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A Method for Computational and Experimental Analysis of the Moored Wind Turbine Seakeeping

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Abstract

The paper presents a proposal of the method for analysis of the moored wind turbine's float seakeeping, elaborated by Ship Design and Research Centre S.A. for the purpose of the project realized for VISTAL WIND POWER Ltd. The analysis started with preliminary seakeeping prediction realized with the use of CFD solver coupled with 6DOF module, in which the sliding mesh approach was used to handle the moving object. The numerical analysis included modelling the characteristics of the mooring tethers with equivalent force approach (such an approach was presented e.g. by Pascoal et al. [1]). Evaluation of the tether characteristics was realized numerically with the use of lumped mass method. As the results of numerical study revealed satisfactory performance of the proposed wind turbine float design, further experimental tests of the physical model of the float were realized. The mooring tethers were modelled by direct scaling of the full scale tethers, which prevented truncation errors and allowed for direct validation of the numerical analysis. The paper is focused on the reliability and accuracy of the numerical methods used in the analysis of slender moored object.

Introduction

The goal of the realized numerical computations and experiments was the assessment of maximum tension in mooring lines and maximum amplitudes of the float's motion in assumed extreme weather conditions and at worst direction of wind and wave, i.e. both aligned with one pair of the mooring tethers. Numerical analysis of the floating, moored wind turbine turned out to be a quite challenging problem for CTO S.A. due to lack of ready, dedicated tools for time-domain simulations of off-shore objects with taking into account the dynamics of the mooring system. It was decided to use a combined approach, based on in-house software for mooring analysis and versatile, but time-consuming RANSE-CFD flow solver. Using RANSE for seakeeping analyses is still unusual but not completely new; one of the first significant works focused on using the RANSE solver for simulations of floating objects in waves was presented already in 2001 by Azcueta [2] (simulations in regular waves). During last years, complex simulations in irregular waves were presented (Ley et al. [3]). In the present work, two attempts on numerical assessment of the required quantities were done:

- In first of them, the object was exposed to series of regular waves in order to evaluate the response amplitude operators (RAO). The parameters of hydrodynamic response were then evaluated using the computed RAOs and spectral density of the energy of specified irregular wave;
- Second attempt consisted in exposing the floating wind turbine directly to irregular wave of specified spectrum type, characteristic height and peak period.

Preliminary numerical verification of the floating turbine was followed by seakeeping tests in the towing tank. Due to the fact that the mooring tethers in the analysed case were aligned with the wave direction, it was possible to reproduce their geometry directly in narrow tank, which improved the reliability of the experiment and allowed for providing a good material for verification of the numerical method.

Method of Numerical Computations

Basic Assumptions

- The RANSE flow model was applied, and the free surface problem was solved using the volume of fluid method. The computations were carried out at model scale to reduce computational time and to enable direct comparison with the experiment. The STAR-CCM+ solver was used;
- The flow solver was coupled with the rigid body motion module. In the analysed case, only three degrees of freedom were considered: pitch, heave and surge. Also, due to symmetry of the flow, only one half of the geometry was represented directly;
- Presence of the pair of mooring tethers aligned with the wave direction was modelled by equivalent force; it is assumed that this force is a function of the fairlead location only, i.e. dynamics effects were neglected. It was proved that such an approach is justified for the analysed case – the details are given in the subsection concerning modelling the mooring system.

Modelling the Waves

Both approaches (regular and irregular waves) require correct modelling of the wave motion of water, i.e. the waves propagating in the computational domain must preserve the required parameters (height and period), and reflections of the waves within the domain must be minimized. Generating of the waves in the computational domain is realized by application of appropriate boundary condition at the domain inlet, i.e. unsteady water level and unsteady velocity distribution, both evaluated according to linear wave theory. Preventing the reflections of wave within the computational domain is possible by introducing the damping zone in the vicinity of the outlet of the domain, in which artificial momentum source terms are active, resulting in damping of the vertical component of the water velocity.

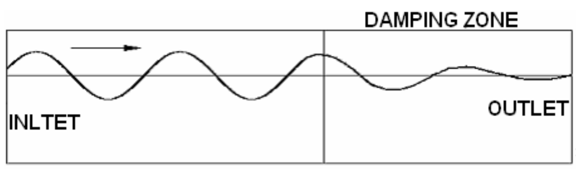

Figure 1. Modelling the waves – scheme

Subsequent 2D test computations were carried out in order to find out the solver setting allowing for correct modelling of both regular and irregular waves.

