptions such as the older frozen or generalized wake models.

We present simulations for two different combinations of the heave modal period T_m and significant heave height H_s corresponding approximately to sea states 6 and 8, with reduced modal periods as observed in closed seas like the Mediterranean Sea. For each $\{T_m,H_s\}$ combination, we select two different instances of random heave time-records, for a time interval equal to two modal periods. Results for the propulsive thrust and power, transverse force and the power needed for the active pitch control, are then presented as functions of time for the two different heave time-records, the two $\{T_m,H_s\}$ selections and two different values of the pitch control parameter to be defined in the next section. It is shown that in every case considered, the proposed active pitch control results in thrust producing operational regimes with significant propelling power production. Moreover, the developed transverse forces act always beneficially towards reduction of the ship's motions. Calculated power required for the active pitch control is minimal, making thus the application of the device very tractable.

2. Biomimetic wing geometry and motion

For the needs of our simulation we select a wing with a span equal to 6 m, a chord at mid-span equal to 1 m and a tip-chord equal to 0.5 m. The wing has a small skewback of 9°, defined on the 33% chord (from leading edge) line in the span-wise direction. A NACA 0012 section has been used. This selection of the wing span has to do with the principal dimensions