ITTC Quality System Manual

Recommended Procedures and Guidelines

Guideline

Laboratory Modelling of Wind

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
7.5-02-07-01.5	Laboratory Modelling of Wind

Updated / Edited by	Approved
Specialist Committee on Modelling Environmental Conditions of 29th ITTC	29th ITTC 2021
Date 1/2020	Date 06/2021

Table of Contents

Laboratory Modelling of Wind

1. PURPOSE OF GUIDELINE

The purpose of this recommended guideline is to help laboratories in conducting tests on wind above water surface. Basic considerations for model tests with wind are presented in this guideline. The guideline addresses, among other things, interaction with waves, vertical and horizontal variations and different measurement techniques.

2. WIND MODELLING

Wind loading is one of the important environmental loads to be considered for the design of offshore structures, especially in the design of station keeping systems.

Wind velocity consists of mean and fluctuating parts in space and time, and the induced wind load has mean and fluctuating parts accordingly. In the following sections aspects of mean (steady) wind and fluctuating (irregular) wind are discussed.

2.1 Steady wind

As the wind fluctuation frequency is often higher than the ship or offshore structure motions, the steady wind force becomes the dominant factor to assess floater responses. In that case steady wind resulting in steady wind forces may be used in model tests. Ideally, a low level of wind fluctuation in the tests is desirable. However, if low frequency excitation is an important design factor, e.g. for station-keeping tests of an offshore platform, a wind spectrum shall be applied.

In the design of offshore structures, steady wind speeds are generally taken as the average speed occurring over a period of one hour. The steady speeds are considered to be the mean speed measured at a reference height, typically 10 m (full scale) above the mean still water level. A mean wind speed corresponding to a 100-year return period should be used in the design, based on the marginal distribution of wind speeds at the specific location, Chakrabarti (2005).

2.2 Wind Spectra

Wind gusting is commonly assumed to be a Gaussian stochastic process, which can be fully described by a wind spectrum.

Many spectral models have been proposed such as API (The American Petroleum Institute), NPD (The Norwegian Petroleum Directorate) wind spectrum, etc. In API (2005), DNV (Det Norske Veritas (2014) also an overview of wind spectra is presented. A selection of wind spectrum formulations are given in the following:
(API)

$$S_{API}(f) = \frac{\sigma(z)^2}{f_p\left(1+1.5\frac{f}{f_p}\right)^{5/3}} \tag{2.1}$$

where, $S_{API}(f)$ [(m/s)^2/Hz] is the spectral energy density at frequency f [Hz],
with

$$\sigma(z) = I(z)U(z) \tag{2.2}$$

$$I(z) = \begin{cases} 0.15\left(\frac{z}{z_s}\right)^{-0.125} & \text{for } z \le z_s \\ 0.15\left(\frac{z}{z_s}\right)^{-0.275} & \text{for } z > z_s \end{cases} \tag{2.3}$$

where z is the elevation above sea level [m], z_s= 20 m is the thickness of the “surface layer”, $U(z)$ is the 1-hour mean wind speed at elevation z, and

$$f_p = \frac{\alpha}{z} U(z) \tag{2.4}$$

with $0.01 \leq \alpha \leq 0.1$.

For measured wind spectra the average value of f_p is given by $\alpha = 0.025$.

(NPD)

$$S_{NPD}(f) = \frac{320\left(\frac{U_0}{10}\right)^2 \left(\frac{z}{10}\right)^{0.45}}{\left(1+\tilde{f}^{0.468}\right)^{3.561}} \tag{2.5}$$

where $S_{NPD}(f)$ [(m/s)^2/Hz] is the spectral energy density at frequency f [Hz], and

$$\tilde{f} = \frac{172 f \left(\frac{z}{10}\right)^{2/3}}{\left(\frac{U_0}{10}\right)^{3/4}} \tag{2.6}$$

where U_0 is 1-hour mean wind speed at an elevation of 10 m above sea level [m/s].

Also in Davenport (1961), and Ochi and Shin (1988) typical wind spectrum formulations are presented.

The specified duration of random simulations of wind is important to achieve stationary irregular conditions: typically, a duration of 1 hour for seakeeping and 3 hours in offshore engineering is applied, same as for wave conditions.

