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Experimental investigation of pressure pulses and radiated noise for two alternative designs of the propeller of a high-speed craft

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ABSTRACT

The present paper is focused on an experimental investigation of pressure pulses and radiated noise for two alternative designs of a propeller of a high-speed craft.

The propellers have been designed in the context of a research project starting from two different rake distributions (forward rake to increase thrust and efficiency, backward rake to reduce cavitation), using different techniques (traditional lifting line / lifting surface and optimization algorithm coupled with a panel code), leading thus to rather different geometries. Propellers have been tested through cavitation tunnel experiments. The activity represents an interesting case study for this kind of measurement in presence of rather large cavitation extensions. The effects of cavitation on different components of pressure pulses and noise are investigated for the different rake distributions adopted. Results clearly shows the effects of this geometrical characteristic on cavitation and pressure pulses pointing out that, in some cases, propeller hydrodynamic performances may determine pressure pulses intensity more than cavitation extensions. A simplified numerical approach, adopting stationary RANS calculations, for the evaluation of the effects of propeller geometry, has been proposed. Results show a good correlation with measurements allowing to have an insight into the phenomenon and confirming the effect of the rake.

1. Introduction

Propeller design is always one of the most challenging activities in naval architecture, being strictly connected with different requirements and characteristics of the ship. The development of modern numerical methods provides the designers powerful tools for this purpose and for the prediction of the behavior of the final designs. These increased capabilities allow coping with the always increasing requirements, no more limited only to the overall performances of the propeller but also dealing with the control of cavitation and its unwanted side effects.

Numerical methods are commonly used for the prediction of cavitation inception and extensions, however, when moving to the study of pressure pulses and radiated noise their effectiveness is reduced and still to be validated (especially in the case of radiated noise); from this point of view, experimental data are still needed in order to study most complex problems.

Looking more in details into this topic, main problems are encountered from the point of view of broadband pressure fluctuations, both for what regards the numerical prediction and the measurement and scaling of data from model scale experiments.

Actually pressure fluctuations induced by the propeller on the aft part of the hull, in correspondence to the blade passage frequency and its multiples, are commonly predicted with satisfactory results adopting simple and fast potential codes. Anyway, when large cavitation extensions are present, these methods often overestimate the impact of cavitation on the induced pressure, especially for the first harmonic, as shown for example in (Gaggero et al., 2016) for a fast twin-screw vessel. Similar results have been evidenced looking to the numerical results obtained for the PPTC test case (Kinnas et al., 2015).

Clearly, better results may be achieved considering more sophisticated numerical methods, as shown in Da-Qing et al. (2015) and Paik et al. (2013), nevertheless, experimental results are still of great interest for what regards the study of the deterministic part of the propeller induced pressure pulse and, of course, for validation of numerical computations.

Moreover, great importance has been given during years to the

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Nomenclature

A_E/A_O	Expanded area ratio
BPF	Blade passage frequency ($BPF=N\bullet Z$)
D	Propeller diameter [m]
DO2	Oxygen content level [ppm]
g	Gravitational acceleration [m/s2]
J	Advance ratio ($J=\frac{V_A}{nD}$)
K_Q	Torque coefficient ($K_Q=\frac{Q}{\rho n^2 D^5}$)
K_T	Thrust coefficient ($K_T=\frac{T}{\rho n^2 D^4}$)
K_P	Non-dimensional pressure coefficient
h	Propeller disk center depth [m]
L_{KP}	Level of non dimensional pressure coefficient [dB re 10−6]
L_{KPN}	Net level of non dimensional pressure coefficient [dB re 10−6]
L_P	Sound pressure level [dB re 1 μPa2/Hz]
n	Shaft revolution rate [RPS/RPM]
p	Pressure [Pa]
p_V	Saturation Pressure of Water [Pa]
P_∞	Undisturbed pressure [Pa]
P_{ref}	Acoustic reference pressure ($P_{ref}=10^{-6}$ $[Pa]$ in water)
$(P/D)_{0.7R}$	Pitch to diameter ratio at 0.7 R
Q	Propeller torque [Nm]
r	Distance from the acoustic source [m]
R	Propeller radius [m]
T	Propeller thrust [N]
V_A	Advance velocity [m/s]
V_S	Ship speed [kn]
Z	Number of blades

Greek symbols

α	oxygen content [ppm]
η_O	Open water efficiency ($\eta_O=\frac{J}{2\pi}\frac{K_T}{K_Q}$)
ρ	Water density [kg/m^3]
σ_N	Cavitation index based on propeller revolution ($\frac{2(p_\infty+\rho g h-p_V)}{\rho n^2 D^2}$)

prediction of tonal components of the pressure fluctuations, because their amplitude may be higher than that of broadband components by some order of magnitude and because their cyclic nature. However, the continuous increase of ship performances and quality, led to the study of the pressure pulses also from the point of view of their broadband components. The importance of this aspect is obviously dependent on the type of ship and more relevant in cases when a good onboard comfort level is required, as for passenger ships and pleasure crafts.

