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Energy balance analysis of model-scale vessel with open and ducted propeller configuration

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ABSTRACT

This paper focuses on performance analysis of a model scale vessel equipped with an open versus a ducted propeller in self-propulsion using a control volume analysis of energy, applied on Computational Fluid Dynamics (CFD) results. An energy balance analysis decompose the delivered power for each system into internal and turbulent kinetic energy fluxes, i.e. viscous losses, transverse kinetic energy losses, and pressure work and axial kinetic energy fluxes. Such a decomposition can facilitate understanding of system performance and pinpoint enhancement possibilities. For this specific case it is shown that the much higher required power for the ducted propeller configuration to the largest extent is due to higher viscous losses, caused by mainly propeller duct and different rudder configuration. The energy balance analysis is a post-processing tool with the only additional requirement of solving the energy equation, which can be employed with any CFD-code based on commonly available variables.

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 thus may 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.

In a previous paper (Andersson et al., 2018) an alternative approach to study the interaction effects between hull and propulsion system, based on control volume analysis of energy was outlined and applied on a propeller operating in open water. This method implies that the hydrodynamic losses associated with a high and/or uneven acceleration of the flow, slipstream rotation and viscous losses can be tracked. Quantification of the viscous losses is made possible through solving the energy equation for the flow around the vessel. A similar method aimed for marine applications have earlier been presented by van Terwisga (2013). He suggested an energy balance over a control volume enclosing the entire vessel including propulsion unit. However, through the assumption of a uniform control volume inflow, the evaluation of the fluxes were limited to the control volume downstream boundary. The method was not demonstrated in practice. More recently, 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 were 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 and turbo-machinery industries, using control volume analyses of energy/power, 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 dealing with very similar design challenges as ship propulsion system designers, with propulsion units operating in the wake of the craft, where the counteracting forces of thrust and drag cannot be studied separately.

Eslamdoost et al. (2017) applied a control volume analysis of energy on a self-propelled axisymmetric body to investigate the effect of propeller diameter variation on the system performance. However, to the authors knowledge, there are no other published studies where similar methodologies have been utilized for analyzing complete marine

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vessels with propulsion system.

The objective of this paper is to apply a methodology based on control volume analysis of energy for analyzing the ship propulsion interaction effects. The method will be exemplified on a model-scale 120 m single-screw cargo vessel to study the performance of an open and a ducted propeller in self-propulsion. The study is limited to one operating point, close to the design speed of the vessel.

2. Energy balance method

The methodology is based on evaluation of the energy equation over a control volume surrounding the propulsion system, with the flow field obtained through CFD. Control volume analyses, i.e. application of Reynolds Transport Theorem, is a well known tool within fluid mechanics. The specific application to marine propulsion units is described in Andersson et al. (2018) and Schuiling and van Terwisga (2016). Traditionally, the delivered power (P_D) is obtained from the propeller torque, i.e. forces on the propeller surface, and its rotation rate. However, by applying the energy balance method over a control volume enclosing the propulsion unit, P_D can also be obtained by integrating the energy fluxes and pressure work over the surfaces forming the control volume (CS),

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

where $\vec{V}$ denotes the velocity vector, ρ density and $\vec{n}$ the normal vector to the control volume surface (positive outwards). Axial, tangential and radial velocity components are denoted by x, t and r, respectively. The energy flux is decomposed into kinetic energy in axial direction, kinetic energy in transverse directions, internal energy ($\hat{u}$) and turbulent kinetic energy (k). The axial direction is defined as the vessel sailing direction, i.e. not necessary identical to the propeller axis. There is also a contribution from pressure work (p) on the virtual (i.e. non-material) control volume surfaces. $\dot{W}_{v,virtual}$ is the work done by shear stresses on the virtual control volume surfaces, which often can be neglected, especially if the control volume surface is placed in regions without strong velocity gradients.

