ITTC Quality System Manual

Recommended Procedures and Guidelines

Guideline

Laboratory Modelling of Currents

7.5	Process Control
7.5-02	Testing and Extrapolation Methods
7.5-02-07	Loads and Responses
7.5-02-07-01	Environmental Modelling
7.5-02-07-01.6	Laboratory Modelling of Current

Updated / Edited by	Approved
Specialist Committee on Modelling Environmental Conditions of 29th ITTC	29th ITTC 2021
Date 10/2020	Date 06/2021

Table of Contents

Laboratory Modelling of Currents

1. PURPOSE OF GUIDELINE

The purpose of this recommended guideline is to help laboratories in conducting tests on current. The guideline addresses, among other things, current interaction with waves, turbulence intensity, horizontal and vertical variations, and measurement techniques.

2. INTERACTION WITH WAVES

Interaction between waves and current shall be considered when modelling current in wave basin, as the interaction with waves may affect the wave steepening.

Regarding the mutual wave-current interaction, it is generally conceived that currents can significantly affect wave fields, especially when waves propagate in opposite direction (Peregrine et al. (1976)). Significant attention has been paid to the modulation instability of gravity waves under the influence of background currents, which is regarded as a significant mechanism in the generation of rouge waves. Most of these studies have been primarily theoretical and numerical. Hjelmervik and Trulsen (2009) derived a nonlinear Schrodinger equation suitable for waves propagating on inhomogeneous currents, and studied the generation of freak waves on opposing currents and the effect of nonlinearity on the linear refraction effect. Onorato et al. (2011) transformed the modified NLS equation of Hjelmervik and Trulsen (2009) to a standard form. The numerical results show that freak waves can be triggered after a stable wave train encounters an opposing current. Furthermore, it is found that the maximum amplitude of the freak wave depends on the ratio of current velocity and wave group velocity. Toffoli et al. (2013) experimentally confirmed the results of Onorato et al. (2011). Choi (2009) investigated the evolution of fully nonlinear modulated wave trains in both positive and negative shear currents using a pseudo-spectral method, and revealed that the envelope of the modulated wave train grows faster in a positive shear current and slower in a negative shear current. Similar results have also been found in Nwogu (2009). Cheng et al. (2009) used the homotopy analysis method to investigate nonlinear wave-current interaction.

All the above studies were focused on deep-water waves. In the case of finite depth, a significant change on the evolution of modulated wave trains has been observed. Ma et al. (2013) conducted wave basin experiments to investigate the influence of opposing currents on the growth of the modulation instability in finite depth. The results show that opposing currents can speed up the growth of modulation instabilities.

It is well known that modulation instability of gravity waves is a special phenomenon of near-resonant interactions, but it is unclear how the exact resonance can be affected by the background current field. Further extension to exact resonance was performed by Waseda et al. (2015). A series of experiments were conducted in a narrow channel to investigate the four-wave exact resonant interactions under the influence of current. It was found that the effect of advection and refraction of the surface gravity wave by the random current field can be considered as the resonance detuning factor, and the spectral tail tends to be suppressed as a result of the resonance detuning operated by the current.

The previous mentioned analyses are limited to the evolution of regular wave packets including near-resonant and exact-resonant waves.

Despite some attempts with irregular wave fields (e.g. Toffoli et al. (2011)), it is not clear yet whether, and to what extent, the current field affects wave amplitude growth and the probability of extremes in more realistic random wave fields. Recently, the dynamics of random waves on adverse current gradients is assessed experimentally in three independent facilities by Toffoli et al. (2015). It indicates that the presence of a current is capable of amplifying nonlinear wave dynamics and thus can enhance the occurrence of extremes in a random wave field.

3. VERTICAL PROFILES

Many previous studies indicated that the vertical velocity profiles of an open channel flow and long shore currents are well described by the logarithmic law. In wave basins or flumes, current velocity profiles can be reproduced by different layers of pumps or specific devices such as perforated walls. (see for instance Lu et al. (2006, 2007, 2008), Shan et al. (2010)). For example by running six powerful pumps and the rpm's of each pump are tuned individually to reproduce stratified current profiles, as described in Buchner et al. (2008).

