Validation of Offshore load simulations using measurement data from the DOWNVInD project

M. Seidel, F. Ostermann
REpower Systems AG
Franz-Lenz-Str. 1, 49084 Osnabrück, Germany
Mail: m.seidel@repower.de

Curvers, A.P.W.M. – Energy research Centre of the Netherlands (ECN), Petten, The Netherlands
Kühn, M.; Kaufer, D. – Endowed Chair of Wind Energy, University of Stuttgart, Germany
Böker, C. – ForWind, Institute for Steel Construction, Leibniz University Hannover, Germany

Summary

Integrated analysis of the wind turbine including the complete support structure is an important task for modern wind turbines. This paper presents calculation methods to accomplish this task and validation results from comparative calculations and measurements. The results show that the coupling methods yield good results, although additional validation is still required to finally conclude on the accurateness which can be expected.

1. Introduction

As Offshore wind turbines are erected in deeper waters, substructures are becoming more complex. This does require more sophisticated methods and analysis tools compared to standard codes available because the interaction of the RNA (rotor-nacelle-assembly) and substructure as well as local dynamics become more pronounced. Fig. 1 is showing examples of mode shapes involving both RNA and the substructure (globally as well as locally) which need to be considered adequately in the design calculations.

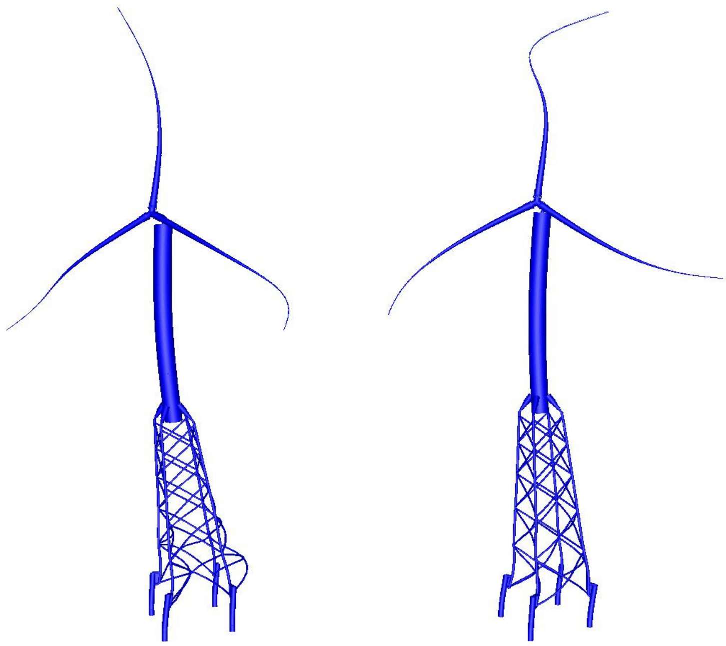


Fig. 1: Example of mode shapes with coupling of rotor and substructure

This paper presents results from enhanced calculation tools and some validation with measurements conducted within the DOWNVInD research project [1].

2. Measurements within DOWNVInD

The main objective of the measurement program within the DOWNVInD project was to generate data with which the tools used for load simulations of the complete turbine structure can be verified. The work package WP 5.11: 'Offshore Structure Verification Programme', within the DOWNVInD project, therefore consisted of the following main items:

- Instrumentation of the REpower 5M wind turbines and substructures;
- Carrying out a mechanical and dynamical load measurement campaign during one year to assess the real load spectrum of the whole wind turbine structure;
- Analyses of the measurement results with respect to evaluation and verification of the turbine structure's design.

The objective of the measurement programme is:

- Gain knowledge of the real load spectrum to assess fatigue lifetime of the main components: substructure, tower and rotor blades;
- To validate the load prediction models to increase the reliability of the future 1.000 MW wind farm.

The group 'Experiments and Measurements' of ECN Wind Energy instrumented the wind turbines and carried out the subsequent measurements. The measurement plan has been drafted together with Teknikgruppen (SE).