In case of regular waves, control of correctness of the resulting wave is relatively simple. A visual assessment of the wave shape in the time intervals corresponding to one theoretical wave period allows for verification if the wave height and period are preserved. Oscillations or numerical damping can be easily detected. Figure 2 shows the shape of regular wave (in distorted scale) after 1 period and after 25 periods for two different settings of the solver.

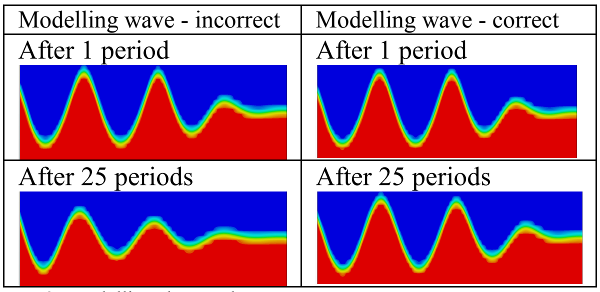

Figure 2. Modelling the regular waves

It was found that the following solver's settings are sufficient for correct modelling of regular waves at model scale typical for towing tanks: time step 0.005 s, 5 iterations per one time step, second-order discretization of unsteady terms in momentum equations. This is obviously not the only possible combination – such settings were selected as a reasonable compromise between accuracy and computational time. The detailed mesh dependency study was not realized, as it is difficult to make general statements in this case. The mesh used in the 2D tests and later on in real case was characterized by approximately 15 cells per wave height and 40 cells per wave length. Such a density proved to be sufficient.

Control of the correctness of irregular wave modelling is much more complex and requires spectral analysis of the resulting wave to enable comparing the obtained energy spectrum with the theoretical one. Sampling the wave elevation vs. time can be done by integrating the volume fraction of water in selected vertical section of the domain. A comparison between theoretical JONSWAP spectrum and the spectrum of the wave simulated with CFD is shown in figure 3. The wave was simulated with the solver settings based on the regular wave analysis described above.

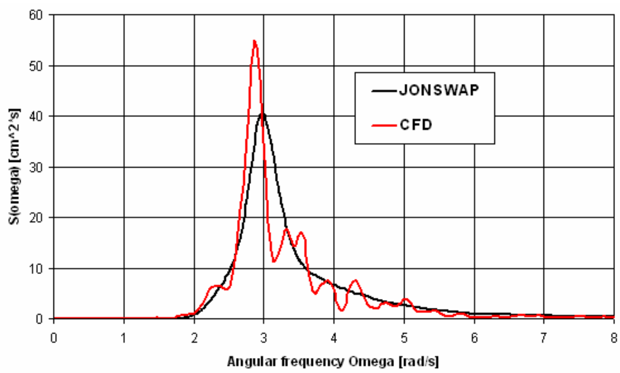

Figure 3. Comparison between theoretical JONSWAP spectrum and actual spectrum of the wave obtained in CFD

Noticeable discrepancies can be observed between theoretical and actual spectrum, and the characteristic parameters are also somewhat different, i.e. significant height of the actual wave is lower by 13%, and the characteristic period is longer by 7%. However, it was decided to continue the analysis with the obtained wave as presented above, as it was considered sufficient for the purposes of preliminary analysis.

Modelling the Mooring System

As mentioned above, the mooring system was modelled in the CFD computations using the equivalent force approach. This means that the force exerted by the mooring system is computed in each time step according to algebraic formula, evaluated on the basis of known characteristics of the mooring system, identified previously with the use of external software.

In the presented case, characteristics of the mooring tethers were identified with the use of in-house software based on lumped mass method and the algorithm described in [4]. The lines and chains are discretized by point masses linked with linear, weightless springs, as presented in figure 4.

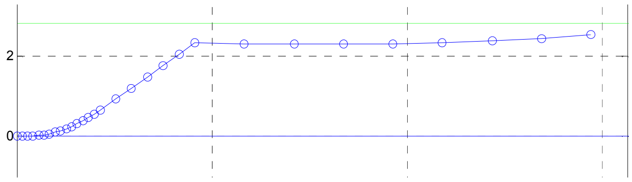

Figure 4. Discretization of the mooring tether in the lumped mass method

The mentioned algorithm is dedicated for dynamic analyses of the mooring tethers, i.e. it usually becomes unstable if the end point of the tether does not move at all. However, it can be used for evaluating also static characteristics of the tethers by enforcing small oscillations of the end point around specified point. Figure 5 shows the comparison of computed static characteristics of a multi-component tether at model scale, compared with measured characteristics. Very good agreement was achieved.

