International Journal of Naval Architecture and Ocean Engineering xxx (2017) 1–13

Contents lists available at ScienceDirect

International Journal of Naval Architecture and Ocean Engineering

journal homepage: http://www.journals.elsevier.com/international-journal-of-naval-architecture-and-ocean-engineering/

Uncertainty assessment for a towed underwater stereo PIV system by uniform flow measurement

Bum Woo Han [a], Jeonghwa Seo [b,*], Seung Jae Lee [b], Dong Myung Seol [c], Shin Hyung Rhee [b,d]

[a] Hyundai Maritime Research Institute, Hyundai Heavy Industries, Co. Ltd., Ulsan, Republic of Korea
[b] Research Institute of Marine Systems Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul, Republic of Korea
[c] Defense Acquisition Program Administration, Seoul, Republic of Korea
[d] Dept. of Naval Architecture and Ocean Engineering, Seoul National University, Seoul, Republic of Korea

ARTICLE INFO

Article history:
Received 26 December 2015
Received in revised form
1 November 2017
Accepted 24 November 2017
Available online xxx

Keywords:
Stereoscopic particle image velocimetry
Towing tank experiment
Test uncertainty

ABSTRACT

The present study aims to assess test uncertainty assessment method of nominal wake field measurement by a Stereoscopic Particle Image Velocimetry (SPIV) system in a towing tank. The systematic uncertainty of the SPIV system was estimated from repeated uniform flow measurements. In the uniform flow measurement case, time interval between image frames and uniform flow speed were varied to examine the effects of particle displacement and flow around the SPIV system on the systematic standard uncertainty. The random standard uncertainty was assessed by repeating nominal wake field measurements and the estimated random standard uncertainty was compared with that of laser Doppler velocimetry. The test uncertainty assessment method was applied to nominal wake measurement tests of a very large crude oil carrier model ship. The nominal wake measurement results were compared with existing experimental database by other measurement methods, with its assessed uncertainty.

1. Introduction

The flow field around a ship's hull is a very important issue in improving its hydrodynamic performance; however, it is highly complex due to flow characteristics, that is, turbulence, Three-Dimensional (3D) separation, and free-surface effects. Because of difficulties in direct measurements of a flow field around a full-scale ship, flow field measurements and analysis around a hull have mainly been attempted in laboratory scale models. For example, wake flow measurement results of a scaled model have been used for practical ship and propeller design.

For provision of flow field measurement results, test uncertainty of experiments must be assessed and given with test results. Longo and Stern (2005) suggested a method for investigating test uncertainty associated with towing tank tests and applied it to assess uncertainty of a flow measurement test using Pitot tubes for a surface combatant model. Kume et al. (2006) investigated flow field around Very Large Crude oil Carrier (VLCC) model and provided the results with the test uncertainty. The International Towing Tank Conference (ITTC) (ITTC, 2008a) provides a practical guidance to assess test uncertainty of conventional flow and force measurements in a towing tank.

In recent years, a non-intrusive optical technique such as particle image velocimetry (PIV) has been applied to flow measurements in towing tanks and replacing conventional Pitot tube measurements of which test procedure and uncertainty assessment are well established, as stated above. Gui et al. (2001a, 2001b) applied the window masking technique to a Two-Dimensional (2D) PIV system in a towing tank for measuring a wake field behind a surface-piercing plate. They also reconstructed Three-Dimensional (3D) wake structure by stacking 2D flow measurement results for a surface combatant without a propeller. The window masking technique was made possible to reduce systematic errors on the mean velocity and Reynolds stress measurement. Seo et al. (2016a) carried out 2D PIV measurements of the wake behind a VLCC model in self-propulsion conditions.

The Stereoscopic PIV (SPIV), which employs two cameras to get a planar velocity field with Three-Component (3C) velocity vectors, has been introduced to towing tank tests: wake flow measurements behind a propeller (Anschau and Mach, 2007; Seo et al.,

* Corresponding author.
E-mail address: thamjang@snu.ac.kr (J. Seo).
Peer review under responsibility of Society of Naval Architects of Korea.

https://doi.org/10.1016/j.ijnaoe.2017.11.005
2092-6782/

Nomenclature

b	Systematic standard uncertainty [-]
D	Dynamic range [-]
Fr	Froude number based on L_{PP} and U_{input} [-]
k	Turbulence kinetic energy $\left(\frac{1}{2}(\overline{u'u'}+\overline{v'v'}+\overline{w'w'})\right)$ [m^2/s^2]
L_{PP}	Length between perpendiculars [m]
N	Number of data samples [-]
R	Radius of the propeller model [m]
Re	Reynolds number based on L_{PP} and U_{input} [-]
s	Random standard uncertainty [-]
T	Thickness of the laser sheet [m]
Δt	Time interval between laser pulses [μs]
U_{95}	Expanded uncertainty with 95% confidence level [-]
U_{beacon}	Beacon-measured towing carriage speed [m/s]
U_{input}	Towing carriage speed input [m/s]
U_{wheel}	Wheel encoder-measured towing carriage speed [m/s]
u, v, w	Velocities in (*x, y, z*) directions [m/s]
$\overline{u}, \overline{v}, \overline{w}$	Ensemble-averaged velocities in (*x, y, z*) directions [m/s]
$\overline{u'u'}, \overline{v'v'}, \overline{w'w'}$	Reynolds normal stresses in (*x, y, z*) directions [m^2/s^2]
$\overline{u'v'}, \overline{u'w'}, \overline{v'w'}$	Reynolds shear stresses [m^2/s^2]
x, y, z	Cartesian coordinates in the physical coordinate system [m]

2016b), a tidal stream turbine (Seo et al., 2016c), and a model ship in captive dynamic maneuvering tests (Yoon et al., 2015). Although SPIV is now a relatively mature measurement technique, its practical applications in a towing tank are still in a development phase, thus a test uncertainty assessment procedure for towing tank tests is in demand.