2.1. Measurement set up

In the wind turbine incl. support structure the following loads were measured:

- In-plane and out-of plane bending moments in all three rotor blade roots
- Torque and bending moments in the main shaft
- Bending moments in two directions at the tower top and the tower base.

- In the substructure normal forces were measured in all four legs and in-plane and out-of plane bending moments are measured in the main legs and braces of bay 5 and 6; in total at 26 different locations.

- Accelerations are measured in the nacelle and tower base.

An overview of signals in is shown in Fig. 2 and signals functional for evaluation are shown in Fig. 3.

2.2. Applied measurement system

All signals are connected to two Dante data acquisition systems; one in the nacelle and one in the tower base. The Dante systems are connected via the wind turbine’s Ethernet system. The Dante system in the tower base mainly gathers the substructure load signals. From that position the Wheatstone bridges are powered and measured.

All load and vibration signals are sampled with 32 Hz and stored as 10 minute time series. The data is also stored on a data server located on Beatrice Alfa via a glass fiber connection. From there data is transported to ECN once a week and stored in the measurement data base.

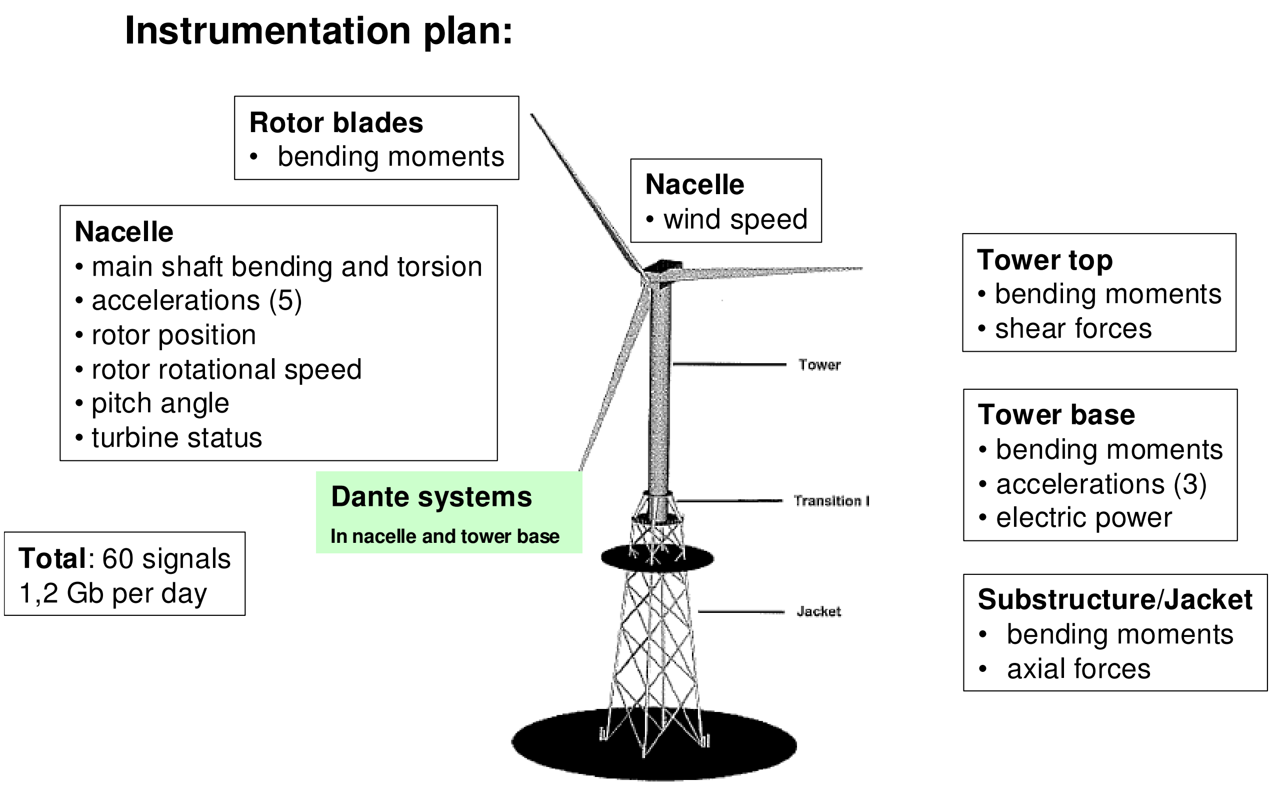


Fig. 2: Overview of measurement system

2.3. Problems during measurement campaign

Unfortunately, the measurement campaign was extremely ill-faited. Due to several adverse events and conditions, the measurements could not be conducted as planned. As a result, only limited data is available. This does concern the following:

- Measurements are only available for a relatively short period of time (January '08 Until March '08)
- Simultaneous data of external conditions (wind & waves) and load measurements is not available.
- Due to long waiting times several strain gauges have been found to be defect until measurements started (mainly in the substructure).

