Verification and implementation of a State-Space hydrodynamic model for wind tunnel-HIL application on FOWT

Ilmas Bayati*, Marco Belloli, Alan Facchinetti

Dipartimento di Meccanica, Politecnico di Milano

Via La Masa 1, 20156, Milano, Italy. Ph:+39 0223998486, Mob:+39 3772855518

ilmasandrea.bayati@polimi.it

Abstract

Aim of this work is the implementation of a *state-space* hydrodynamic model, suitable for a fast hardware-in-the-loop (HIL) real-time implementation, with general application to wind tunnel tests of floating structures and specific focus on offshore wind turbines. The model was implemented in Matlab/Simulink environment for a direct application to real-time hardware. The 2 Degrees of Freedom (Surge and Pitch) model was verified against the aero-hydro-elastic code FAST 7 for regular and irregular sea state in different conditions. As an example, results for rated condition are reported. An overview on the ongoing research based on this work is given.

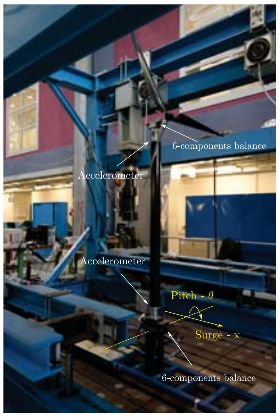

Figure 1: 2 DoF experimental rig, off-line session (out of PoliMi Wind Tunnel [2]).

1 Hardware-In-The-Loop experimental rig

The novel approach [1] of testing offshore wind turbine scaled rigid models in a wind tunnel facility [2] is based on an hybrid (measuring/computing) testing set-up: the wind turbine scale model is placed upon a mechanical system reproducing the motion along 2 Degrees of Freedom (DoF) $\underline{x}^T = [x, \theta]$, Surge and Pitch [1] or all the 6-DoF of the floater [3]. Forces and accelerations of the model, due to the wind, are measured, conditioned and given to the real-time hardware as input for hydrodynamic computations. The related output, in terms of displacements at the tower's base, are converted again to signals and then to motion of the scale model, closing the loop. This procedure is reported in Fig.2.

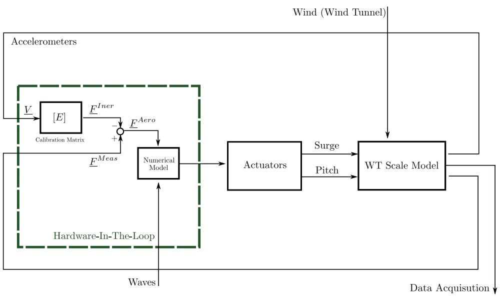

Figure 2: 2-DoF Hardware-In-The-Loop scheme.

2 State-Space Model

The hydrodynamic model, that is supposed to run as fast as possible in real time, can't rely on the classical Cummins formulation reported in the Eq.1, due to the second term, the convolution of the retardation function (memory effect), that depends on the wave-frequency dependent added mass $[A(\omega)]$ and damping $[B(\omega)]$ of the platform, Eq.2.

$$[M + A_\infty]\underline{\ddot{x}}(t) + \int_0^\infty [K(\bar{t} - \tau)]\underline{\dot{x}}(t)d\tau + [C]\underline{x}(t) = \underline{F}^{Diff}(t) \quad (1)$$

$$[K(\omega)] = [B(\omega)] + j\omega([A(\omega)] - [A_\infty]) \quad (2)$$

This term is not suitable for HIL implementation because it requires the storage of a large amount of data (potentially infinite) of previous time instants to provide reasonable values, that turns out to be real-time inconsistent. To overcome this issue, this work considers, as a starting point, the identification methods proposed in [4] to obtain an approximating parametric transfer function $[\tilde{K}(\omega)]$ of the retardation function $[K(\omega)]$, Eq.3.

$$[K(\omega)] \approx [\tilde{K}(\omega)] \rightarrow \begin{cases} \dot{y} = [A_r]y + [B_r]\dot{x} \\ \mu = [C_r]y \end{cases} \quad (3)$$

This approach allows to build a state-space model of the global dynamics of the floating system, included the memory effect μ, being directly applicable for real-time tests. Furthermore, since the identification methods of [4] deal with "full scale" matrices $[A(\omega)]$ and $[B(\omega)]$, whereas the target of this work is a "model scale", the identification approach proposed in [4] brings about some numerical issues, if directly applied to "model scale", that need some numerical precautions.
The complete equations of motion can be written as:

$$[M]\underline{\ddot{x}} + [C]\underline{\dot{x}} + [K]\underline{x} + \underline{\mu} = \underline{F}^{Diff} + \underline{F}^{Aero} \quad (4)$$

where the $\underline{F}^{Aero}$ of the Eq.4 must be gathered from measurements $\underline{F}^{Meas}$ in real time, as expressed in the Eq.5.

$$\underline{F}^{Aero} = \underline{F}^{Meas} - \underline{F}^{Iner} = \underline{F}^{Meas} - [E]\underline{V} \quad (5)$$

where $[E]$ refers to the calibration matrix that converts the accelerometer signals $\underline{V}$ into inertial forces $\underline{F}^{Iner}$ about Surge and Pitch. The definition of the calibration matrix $[E]$ is given, in Least Square, sense from the measurements gathered moving actuators by sine functions, singularly along Surge and Pitch (Fig.1), for different amplitudes and frequencies. This procedure is fundamental to also define precisely the total mass and moment of inertia of the scale model Fig.1.