4. HORIZONTAL VARIATION

Buchner et al. (2008) measured the current velocity at different positions in the facility, over the measurement area (about 20 m wide). It was observed that for the typical measurement area of a project (a few squared meters) the mean current velocity variations are within a few percent. It was concluded that with a dedicated current modelling system in a model basin, it is possible to achieve a constant current over the measurement area with low variations in time and space.

To produce horizontal variations of currents, Chawla and Kirby (2002) used a modified flume with a gradually narrowed part to generate gradually increasing currents. Ma et al. (2010) used a bottom topography (a smooth, impermeable submerged bar) to increase the speed of the opposing current up to reach wave blocking.

5. CURRENT GENERATION

Current is generated by re-circulating the water, either in the basin or outside the basin. Typical aspects for the generation of currents depend on the system used for circulating the water. In general, current generation in shallow water is easier than in deep water because of the smaller volume of water that needs to be displaced. The following aspects have to be accounted for in generation of currents:

- Horizontal profile: the generated current needs to be as constant as possible over the width of the test section
- Vertical profile: the generated current needs to follow the specified vertical profile as close as possible.
- Turbulence: current turbulence is generally defined by:

$$T_{VF} = \frac{\sigma(V_F)}{\overline{V_F}}$$

where $\sigma(V_\mathrm{F})$ is the standard deviation of the current velocity and $\overline{V_\mathrm{F}}$ is the arithmetic mean of the current velocity.

The turbulence should ideally match the prototype situation, but in practice the prototype turbulence level is unknown. As viscous effects are not scaled properly, the model scale turbulence can be expected to be higher than in the prototype situation.

Considering that the turbulence levels of flow field can affect the accuracy of the results of deepwater model tests, it is essential to investigate the turbulence distribution in the measuring area. In general, the turbulence intensity in the measuring area should be below 5%. In order to achieve low turbulence intensity, specific structures such as perforated walls, flow guiding vanes, mixing chambers and turbulence grids etc. need to be set in the inflow and outflow culvert (e.g. Lu et al. (2006)).

However, evaluation of the turbulence level based on standard deviation only is not sufficient. A spectral analysis of measured current velocity should be performed to evaluate the current turbulence near the natural frequencies of the mooring system, to avoid large (unnatural) effects on the low frequency mooring behaviour (Buchner et al. (2001)).

In some cases a highly sheared vertical current profile is specified, e.g. for a hurricane inertial current (Buchner et al. (2008)). It is important to realise that generating such as sheared current in a model basin can lead to extreme turbulence levels due to the viscosity of water at model scale and the strong changes in velocity between current layers.

6. OSCILLATORY FLOW

As a typical prototype of tropical storm conditions, oscillatory flow is applied in current experiments or simulations by applying sinusoidal oscillatory flow, random oscillatory flow and any combination of the above conditions. For example, an oscillatory velocity of up to 2.5 m/s with a period of 13.0 s is representative of a prototype 100-year return period tropical storm condition in a water depth greater than 40 m in the region of the North West Shelf in Australia, An et al. (2013).

Oscillatory flow around a circular cylinder is governed by the Keulegan-Carpenter number:

$$K_{\mathrm{C}} = \frac{A_{\mathrm{VF}} T}{D}$$

and frequency number:

$$\beta = \frac{Re}{K_C} = \frac{D^2}{\nu T}$$

where A_{VF} is the amplitude of oscillatory velocity, T is the period of the oscillatory velocity, ν is the kinematic viscosity of fluid, Re is the Reynolds number and D is the diameter of the cylinder (characteristic linear dimension).

Under certain conditions, the flow in the boundary layer is only dependent on the vertical coordinate z that is perpendicular to the seabed and can be described by a one dimensional vertical (1DV) wave boundary layer (WBL) model. In the existing investigations, both oscillatory flow (e.g. Jensen et al. (1989), Yuan and Madsen (2014)) and surface waves (e.g. Sleath (1970)) are used to study the wave induced flow near the seabed.