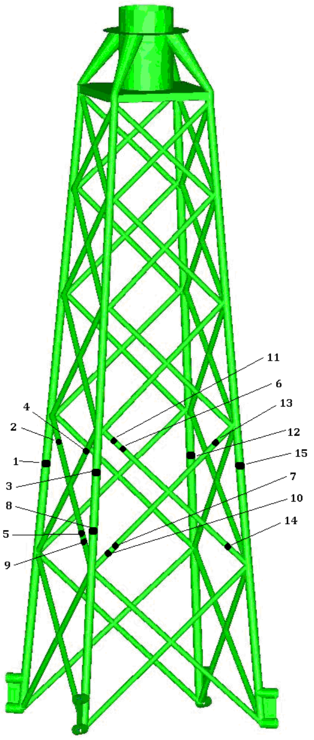


Fig. 3: ASAS(NL) model of the DOWNVInD jacket with measurement locations

3. Coupling methods

3.1. Sequential coupling

The sequential coupling using Flex 5 and the FE code ASAS(NL) has been described in [2]. The main principle of that method is that the Guyan reduction as employed by Flex 5 for the Monopile is retained for arbitrary structures. The substructure is hence generalized to six degrees of freedom (DOFs) and the generalized system matrices (mass, stiffness, damping) as well as a generalized wave loading time history are generated by ASAS(NL) and used by Flex 5. This is very similar to the approach used by Flex 5 itself for the Monopile, expect for the fact that relative velocities for the drag part of the wave loading is neglected because the wave loading time history is generated before the Flex 5 run.

In order to obtain member forces for the entire substructure, a "retrieval run" is performed. This is either done by performing a quasi-static superposition using the force and moment time histories at the interface node or by a dynamic recovery using kinematics at the interface node. Details are explained in [2] or [3].

3.2. Full coupling

The drawback of the sequential coupling is that Guyan reduction is (strictly speaking) only accurate for static loads, not for dynamic loads. Esp. for substructures with large masses inside the substructure, this leads to errors in the calculations. Therefore, an improved method was developed at the Endowed Chair of Wind Energy in Stuttgart, see [4].

The main idea of this method is to retain the full substructure in the FE code (e.g. ASAS(NL)) and include the Flex 5 matrices in the solution process. Information from Flex 5 is passed to the FE code in each time step and results (kinematics for the DOFs of Flex 5) are passed back, see Fig. 4. This can be regarded as implementing Flex 5 as a superelement within the FE code.

