Demonstration of Using Digital Twins for Offshore Wind Turbine Foundation Monitoring

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ABSTRACT

Operation and maintenance of offshore wind turbines (OWTs) require accurate, robust, and continuous monitoring of all components. In this sense, nonlinear and vibration-based techniques have been proposed to enable remote monitoring and deterioration analysis; however, such works tend to focus on the superstructures while simplifying the foundation behavior. Conversely, structural health monitoring tools that incorporate the foundation tend to be deterministic and rely on modal analysis, which limits their application to linear and well-conditioned systems. This paper attempts to bridge these gaps and presents a digital twin for monopile-supported OWTs that includes a comprehensive foundation model and a nonlinear updating method. The digital twin is a beam finite element model with soil-structure interaction of the Winkler type, and it employs nonlinear optimization to identify operational soil parameters using acceleration data. This approach allows time-domain and continuous monitoring of OWTs' foundation and global responses. Results show that the proposed methodology accurately identifies soil parameters and tracks their changes.

INTRODUCTION

The offshore wind sector has grown significantly in recent years, and monopiles are the most commonly-adopted support system [1]. Monopile-supported OWTs are dynamically sensitive structures that must withstand onerous and complex loads. Therefore, they experience continuous deterioration and changes in the support condition [2–4]. For these reasons, suitable monitoring and maintenance is fundamental for their proper operation, safety, and economic viability.

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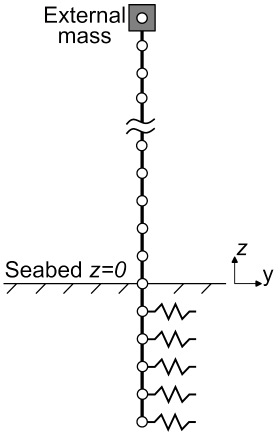

Figure 1. Schematic representation of the OWT model. Axes orientation are indicated by the arrows on the right.

Structural health monitoring for OWTs is adopting nonlinear and vibration-based approaches to study deterioration and overcome expensive on-site inspections and tests [5, 6]. Operational modal analysis has been employed to monitor modal properties or estimate foundation stiffness using vibration data [7, 8]; nonetheless, this analysis only applies to linear systems. Other researchers have developed a time-domain updating method to identify soil parameters, structural properties, and wind loads of monopile-supported OWTs [9, 10]; however, this approach simplifies the foundation to a macro element or a fixed support, which prevents a detailed monitoring of the soil and foundation responses. Current practice achieves this analysis by modeling the monopile as an embedded beam and representing the lateral soil response with nonlinear $p - y$ curves [11–13].

This paper introduces a digital twin for monopile monitoring, which estimates operating soil parameters using vibration data. To this end, the paper presents a model for monopile-supported OWTs and a nonlinear updating methodology; the OWT model includes a comprehensive foundation model, and the nonlinear updating works in the time domain. The framework is validated by creating two digital twins of a reference OWT model with soil degradation. Results are compared to demonstrate the importance of foundation monitoring.

DIGITAL TWIN FOR MONOPILE MONITORING

Figure 1 depicts the model for monopile-supported OWTs; it corresponds to a finite element model (FEM) with Winkler-type soil-structure interaction (SSI). This SSI models the soil response (reaction and stiffness) with independent linear springs along the embedded pile. On the other hand, the FEM discretizes the OWT structure with locking-free Timoshenko beam elements [14], and represents the rotor-nacelle assembly as an external mass with different moments of inertia in the fore-aft (FA) and side-to-side (SS) directions. The FEM also employs Rayleigh damping, with the first and second FA-SS mode pairs, to account for energy dissipation within the structure.