2.3 Turbulence

It is known that the turbulence intensity of wind in the boundary layer on sea surface is about 0.1~0.2. The definition of the turbulence intensity is presented as follows:

$$\sigma_T(z) = I(z)/U(z) \ldots \text{for } z>z_s \tag{2.7}$$

Here $I(z)$ is the wind velocity variance and $U(z)$ is the mean wind speed at elevation z. The level of turbulence intensity should be measured in the model tests.

Simulation of turbulence characteristics of wind was presented in Ozono et al. (2006), using a multi-fan type wind tunnel. A uniformly active mode (usually employed in tank tests) can reproduce longitudinal fluctuations. Details of wind generation techniques are presented in Section 3 of this guideline.

2.4 Gusting and squalls

2.4.1 Gusting

Wind gusting is commonly assumed to be a Gaussian stochastic process, which can be fully described by a wind spectrum.

Kristensen et al. (1991) revealed that gusting is a statistical measure and the probability density function can be derived from the spectrum of wind-speed variations. Myrhaug (2007) considered the wind gust spectrum affected by wave age and the results demonstrated a clear effect of wave age on the wind gust spectrum over wind waves. Prediction of wind gusts today still relies on parameterizations. Sheridan (2011) conducted a review of techniques and research for gust forecasting and parameterization. Beran et al. (2005) used the MM5 to model and forecast offshore winds and conducted series of validations.

There is no widely accepted expression for elevation and gust factors suitable for engineering purpose. At present, measurements available for West Africa from Nigeria to Angola, (Santala et al. (2014)) and in the Gulf of Mexico, (Jeans et al. (2014, 2016)) may be useful.

Although limited information on gust on the sea is currently available as reference for modeling of wind gusts in model tests, fluctuating wind velocities can be reproduced with a wind generator. In the region of minimum and maximum wind velocity, it should be confirmed that the Reynolds effect of the wind can be ignored. Whether this is the case depends on the objective of the model tests. This is further discussed in Section 3 of this guideline.

2.4.2 Squalls

A squall is a strong transient wind event generated by a convective storm. There are no widely accepted elevation and gust factors for squalls suitable for engineering purpose at present. Santala et al. (2014) compared the expressions of the wind gust elevation profile and gust factors for squall winds with that for non-squall winds presently in API and ISO standards. The presented results may lead to an improved treatment of squall events for offshore engineering applications. In case of calibration of squall conditions in model tests, this information may be used as reference.

As a squall measurement system in the actual sea, the West Africa Gust (WAG) Joint Industry Project (JIP) may present useful information (Jeans et al. 2008). The reference discussed in the previous paragraph refers to the same JIP.

2.5 Vertical profiles

Very limited full-scale data along the height is available to identify and reliably establish a description of the vertical wind profile. It is well known, however, that the vertical profile of the wind is developed by the sea surface roughness. When a more detailed model test condition is expected to reproduce a real sea situation, it is desirable to also reproduce the vertical wind profile in the basin. This can however be challenging in practice, as it requires a large number of wind fans in vertical direction (see Section 3).

As conventional treatment, there is the power law model, the average 1-hour wind speed at a height z above sea level (the 1-hour mean wind profile) is given by (API, 2005),

$$U(z) = U_0 \left(\frac{z}{z_R}\right)^{0.125} \tag{2.8}$$

where $U(z)$ is 1-hour mean wind speed at elevation z [m] above sea level [m/s], U_0 is 1-hour mean wind speed at elevation of 10 m above sea level [m/s], z_R=10 m is the reference elevation above sea level.

Vertical wind profiles in tornadic and non-tornadic supercell environments, Markowski et al. (2003), show that considerable differences exist in vertical profiles within 1 km from ground.

Analytical/empirical models of downburst winds that characterize their spatiotemporal features are employed in terms of a time function and a vertical profile of gust-front winds Kwon and Kareem (2013).

The shape of the vertical wind profiles and the related parameter of the Weibull distribution are impacted by the atmospheric internal boundary layers developing from the coast along the wind direction Calidonna et al. (2015).

2.6 Horizontal variation

Generated wind by blowers or fans should cover the entire model, considering the range of wave motions and drift in the facility. In case of wind energy convertor’s the area of complete wind farms can extend to several square kilometers. In the model test, the modeled wind field is expected to simulate the real situation with respect to velocity and variance in the entire area. In practice however, it can be difficult, to control a state of the wind in transverse direction. Variance in horizontal wind direction can only be realized in the basin using multiple wind generators.

2.7 Geographical consistency of wind conditions

It is recommended that the characteristic wind spectrum of the installation area is also employed in the model test. Examples of specific phenomena occurring in some conditions or specific locations can be provided.