Fig. 1 illustrates the decomposed energy fluxes over a control volume surrounding the propeller and duct. Note that this is just a general representation, there will be inflow and/or outflow over all control volumes surfaces. Studying for instance the internal energy flux in Fig. 1: There will be a certain internal energy inflow to the control volume due to viscous dissipation occurring upstream the control volume, however the outflow of internal energy will exceed the inflow due to viscous dissipation within the control volume. The internal energy flux for this control volume will then constitute the difference between inflow and outflow. The sum of all energy fluxes over the control volume surfaces should match the delivered power to the propeller, evaluated based on forces on the propeller blades.

Decomposition of the delivered power into separate energy fluxes can be an aid for the designer to better understand and improve the performance of a system. This approach can also in the future be coupled with automated optimization procedures since it provides quantitative information on the hydrodynamic losses.

The analysis focuses on the performance within a certain control volume, implying that the control volume has to enclose the domain of interest. Possible options could be to enclose the entire vessel or only the aft ship. It is important to note that the control volume extension plays an important role in how one can distinguish and interpret the beneficial energy components from the unfavorable ones. For a control volume enclosing the entire vessel including the propulsion unit it is possible to distinguish the unfavorable energy components. This is more troublesome for a control volume only including a fraction of the hull, below we will elaborate on why. However, such a control volume can still be beneficial due to other reasons as will be discussed in Section 4.

Firstly, we discuss a control volume enclosing the entire vessel. In the ideal case, the propeller's slipstream would completely fill the wake behind the hull such that no axial kinetic energy flux is left behind the vessel. We also assume there will be no transverse kinetic energy flux over the control volume for an ideal vessel, and the viscous losses would be reduced to a minimum, i.e. zero (potential flow). Under these conditions it also holds that the rate of pressure work over the control volume would be zero. So, for an ideal vessel the sum of energy fluxes over the control volume would be zero, which implies zero delivered power to keep a constant speed forward. This idealization is naturally not practically possible, but it shows that for a control volume enclosing the entire vessel, all energy fluxes can be considered as unfavorable energy components, i.e. losses.

On the other hand, if the control volume only encloses a certain domain of the vessel, such as the aft ship, there needs to be an excess of useful energy flux over the control volume to be able to propel the remaining part of the hull at a constant speed. This implies that a fraction of the rate of pressure work and axial kinetic energy flux terms must be useful. In Andersson et al. (2018), the rate of pressure work and axial kinetic energy flux terms were decomposed into thrust power (useful) and axial non-uniformity loss. These axial non-uniformity losses are irreversible losses of pressure work and axial kinetic energy flux. They correspond to the total dissipation of pressure work and axial kinetic energy flux to internal energy that will occur downstream the control volume due to mixing out of spatial wake non-uniformity, i.e. the equalizing of pressure and velocity gradients to a homogeneous flow state. For a propeller operating in undisturbed inflow, the useful thrust power can be separated from the axial non-uniformity losses using either, an ideal control volume, or indirectly based on the forces

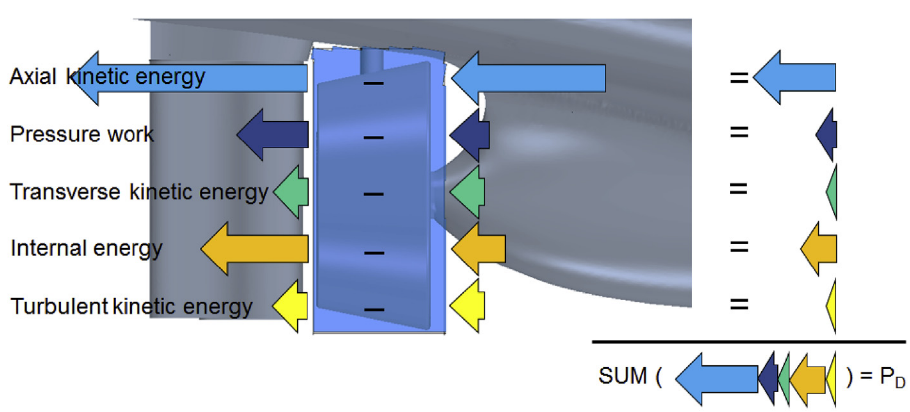

Fig. 1. General sketch of the decomposed energy fluxes over a control volume surrounding a ducted propeller operating behind a vessel. Note that this is just a general representation, there will be inflow and/or outflow over all control volumes surfaces.