PO. 107

A novel Digital Twin-based Structural Health Monitoring solution for offshore wind turbine platforms

Julio García Espinosa[1], Borja Serván Camas[2], Andrés Pastor[1], Daniel DiCapua[2]
1 Technical University of Madrid (UPM). Escuela Técnica Superior de Ingenieros Navales. Madrid, Spain.
2 Centre Internacional de Mètodes Numèrics en Enginyeria (CIMNE). Barcelona, Spain.

We introduce an innovative Structural Health Monitoring solution for offshore wind platforms, featuring an advanced Digital Twin built on a 3D fully-coupled aero-servo-hydro-elastic model. Adhering to the main certification standards, the model delivers precise, near-time structural analyses -a reliable tool for implementing predictive maintenance and assessing the lifespan of structural components.

Summary

This work introduces an innovative Structural Health Monitoring (SHM) solution for offshore wind platforms, featuring an advanced Digital Twin (DT) built on a fully-coupled aero-servo-hydro-elastic model. Our approach utilizes a detailed Finite Element model of the structure, meeting the requirements of the main assessment/certification standards. The application of the unique Enriched Modal Matrix Reduction technique leads substantially reduces CPU time, enabling near real-time calculations without compromising accuracy compared to the original FE model.

The SHM system is completed with an optimized sensors setup to monitor the most relevant deformation modes. Additionally, it enables precise fine-tuning of the DT model using machine learning, resulting in an accurate Hybrid Analysis Model.

The solution is modular and flexible and can be customized for any offshore wind platform concept, covering substructure, towers, mooring, and umbilicals. The solution is demonstrated through sea trials on Enerocean's W2Power prototype.

Physics-based digital twin

While data-driven modeling has gained enormous popularity, its inherent data-intensive and black-box characteristics, along with challenges such as poor generalizability, inherent bias, and a lack of robust theoretical frameworks for assessing model stability, hinder its acceptability in complex systems.

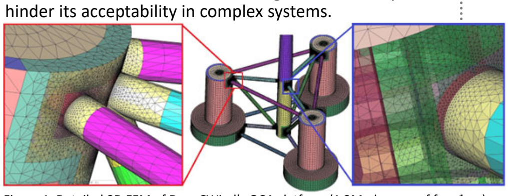


Figure 1. Detailed 3D FEM of DeepCWind's OC4 platform (1.3M. degrees of freedom).

In contrast, our solution employs a hybrid approach that combines deterministic (physics-based) and statistical model components. The physics-based model utilizes an advanced aero-servo-hydro-elastic model with a tightly coupled seakeeping-structural dynamics solver. The latter is based on a detailed Finite Element Model (FEM), meeting the requirements of the main assessment standards.

The tightly coupled hydro-elastic approach is enabled through a FEM-based time-domain seakeeping solver (SeaFEM). The analysis tool is completed with an extended version of OpenFAST, resulting in a highly accurate and robust aero-servo-hydro-elastic model.

To address the significant CPU demand of such a complex model, we introduce an original modal superposition-based technique called Enriched Modal Matrix Reduction (EMMR).

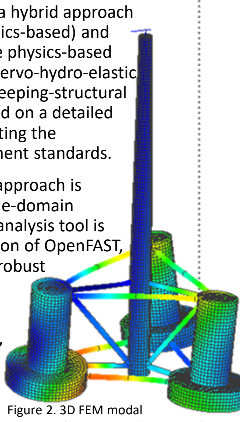


Figure 2. 3D FEM modal analysis of DeepCWind's OC4 platform.

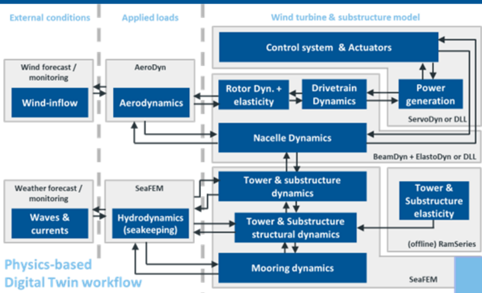
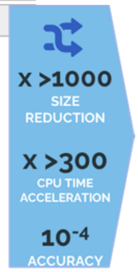


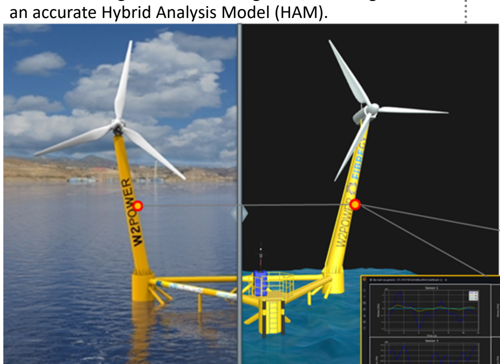
Figure 3. Physics-based aero-servo-hydro-elastic model.