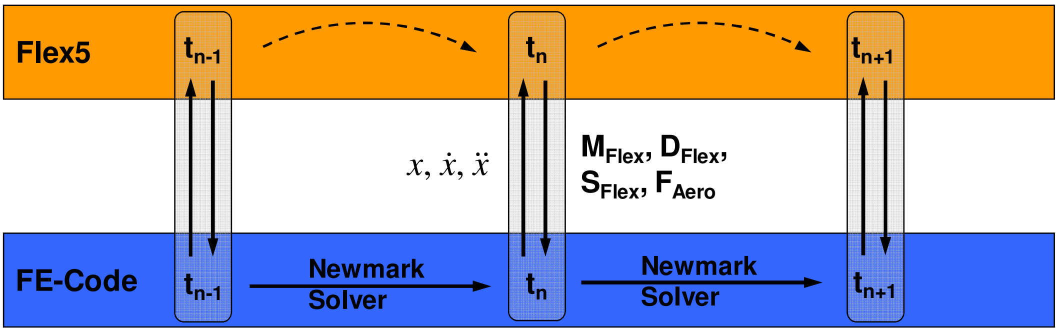


Fig. 4: Communication process of the coupled codes [4]

3.3. Validation

The new coupling approach has been thoroughly tested with two FE codes: ASAS(NL) and Poseidon (Poseidon is a research code which has been developed by Cord Böker within his PhD project [3]). This has been done by a series of validation runs with increasing complexity of the coupled simulations against Flex 5 alone:

1. Static simulations without wind (just dead weight)
2. Simulation with static wind
3. Simulation with turbulent wind

These simulations have been performed with just one node in the FE model, i.e. just the equation solving has been "outsourced" to the FE code. This way, the approach could be validated technically as the results should theoretically be identical. These tests were completed successfully, i.e. differences were neglectable.

Subsequently, tests with a Monopile were run. In this case, some (small) differences were to be expected as the Monopile is reduced to four DOFs in Flex 5 (torsion and vertical displacement are cancelled) while the full model was considered in the coupled simulations. Still, the results are very close as the generalization to four DOFs by static condensation does not cause a significant error for a Monopile. An example of the comparison is shown in Fig. 5.

The results from the validation process have shown that the method works reliably. Nevertheless, care must be taken when implementing this approach. Special attention must e.g. be paid to the controller implementation and behaviour. It has been found that some controller settings do not work well with the implemented method as the controller is always one time-step behind the simulation. Also damping implementation is important.

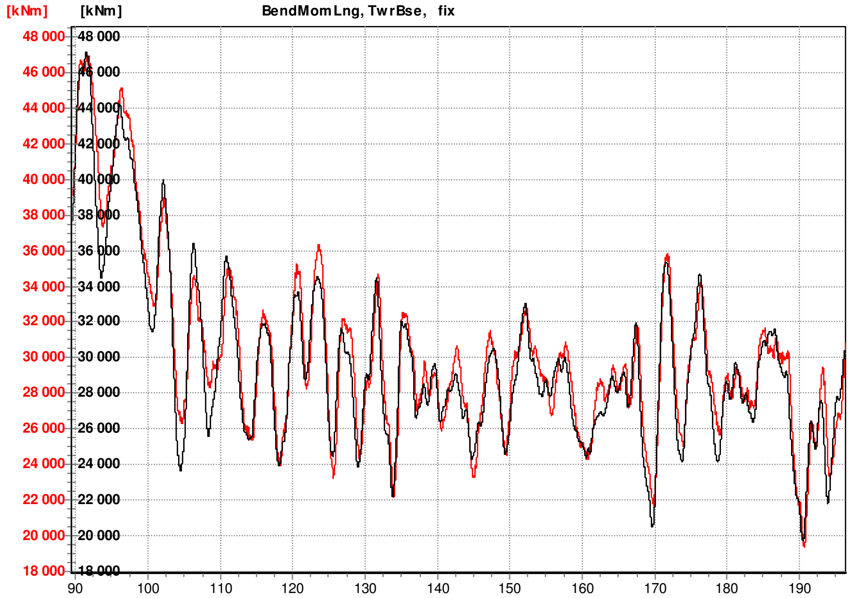


Fig. 5: Validation of Flex5-ASAS(NL) coupling against Flex5 at tower base (example)

3.4. Practical aspects

One of the main advantages of Flex 5 as a stand-alone is simulation speed. A turbulent 10min. time series with 10ms time step just takes a few minutes to run. Furthermore, cluster environments can be used as Flex 5 is not limited w.r.t. number of licenses. This is different for the coupling – for large models (e.g. jackets) simulation time for a 10min. time series can be several hours. Additionally, at least in the case of ASAS(NL) using cluster environments is limited by the number of available licenses. Hence, the full coupling is only suitable for verification of simpler methods, not for full certification calculations with several thousands of time series.