Uncertainty of convectional PIV with Two-Components (2C) has been investigated in many studies (Raffel et al., 1998; ITTC, 2008b; Nobach and Bodenschatz, 2009; Timmins et al., 2012; Sciacchitano et al., 2013; Wilson and Smith, 2013). It is known that a significant portion of the overall uncertainty of PIV systems comes from cross-correlation and sub-pixel estimation algorithms. However, test uncertainty of a PIV system in the towing tank can be more sensitive to certain environmental conditions than analysis algorithms (Seol et al., 2013). The environmental factors include flow-induced vibration of submerged optical instruments, large distortion of images due to limitations of optical arrangements, and limited number of images acquired during a towing carriage run.

Measuring a low-turbulence uniform flow is an effective approach to estimate the systematic uncertainty of PIV systems for use in a towing tank. Grizzi et al. (2010) suggested a novel calibration approach based on uniform flow measurements. Their flow-based method does not require the target plate for spatial calibration of the SPIV system, thus eliminating errors derived from the calibration target misalignment. By uniform flow measurements, Yoon et al. (2015) carried out systematic uncertainty assessment of atowed underwater SPIV system.

In this paper, we present a test uncertainty assessment method of a SPIV system in a towing tank, focusing on nominal wake measurement. This paper was intended as a comparable reference for researchers or experimenters who are carrying out SPIV measurements in a towing tank. A SPIV system was installed to the towing tank of Seoul National University (SNU) and its test uncertainty was assessed based on the procedure of ITTC (2008b) and Yoon et al. (2015). The test uncertainty assessment method was applied to nominal wake measurement for a VLCC model and the results and uncertainty are compared with existing experimental data obtained by different experimental methods.

This paper is organized as follows. Section 2 shows principles of test uncertainty assessment for nominal wake measurement tests. Details of the experimental setup are followed in Section 3. Section 4 and 5 explain results of uniform flow and nominal wake measurements, respectively. The summary and conclusions of this work are presented in Section 6.

2. Test uncertainty assessment procedure

In SPIV tests, instantaneous velocity vectors (*u, v, w*) are acquired during a carriage run and ensemble-averaged. The ensemble-averaged velocity vectors $(\overline{u}, \overline{v}, \overline{w})$ are presented as test results. The expanded uncertainty of the ensemble-averaged velocity, i.e., $U_{\overline{u},95}$, $U_{\overline{v},95}$, and $U_{\overline{w},95}$, should be assessed.

The expanded standard uncertainty with 95% confidence level is calculated from systematic and random standard uncertainty (ASME, 2005). Data reduction equations of $(\overline{u}, \overline{v}, \overline{w})$ in SPIV measurement are quite complicate, therefore it is hard to identify each elemental error source and assess elemental systematic standard uncertainty, which are required for deriving $b_{\overline{u}}$, $b_{\overline{v}}$, and $b_{\overline{w}}$. In this study, instead of elemental systematic standard uncertainty and uncertainty propagation, uniform flow measurement was repeated to get a measurement population mean for comparison with independent measurements. Random standard uncertainty, $s_{\overline{u}}$, $s_{\overline{v}}$, and $s_{\overline{w}}$ could be evaluated by obtaining the standard deviation of repeated nominal wake measurement with large number of carriage runs.

SPIV measurements provide planar velocity field and the test uncertainty is not homogeneous on the plane. It is reported that test error increases near the edge of the field of view, while the center region shows less error (Seol et al., 2013). A test uncertainty value should consider spatial variation. In this study, a representative standard uncertainty that contains 95% of local standard uncertainty on a measurement plane was defined from the spatial mean and spatial root-mean-square (RMS) of assessed local test uncertainty by assuming Student's distribution, as follows.

$$(\text{Representative standard uncertainty}) = \sqrt{(\text{Spatial mean})^2 + 2 \times (\text{Spatial RMS})^2}$$

Uncertainty propagation in non-dimensionalization procedure is also considered in this study. Once an ensemble-averaged flow field is obtained, physical properties of length and velocity dimensions are non-dimensionalized by R and U_{beacon}, respectively.

In addition, Reynolds stresses are derived from instantaneous velocity field measurement results and presented as dimensionless values, after being divided by U_{beacon}^2. The expanded uncertainty of Reynolds stresses is also assessed in this study.

3. Experimental set-up

3.1. Towing tank

Experimental measurements were conducted in the towing tank, which is 110 m long, 8 m wide, and 3.5 m deep. A schematic drawing of the towing tank is shown in Fig. 1. The towing carriage for speeds from 0.100 to 5.000 m/s is driven by four servo-motors, and its speed is controlled by a closed loop feedback system.