3 Implementation and results

The reference floating wind turbine considered in this work is the 5MW NREL/OC3-Hywind spar-type monopile [5]. The verification of the Matlab/Simulink global dynamic state-space model, herein reported, was carried out against the code FAST 7 developed by NREL [6] [7], for free-decay conditions, as well as for cut-in, rated and cut-off wind turbine's operational conditions. The 2-DoF numerical model was then converted into National Instruments real-time hardware after being properly scaled. For the sake of completeness in the Fig.3 a full-scale comparison with FAST 7 is reported. The new version of FAST 8 actually follows the same state-space approach for the definition of the memory effect

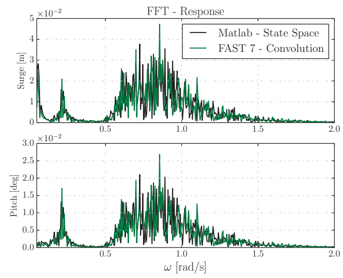

Figure 3: 2-DoF Matlab/Simulink Vs FAST comparison. Jonswap spectrum $H_s = 1.86$m, $T_p = 7.2$ s

A scale factor λ, depending on the physical dimension of the model, is applied to the terms of Eq.4, more specifically:

$$[\lambda_M] = \begin{bmatrix} \lambda^3 & \lambda^4 \\ \lambda^3 & \lambda^5 \end{bmatrix} \quad ; \quad [\lambda_C] = \begin{bmatrix} \lambda^{2.5} & \lambda^{3.5} \\ \lambda^{3.5} & \lambda^{4.5} \end{bmatrix} \quad ; \quad [\lambda_K] = \begin{bmatrix} \lambda^2 & \lambda^3 \\ \lambda^3 & \lambda^4 \end{bmatrix} \quad ; \quad \underline{\lambda_F} = \begin{bmatrix} \lambda^2 \\ \lambda^3 \end{bmatrix} \quad (6)$$

4 Conclusion and ongoing research

Hardware-In-The-Loop tests for wind tunnel application on floating wind turbines represent a useful complementary approach with respect to the water basin counterpart. The implementation of a State-Space hydrodynamic model for fast HIL applications was presented. Good agreement with the complex aero-elastic code FAST 7 was reached (Fig.3). The scaled version of the numerical model was then implemented in the 2-DoF experimental rig of Fig.1. The future works will move these implementation to the more complex 6 DoF Hexapod, designed by Politecnic di Milano [3]. From a numerical point of view, recent studies [8] have shown the importance of modelling also second-order hydrodynamics (QTFs). The new FAST 8 implements these effects, so that future work will extend the procedure reported also to secondary effects, taking FAST 8 as a "full-scale" reference before the physical model tests.

References

[1] Bayati I., Belloli M., Facchinetti A., Giappino S.,*"Wind Tunnel Tests on Floating Offshore Wind Turbines: A Proposal For Hardware-In-The-Loop Approach To Validate Numerical Codes"*.Wind Engineering, vol.37, N.6, 2013.

[2] Diana G., De Ponte S., Falco M., Zasso A., *"A new Large Wind Tunnel For Civil Environmental And Aeronauitcal Application"*, Journal of Wind Enegineering and Industrial Aerodynamics, 74-76, 553-565, 1998.

[3] Bayati I., Belloli M., Ferrari D., Fossati F., Giberti H., *"Design of a 6-DoF Robotic Platform for Wind Tunnel Tests of Floating Wind Turbines"*, Energy Procedia, pp. 313-323, 2014.

[4] Perez T., Fossen T., *"Practical aspects of frequency-domain identification of dynamic models of marine structures from hydrodynamic data"*. Ocean Engineering, Vol 38, pp. 426435, 2011.

[5] Jonkman J., *"Definition Of The Floating System For Phase IV of OC3"*, NREL/TP-500-47535, May 2010.

[6] Jonkman J.,*"Dynamics Modeling and Loads Analysis of an Offshore Floating Wind Turbine"*, PhD Thesis, November 2007.

[7] Jonkman J., Buhl Jr. M., *"FAST users guide"*, NREL TechRep, August 2005.

[8] Bayati I., Jonkman J., Robertson A., Platt A., *"The effects of second-order hydrodynamics on a semisubmersible floating offshore wind, turbine"*, J. Phys.: Conf. Ser. 524, 2014.