A novel variable vector construction method based on sensitivity analysis for Bayesian-based nonparametric modeling of ship maneuvering motion

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ABSTRACT

In this paper, a novel construction method of variable vectors based on sensitivity analysis for nonparametric modeling of ship maneuvering motion is proposed to improve the prediction accuracy and generalization ability of the nonparametric model. Firstly, based on the derivation of the discrete mathematical expressions of Abkowitz model, the relationship between the variables in the variable vectors for system identification of ship hydrodynamic derivatives is discussed. Secondly, in order to optimize the mathematical expressions of the widely used low-dimensional variable vectors, sensitivity analysis of the hydrodynamic derivatives is carried out, and the variables that correspond to the hydrodynamic derivatives with high sensitivity are considered in the variable vectors to perform dimensionality raising. Bayesian-based Gaussian process regression is utilized to establish the nonparametric model of ship maneuvering motion. Finally, contrastive simulation tests are carried out among the low-dimensional variable vectors, the high-dimensional variable vectors and the proposed variable vectors. The results show that no matter the training dataset is clean or polluted by the noise, the proposed method always has the highest prediction accuracy, indicating that reasonable mathematical expressions of variable vectors can break the upper limit of the performance of the identification algorithm.

KEY WORDS: ship maneuvering; nonparametric modeling; sensitivity analysis; feature engineering; variable vector; Gaussian process regression.

INTRODUCTION

In recent years, the development of MASS (Maritime Autonomous Surface Ships) has received increasingly attention because of the multiple needs of shipping companies for reducing crew employment, improving efficiency and enhancing reliability (Ramos et al., 2019). One of the key technologies of MASS is autonomous navigation (IMO, 2018). Thanks to the application of INS (Integrated Navigation System) and IBS (Integrated Bridge System), it is not very difficult for a ship to sail autonomously in the open waters. However, when a ship performs complex operations such as collision avoidance, berthing, formation movement and gate crossing, the existing intelligent control algorithms cannot yet support the complete independence of MASS, which can be attributed to the increasing difficulty of ship manipulation. Without a reliable mathematical model for describing ship’s dynamic characteristics, it is difficult to design a controller with engineering application value (Breivik et al., 2008; Sutulo and Guedes Soares, 2014). Therefore, the modeling of ship maneuvering motion is of great significance for improving the level of ship intelligence and realizing the autonomous navigation.

With the development of system identification (SI) technology, the establishment of ship dynamic model for the prediction of ship maneuvering motion through data-driven method has been extensively studied and achieved satisfactory results. The existing SI technology for ship dynamic modeling can be divided into parametric modeling and nonparametric modeling. The first and key step of these two methods is to construct the variable vector based on the data collected from the free-running model tests or full-scale trials. For parametric modeling approach, the variable vector should be constructed under the consideration of the structure of the identified ship dynamic model. The high-dimensional variable vectors were constructed based on Abkowitz model (Luo and Zou, 2009), with which the hydrodynamic derivatives were identified by support vector machine (SVM). The core idea of the construction method of variable vectors in parametric modeling is to analyze the expression of the definite ship dynamic models, and then get the multiple linear regression equations. Nonparametric modeling approach represented by SVM, artificial neural network (ANN) and Gaussian process regression (GPR) does not need any prior knowledge, which brings the advantages of easy-to-operate on the one hand, but also leads to the lacking clear principles of the variable vector construction on the other hand. Existing studies mostly construct the variable vector as a low-dimensional one with the expression of \([u, v, r, \delta]\), where \(u, v, r\) and \(\delta\) are the motion state variables, and \(\delta\) is the control variable (Wang et al., 2020b; Ouyang and Zou, 2021; Ouyang et al., 2023), and till now, to the best knowledge of the authors, there are no special discussions on the construction method of variable vectors in the nonparametric modeling of ship maneuvering motion. There have been many discussions and studies on the construction method of variable vectors in the machine learning area, especially in the feature engineering. For the dataset with few variables similar to the ship motion data, researchers have proposed various approaches to raise the dimensionality of variable vectors reasonably to achieve better classification or regression results (Jalal, 2018). Liu et al (2008) extended the kernel feature vector of an image to a kernel feature matrix for visual recognition. This extension means using multiple similarities to measure two images. Dai et al (2020) predicted the phase formation of high entropy alloys based on feature engineering with a small dataset, and the descriptor dimensionality is augmented from original small dimension to high dimension by non-linear combinations. Kennedy et al

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