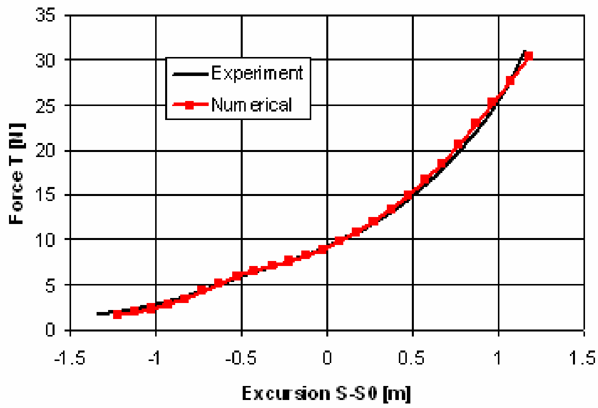

Figure 5. Comparison between computed and measured static characteristics of the mooring tether.

In general case, the reaction of the mooring tether depends not only on the excursion of the fairlead, but also on its velocity and acceleration. However, in some cases neglecting the dynamic effects is acceptable, which greatly simplifies evaluating the formula for equivalent force. The program for analysis of the tethers was then used to check how much the motion frequency influences the amplitude of tension in the tether. It was found that in the range of frequencies, for which the spectral density of energy of analysed wave is significant, the amplitude of tether's tension does not depend on the frequency, so neglecting the dynamic effects is justified in the analysed case. The equivalent force modelling the reaction of the mooring system was then introduced to the simulation as a horizontal force acting on the fairlead, dependent only on the fairlead's excursion relative to specified point of equilibrium; polynomial function was assumed.

Meshing

The analysed situation requires long simulation time both in case of regular waves (multiple runs for subsequent wave frequencies) and irregular waves (the motion records must be long enough to enable reliable spectral analysis). Moreover, the simulation settings result in time-consuming computations due to using second-order temporal discretization. For that reasons, minimizing the number of mesh cells is of highest importance. On the other hand, simple cylindrical shape of the float and its small diameter compared to draught allow using simple mesh structure and narrow domain. Handling the motion of the floating object requires using the dynamic mesh, i.e. the mesh cells must move with the object during the flow simulation. This problem was solved using the "sliding mesh" approach, in which the computational domain is divided into two subdomains: one of them, spherical or cylindrical , surrounding the analysed object, is moving together with it (rotational and translational motion), while the outer subdomain undergoes only translational motion. The details of computational mesh are presented in figures 5 and 6.

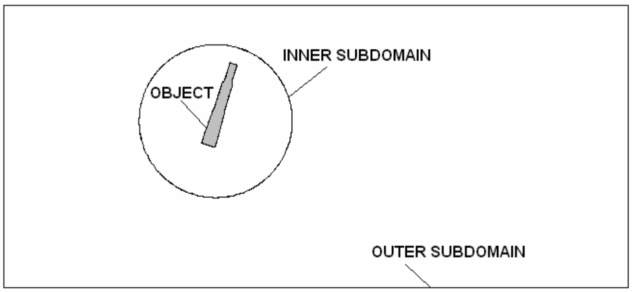

Figure 5. Computational domain

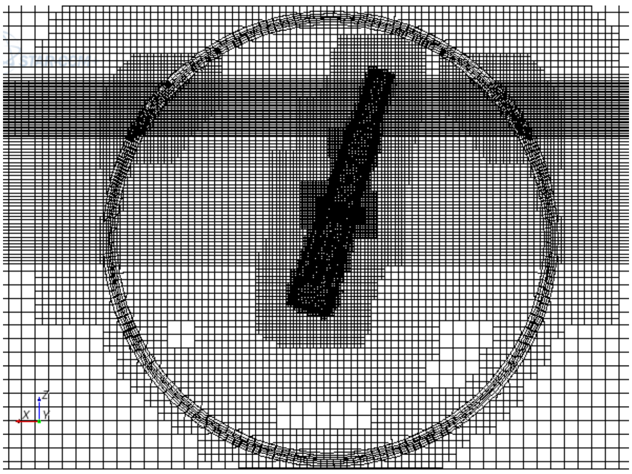

Figure 6. Computational mesh details

The total number of mesh cells was kept low, i.e. about 450 000 cells. Example of visualization of the simulation in irregular wave is presented in figure 7.

