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Hydrodynamic performance of flapping wings for augmenting ship propulsion in waves

Kostas A. Belibassakis *, Gerasimos K. Politis

School of Naval Architecture and Marine Engineering, National Technical University of Athens, Zografos 15773, Athens, Greece

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ABSTRACT

The present work deals with the hydrodynamic analysis of flapping wings located beneath the hull of the ship and operating in random waves, while travelling at constant forward speed. The system is investigated as an unsteady thrust production mechanism, augmenting the overall ship propulsion. The main arrangement consists of a horizontal wing in vertical motion induced by ship heave and pitch, while pitching about its own pivot axis that is actively set. A vertical oscillating wing-keel is also considered in transverse oscillatory motion, which is induced by ship rolling and swaying. Ship flow hydrodynamics are modeled in the framework of linear theory and ship responses are calculated taking into account the additional forces and moments due to the above unsteady propulsion systems. Subsequently, a non-linear 3D panel method including free wake analysis is applied to obtain the detailed characteristics of the unsteady flow around the flapping wing. Results presented illustrate significant thrust production, reduction of ship responses and generation of anti-rolling moment for ship stabilization, over a range of motion parameters. Present method can serve as a useful tool for assessment, preliminary design and control of the examined thrust-augmenting devices, enhancing the overall performance of a ship in waves.

1. Introduction

Biomimetic propulsors is a subject of intensive investigation, since they are ideally suited for converting environmental (sea wave) energy to useful thrust. Research and development results concerning the operation of flapping foils and wings, supported also by extensive experimental evidence and theoretical analysis, have shown that such systems at optimum conditions could achieve high thrust levels and efficiency; see, e.g., Triantafyllou et al. (2000, 2004), Taylor et al. (2010). Exploitation of the above systems for marine propulsion is thus an interesting subject, taking also into account that ship energy efficiency management and reduction of pollution is currently recognized to be an important factor in sea transport. In particular, previous studies by various authors, as the ones by Scherer (1968) and Yamaguchi and Bose (1994), have illustrated the application of oscillating wings to marine propulsion with considerable efficiency. In addition, significant progress has been reported concerning the possibility of such systems to extract energy from waves. In this direction, a two-dimensional oscillating hydrofoil has been examined by De Silva and Yamaguchi (2012) for wave devouring propulsion, and the propulsive performance of 3D flapping wing in unbounded fluid and random heaving conditions has been studied by Politis and Politis (in press) using active pitch control.

A main difference between a biomimetic propulsor and a conventional propeller is that the former absorbs its energy by two independent motions: the transverse to the mean incoming flow motion and the angular with respect to its pivot axis motion, while for the propeller there is only rotational power feeding. In real sea conditions, the ship undergoes a moderate or higher-amplitude oscillatory motion due to waves, and the vertical and/or transverse ship motions could be exploited for providing one of the modes of combined/complex oscillatory motion of a biomimetic propulsion system free of cost; see Rozhdestvensky and Ryzhov (2003). At the same time, due to waves, wind and other reasons, ship propulsion energy demand in rough sea is usually increased well above the corresponding value in calm water for the same speed, especially in the case of bow and quartering seas.

In the present work we consider the operation of randomly oscillating wings, located beneath the hull of the ship, as unsteady thrust-production mechanism, augmenting the overall propulsion system of the ship. The case of a single biomimetic propulsor consisting of a uni-block wing, as shown in Fig. 1, will serve as the basis of our study. The main arrangement is shown in Fig. 1(a) and consists of a horizontal wing undergoing combined vertical and angular oscillatory motion. The vertical motion is induced by ship heave and pitch, while the wing pitching motion about its pivot

* Corresponding author. Tel.: +30 210 7721138; fax: +30 210 7721397.
E-mail address: kbel@fluid.mech.ntua.gr (K.A. Belibassakis).