ASAS(NL) is a well proven product which has been used since several years in the Offshore Oil&Gas sector. Hence, it is well validated and comes with valuable features for wave loaded structures. Poseidon on the other hand is a university code and hence less professionally validated. It is also uncertain how this code will be developed further. So at the current stage, it is just interesting for comparison, not so much for practical use. REpower has used this code within the research project "OWEA", which is part of RAVE (Research at alpha ventus) [5].

4. Comparison of full coupling to sequential coupling

Comparison of full coupling and sequential coupling has been made for the DOWNVInD turbines. It was expected that little difference down to tower bottom would occur as the generalization to six degrees of freedom was deemed to be sufficient to represent the influence of the jacket on global dynamics.

This assumption was found to be correct. Fig. 6 is showing a comparison for an example time series at tower bottom. The frequency response is fairly similar, only minor differences can be found between 1.5Hz and 2Hz which is the range for the second global mode. Here small differences occur due to differences in the modal properties (natural frequency and mode shape representation).

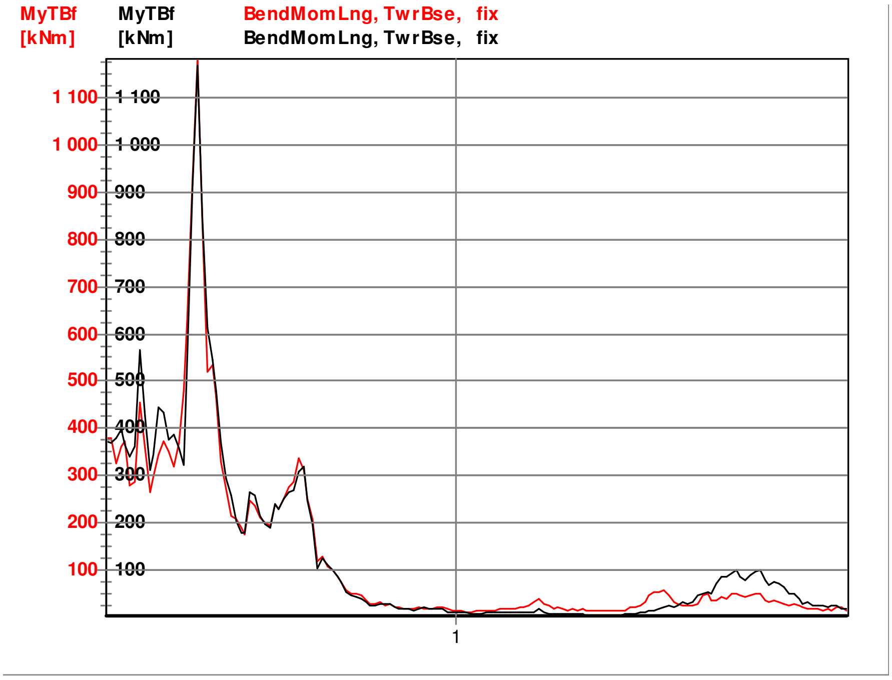


Fig. 6: Comparison of sequential and full coupling at tower bottom (FFT of long. bending moment)

Larger differences occur for some of the local member forces, see Fig. 7. Here, good agreement can be found for frequencies up to 1.5Hz, but above larger differences occur. The sequential approach is predicting a very large response around 2.4Hz. At this frequency a higher order global mode including local bracing deformation occurs. This mode is – due to the reduction of DOFs – not accurately represented in the Flex 5 calculations. Apparently, this leads to overestimation of structural response in the sequential approach because this mode is artificially excited during the recovery run. Generally, it has been found that local response is over-predicted by the sequential approach. This is in agreement with findings from Böker [3], although he predicts that also situations may exist where the sequential approach is not conservative.