For example, in a strong typhoon, turbulence intensity decreases with increasing mean wind speed and remain almost constant when the wind speed becomes high (Cao et al. (2009)). In the German Bight, wind speed turbulence intensity increases with increasing wind speed because of increasing wave height and surface roughness Türk and Emeis (2010)

2.8 Interaction with waves

In heavy sea conditions, wind and wave interaction may not be ignored. The basic interaction between wind and waves is presented in Tian et al (2010) and Buckley and Veron (2016). Moreover, wave interaction effects caused by wind under limited condition are described in Miles (1993), Kharif et al. (2009), Waseda and Turin (1999), and Galchenko et al. (2012).

These publications focus on the wind generation due to the change of wave surface elevation. In this situation, wind condition caused by the rough waves should be represented by the wind profile form developed by the wave condition. Qualitatively and quantitatively analyses of wind interaction effect with waves are expected in model testing.

3. GENERATION TECHNIQUES

Propeller and sirocco type wind generators are typically used in model tests. The wind blowing area should be at least twice the model characteristic length. Numerous small size fans are recommended to simulate wind condition with expected turbulence, profile, horizontal variation as shown in the figure below.

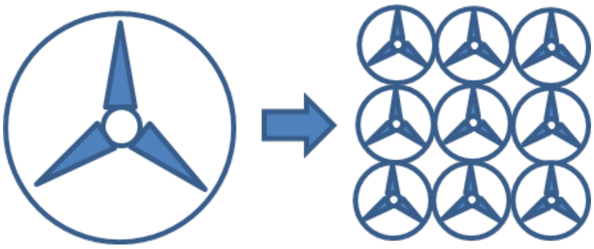

Figure 1: Recommended example (right side) of the wind fan arrangement.

In the simulation of turbulence characteristics using the multi-fan type wind tunnel, Ozono et al. (2006), uniformly in active mode (usually employed in tank tests), relatively large anisotropy and spatial correlation coefficient in stream wise direction, can reproduce longitudinal fluctuations in a plane. Particularly at lower frequencies lack of 3D vertical structures, and the quasi-grid mode has similar characteristics as the conventional grid turbulence.

Most commonly wind *forces* are calibrated rather than wind *velocities* to avoid scale effects of the wind velocities which are generally not reproduced when applying Froude scaling. Furthermore, wind fields may not be constant due to limited number of wind fans and recirculation effects in the basin, (Buchner et al. (1999)). Wind forces can be calibrated with a wind fan setup, by mounting the model in a fixed force frame and deriving a calibration curve of the measured wind loads vs wind fan rpms. Usually, changes of projection area are required even with well fabricated model topsides due to difference of Reynolds number and uncertainties in the model and wind speeds.

In a similar way the required wind loads can also be applied by a wire-winch setup. In both cases target wind loads (mean and fluctuating) can be applied. The advantages and disadvantages of the two systems are discussed below:

Wind fan setup: a setup with wind fans is generally assumed to be most realistic, as it includes dynamic wind effects of floating structure moving in wind and waves, e.g. changes in wind force due to change in heading, lift effects, etc. Also shielding effects needed in tandem model test setups are automatically included when simulating wind by wind fans.

Wind winch setup: with a winch setup the applied load is not changing with heading changes of the model and is always known (measured) throughout the model test. It is therefore easier to include the wind loads measured during model tests in a numerical model. However, dynamic effects and shielding effects are not taken into account when using a wind winch to apply wind loads.

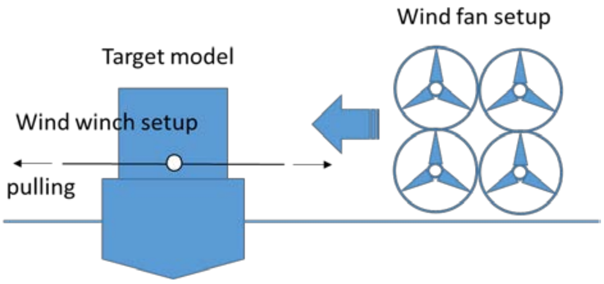

Figure 2: Images of the wind fan setup (right) and wind winch setup arrangement (left) for wind force modelling.