In this case, the problem becomes significantly more complex, both regarding near field pressure pulses and far field radiated noise. Actually, even if numerical models aimed to estimate such quantities are under development (Da-Qing et al., 2015; Lloyd et al., 2015; Lidtke et al., 2016), they are extremely demanding from the computational point of view and still far to be reliably applied.

In parallel, also problems related to the experimental prediction of broadband hull excitation and radiated noise are far from being completely understood. Model scale measurements of pressure pulses may provide a qualitative description of the continuous part of the spectrum and its frequency content, but the mechanisms driving the scaling of such components are still not clear and each facility follows its own procedure, largely based on previous experiences, when available.

Similar (and even larger) problems affects the prediction of radiated noise, even if this topic has been more widely studied since World War Two for military reasons. From this point of view, ITTC guidelines are available for the procedure to be adopted for full-scale prediction, however the level of uncertainties connected with such prediction is still remarkable. This because of the large number of scale effects and facility related issues, which may influence results of model scale tests. In addition, the applicability of commonly used scaling laws is limited to those cases for which model scale tests are carried out with the same cavitation number of the ship. This cavitation number similarity may lead to not consistent results when applied in the case of limited tip vortex cavitation, due to scale effects on tip vortex inception (McCormick, 1962; Briançon et al., 2013).

From the point of view of broadband hull excitations, tip vortex cavitation has been demonstrated, as shown in Raestad (1996), to be the cause of rather high spectral humps which, even if lower than tones, may excite structures natural frequencies and generally increase noise and vibration in the aft part of the ship.

This problem has been largely studied, also in recent years, because tip vortex cavitation is usually the first cavitation typology appearing on marine propellers and it is almost always present at maximum speed. Due to this, many attempts have been made to modify propeller design in order to reduce it, adopting suitable radial load distributions with unloaded tip or exploiting the effect of the tip rake. Nonconventional propellers have been used (and designed by exploiting optimization and high fidelity numerical tools) as well with the aim of reducing tip vortex cavitation or to increase efficiency keeping cavitation acceptable. Some examples are propeller with decelerating ducts, Kappel propellers and CLT propellers, see (Andersen and Andersen, 1986; Andersen et al., 2005; Dang, 2004; Gaggero et al., 2016a, 2016b).

In parallel large effort has been spent trying to understand the mechanisms involved in noise production by cavitating vortices. Depending on the characteristics of the vortex itself and of the flow this kind of cavitation may produce significant noise with a narrow spectral hump, as experimentally observed by Maines and Arndt (1997). This noise production has been attributed to the pulsation of the vortex at its characteristic frequencies. This allowed to theoretically predict frequencies of vortex noise, as done by Morozov (1974), and to apply the same concepts to the more complex case of real ship propellers exploiting both empirical formulations and theoretical models (Bosschers, 2009a, 2009b).

In present work, the study of these different cavitation side effects is addressed for the case of a fast pleasure craft. This kind of vessels belongs to those ship typologies for which the control of noise and vibration is a key factor for the achievement of a high quality standard. In particular, the aspect of onboard comfort is of utmost importance and consequently attention has been largely focused on the measurement of pressure pulses.

For the same application, two propellers are considered with forward and backward rake distributions respectively.

In the paper a large set of experimental data will be presented in order to deeply analyze the effects of cavitation on the different components of the pressure fluctuations, namely, the periodic components at the blade passage frequency (BPF) and its multiples, and the broadband components.

The importance of these analyses is to demonstrate that, in cases like the present one, the blade geometry and its pressure field may have an impact on pressure pulses larger than cavitation extensions, especially in correspondence to the blade passage frequency. This means that the reduction of propeller cavitation is not always strictly correlated to a reduction of propeller induced pressure fluctuations, at least not for all the components.

This fact moves the attention to the study of the effect the adopted rake distributions on pressure pulses. Usually the adoption of forward rake is favorable from the point of view of propeller efficiency while backward rake should have positive effects in terms of cavitation