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Experimental analysis on the risk of vortex ventilation and the free surface ventilation of marine propellers

Anna Maria Kozlowska [a,b,*], Sverre Steen [a,b]

[a] Department of Marine Technology, NTNU, 7491 Trondheim, Trondheim, Norway
[b] Rolls Royce University Technology Centre "Performance in a Seaway", Trondheim, Norway

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A B S T R A C T

The paper presents a discussion of the ventilation inception and air drawing prediction of ships propellers, aiming to predict under what conditions ventilation will happen, and the actual physical mechanism of the ventilation.

Three different types of ventilation inception mechanisms are included in our discussion: free surface vortex ventilation, ventilation by sucking down the free surface without forming a vortex as well as ventilation by propeller coming out of the water. Ventilation prediction is based on a series of model tests, where the propeller is tested in different levels of intermittent ventilation. The use of underwater video gives a visual understanding of the ventilation phenomena.

Ventilation by vortex formation has analogies with other phenomena, such as the inlet vortex in pump sumps, ground vortex at the inlet of the aircraft engines and the Propeller Hull Vortex Cavitation (PHVC). The paper includes comparison between Propeller Hull Vortex Cavitation (PHVC) and Propeller Free Surface Vortex Ventilation (PFSVV) as well as comparison between PFSVV and vortex formations of aero engines during high power operation near a solid surface.

Experimental data based on several different model tests shows the boundary between the vortex forming, non-vortex forming and free surface ventilation flow regimes. For comparison the following parameters, which determined the intensity of the hydrodynamic interaction between the propeller and free surface have been used: propeller load coefficient c_T, tip clearance ratio c/D, propeller submergence ratio h/R, ambient velocity V_i and flow cavitation/ventilation number $\sigma_{cav}/\sigma_{vent}$.

1. Introduction

When a ship propeller operates under highly loaded condition, unsteady line vortex cavitation may occur between the propeller tip and the hull. This type of cavitation is known as propeller – hull vortex cavitation (PHVC) and, if it occurs, it causes strong vibrations and noise in the stern of the ship. When a propeller is operating close to the free water surface, a vortex might form between the propeller and the free surface through which air can be drawn down to the propeller, so that it ventilates – a phenomenon we call Propeller Free Surface Vortex Ventilation (PFSVV). Ventilation typically occurs when the propeller loading is high and the propeller submergence is limited, and when the relative motions at the propeller are large due to heavy seas. Propeller ventilation inception depends on different parameters i.e. propeller loading, forward speed and the distance from the propeller to the free surface, see for instance Califano [2], Kozlowska et al. [9] and Kozlowska and Steen [10]. It is likely that the physical phenomena causing vortex forming of PHVC and vortex ventilation are closely related, see Huse [5]. In this paper, PFSVV will be compared to PHVC with the aim of getting a better understanding of the physical mechanisms causing PFSVV, and on that basis enable the making of better simulation and prediction methods for PFSVV.

Ventilation by vortex formation (PFSVV) has been studied by several researchers see for instance Koushan (2006 I, II and III), Kozlowska et al. [9], Kozlowska and Steen [10], Califano [2], Koushan et al. [8] and Kozlowska et al. [11].

Kozlowska et al. [9] focused on ventilation inception mechanisms, classification of different types of ventilation, thrust loss related to each type of ventilation, and provided a simple calculation method for predicting thrust loss.

* Corresponding author at: Department of Marine Technology, NTNU, Trondheim 7491, Norway.
E-mail addresses: anna.kozlowska@ntnu.no (A.M. Kozlowska), sverre.steen@ntnu.no (S. Steen).

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Nomenclature

Symbols index

a_v	Vortex radius [m]
c	Tip clearance, distance from the top of propeller disk to the surface (hull) [m]
c/D	Tip clearance ratio [–]
c_T	Propeller load coefficient [–]
c_{Tn}	Propeller load coefficient for non- ventilated deeply submerged propeller [–]
$c_{0.7}$	Chord length at 0.7R [m]
$c_{L0.7}$	Lift coefficient at 0.7R [m]
D, R	Propeller diameter, propeller radius [m]
h	Propeller submergence from the propeller axis to the free surface [m]
h/R	Propeller submergence from the propeller axis to the free surface [–]
J	Advance number [–]
J_C	Critical advance coefficient [–]
J_{SC}	Super critical advance coefficient [–]
K_T	Thrust coefficient [–]
K_{Tn}	Time-averaged mean value of the thrust coefficient for deeply submerged non-ventilated propeller [–]
n	Propeller revolutions [Hz]
P/D	Propeller pitch ratio [–]
PFSVV	Propeller free surface vortex ventilation [–]
PHVC	Propeller hull vortex cavitation [–]
Γ	Span-wise circulation [m^2/s]
p_v	Vapor pressure [Pa]
p_o	Atmospheric pressure [Pa]
S	Surface tension of the water [N/m]
T	Propeller thrust [N]
V_A	Speed of advance [m/s]
V_i	Velocity through the propeller disk [m/s]
V_0	Free stream velocity [m/s]
z	Number of blades [–]
β_T	Total thrust loss factor [–]
σ_{cav}	Cavitation number [–]
σ_{vent}	Ventilation number [–]
ρ	Density of water [kg/m^3]
ν	Kinematic viscosity [m^2/s]