For model testing of offshore wind turbines the generation of a high-quality wind field in a model basin is of great importance for the correct coupling between the aerodynamic and hydrodynamic behavior of floating wind turbines (FWT). However, the normal wind quality in a typical model basin is not good enough for the required modelling of the wind field for a wind turbine. In De Ridder et al. (2014) a dedicated wind fan setup for the testing of offshore wind turbines is described. The objective of this setup is to improve the uniformity of the wind field in the area of the wind turbine and reduce turbulence.

Another approach to model the aerodynamic loads on an offshore wind turbine is Real-Time Hybrid Model testing (ReaTHM testing) as described in Sauder et al. (2016). The advantage of this method compared to the physical modelling of the wind in an ocean basin, is that it solves the Froude-Reynolds scaling conflict, which is a key issue in FWT testing. ReaTHM testing allows for more accurate testing also in transient conditions, or degraded conditions, which are not feasible yet with physical wind.

Which generation technique should be applied depends strongly on the application and the objective of the model tests. If the intention is to include wind loading on a model than the wind forces should be calibrated either by applying wind fans or a winch. If the wind velocity is relevant for the application, in most cases for offshore wind turbines, either a dedicated wind fan setup or the ReaTHM approach should be considered.

4. MEASUREMENTS

For practical ocean engineering applications, pitot tubes, hot-wire thermos and ultrasonic anemometers etc. are usually employed to measure the wind velocity to verify turbulence and the realized wind profile. For model testing the same instruments are usually used. Note that for model testing the required accuracy level for Froude-law scaling is much larger. For a 1/100 model scale the required accuracy is 10 times larger.

Depending on the application and on the calibration type, i.e. wind velocity or loads, one or more sensors may be required in the testing area. An indication on the required number of sensors can be found in De Ridder et al. (2014) for the calibration of wind velocities for a wind farm setup.

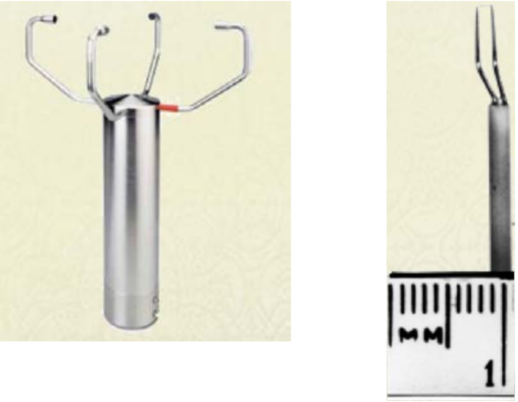

Figure 3: Examples of ultrasonic anemometer (left) and hot wire (right).

5. REFERENCES

API (American Petroleum Institute), 2005, “Design and Analysis of Stationkeeping Systems for Floating Structures”, Recommended Practice 2SK, 3rd Edition, pp. 59-62.

Beran, J., Calveri, L., Lange, B., von Bremen, L., 2005, “Offshore Wind Modelling and Forecast”, WRF/MM5 Users' Workshop, pp.1-5.

Chakrabarti, S., 2005, “Handbook of Offshore Engineering”, Elsevier, pp.123.

Buchner, B., Wichers, J.E.W., De Wilde, J.J., 1999, “Features of the State-of-the-art Deepwater Offshore Basin”, Offshore Technology Conference, OTC-10841, pp.1-11.

Buckley, M.P., Veron, F., 2016, “Structure of the Airflow above Surface Waves”, Journal of Physical Oceanography, Vol.46, pp.1377-1396.

Calidonna, R. C., Gullì, D., Avolio, E., Federico, S., Lo Feudo, T., Sempreviva, A., 2015, “One Year of Vertical Wind Profiles Measurements at a Mediterranean Coastal Site of South Italy”, Science Direct, Energy Procedia, Vol.76, pp.121-127.

Cao, S., Tamura, Y., Kikuchi N., Saito M., Nakayama I., Matsuzaki, Y., 2009, “Wind Characteristics of a Strong Typhoon”, Journal of Wind Engineering and Industrial Aerodynamics, Vol.97, pp.11-21.

Chakrabarti, S., 2005, “Handbook of Offshore Engineering”, Elsevier, Vol. 1, 2005

Davenport, A. G., 1961, “The spectrum of horizontal gustiness near the ground in high winds”, Journal of the Royal Meteorological Society, Vol.87, Issue372, pp.194-211.