The equation of motion of this model is

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{C}\dot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t) + \mathbf{s}(t) = \mathbf{f}(t); \tag{1}$$

where $\mathbf{u}(t)$, $\dot{\mathbf{u}}(t)$, and $\ddot{\mathbf{u}}(t)$ represent the nodal displacements, velocities, and accelerations; $\mathbf{K}$, $\mathbf{C}$, and $\mathbf{M}$ stand for the stiffness, damping, and mass matrices; $\mathbf{s}(t)$ corresponds to an equivalent soil reaction vector; and $\mathbf{f}(t)$ denotes the equivalent nodal forces. The vector $\mathbf{s}(t)$ is zero on the entries of nodes above the seabed, and for the embedded portion $z \leq 0$, it corresponds to

$$\int \mathbf{N_e}(z) p(z) \mathrm{dz}, \tag{2}$$

where $\mathbf{N_e}(z)$ is the elemental shape function matrix, $p(z) = k_s(z) u_y(z)$ denotes the reaction of the soil spring at z, $k_s(z)$ stands for the spring stiffness, and $u_y(z)$ represents the lateral displacement at z associated to $\mathbf{u}(t)$. The OWT response to an external excitation is obtained by solving Eq.(1) with the generalized-α method [15].

The digital twin is constructed by updating the stiffness of the soil springs $k_s(z)$ with measurements $\mathbf{y}_i \in \mathbb{R}^{N_c \times 1}$. The updating methodology is the nonlinear optimization of the error function

$$J(\theta) = \frac{1}{2N_c N_t} \sum_{i=1}^{N_t} [\mathbf{y}_i - \hat{\mathbf{y}}_i(\theta)]^T (\boldsymbol{\sigma}^{\mathbf{2}})^{-1} [\mathbf{y}_i - \hat{\mathbf{y}}_i(\theta)], \tag{3}$$

where θ is a stiffness multiplier and the updating parameter, $\hat{\mathbf{y}}_i(\theta)$ represents the measurements predicted by the model with soil stiffness $\theta k_s(z)$, $\boldsymbol{\sigma}^{\mathbf{2}}$ stands for a variance matrix, and N_t and N_c denote the number of measurements and their dimensionality. The optimal θ provides the operational soil stiffness for the analyzed interval, and it is used as the initial point for the updating in the following interval. The measurements are restricted to displacements, strains, velocities, and accelerations to keep the framework in the time domain.

CASE STUDY

The digital twin framework is validated with a reference model of a 15 MW monopile-supported OWT [16]. This model is developed in MATLAB and employs design-based mass distributions and geometry, an idling conditions damping ratio, and wave loads derived from the Airy theory and *JONSWAP* spectrum. The SSI model computes the stiffness of the soil springs $k_s(z)$ from 3D finite element analyses informed by site-specific characteristics [17]. Table I summarizes the main properties of the reference model. Vibration data is obtained by running the model for 800 seconds with a time step of 0.05 seconds. At 560 seconds, there is a 20% drop in the stiffness of every soil spring; even though this uniform reduction is unrealistic, it emulates soil deterioration and makes the analysis nonlinear. The first 200s of data are discarded to avoid the initial transient response, and the accelerations at 5m and 15m above the seabed and the tower top are taken and polluted with a 5% Gaussian noise. Figure 2 shows the last 30 seconds of the noisy accelerations.

TABLE I. Structural and environmental parameters of the OWT, adapted from [16]

	Parameter	Value
Tower	Length	125 m
	Diameter (lower - upper)	8 m - 6.50 m
	Wall thickness (min - max)	0.02 m - 0.075 m
	RNA mass	815000 kg
Monopile	Length	110 m
	Diameter (lower - upper)	11.5 m - 8 m
	Wall thickness	0.08 m
	Embedded length	27.5 m
	Cone length	24 m
Sea	Depth	60 m
	Significant wave height	8 m
	Peak period	12 s

Two digital twins are constructed with these accelerations. For both, the initial model is the reference model with a stiffness of the soil springs $k_s(z)$ 25% higher than that of the accelerations. Furthermore, the updating employs the gradient-descent algorithm to optimize the multiplier θ. It also divides the data in windows of 2 minutes, and it computes the error only with the accelerations of the second minute to avoid the transients produced by the variation of θ. The first digital twin updates the stiffness on the complete foundation, whereas the second only updates it for the first 7m of soil, the top quarter. This latter case has an underlying and irreversible error but tests the robustness of the framework against modeling noise.