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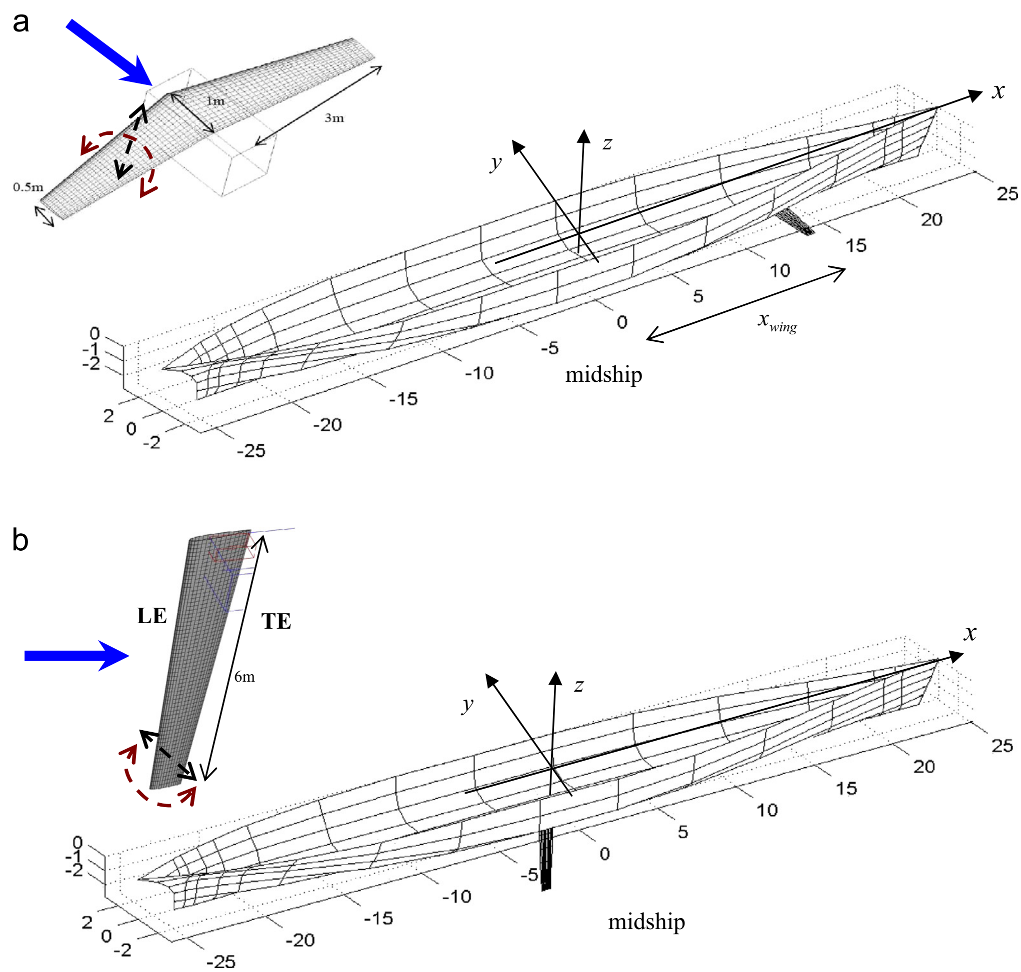

Fig. 1. (a) Ship hull equipped with a horizontal flapping wing located below the keel, forward the midship section. (b) Same hull with a vertical flapping wing located below the keel, at midship. Geometrical details of the flapping wings are included in the upper subplots, where the main flow direction is indicated by using a blue arrow and the oscillatory motions by using dashed black (ship induced oscillation) and red lines (controlled oscillation), respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

axis is actively set in terms of the vertical motion. A second arrangement is also considered, as shown in Fig. 1(b), consisted of a vertical oscillating wing beneath the hull of the ship. In this case, the transverse oscillatory motion is induced by ship rolling and swaying, and the pitching motion of the wing about its pivot axis is properly selected in order to produce thrust with significant generation of anti-rolling moment for ship stabilization.

Ship flow hydrodynamics are modelled in the framework of linear theory using a Rankine source-sink formulation and ship motions are calculated taking into account the additional forces and moments due to the above flapping propulsion system (see, e.g., Sclavounos and Borgen, 2004). The latter are formulated using a combination of unsteady lifting line theory, in conjunction with unsteady hydrofoil theory (e.g., Newman, 1977, Section 5). At a second stage, a fully 3D non-linear panel method developed by Politis (2009, 2011) is applied to obtain the detailed characteristics of the lifting flow around the flapping wing. Free-wake analysis is incorporated to account for the effects of non-linear wing wake dynamics at high translation velocities and amplitudes of the oscillatory motion. Predictions of the performance of the present system obtained by the above simplified model are compared against the 3D panel time-stepping method which includes the complex unsteady trailing vortex rollup in the modelling of biomimetic wing flow dynamics. From this comparison experience is gained regarding tuning corrections of the simplified model to better approximate larger amplitudes of oscillatory wing motions. It is shown that the linearized theory offers a generally good approximation to our problem, due to the relatively small Strouhal number (and reduced frequency) in which the flapping wings operate. Finally, numerical results are presented concerning the thrust produced by the examined biomimetic system as well as the resulting reduction in ship responses over a range of motion parameters, showing that the present method can serve as a useful tool for the assessment and the preliminary design and control of such thrust-augmenting devices, enhancing the overall propulsive performance of a ship in a wavy environment.

The present paper is structured as follows: In Section 2 the main kinematics and dynamics of flapping foils and wings in infinite flow domain are reviewed and the geometrical details of the examined configurations are presented. Subsequently, the mathematical models applied to treat the ship and flapping wing hydrodynamics are presented in Sections 3 and 4, respectively, where also additional references to previous research are provided. Specific examples of the examined system responses in harmonic waves are presented and discussed in Section 5, illustrating the thrust generation in conjunction with reduction of responses by the operation of the flapping wing as first evidence concerning energy extraction from waves. Finally, in Section 6 behaviour of the above system is examined in random waves, represented by frequency spectra, and numerical results are provided concerning the generation of thrust and anti-rolling moment by both arrangements considered.