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Computation of hydrodynamic mass and damping coefficients for a cavitating marine propeller flow using a panel method

M. Gaschler*, M. Abdel-Maksoud[1,2]

Institute for Fluid Dynamics and Ship Theory, Hamburg University of Technology, Schwarzenbergstraße 95 C, 21073 Hamburg, Germany

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ABSTRACT

The present paper deals with the numerical calculation of hydrodynamic mass and damping coefficients under consideration of unsteady sheet cavitation on marine propeller flows. In the first part of the paper, the mathematical and numerical background behind the numerical method is introduced. The numerical calculations carried out in this work are based on a low-order panel method. Panel methods belong to the class of collocation techniques and are applied to obtain a numerical solution of a potential flow based system of boundary integral equations. They are suitable for the present application because of their short computation time which makes them applicable in the design process of marine propellers.

Additionally, two different approaches for the determination of hydrodynamic masses and damping are introduced in this work. The hydrodynamic masses and damping are important in studies of the ship motion in seaway and in the analysis of vibrations of a vessel and its appendages. The developed approaches are applied on a propeller flow in heave motion. Hereby, the calculations are performed for a non-rotating and rotating propeller under non-cavitating and cavitating conditions. The results obtained from the simulations are discussed in detail and an outlook is given.

1. Introduction

This paper is dedicated to the numerical investigation of hydrodynamic mass and damping coefficients for a marine propeller under consideration of unsteady partial sheet cavitation. Cavitation in general develops in a liquid flow when the pressure in the flow falls below the vapour pressure of the liquid. This phenomenon is mostly caused by high local fluid velocities in the vicinity of the propeller blades. There can exist different types of cavitation, e.g. bubble, tip vortex, partial sheet cavitation and supercavitation. In this work only the investigation of partial sheet cavitation is addressed. Partial sheet cavitation is a type of cavitation which occurs in the form of a vapour sheet attached to the solid body surface. It is one of the main causes of high pressure fluctuations on a ship hull and can lead to vibrations and noise. On this account, the prediction of sheet cavitation on propeller blades and estimation of its effects on propeller's performance is one of the most interesting aspects in propeller design process. Since model experiments are hardly applicable in the design stage, numerical simulation

* Corresponding author. Tel.: +49 40 42878 6147; Fax: +49 40 42878 6055.
E-mail addresses: m.bauer@tuhh.de (M. Gaschler), m.abdel-maksoud@tuhh.de (M. Abdel-Maksoud).
URLS: http://www.panmare.de (M. Gaschler), http://www.tuhh.de/fds (M. Abdel-Maksoud).
[1] Tel.: +49 40 42878 6053.
[2] Fax: +49 40 42878 6055.

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Nomenclature

D	propeller diameter
$\mathbf{F}$	force vector
g	gravity constant
J	advance coefficient of the propeller
k_t	propeller thrust coefficient
$\mathbf{M}$	moment vector
n	rotational speed of the propeller
$\mathbf{n}$	normal vector
p	local pressure
p_v	vapour pressure of water
p_∞	atmospheric pressure
$\mathbf{s}$	coordinates of the local surface-fitted coordinate system
$\mathbf{s}_{d.p.}$	inception point of sheet cavitation
$\mathbf{s}_{d.p.}$	closure point of sheet cavitation
S	boundary of the flow domain Ω
S_B	body surface
S_W	wake surface
S_C	cavitation surface
S_{B_C}	cavitating part of the body surface
t	time variable
$(\mathbf{t_1}, \mathbf{t_2}, \mathbf{t_3})$	vector basis of the local surface-fitted coordinate system
$\mathbf{V}$	total velocity
$\mathbf{v}_{\text{ind}}$	induced velocity
$\mathbf{V}_\infty$	undisturbed velocity
$\mathbf{V}_{\text{inflow}}$	parallel inflow velocity
V_{ship}	ship speed
$\mathbf{V}_{\text{wake}}$	nominal ship wake field
$\mathbf{x}$	space variable
z_∞	distance to the free water surface
η	cavitation thickness
μ	dipole strength
ρ	water density
σ	source/sink strength
σ_v	cavitation number
Φ	total potential
ϕ	induced potential
Φ_∞	undisturbed potential
Ω	potential flow domain
$\boldsymbol{\omega}$	angular velocity
f_{nW}	nth derivative of the function f with respect to the variable W

tools can be used to predict sheet cavitation on a propeller. Such tools should not only be reliable and stable on the one hand but they should also be fast in order to be used in the design procedure. A type of methods that fulfil these requirements are the panel methods. In this work the simulation tool *pan* MARE based on a three-dimensional low-order panel method is used (see Bauer and Abdel-Maksoud, 2012).

In Section 2, the governing equations of the flow problem as well as the details on the sheet cavitation model are introduced. Section 3 presents the numerical scheme and outlines the specifics in dealing with the unsteady terms in the cavitation model. In Section 4, two different approaches for the prediction of hydrodynamic mass and damping coefficients are introduced. In the last section, the abilities of the numerical method are demonstrated on an example propeller for different application cases. The flow of the propeller is simulated in heave motion subject to a homogeneous inflow both under non-cavitating and cavitating conditions and the hydrodynamic mass and damping coefficients are calculated by means of the developed approaches.

2. Mathematical description

This section presents the governing equations which are used for the implementation of the numerical scheme in the simulation code *pan* MARE. Hereby, the focus lies on the characterisation of different reference frames and motion models of the submerged bodies in the flow as well as in the mathematical description of the unsteady sheet cavitation phenomenon.

2.1. Coordinate systems and motion models

In this work the flow past a single or multiple bodies with an individual rotational and/or translational speed is considered. For that purpose two different reference frames are defined. A Cartesian reference frame which is fixed in the space and a Cartesian reference frame moving together with the considered body. The reference frame fixed in space is described by the coordinates $\mathbf{X} = (X, Y, Z)$, whereas the body-fixed Cartesian reference frame is identified by the coordinates $\mathbf{x} = (x, y, z)$ and the z-axis is positive upwards (see Fig. 1).

For the treatment of the sheet cavitation model, to be introduced later, it is more convenient to use a local surface-fitted curvilinear coordinate system. Thus, an additional local body-fixed coordinate system with non-orthogonal base unit vectors $\mathbf{t_1}$, $\mathbf{t_2}$, $\mathbf{t_3}$ and local coordinates $\mathbf{s} = (s_1, s_2, s_3)$ is introduced (see Fig. 2). An arbitrary vector $\mathbf{b}$ is converted from the surface-fitted coordinate system to the global body-fixed Cartesian system using the transformations:

$$\mathbf{b}^{\text{glob}} = \frac{\mathbf{t}_1}{|\mathbf{t}_1 \times \mathbf{t}_2|^2}(b_{s_1} - (\mathbf{t}_1 \cdot \mathbf{t}_2) b_{s_2}) + \frac{\mathbf{t}_2}{|\mathbf{t}_1 \times \mathbf{t}_2|^2}(b_{s_2} - (\mathbf{t}_1 \cdot \mathbf{t}_2) b_{s_1}) + \mathbf{t}_3 b_{s_3} + \mathbf{x}_0, \tag{1}$$

where $\mathbf{x}_0$ describes the Cartesian origin and $\mathbf{b}^{\text{glob}}$ is the transformed vector in the global body-fixed Cartesian coordinates.