De Ridder, E., Otto, W., Zondervan, G. J., Huijs, F., Vaz, G., 2014, “Development of a Scaled-Down Floating Wind Turbine for Offshore Basin Testing, In Proceedings of the ASME 33th International Conference on Offshore Mechanics and Arctic Engineering, OMAE2014-23441, pp.1-11.

DNV (Det Norske Veritas), 2014, “Environmental Conditions and Environmental Loads”, Recommended Practice, DNV-RP-C205, p.18.

Galchenko, A., Babanin, A. V., Chalikov, D., 2012, "Influence of Wind Forcing on Modulation and Breaking of One-Dimensional Deep-Water Wave Groups", Journal of Physical Oceanography, Vol.42, pp.928-939.

Jeans, G., Cooper, C., Yetsko, C., Bryan ,G., 2014, "Squall Characterization in the Gulf of Mexico", Offshore Technology Conference, OTC-25357, pp.1-13.

Jeans, G., Cooper, C., Yetsko, C., 2016, "New Squall Wind Criteria for the Gulf of Mexico", Offshore Technology Conference, OTC-27204, pp.1-13.

Jeans G., Redford S., Bellamy I., Mundy R., 2008, "The WAG Squall Measurement System", In Proceedings of the ASME 27th International Conference on Offshore Mechanics and Arctic Engineering, Estoril, Portugal, OMAE2008-57337.

Kharif, C., Giovanangeli, J. P., Touboul, J., Grare1, L., Pelinovsky, E., 2009, "Influence of Wind on Extreme Wave Events: Experimental and Numerical Approaches", Journal of Fluid Mechanics, Vol. 594, pp.209-247.

Kristensen, L., Casanova, M., Courtney, M.S., Troen, I., 1991, "In Search of a Gust Definitio", Boundary-Layer Meteorology, Vol. 55, pp.91-107.

Kwon D. K., Kareem, A., 2013, "Generalized Gust-Front Factor: A Computational Framework for Wind Load Effects", Engineering Structures, Vol.48, pp.635-644.

Markowski, P., Hannon, C., Frame, J., Lancaster, E., Pietrycha, A., 2003, "Characteristics of Vertical Wind Profiles near Supercells Obtained from the Rapid Update Cycle", Weather and Forecasting, Vol.18, pp.1262-1272.

Miles, J., 1993, "Surface-Wave Generation Revisited, Journal of Fluid Mechanics, Vol. 256, pp.427-441.

Myrhaug D., 2007, "Wind Gust Spectrum Over Waves: Effect of Wave Age", Journal of Ocean Engineering, Vol. 34, pp.353–358.

Ochi, M. K., Shin, Y. S., 1988, "Wind Turbulent Spectra for Design Consideration of Offshore Structures", Offshore Technology Conference, OTC5736.

Ozono S., Nishi A, and Miyagiet H., 2006, "Turbulence Generated by a Wind Tunnel of Multi-Fan Yype in Uniformly Active and Quasi-Grid Modes", Journal of Wind Engineering and Industrial Aerodynamics, 94. pp.225-240.

Santala J. M., Calverley, M., Taws, S., Grant, H., Watson, A., Jeans, G., 2014, "Squall Wind Elevation/Gust Factors and Squall Coherence", Offshore Technology Conference, OTC-25249-MS, pp.1-8.

Sauder, T., Chabaud, V., Thys, M., Bachynski, E. E., Sæther, O. L., 2016, "Real-Time Hybrid Model Testing of a Braceless Semi-Submersible Wind Turbine. Part I: the Hybrid Approach, In Proceedings of the ASME 35th International Conference on Offshore Mechanics and Arctic Engineering, OMAE2016-54435, pp.1-13.

Sheridan, P., 2011, "Review of Techniques and Research for Gust Forecasting and Parameterization", Forecasting Research Technical Report, Vol. 570, Met office, pp.1-19.

Tian, Z., Perlinet, M., Choi, W., 2010, "Observation of the Occurrence of Air Flow Separation Over Water Waves", In Proceedings of the ASME 29th International Conference on Offshore Mechanics and Arctic Engineering, OMAE2010-20576, pp.1-9.

Türk, M., Emeis S., 2010, “The Dependence of Offshore Turbulence Intensity on Wind Speed”, Journal of Wind Engineering and Industrial Aerodynamics, pp.466-471.

Waseda, T., Tulin, P.M., 1999, “Experimental Study of the Stability of Deep-Water Wave Trains Including Wind Effects, Journal of Fluid Mechanics, Vol. 401, pp.55-84.