The equation of motion for 1DV WBL can be written as (Nielsen, 1992)

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\partial}{\partial z}\left(\nu_e \frac{\partial u}{\partial z}\right)$$

where u is the horizontal velocity, t is the time, ρ is the density of the fluid, x is horizontal coordinate, z is the vertical coordinate measured from the theoretical bottom elevation of the bed and ν_e is the eddy viscosity. Considering the pressure is hydrostatic in the horizontally uniform flow and we have the term (Nielsen, (1992))

$$\frac{\partial U_0}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial x}$$

where U_0 is the horizontal velocity in the free stream. For a sinusoidal wave U_0 can be written as $U_0 = U_\infty e^{i\omega t}$, where U_∞ is the velocity amplitude in the free stream; ω is the angular frequency. Then the equation of motion becomes (Nielsen, (1992))

$$\frac{\partial}{\partial t}\left(u - U_\infty e^{i\omega t}\right) = \frac{\partial}{\partial z}\left(\nu_e \frac{\partial u}{\partial z}\right)$$

The solution for the equation of motion can be described by the following equation,

$$u(z,t) = [1 - \chi(z)]U_\infty e^{i\omega t}$$

where $\chi(z)$ is the so-called defect function (see Nielsen (1992)), denoted as *DF* hereafter, which represents the velocity deficit relative to the free stream velocity.

7. MEASUREMENTS

Regarding current measurement techniques, the 27th ITTC Specialist Committee on Detailed Flow Measurements provided a comprehensive review of the state-of-the-art for flow-field and wave-field measurements in ship hydrodynamics and ocean engineering applications. Applications of Particle Image Velocimetry (PIV), stereoscopic PIV (SPIV), Laser Doppler Velocimetry (LDV), Particle Tracking Velocimetry (PTV), holography, and other emergent methods for the measurements of flow separation, wake, vortex strength, etc., are described in detail in ITTC (2014).

In addition to the methods mentioned in the review above, Song et al. (1994) measured the velocity and turbulence structure of non-uniform flows using the acoustic Doppler velocity profiler (ADVP). Song and Chiew (2001) measured the velocity profile of non-uniform flows using acoustic Doppler velocimetry (ADV) and confirmed that the vertical velocity was non-zero. Lu et al. (2007, 2008) also adopted ADV to measure the current speed in the wave basin.

Figure 1. Example of Acoustic Doppler Velocimeter (from Shan et al. (2010))

8. REFERENCES:

An, H., Luo, C., Cheng, L., White, D., 2013, "A New Facility for Studying Ocean-Structure - Seabed Interactions: The O-Tube", Coastal Engineering, Vol. 82, pp 88 – 101.

Buchner, B., de Wilde, J., Dijk, A. V., 2001, "Numerical Multiple Body Simulations of Side-by-Side Mooring to an FPSO", Proceedings of the International Society of Offshore and Polar Engineering, ISOPE, Vol. 1, pp 343 – 353.

Buchner, B, de Wilde, J., 2008, "Current Modeling Experience in an Offshore Basin", Proceedings of the ASME 27th International Conference on Ocean, Offshore and Arctic Engineering, OMAE2008-57597, Estoril, Portugal.

Chawla, A., Kirby, J.T., 2002, "Monochromatic and Random Wave Breaking at Blocking Points", Journal of Geophysical Research, Vol. 107, pp 4-1 – 4-19.

Cheng, J., Cang, J., Liao, S.J., 2009, "On the Interaction of Deep Water Waves and Exponential Shear Currents", Zeitschrift für angewandte Mathematik und Physik, Vol. 60, pp 450 – 478.

Choi, W., 2009, "Nonlinear Surface Waves Interacting with a Linear Shear Current", Mathematics and Computers in Simulation, Vol. 80, pp 29 – 36

Hjelmervik, K., Trulsen K., 2009, "Freak Wave Statistics on Collinear Currents", Journal of Fluid Mechanics, Vol. 637, pp 267 – 284.

ITTC, 2014, "Specialist Committee on Detailed Flow Measurement Techniques", Final Report and Recommendations to the 27th ITTC, 2014.

Jensen, B. Sumer, B. M., Fredsøe, J., 1989. "Turbulent Oscillatory Boundary Layers at High Reynolds Numbers", Journal of Fluid Mechanics, Vol. 206, pp 265 – 297.

Lu, H. N., Yang, J. M., Peng, T., 2006, "Characteristics of Current Generation in the New Deepwater Offshore Basin", Proceedings of the ASME 25th International Conference on Ocean, Offshore and Arctic Engineering, OMAE2006-92140, Hamburg, Germany.

