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Efficient and multi-objective cavitating propeller optimization: An application to a high-speed craft

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ABSTRACT

The design of a propeller for a high-speed craft is addressed by using a multi-objective numerical optimization approach. By combining a fast and reliable Boundary Elements Method (BEM), a viscous flow solver based on the RANSE approximation, a parametric 3D description of the blade and a genetic algorithm, the new propeller shape is designed to improve the propulsive efficiency, reduce the cavitation extension, increase the cavitation inception speed and maximize, at the same time, the ship speed. Rather than by constraining the propeller delivered thrust, indeed, the proposed procedure works together with an engine-propeller matching algorithm that, each time a new propeller is defined, identifies the achievable maximum ship speed and the resulting engine functioning point that turn in additional goals for the multi-objective optimization. A set of optimal propellers, obtained through the design by optimization based on potential flow calculations (via the Boundary Elements Method), are selected for additional viscous analyses (RANSE calculations) in order to further validate the results of the BEM calculations and provide a deeper insight into the complex flow fields of high speed propellers. Among this subset of optimal configurations, a final geometry is selected to verify the reliability of the design procedure by means of dedicated cavitation tunnel tests and full-scale measurements on a high-speed craft provided by Azimut|Benetti.

1. Introduction

The state of the art of fast propeller design codes is commonly based on classical vortical theories. These methods, all derived by the vortex line theory of Lerbs [1] with surface exact or approximated corrections, as developed in the 60′s for example by Morgan et al. [2], Eckhardt and Morgan [3] or by Van Oossanen [4], have been used and adapted in many propeller design codes. Grossi [5] developed, for instance, a lifting surface code that is routinely adopted for the propeller preliminary design of many of the Fincantieri Group ships while, recently Diniz and Brizzolara [6], Brizzolara et al. [7] and Brizzolara et al. [8] have applied a similar approach for counter-rotating propellers.

A significant step towards the design of highly-loaded or unconventional geometries was represented by the variational approach by Kerwin et al. [9] and by Coney [10], extensively adopted for the design of different types of propellers also under severe working conditions. In the classic theory, the problem of the optimal circulation distribution was solved by an integral approach, which resulted in the Betz [11], or Lerbs [1], optimum criteria that requires linearization and application of the Munk displacement theorem in order to solve the problem. With the discrete distribution of circulation proposed by Kervin et al. [9] and Coney [10], instead, the definition of the optimal circulation did not require anymore any linearization. Based on this approach, Andersen and Andersen [12] and Andersen [13] proposed a lifting line design code specifically tailored for the design of tip-rake propellers with the inclusion of skew and rake in the geometrical definition of the shape of the lifting line and, consequently, for the calculation of the optimal circulation distribution. Moreover, Olsen [14] developed a vortex-lattice/lifting surface approach based on the same variational method of Kerwin and Coney to include the effect of the entire blade geometry in the circulation optimization process and examine the influence of the 3D propeller shape on the optimum distribution of load. In any case, most of the effort was aimed to develop classical design strategies for the purpose of

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achieving the highest efficiency for a given thrust. Recently, Epps et al. [15] extended the variational approach to consider simultaneously efficiency and cavitation performance at the endurance speed design point and at maximum speed off-design point, setting chord lengths and thickness to prevent cavitation at both operational conditions by using nested design loops.

All these approaches do take into account important design constraints, such as inception of cavitation and structural strength. However, the crude simplifications contained in these methods make them often insufficiently accurate in case of modern fast propellers geometries having, for example, highly skewed blades, non-conventional profiles or mixed type of cavitation. Typically, the chord distribution is optimized for the design speed with some margin to prevent off-design cavitation that is only considered a posteriori, with some modifications to mitigate its negative influence in high-speed operations. On the contrary, the combination of chord and thickness should be better set through the design process to a minimum able to maximize efficiency and still prevent cavitation (sheet and midchord bubbles) in correspondence to any of the functioning conditions under investigation. In addition, the usual design tables of Brockett [16] or the curve envelopes of the minimum pressure coefficient [10,17] generally are not suitable when multiple design points are considered, when unconventional profile shapes are employed or when wide chords at tip are preferred [18]. Moreover, neglecting (or approximating) the influence of the blade thickness may represent a serious drawback of a traditional lifting line/lifting surface approach in dealing with off-design conditions that may involve midchord bubble cavitation. Cavitation and unsteadiness, indeed, play the most important role in the design of high performance propellers for high-speed boats. In these vessels, propellers are often subjected to strong non-uniform inflow and the unsteady cavitation could reduce their performance, in addition to the risk of corrosion and induced noise and vibrations that certainly have to be minimized in the case of pleasure yachts. These requirements definitely require more advanced design tools, based on (more) accurate flow solvers and able to deal with the multi-objective nature of each new innovative design.