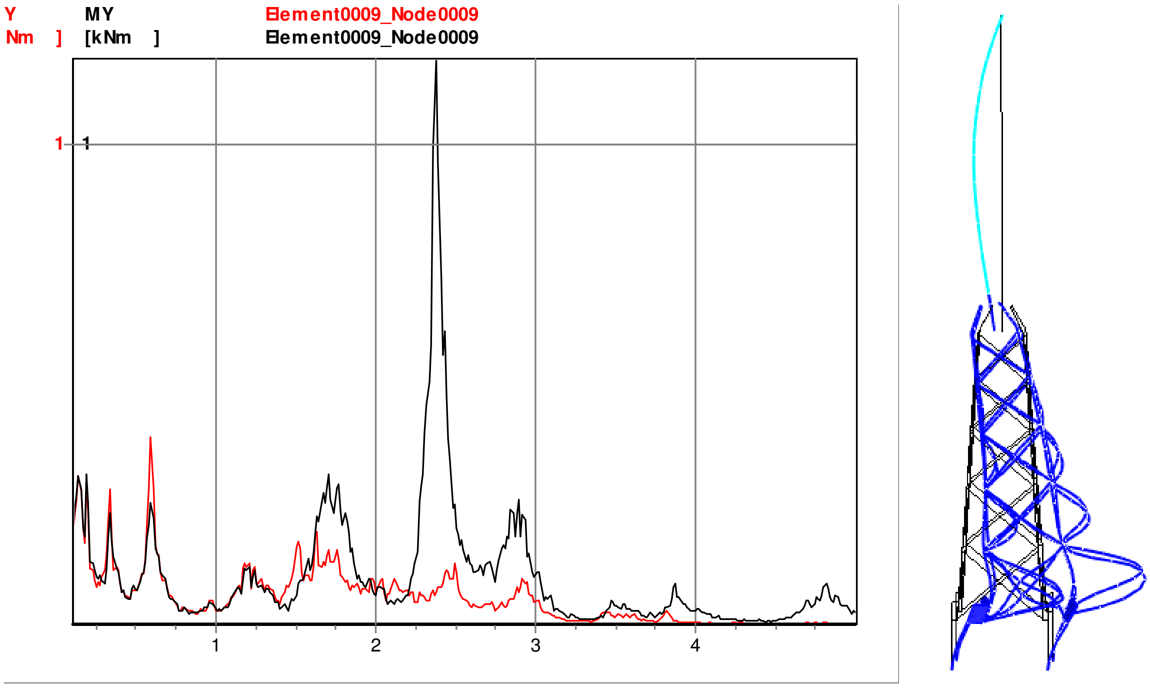


Fig. 7: Comparison of sequential and full coupling for local jacket member forces (out-of-plane bending moment at location 9, compare Fig. 3) and mode shape @ 2.4 Hz

5. Comparison with measurements

It was the aim to make a thorough comparison to measured data within the DOWNVInD project, but due to the problems described in section 2, this could only be achieved partially. Nevertheless, valuable information could be extracted from the measurements and by comparison with the simulations.

5.1. Modal analysis

A prerequisite to successful comparison of measured and simulated data is realistic modeling. For the substructure, this can be validated by comparing measured and predicted eigenfrequencies.

For the DOWNVInD turbines, very good agreement was achieved, with only little modification to the original model used for design purposes. First and second global modes (involving tower and substructure) were almost identical comparing measurement and simulation.

Modes which involve local significant deflections are starting at about 2.4Hz (Fig. 8). As the measurements are performed in the second bay from the bottom, it is also of interest to know frequencies involving pronounced local modes in this part of the structure. This bay is also participating in the first mode shapes, but particularly pronounced modes are found between 4Hz and 5Hz (Fig. 9). When analyzing out-of-plane moments in the bracing system it does in deed turn out that some response can be seen in this region. Hence, it can be assumed that the model is also accurate in this part of the substructure, although this is more difficult to prove precisely.

