Available online at www.sciencedirect.com
ScienceDirect
Journal of Hydrodynamics
2017,29(5):879-893
DOI: 10.1016/S1001-6058(16)60800-4
www.sciencedirect.com/
science/journal/l0016058

Particle image velocimetry measurement of velocity distribution at inlet duct of waterjet self-propelled ship model *

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(Received July 8, 2015, Revised March 7, 2016)

Abstract: A vehicle-mounted three-dimensional underwater particle image velocimetry (PIV) device is used in a towing tank to measure the velocity distribution of the inlet duct of a waterjet ship model in a self-propulsion test. The following points are shown through a comparison of the influences of the stationary and free states of the ship model on the measured results: (1) during the test, the ship attitude will change, specifically, the ship model will heave and trim, (2) the degree of freedom disturbs the processing of the pixel images enough to distort the subsequent image processing, (3) the stationary state of the ship model is the optimal mode for measuring the velocity distribution using the PIV device, and (4) if the changes must be considered, the man-made heaving and trimming may be pre-applied, and be made a corrected stationary mode. In addition, the momentum effect coefficient and the energy effect coefficient are calculated in a non-uniform inflowing state, and the related factors affecting the two coefficients are analyzed. The test results show that the pumping action of the waterjet creates a transverse vector in the cross-sectional speed, which increases the non-uniformity of the inflow. These results could help to establish the design requirements for a waterjet-propelled ship type.

Key words: Particle image velocimetry (PIV), velocity distribution profile, degree of freedom, transverse vector

Introduction

The waterjet propulsion is used for high-speed ships with an increasing frequency. Compared with a traditional propeller system, the waterjet propulsion is characterized by the high resistance to cavitation, the low appendage resistance, the low noise, the good operability, and the adaptability to a wide range of working conditions[1]. The common types of waterjet-propelled ships include the high-speed catamarans, the hydrofoil craft, the sidewall hoverships, and the trimarans.

In its 20th general meeting, the International Towing Tank Conference (ITTC) organization formed the Specialist Committee on Waterjets, which is committed to the experimental research of waterjet-propelled ships. After research and development for a period of more than a decade, during its 24th general meeting, the ITTC standardized a test procedure for the waterjet propulsion, that is, the testing and extrapolation methods for predicting the waterjet propulsive performance of a high-speed marine vehicle[2]. In this test procedure, the momentum flux method is used to determine the propulsive performance of a waterjet propulsor in a ship model. When the waterjet propulsor is in operation, a portion of the inflow is the water flow close to the ship's hull. According to the boundary-layer theory[3], the velocity of the water flow has a large gradient and is lower than the ship's speed[4]. The proportion of the low-speed flow pumped into the propulsor has a great effect on the propulsion system[5]. Therefore, the waterjet propulsion theory introduces the momentum effect and energy effect coefficients, to be used to describe the effects of the non-uniform inflow caused by the ship's hull on the propulsive performance and to analyze the conversion of the system efficiency more accurately in a later stage.

The research results show that the accurate measurement of the velocity distribution at each station in the test procedure is the key to the determination of the propulsive efficiency and the performance of the waterjet propulsion system[6]. Therefore, this is the

* Project supported by the National Natural Science Foundation of China (Grant Nos. 51379043, 51209048 and 51409063).
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most important and challenging part of the experimental research. Over the past few decades, there has been continuous development work done on self-propulsion tests for waterjet propelled ship models[7,8]. There are three test methods for measuring the velocity distribution of each station: (1) using a differential pressure transducer, (DPT), (2) the laser Doppler velocimetry (LDV), and (3) the particle image velocimetry (PIV). The DPT is essentially a mechanical measurement technology, whose sensitivity and resolving ability will affect the accuracy of the measurement. The LDV is targeted at a single point in space, and its applications are very limited. The PIV can be used to measure a complex flow field, and to provide rich spatial information and flow characteristics about the flow fields of an entire plane.