Among the potential based theories, Boundary Elements Methods (BEM) have inherent better abilities to capture the thickness effect of the blade, of the hub and, eventually, also the effect of cavitation. Panels discretizing the surfaces are placed on the real geometry rather than on simplified and approximated representations as in the case of usual low fidelity methods like lifting line/lifting surface design approaches and the inclusion of the influence of the thickness is, for instance, of particular importance when monitoring the risk of bubble midchord cavitation. The method developed at the University of Genoa [19], similarly to those developed by different research groups [20–22] can effectively predict the steady and the unsteady flow around the propeller with sheet cavitation, including supercavitation [23]. Nevertheless all such models, which capture (and hence require in turn) more detailed information about the propeller geometry, cannot be directly integrated into an direct design procedure, differently from the more simpler ones previously cited and, in fact, they are often used for validation of a given propeller design. Their level of accuracy is close to RANSE solvers [19,24] at the design point while in very off-design conditions some discrepancies may be observed [25,26] but their computational efficiency is particularly high, allowing their systematic application in an inverse design process. A parametric optimization procedure represents, actually, the ideal application of BEMs for the design of such specific propellers, allowing for a more congruent and effective search of the best geometry subjected to more strict constraints and requirements. Into an optimization procedure, which can systematically change the main geometric parameters of the blades to converge on the multi-objective optimum Pareto solution, Boundary Elements Methods can be directly employed as they had been developed for, namely as analysis methods, taking advantages of all their specific peculiarities. In addition, population-based algorithms can natively handle multi-objective optimization tasks, overcoming the well-known limitations of gradient-based searching algorithms and they can exploit the computational efficiency of the BEMs for the evaluations of the thousands of solutions required for the Pareto convergence.

Such applications have been successfully carried out in the case of conventional and unconventional propellers. Bertetta et al. [27,28] designed a controllable pitch propeller using a panel method, a robust parametric description of the blade geometry and an evolutionary algorithm of genetic type to define a geometry, whose requirements were to maximize efficiency and reduce the cavity extension in correspondence of two very different operative speeds achieved by changing the propeller pitch. Similarly, [29] the same approach was adjusted in order to deal with ducted propellers and some improvements of an already well-designed propulsor based on the decelerating duct concept were even obtained. More recently [30], the design by optimization based on BEM calculations leads to significant improvements of the performance of Contracted and Tip Loaded propellers and sets the state of the art for the design of a new class of tip loaded propellers [31] with particular emphasis on cavitating tip vortexes and induced pressure pulses. In this latter case, the need of a robust parametric description of the unconventional blade geometry arose as a key point of the design process to avoid unrealistic improvements from unfeasible shapes.

In the present paper an example of the application of the design by optimization to a high-speed boat propeller is given. The attention is focused on the optimization (maximization of efficiency and reduction of cavitation) of a custom propeller for a 95 feet high-speed craft by Azimut|Benetti. Differently from the previous proposed designs by optimization, the propeller performance are not prescribed by constraining the delivered thrust. The presence of performance constraints, in addition to the geometrical ones that generally cannot be avoided (minimum thickness or tip clearance as from classification society rules for instance), may excessively thwart the optimization and permit the definition of geometries that only satisfies those constraints. Consequently, the propeller performance are monitored through the boat achievable maximum speed that, each time a new propeller is defined inside the optimization loop, is calculated by a traditional propeller-engine matching procedure based on the actual propeller performance, de facto turning the desired engine loading into an additional objective rather than in a constraint. Similarly, also the objectives (or the constraints) on cavitation need to be revised in the light of the working conditions of such kind of high-speed propellers. Rather than requiring the minimization of the predicted cavity extension (or volume) or a sort of "advanced cavity constraints" like those successfully proposed by Vesting et al. [32], a simpler analysis of the pressure distributions over the blade has been preferred. The minimization of the cavity extension, indeed, was successful in the case of conventional and unconventional geometries [27,28,30,31] but, in those cases, the propellers were subjected mainly to leading edge sheet cavitation that is the kind of cavitation Boundary Elements Methods can effectively deal with. High-speed propellers, generally, are from moderately to highly loaded and the higher value of the expanded blade area, while preventing severe suction pressure at the leading edge, flattens the pressure distribution and increases the risk of michord bubble cavitation. A design by optimization based on the minimization, among the others, of the midchord bubble extension seems questionable in the light of the further approximations to be accepted within the Boundary Elements Methods to deal with this phenomenon. A simple avoidance objective (or maximization of the margin against midchord cavitation), on the contrary, seems more reliable and, being based on