A Dimensionality Reduction Method Based on Principal Component Analysis for Ship Hull Form Optimization

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ABSTRACT

In the stage of hull form optimization, simulation-based design technology uses a series of design variables to modify the hull shape, to explore the design space. Massive design variables are often set to optimize the ship hull, which will obtain enough degrees of freedom, but also bring a large amount of calculation. In this paper, a shape optimization method called PCA (Principal Component Analysis) is used for dimensionality reduction. PCA uses eigenvalues and eigenmodes to map the multidimensional vectors formed in the original design space to the new reconstruction space formed by linear independent vectors with fewer dimensions. This method maintains the original design space to a large extent, which does not require design-performance analyses. The KRISO Container Ship (KCS) has been used as a verification model to optimize the bulbous bow. The Multi-Island Genetic Algorithm (MIGA) is applied to explore the optimal hull of the reconstitution space. The reconstitution space achieved 80% dimensionality reduction with the aid of PCA and an approximately 99% accuracy. As a result, the wave resistance of KCS at service speed is reduced by 18%. The result shows that the method has better effectiveness and less time consumption in the ship hull optimization.

KEYWORDS: Design space dimensionality reduction, Ship hull optimization, PCA (Principal Component Analysis), T-spline

INTRODUCTION

New restrictive regulations on carbon emissions will be implemented by the International Maritime Organization (IMO) in the coming years. Ship hull form design has an important influence on ship resistance performance, and ship resistance performance optimization is an effective method for meeting the energy efficiency design index (EEDI) requirements proposed by IMO. With the rapid development of computational fluid dynamics (CFD) and optimization algorithm, simulation-based design optimization (SBDO, Diez et al. 2018) technology opens up a new situation for ship hull form design. This technology can help design engineers to explore the design space under constraints and automatically get the optimal design plan (Van et al., 2006; Vasudev et al., 2014; Cheng et al., 2018; Guan et al., 2022). An automated SBDO needs to integrate (i) simulation tools (ii) optimization algorithms (iii) auto geometry representation and modification (see the left box of Fig.1). Although the computational power and robustness of numerical algorithms have been improved, high fidelity SBDO for shape optimization is still a challenging process. One of the key challenges is the time-consuming problem caused by a large number of calculations because there are too many optimization variables for geometric deformation. However, a large number of variables means that the deformation space is large enough to allow the existence of an optimal hull solution. Therefore, with regard to excessive optimization variables, to find the right balance between the sufficient spatial flexibility and excessive computation is a non-trivial task to be accomplished. In this work, we focus on dimensionality reduction of design space to reduce optimization variables.

Flexible and abundant deformation space often means a high-dimensional optimization problem caused by excessive variables. If there are excessive variables controlling the changes of hull shape which means more diverse geometry variations, a large number of samples are required to get an optimal ship shape. Dimensionality reduction technologies for the design space have been proposed to reduce data dimension while retaining a prescribed level of geometric variance of the design space. POD (Proper Orthogonal Decomposition), also known as PCA (Principal Component Analysis) or KLE (Karhunen-Loève Expansion) (Pearson, 1901; Wold et al., 1987; Sirovich, 1987), is one of the most classical and widely used linear dimensionality reduction methods. However, the application of PCA dimensionality reduction technology in the field of hull form optimization is relatively rare. Chen et al. (2014) used a KLE based quantitative approach to assess the shape modification variability and build a reduced dimensionality global model of the design space for the optimization of a high-speed catamaran. Diez et al. (2015) reduced the 20-dimensional design space to 4, retaining up to the 95% of the geometric variance associated to the original space. Gaggero et al. (2020) applied POD techniques to generate propeller geometries based on reduced dimensionality design spaces. By using KLE method, D’Agostino et al. (2020) optimized the calm-water resistance of DTMB-5415 ship by reducing the dimensionality of the design space.