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Enhancing Ship Propeller Design via Physics-Informed Parametric Model Embedding

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ABSTRACT

High-dimensional design spaces are the most common obstacle to optimization-based design approaches, especially when computational expensive medium- and high-fidelity tools for the evaluation of the key performance indicators (KPIs) of the design are employed [1]. Simulation-driven designs of marine propellers are not exempt from this issue [2]. In this context, medium-fidelity Boundary Element Methods (BEM) are commonly used for efficient design frameworks, but for large design spaces (e.g., over 50 parameters) and multiple objectives (e.g., optimizing for varying operating conditions), convergence time remains problematic [3]. High-fidelity tools like RANS, necessary for unconventional shapes or complex conditions, are limited to simplified cases due to computational costs spanning weeks or months [4]. Surrogate-aided optimizations offer a solution but introduce additional uncertainties through model approximations [5].

Recently, Parametric Model Embedding (PME) [6] has emerged as a costless design-space dimensionality reduction technique to reparametrize design spaces, facilitating optimization without added uncertainty in KPI evaluation. However, while reducing variables while preserving geometric coherence, PME alone may not capture complex physical interactions governing performance. This limitation is critical for marine propellers, where geometric variations may overlook localized risks like cavitation. Physics-Informed PME (PI-PME) extends PME by incorporating physical insights into dimensionality reduction, enhancing its capacity to describe performance variability and enabling a more holistic design exploration.

The advantages of PI-PME are demonstrated on a cruise ship propeller design. Optimization is performed using efficient BEM calculations to maximize propulsive efficiency at the design point (under required thrust) and minimize cavitation risks over varying speeds, both in the original and reduced spaces. Comparisons show that incorporating physical information in PME significantly improves optimization outcomes, enabling reliable and efficient use of high-fidelity tools for marine propulsor design.

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