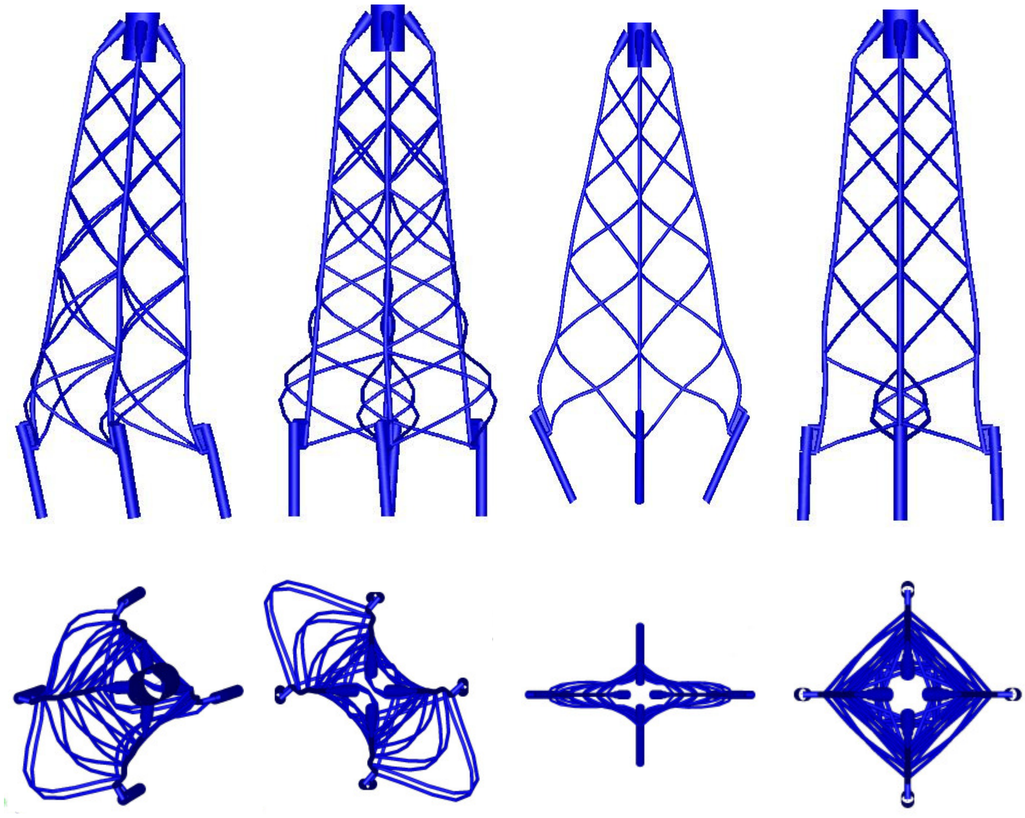


Fig. 8: First mode shapes with significant local deflections

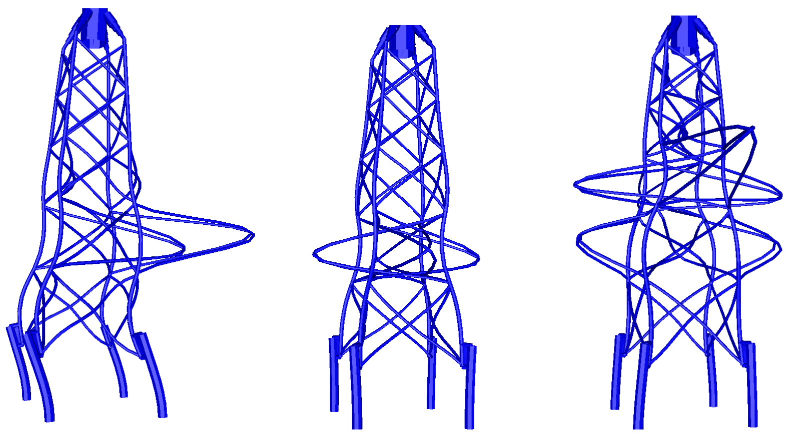
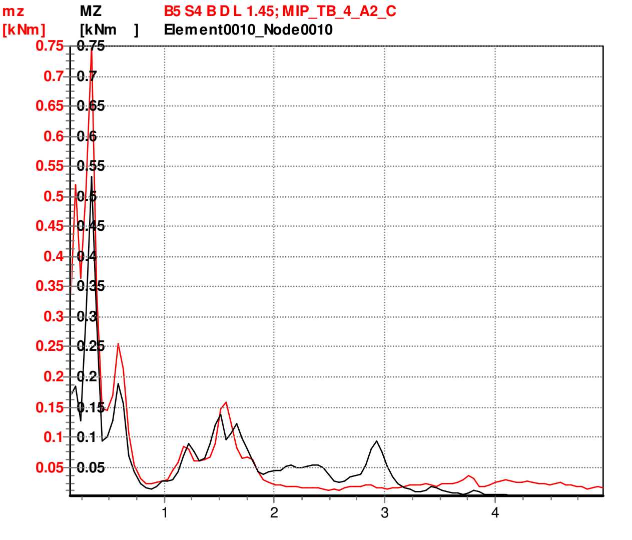


Fig. 9: Mode shapes in the region of 4Hz to 5Hz

5.2. Time history validation

Comparison to the measurements was difficult due to the problems described above. Therefore, the following approach was used: Input parameters were guesstimated sensibly from the nacelle anemometer regarding wind speed. Turbulence intensity was adjusted such that the tower bottom bending moments where in reasonable agreement. It could then be judged how well the local jacket member forces are predicted.

The frequency response, i.e. location of peaks in the FFT of signals, was generally in quite good agreement. For many signals, there was also a good quantitative agreement, see e.g. the left plot in Fig. 10. In cases where the agreement was not so good quantitatively, the response was over-predicted by the simulation; see e.g. the right plot in Fig. 10.



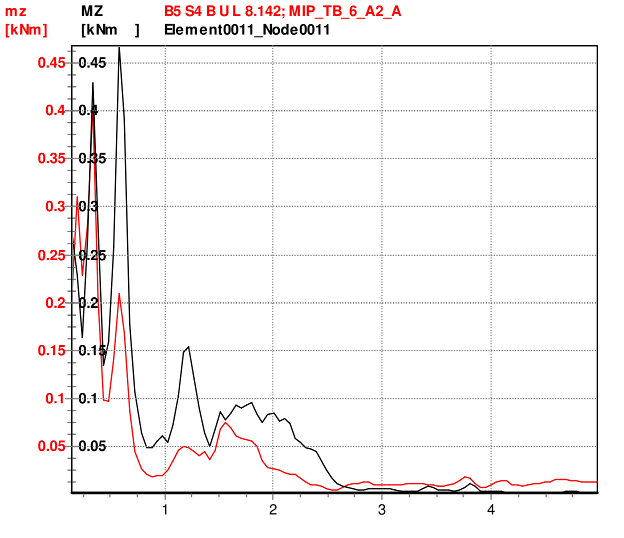


Fig. 10: Comparison of measurements (red) to full coupling (black) for a axial force in a brace (left) and an out-of-plane moment in a brace (right)

This rather qualitative comparison indicates that the fully integrated coupling is capable of predicting the structural response of complicated structures with good accuracy. Further work with more concise measurement data is required, though, to finally validate the method.

6. Summary and outlook

Methods and validation results for two coupling approaches – sequential and full – have been presented. It has been found that the simpler sequential method yields conservative results, hence some optimization potential may exist using the full coupling. Due to problems with the measurement campaign within the DOWNVInD project, results could only partially be validated by measurements. It has been found, though, that the measurements agree quite reasonably with the fully integrated method. Further validation with additional measurement data is thus required. This is planned within the RAVE project [5].

References

[1] Homepage “Beatrice Windfarm Demonstrator Project”: http://www.beatricewind.co.uk; Homepage “DOWNVInD”: http://www.downvind.com

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