These three test methods have been used in a large number of studies in both China and abroad. In its 23rd general meeting, the ITTC selected the scientific survey ship “Athena” of the United States Navy as the prototype for research on a waterjet propulsor and ship hull system[9,10]. In its 24th general meeting, the participant institutions submitted their research results on the self-propulsion test. Park et al.[11,12] conducted experimental research of the pressure distribution of the flow channels of a waterjet propulsor in a wind tunnel without using the water medium, to provide a detail understanding of complicated flow phenomena of a flush type intake duct of waterjet. Kim and Chun[13] conducted experimental research of an axial-flow waterjet propulsor model. During this test, the DPT technology was used to measure the velocity distribution at each station of the waterjet propulsor with the water medium, In addition, the effect of the gap between the blade tip and the tube wall on the propulsive performance of the waterjet propulsor was studied, and results showed that the efficiency difference according to the gap variation (1.5% of diameter and 0.7% of diameter) was about 25% in their overall efficiency. Chun et al.[14] and Kim et al.[15] conducted numerical and experimental researches of a waterjet propulsion system, and applied the waterjet propulsion system to an amphibious tracked vehicle, to analyze the effect of different impeller diameters on its propulsive performance, with the conclusions that the waterjet size should be optimized according to the weight and the size of amphibious military vehicles. Jessup et al.[16] conducted research of the hydrodynamic performance of a joint high-speed sealift (JHSS) ship model with four axial-flow waterjet propulsors. The LDV technology was used to measure the velocity distribution at stations 1, 3, and 6 on the starboard side of the ship model, and together with the wall static pressure waterhead, the technology was also used to measure the pressure distribution at each station. Meanwhile, Jessup conducted research of the power-performance differences between axial and mixed flow waterjets for different ship types, and the results showed that the axial flow waterjet is better suited for high speed ships. The LDV measurement method that he used was subsequently integrated into the test procedure of the ITTC[17]. Wu et al.[18,19] used the two-dimensional PIV and the three-dimensional PIV, respectively, to conduct experimental research of the tip leakage vortex of an axial-flow waterjet propulsion pump blade. Although their research focused on the performance of the impeller blade, it also involved a few important applications of the PIV technology to a waterjet propulsor.

In China, the Marine Design and Research Institute of China (MARIC) has built a comprehensive performance test bench for the waterjet propulsion[20], which can be used to conduct the pump performance tests, the internal characteristics tests, and the reliability tests for both model pumps and real pumps. Chang et al.[21] conducted a bench performance test and a self-propulsion research for a new type of waterjet propulsor. In their self-propulsion research, a numerical simulation was conducted by using the computational fluid dynamics (CFD). With the DTMB5415 ship model as a prototype ship in full scale, Yang et al.[22] conducted comparative research of the noise source distributions and the hydrodynamic performances of the waterjet propulsion and a traditional propeller system, and analyzed the effects of waterjet propulsion on the free surface of the ship’s stern. In their studies, numerical computations were used without any actual experiment. In China, self-propulsion tests for waterjet-propelled ship models also started. However, in view of the rigorous requirements placed on the testing device and the complexity of the analysis and processing of self-propulsion test data, most of the research results of self-propulsion tests in China were limited to numerical computations.

Judging by the above mentioned research history, a great progress has been made on the self-propulsion tests for waterjet-propelled ship models. Due to the constraints of the PIV equipment and experiment conditions[23,24], experiment researches based on the applications of the PIV equipment were few in the velocity distribution measurement for a waterjet self-propelled ship model in a towing tank. The accurate measurement of the velocity distribution at each station in the test procedure is the key to the calculation of the inlet duct loss coefficient, the outlet nozzle loss coefficient, the pump efficiency and the volume flow rate through the waterjet system. Therefore, this is the most important and challenging part of the experimental research. As one of the most advanced test method, the successful application of the PIV will contribute to the methods for measurements of the velocity distribution. The flow details in