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A novel strategy to surrogate the transient response of wind turbine simulations

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Abstract: Wind turbines have proven to be a reliable and cost-effective technology for harvesting energy from the wind. Since wind energy is also a renewable source of energy, interest in using wind turbines to substitute fossil fuels in energy supply has increased greatly in recent decades [3]. However, their potential in the energy industry is offset by a challenging design process. On the one hand, energy efficiency is to be increased and production and maintenance costs reduced, on the other hand, safe operation must be ensured throughout the lifetime of the turbine.

Within the Horizon 2020 EU program, the HIPERWIND project aims at reducing the levelized cost of offshore wind energy, while increasing the safety and reliability of offshore wind turbines, by better managing the uncertainties of wind and waves, and thus the loads acting on the turbine. One of the first steps toward this goal is to reduce the high computational cost of wind turbine simulations.

To this end, surrogate models have a proven record of efficiently mapping vectors of input parameters to scalar output quantities [2], and are therefore powerful tools to facilitate reliability-based design of engineering structures. By incorporating dimensionality reduction techniques, they can handle relatively high-dimensional problems [1]. However, they are usually limited to static problems and in most cases cannot emulate the transient response of complex systems, typical for wind turbines.

Wind turbines are modeled with aero-servo-elastic (ASE) simulators, which take the turbulent wind as input and provide as output the transient response of selected quantities of interest (QoIs), such as power generation or loads on the blades and tower. The turbulent wind is modeled as a discretized random field, called a turbulence box:

$$\boldsymbol{v} : \mathcal{T} \rightarrow \mathbb{R}^{\nu_w \times \nu_y \times \nu_z}, \tag{1}$$

where $\mathcal{T} = \{0, 1, 2, \ldots, N\}$ is a discrete time axis, ν_w is the number of wind speed components, and ν_y and ν_z correspond to the spatial discretization of the turbulence box (a regular grid of size $\nu_y \times \nu_z$ in the plane of the blades). A single transient response quantity is defined analogously as:

$$f : \mathcal{T} \rightarrow \mathbb{R}. \tag{2}$$

To emulate this time-dependent output $f(t)$ of an ASE simulator $\mathcal{M}$, a surrogate $\widetilde{\mathcal{M}}$ must be constructed such that:

$$f(t) = \mathcal{M}(\boldsymbol{v}(\leq t)) \approx \widetilde{\mathcal{M}}(\boldsymbol{v}(\leq t)), \tag{3}$$

where the dimensionality of $\boldsymbol{v}(t)$ is usually of the order $\mathcal{O}(10^{2-3})$ and the notation "$\leq t$" means that the history of the wind velocities up to time t is accounted for. The transient response $f(t)$ generally depends on the state of the wind turbine (e.g., rotor orientation) and certain degrees of freedom of the turbine (e.g., pitch angle) are dynamically adjusted by a control system.

To tackle this problem, we propose a new surrogate modeling approach called mNARX (manifold auto-regressive model with exogenous input). In this approach, we first represent the spatial components of the turbulence box with a truncated spectral expansion, which allows us to compress it into a small number of time-dependent spectral coefficients. Based on this reduced space, we build a chain of auto-regressive surrogate models in which we first predict relevant control and state variables as auxiliary quantities.

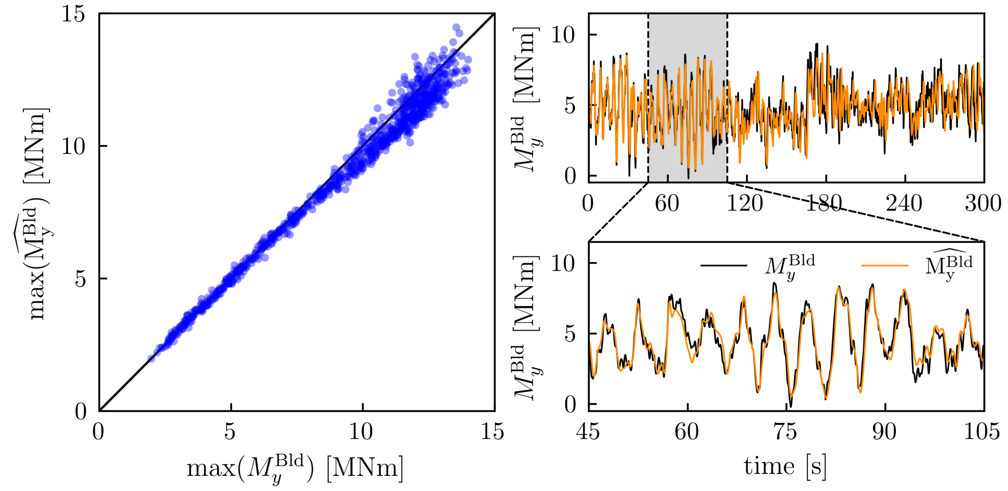

Figure 1: Left: Maximum value of the flapwise blade root bending moment extracted from the true output, M_y^{Bld}, and the one from the surrogate response, $\widehat{M_y^{\mathrm{Bld}}}$. Right: Exemplary true output trace (black) and the surrogate trace (orange).

The auto-regressive model allows us to exploit the temporal coherence of input and output and the auxiliary quantities or extracted features are used to construct a new input manifold. This manifold acts as an exogenous input to a new auto-regressive model which then predicts the primary quantities of interest, such as loads or power output. Because for all surrogates the transient response is dominated by the exogenous input turbulence box, we achieve long-term stable prediction for auxiliary and primary quantities.

Figure 1 showcases an application of mNARX as a surrogate of the flapwise bending moment at the root of a rotor blade, M_y^{Bld}. To assess the accuracy of the emulator, we compare the maximum moment over a 10-minutes simulation for an out-of-sample validation set of about 900 traces, extracted from the true and predicted output (Figure 1, left) and show the first 300 s of a true output trace and the corresponding predicted trace (Figure 1, right).

Our results demonstrate that mNARX can be used to accurately predict even complex wind turbine dynamics for many output quantities of interest, at a relatively low training cost of $\mathcal{O}(10^2)$ model runs.

References

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Short biography – Styfen Schär received his MSc in civil engineering from ETH Zürich in 2021. In the same year, he joined the Chair of Risk, Safety and Uncertainty Quantification at ETH Zurich as a Ph.D. student. As part of the European HIPERWIND project, he is developing new surrogate modeling techniques to accelerate wind turbine design and optimization, with the overall goal of reducing the cost of wind energy and making wind turbines safer to operate