$J = V_A/n\,D$ Advance coefficient

$K_T = \frac{T}{\rho n^2 D^4}$ Thrust coefficient

$c_T = \frac{8}{\pi} \cdot \frac{K_T}{J^2}$ Propeller load coefficient

$c = (h - R)$ Tip clearance, distance from the top of propeller disk to the free surface (hull)

$\sigma_{cav} = \frac{p_0 - p_0}{0.5\rho (V_A)^2}$ Cavitation number (propeller axis is the reference pressure for the cavitation number)

$\sigma_{vent} = 2gh/(V_\infty)^2$ Ventilation number

$We = nD\sqrt{\rho D/S}$ Weber number

Kozlowska and Steen [10] focused on comparison between ventilation in static and dynamic conditions (heave motion) both for open and ducted propeller, and discussed how to estimate thrust loss. As a conclusion, a new formulation of the relations between ventilation and thrust loss was developed.

Kozlowska et al. [11] presented comparison between model tests and numerical calculations of thrust loss due to ventilation. The comparison contains two main aspects: comparison between blade forces and moments during non-ventilating and ventilating phase and comparison of results of flow visualization using high speed video (experiments) with CFD simulation results. The comparisons aim at identifying the degree of correlation and discuss reasons for deviations.

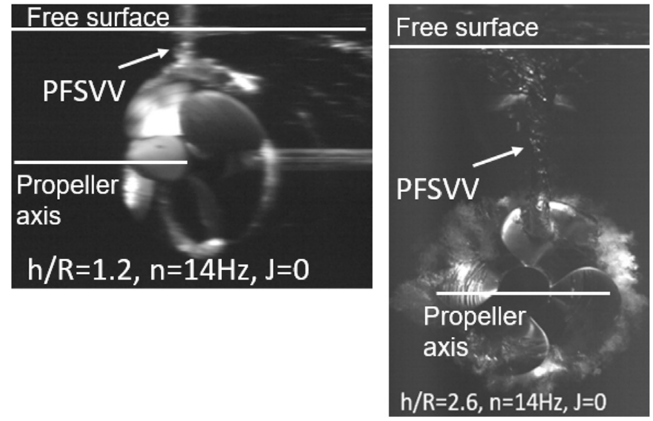

Fig. 1. Impact of the free surface ventilation (PFSVV) for complete submerged propellers.

PFSVV occurs for completely submerged, highly loaded propellers at low advance speed. The vortex funnel can reach the surface quite far from the propeller disc, especially for large submergence ratios. Fig. 1 shows two examples of PFSVV. Note that submergence h is the distance from the undisturbed free surface to the propeller axis.

The PHVC phenomenon was first reported by Huse [5]. Systematic observations had been carried out to investigate the effect of the afterbody form, tip clearance c/D, propeller loading c_T and cavitation number σ_{cav}. Experimental observation with a flat, horizontal plate above the propeller in a cavitation tunnel showed that PHVC is more likely to occur for small tip clearances (up to 20% of propeller diameter, $c = 0.2D$) for low advance coefficient J.

Based on experimental investigations four hypotheses have been suggested for criteria leading to PHVC: a so called "starting vortex", "vortices created by the shear flow in the wake field", "vortices created in other regions of the flow field" as well as "the pirouette effect", see Fig. 2. The "Starting vortex" hypothesis is based on Helmholtz's second theorem, which states that a vortex must be either closed or terminate on the boundary of the fluid. Fig. 2 below shows the corresponding vortex line representation of a propeller blade. Circulation will also be closed on the shortest possible way. This means that the tip clearance must be less than the blade length and axial flow velocity in the region between hull and blade tip should be close to zero. Hypothesis based on "vortices created by shear flow in the wake field" means that a high wake peak in the upper part of the propeller disk gives rise to intense shear flow in the region of highest velocity gradient. This represents a vorticity in the flow field that may "curl up" to form the concentrated vortices necessary to create PHVC.

The basic idea for the hypothesis based on "vortices created in other regions of the flow field" is that the cores of vortices will cavitate when entering the low pressure region between propeller and hull.

Huse [5] concluded that the hypothesis based of the "pirouette effect" is probably the most correct. By this hypothesis the effect of tip clearance, randomness, effect of blade angular position and effect of vertical fins can be satisfactory explained. The basic phenomena related to "pirouette effect" were further explain later by Martio et al. [12]. As the gap between the propeller blade tip and the wall is decreased, the blade suction side does not obtain enough water from the inlet side, so water is also sucked from downstream, causing a rotation of the flow, which is concentrated into a vortex by the so-called pirouette effect (rotational velocity has to increase considerably in order to keep the angular momentum constant,