Ocean Engineering 158 (2018) 162–170

Contents lists available at ScienceDirect

Ocean Engineering

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

Energy balance analysis of a propeller in open water

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ARTICLE INFO

Keywords:
RANS
Propeller in open water
Reynolds transport theorem
Energy balance
Hydrodynamic losses

ABSTRACT

This paper proposes a methodology based on control volume analysis of energy, applied on Computational Fluid Dynamics (CFD) results, for analyzing ship propulsion interaction effects as a complement to the well-established terminology, including thrust deduction, wake fraction and propulsive efficiency. The method, titled *Energy Balance Analysis*, is demonstrated on a propeller operating in open water. Through consideration of a complete energy balance, including kinetic energy flux, turbulent kinetic energy flux, internal energy flux (originating from dissipation) and pressure work, all possible hydrodynamic losses are included in the analysis, implying that it should be possible to avoid sub-optimized solutions. The results for different control volumes and grid refinements are compared. The deviation of the power obtained from the proposed energy balance analysis relative to the power based on integrated forces on the propeller is less than 1%. The method is considered promising for analyzing and understanding propulsor hull interaction for conventional, as well as novel propulsion configurations. The energy balance analysis is conducted as a post-processing step and could be used in automated optimization procedures.

1. Introduction

The interaction effects between hull and propulsion system are most commonly described using a well-established terminology, including thrust deduction, wake fraction, propulsive efficiency etc. However this decomposition has its primary origin in the experimental procedures used to establish ship scale performance rather than from principles of hydrodynamics. This can imply limitations in design and optimization of hull and propulsion system, as the interaction may thus not be correctly represented. We believe that the reliability and capacity of modern Computational Fluid Dynamics (CFD) has reached a high level of maturity which can be used to extract detailed data of the flow around vessels and propulsion units, even in full scale.

Different methods for analyzing interaction effects based on CFD or other calculated results have been proposed in the literature. Dyne (1995) suggested a propulsive efficiency based on wake losses and gains. The method was derived based on potential flow assumptions, which implies that it is not applicable for analyzing viscous flow simulation results. However, it is an appealing idea and easily understandable concept to separate the flow features in losses and gains. Dang et al. (2012, 2015) evaluated the dimensionless kinetic energy in the wake for comparison of different propulsion systems. This methodology focuses on axial and transverse kinetic energy, without accounting for all the energy transferred from the propeller to the water. A more comprehensive methodology was proposed by van Terwisga (2013) based on an energy balance over a control volume enclosing the entire vessel including propulsion unit. Through the assumption of a uniform control volume inflow, the evaluation of the fluxes were limited to the control volume downstream boundary. However, the method was not demonstrated. Schuiling and van Terwisga (2016) suggested a methodology for performing an energy analysis based on evaluation of the energy equation over a control volume, and applied it on a propeller operating in open water. The viscous losses are obtained through volume integrals of the dissipation terms. Thus, the numerical dissipation, which cannot be evaluated from CFD, has to be obtained indirectly from the difference between delivered power, obtained from forces acting on the propeller, and the other energy components.

Interaction effects and wake analyses has also been studied within the aircraft industry, using control volume analyses of energy, for instance by Denton (1993), Drela (2009) and Capitao Patrao et al. (2016). Designers developing novel aircraft concepts, such as Boundary Layer Ingestion (BLI), are actually facing very similar design issues as ship propulsion

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https://doi.org/10.1016/j.oceaneng.2018.03.067
Received 10 November 2017; Received in revised form 16 February 2018; Accepted 26 March 2018

system designers, with propulsion units operating in the wake of the craft.

The objective of this paper is to propose a methodology based on control volume analysis of the energy equation for analyzing ship propulsion interaction effects. Unlike other proposed methods for hull propulsion system interaction the energy equation is solved, which provides a clearer picture of the hydrodynamic losses caused by dissipation of kinetic energy. The method will be demonstrated on a simplified case, a propeller operating in open water.

2. Energy balance method

The methodology is based on the evaluation of the energy equation over a control volume surrounding the propulsion system, with the flow field obtained through CFD. It will be possible to express the delivered power, which traditionally is evaluated through the torque acting on the blades, as a sum of energy fluxes through the control volume surface. The reason for selecting energy, and not momentum, for the control volume analysis is described by van Terwisga (2013). As long as a ship moves at a steady speed, for a control volume enclosing the entire ship with propeller, no net momentum change in the flow exists whereas an energy change over the control volume can be measured. Thus, all effects of a new design, which appear in form of different energy losses in the flow, can be identified by means of studying the energy change through the control volume.