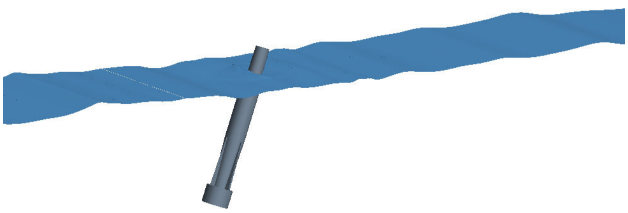

Figure 7. Visualization of the CFD results

Method of the Experiment

The experimental analysis of the seakeeping of wind turbine's float was carried out in auxiliary towing tank (65m x 7m x 3m) equipped with paddle wavemaker and wave damping beach The water elevation was recorded by single wave probe located at the same distance from the wavemaker as the float. The model scale was adjusted to the wavemaker capacity, i.e. largest possible model was built, for which the wavemaker was able to reproduce the required sea state at model scale. The assumed water depth was also reproduced almost exactly. The wave loads were modelled directly by generating the wave characterized by specified energy spectrum, while the steady wind load was modelled by using reverse "fan approach", i.e. the propeller mounted on the float was working as a fan, generating the specified force. The thrust vs. rpm characteristics of the fan were identified previously on a separate stand. The mooring system of the analysed wind turbine consists of four tethers, and the analysed case corresponds to extreme load of one tether, i.e. the wave propagation direction and the wind direction are coincident and aligned with one pair of the tethers (figure 8).

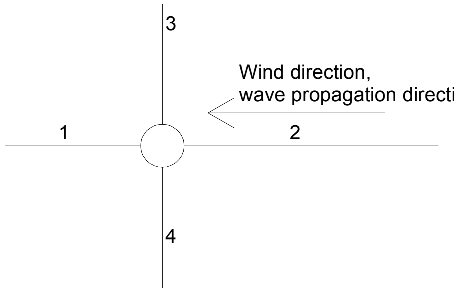

Figure 8. Scheme of the analysed situation

In the situation shown above, modelling of tethers denoted with 3 and 4 becomes of minor importance and it is sufficient to take them into account only by introducing constant tension, which was realized by appropriate weights hanging on both sides of the towing tank. On the other hand, tethers 1 and 2, which are crucial in this analysis, could be modelled directly due to sufficient space in the longitudinal direction of the towing tank. The length of entire installation was approximately 31m.

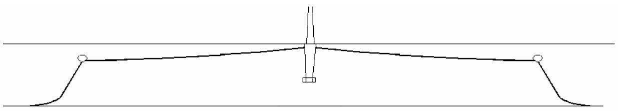

Figure 7. Scheme of the analysed situation

The measurement equipment consisted of the 6DOF trajectory tracking system KRYPTON and two load cells, measuring the tension in the mooring tethers. The model tests were carried out primarily in irregular waves. Only sample runs in regular waves were realized to provide a direct reference for validation and further refinement of the CFD model.

Results of CFD vs. Results of Model Test

At first, the in-house software used for analysis of the mooring tethers was verified by applying the measured motion of fairlead to the end point of the tether and comparing the computed tension with measured tension. The comparison is presented in figure 10. Good agreement reveals satisfactory accuracy of the developed software. The measured motion of fairlead was also used as an input for the formula used in the CFD simulation for computing the equivalent mooring force. Also in this case, the resulting time history of the tether tension was very close to the measured one, which confirms the validity of the assumption that the influence of dynamic effects on the tether tension can be neglected in the analysed situation.

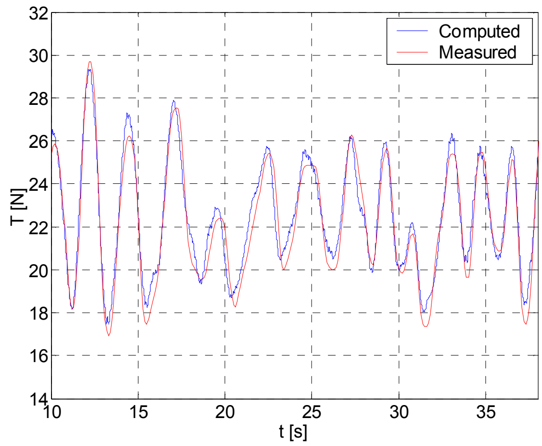

Figure 10. Computed vs. measured tension of mooring tether

The CFD computations in regular waves were carried out in order to identify the response amplitude operators (RAO) of the object's response to waves. Interpretation of the results was problematic due to the fact that the resulting response to periodic wave was non-periodic. An example of computed pitch angle in short regular wave is presented in figure 11.