Lu, H. N., Yang, J. M., Peng, T., 2007, "Hydraulic Performances of Current Generation System in the New Deepwater Offshore Basin", Proceedings of the ASME 26th International Conference on Ocean, Offshore and Arctic Engineering, OMAE2007-29087, San Diego, USA.

Lu, H. N., Yang, J. M., Li, R. P., 2008, "Features of Current Generation and the Application in New Deepwater Offshore Basin", Proceedings of the ASME 25th International Conference on Ocean, Offshore and Arctic Engineering, OMAE2008-57120, Estoril, Portugal.

Ma, Y., Ma, X., Perlin, M., 2013, "Extreme Waves Generated by Modulational Instability on Adverse Currents", Physics of Fluids, Vol. 25.

Ma, Y., Dong G.H., M. Perlin, X.Z. Ma G. Wang, J. XU, 2010, "Laboratory Observations of Wave Evolution, Modulation and Blocking Due to Spatially Varying Opposing Currents", Journal of Fluid Mechanics, Vol. 661, pp 108 – 129.

Musumeci, R.E., Cavallo, L., Foti, E., Scandura, P., 2006, "Waves Plus Currents Crossing at a Right Angle: Experimental Investigation", Journal of Geophysical Research, Vol. 111.

Nielsen, P., 1992, "Coastal Bottom Boundary Layers and Sediment Transport", Advanced Series on Ocean Engineering, Vol. 4

Nwogu, O. G., 2009, "Interaction of Finite-Amplitude Waves with Vertically Sheared Current Fields", Journal of Fluid Mechanics, Vol. 627, 179 – 213.

Olabarrieta, M., Medina, R., Castanedo, S., 2010, "Effects of Wave–Current Interaction on the Current Profile", Coastal Engineering, Vol. 57, pp 643 – 655.

Onorato, M., Proment, D., Toffoli, A., 2011, "Triggering Rogue Waves in Opposing Currents", Physical Review Letters, Vol. 107.

Peregrine, D. H., 1976, "Interaction of Water Waves and Currents", Advances in Applied Mechanics, Vol. 16, pp 9 – 117.

Qi, W. G., Gao, F. P., 2014,. "Physical Modeling of Local Scour Development Around a Large-Diameter Monopile in Combined Waves and Current", Coastal Engineering, Vol. 83, pp 72 – 81.

Toffoli, A., Bitner-Gregersen, E., 2011, "Extreme and Rogue Waves in Directional Wave Fields", The Open Ocean Engineering Journal, 4, 24-33.

Toffoli, A., Waseda, T., Houtani H., 2013, "Excitation of Rogue Waves in a Variable Medium: An Experimental Study on the Interaction of Water Waves and Currents", Physical Review E, Vol. 87.

Toffoli, A., Waseda, T., Houtani, H., 2015, "Rogue Waves in Opposing Currents: an Experimental Study on Deterministic and Stochastic Wave Trains", Journal of Fluid Mechanics, Vol. 769, pp 277 – 297.

Shan, T., Lu, H., Yang, J., Li, R., 2010, "Numerical, Experimental and Full-Scaled Investigation on the Current Generation System of the New Deepwater Offshore Basin", Proceedings of the ASME 29th International Conference on Ocean, Offshore and Arctic Engineering, OMAE2010-20604, Shanghai, China.

Sleath, J., 1970, "Velocity Measurements Close to the Bed in a Wave Tank", Journal of Fluid Mechanics, Vol. 42, Vol. 111 – 123.

Song, T., Graf, W. H., Lemmin, U., 1994, "Uniform Flow in Open Channels with Movable Gravel Bed", Journal of Hydraulic Research, Vol. 32, pp 861– 876.

Song, T., Chiew, Y., 2001, "Turbulence Measurement in Nonuniform Open-Channel Flow Using Acoustic Doppler Velocimeter (ADV)", Journal of Engineering Mechanics, Vol. 127, pp 219 – 231.

Waseda, T., Kinoshita T., Cavaleri, L., 2015, "Third-Order Resonant Wave Interactions Under the Influence of Background Current Fields", Journal of Fluid Mechanics, Vol. 784, pp 51 – 73.

Yuan, J., Madsen, O. S., 2014, "Experimental Study of Turbulent Oscillatory Boundary Layers in an Oscillating Water Tunnel". Coastal Engineering, Vol. 89, pp 63 – 84.