Control volume analyses, i.e. application of Reynolds Transport Theorem, is a well established tool, but has traditionally not been applied on CFD simulation results. Reynolds transport theorem states that *the change of any fluid property within the system is the sum of the change within the control volume, plus the outflow from the control volume, minus the inflow to the control volume.* The control volume could be of arbitrary shape, which is of importance to facilitate analyses of various kind of propulsion systems. Fig. 1 illustrates a possible control volume surrounding skeg, propeller and rudder. The control volume is bounded by both the virtual control volume surface (shown in blue), as well as the material surfaces, i.e. some proportion of the hull, the rudder and the propeller surfaces. To establish an energy balance accounting for all propulsive energy, the propulsion unit needs to be fully enclosed by the control volume. Selection of an appropriate control volume for the analyses will be further discussed in Section 4.

The energy conservation equation reads (White, 2008);

$$\Delta E = \dot{Q} - \dot{W}, \tag{1}$$

where E represents energy, $\dot{Q}$ denotes the rate at which heat is added to the system and $\dot{W}$ denotes the rate at which work is done by the system. Heat transfer from ship and propulsion unit to surrounding water is neglected for these analyses, since associated energy fluxes do not contribute to the hydrodynamic analyses. For simplicity we describe a stationary system, i.e. a steady state or periodic unsteady flow, it is however possible to generalize the method for analyzing unsteady flows as well. Denoting energy per unit mass with e, the energy conservation equation without heat transfer using the Reynolds Transport Theorem for stationary flow yields (White, 2008),

$$\Delta E = -\dot{W} = \int_{CS} e\rho(\vec{V}\cdot\vec{n})dA, \tag{2}$$

where CS denotes the control volume surface, $\vec{V}$ the velocity vector, ρ density and $\vec{n}$ the normal vector to the control volume surface (positive outwards). Note, for a periodic unsteady flow, the energy balance analysis needs to be evaluated as time-average over at least one period. The work done by the system constitutes work done by pressure and shear stresses on the control volume surface,

$$\dot{W} = \dot{W}_p + \dot{W}_v = \int_{CS}(p(\vec{V}\cdot\vec{n}) - \vec{\tau}\cdot\vec{V})dA, \tag{3}$$

where p denotes pressure and $\vec{\tau}$ is the shear stress vector on the elemental surface dA. The pressure and shear stress work acting on the rotating material surfaces of CS constitutes the delivered power (P_D) and can be expressed as,

$$P_D = 2\pi nM, \tag{4}$$

where M is the torque evaluated over all rotating material surfaces in CS and n denotes rotation rate. Compared to the classical notation, as shown in Eq. (1), the delivered power is here defined as power added to the system.

The pressure and shear stress work (Eq. (3)) also act on the virtual control volume boundaries of CS; these terms are moved to the right hand side of Eq. (2) and evaluated together with the energy fluxes. The work done by shear stresses on virtual boundaries of the control volume ($\dot{W}_{v,virtual}$) can often be neglected, this will be further examined in Section 4.1. Due to no-slip and no flux protruding the hull, no work is done by the system on the material surfaces in CS fixed relative to the control volume.

To increase the level of detail in the energy balance, the energy per unit mass (e), occurring on the right hand side of Eq. (2), could be further decomposed. It is proposed to split the term into kinetic energy in axial direction, kinetic energy in transverse directions, internal energy and turbulent kinetic energy:

$$e = \frac{1}{2}V_x^2 + \frac{1}{2}(V_t^2 + V_r^2) + \hat{u} + k, \tag{5}$$

where tangential and radial velocity components are denoted by V_t and V_r, respectively. In a Cartesian coordinate system these components should be replaced with the non-axial velocity components V_y and V_z. Introducing Eq. (5) and the above mentioned decomposition of the work rate into Eq. (2), we obtain:

$$P_D = \int_{CS}\left(\frac{p}{\rho} + \frac{1}{2}V_x^2 + \frac{1}{2}(V_t^2 + V_r^2) + \hat{u} + k\right)(\vec{V}\cdot\vec{n})dA + \dot{W}_{v,virtual}. \tag{6}$$

The presented approach, referred to as energy balance analysis in the rest of this paper, will be employed for the evaluation of a propeller

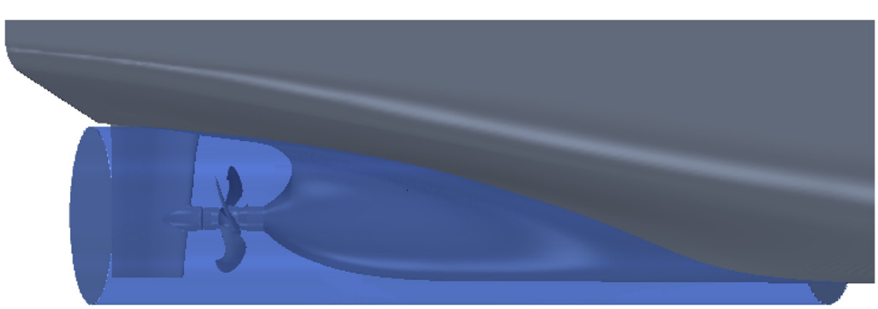

Fig. 1. Cylindrical control volume (in blue) surrounding skeg, propeller and rudder. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)