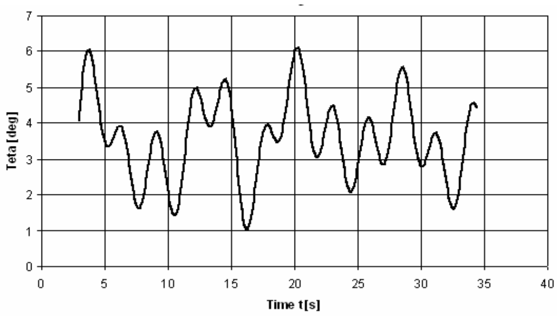

Figure 11. Pitch angle in regular wave, computed with CFD

Such a result was initially considered an error of numerical model and the amplitudes of response were estimated by averaging the amplitudes of subsequent oscillations. However, sample experimental runs in regular waves revealed that the response of analysed wind turbine to regular waves is indeed non-periodic. The actual cause of such behaviour was not yet identified. As a result, the response amplitude operators based on CFD turned out to be considerably underestimated, and so was the prediction of seakeeping in irregular wave. Table 1 presents sample results of prediction based on CFD vs. experimental prediction.

	CFD	Exp	Err. %
Heave [cm]	2.53	3.70	-31.5
Pitch [deg]	1.37	1.62	-15.4

Table 1. Results of CFD in regular waves vs. experiment

The discrepancy of predicted force in mooring tether was even larger and definitely not acceptable, even at preliminary stage.

As a reference for CFD computations in irregular wave, one of trial experimental runs was selected, for which the wave energy spectrum was also not perfectly fitting the theoretical JONSWAP spectrum, but was close to CFD spectrum (see figure 12). Comparison of significant amplitudes of surge, heave, pitch and force in windward mooring tether obtained from CFD and experiment is presented in table 2. It can be seen that reasonable agreement between CFD and experiment was achieved for all analysed quantities.

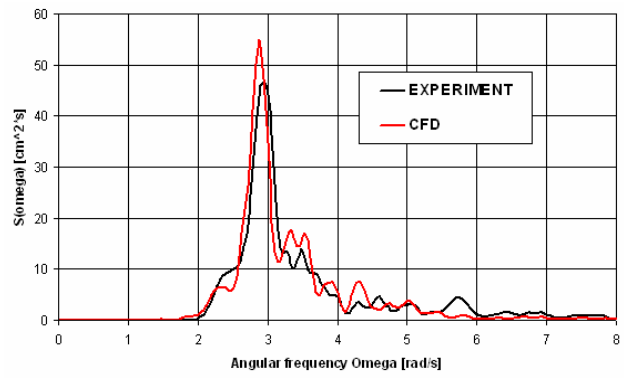

Figure 12. Wave energy spectra – CFD vs. experiment

	CFD	Exp	Err. %
Surge [cm]	7.66	7.11	-7.7
Heave [cm]	3.20	3.04	-5.3
Pitch [deg]	1.83	1.96	6.6
Force [N]	6.39	6.78	5.8

Table 2. Results of CFD in irregular waves vs. experiment

Conclusions

- The software for numerical analysis of the mooring tethers, based on lumped mass method, provided very accurate prediction of static characteristics of the multi-component tether. It also allowed checking how much the dynamic effects influence the mooring line tension. The experiment proved that neglecting the dynamic effects was a justified simplification.
- CFD analysis in regular waves turned out to be inefficient due to problems with correct evaluation of response amplitude operators for motion and forces in mooring lines.
- The results of CFD analysis in irregular wave are in good agreement with the experimental results, obtained for the wave characterized by similar energy spectrum. Moreover, the computational time is comparable to total time of analysis in regular waves due to the fact that the results are one long run instead of many short runs (the computational time of the run in irregular wave was 4 days on 8 processors).
- The elaborated numerical method of seakeeping analysis of moored objects can be thus considered a valid tool for verification of the construction at design stage.

Acknowledgments

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