This innovative approach retains a substantial number of modes and enriches the modal basis with selected displacement fields, reducing the number of unknowns (DOF) in the structural dynamics problem by about 1000-fold. This significantly cuts the computational cost while maintaining a high precision of the model. It enables the effective utilization of a detailed 3D FEM of the structure during both design and operation (digital twin).



Digital twin-based SHM

The developed Structural Health Monitoring solution is completed with an optimized monitoring setup, based on cost-effective sensors -and specialized solutions for mooring. The sensor network configuration aligns with the DT analysis. An optimization process -including practical positioning constrains-, allows to place the sensors optimally to monitor the modal coordinates of the most energetic deformation modes. The other way around, the monitoring information enables a fine-tuning of the DT model using machine learning tools, resulting in an accurate Hybrid Analysis Model (HAM).



It is noteworthy that this methodology enables a robust SHM solution, achieving higher accuracy with the optimum -minimum- number of sensors, while considering practical restrictions. Besides, the HAM approach provides a dependable and sensor fault tolerant solution, requiring minimal maintenance.

Structure Assessment procedure

As mentioned earlier, our SHM solution integrates a detailed Finite Element model of the structure, crafted in adherence to the main standards (BV, DNV, LR, IEC, ISO, …) for the certification / assessment of offshore structures. Continuously in operation, the model performs structural strength analyses under measured -or forecasted- conditions. Simultaneously, accumulated and forecasted fatigue damage -based on a cycle counting algorithm- and degradation (e.g. corrosion) are evaluated on critical hot-spots, ensuring compliance with the referred standards. These serve as a reliable tool for continuously assessing the Remaining Useful Life (RUL) of structural components of the asset.

The overarching objective of our SHM methodology is to offer a proactive decision support framework to prevent costly and unnecessary inspections, or excessively prolonged inspection intervals, through a dynamically adapted inspection and maintenance plan -predictive maintenance-. It also offers a reliable support for manual shutdown decisions and establishes a dependable foundation for ensuring and even extending the structure's lifespan.

Demonstration

The presented methodology is demonstrated during sea trials of the W2Power 1:6 scale prototype, conducted within the H2020 project FibreGY at the PLOCAN test site (Canary Islands). W2Power is a twin-turbine floating concept developed by EnerOcean, which enables a power rating of 12 MW. Within FibreGY, new carbon fiber towers have been built and replaced the original ones. The key characteristics of the developed DT are outlined below:

- Structural dynamics FEM model (tower + substructure): 1.2 million DOFs (RamSeries) reduced to 5000 modes (2.77Hz-406.76Hz).
- Seakeeping (radiation-diffraction) + dynamics FEM model: 0.5 million DOFs (SeaFEM)
- Mooring dynamics: linear model.
- Rotor + power generation: in-house linear model.

The W2Power's SHM solution has been implemented within the OSI4IOT platform OSI4IOT. OSI4IOT is an IoT open-source web-based platform developed in the context of the H2020 project Fibre4Yards.

Acknowledgements

This work was funded by the European Commission under grant agreements FibreGy (ref. 952966) and Fibre4Yards (ref. 101006860). The authors are especially thankful to Compass IS' team for helping to implement the DT methodology on their software tools SeaFEM and RamSeries. We also want to express our gratitude to EnerOcean's team for their collaboration in implementing the SHM system on the W2Power platform.

References

The main references for this work are accessible via the QR code to the right.

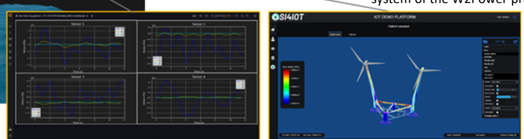


Figure 4. OSI4IOT: Web platform of the DT-based SHM system of the W2Power prototype.

Corresponding author:
Julio García-Espinosa
Full Professor of Shipbuilding Technology
Technical University of Madrid