RESULTS

Table II shows the optimal θ and its corresponding error for each window and digital twin. Both cases have similar errors, being low on all the intervals. The first digital twin (complete foundation updating) identifies $\theta \approx 0.8$ for the first three windows and $\theta \approx 0.64$ for the last two, which are the correction for the initial 25%-higher stiffness and the 20% drop at 560s. In the second twin (top 7m updating), θ has the same trend but around lower values, which implies that the top soil is softer to alleviate the stiffer bottom. That OWT model has a wholly different stiffness $k_s(z)$ than the reference model; nonetheless, the small errors suggest that it captures the dynamics of the reference model and can be considered its digital twin.

Even though the digital twins achieve similar accuracy, their responses have significant differences. Table III reports the number of cycles and the maximum amplitude of the lateral displacement at four locations along the embedded portion; these

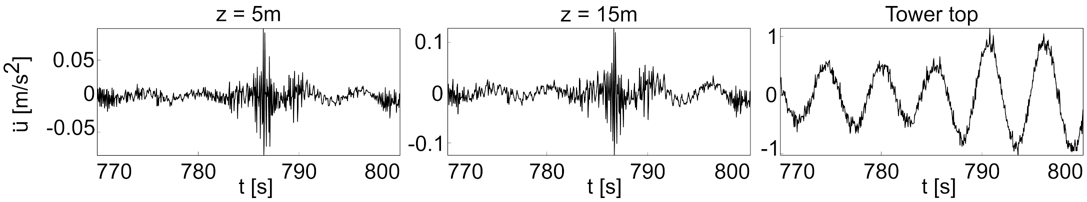

Figure 2. Accelerations of the reference model.

TABLE II. Updating results of the digital twins

Window	1^{st} digital twin		2^{nd} digital twin	
	θ_{opt}	$J(\theta_{\text{opt}})$	θ_{opt}	$J(\theta_{\text{opt}})$
200s - 320s	0.809	$2.45 \cdot 10^{-2}$	0.763	$2.45 \cdot 10^{-2}$
320s - 440s	0.798	$2.33 \cdot 10^{-2}$	0.742	$2.33 \cdot 10^{-2}$
440s - 560s	0.796	$2.41 \cdot 10^{-2}$	0.742	$2.41 \cdot 10^{-2}$
560s - 680s	0.684	$2.59 \cdot 10^{-2}$	0.634	$2.71 \cdot 10^{-2}$
680s - 800s	0.619	$2.48 \cdot 10^{-2}$	0.484	$2.49 \cdot 10^{-2}$

two variables are key for fatigue analysis. It shows that the digital twins perform similarly close to the seabed but differ on most of the depth. Despite these differences, the above results highlight the versatility of the digital twin because they imply that for a given accuracy level, the digital twin can model multiple responses of the embedded structure. In contrast, simplified foundation models, such as macro-elements or fixed base supports, cannot provide information below the seabed and therefore lead to significant monitoring uncertainty.

CONCLUSIONS

This paper presented a digital twin for monopile monitoring that estimates operating soil parameters using vibration data. It also described the underlying OWT model, the foundation model, and the time-domain updating that allowed monitoring of the embedded structure under changing support conditions. A validation study was performed on a reference model of a 15 MW monopile-supported OWT. There, the digital twin could capture the dynamics of the reference model in the presence of soil degradation, measurement noise, and modeling errors, showing its accuracy and robustness. Additionally, the validation study showed that different responses of the embedded structure can match a set of superstructure's accelerations, which highlights the necessity of monitoring the complete foundation.

ACKNOWLEDGMENT

The authors are grateful for the financial support provided by UKRI through Innovate UK and the KTP initiative. FRONTIErS DN has received funding from the European Union's Horizon Europe Programme under the Marie Sklodowska-Curie actions HORIZON-MSCA-2021-DN-01 call (Grant agreement ID: 101072360), and from UK Research and Innovation (Grant Ref: EP/X027910/1 and EP/X027821/1).

TABLE III. Foundation displacements' maximum amplitude and number of cycles

Location	1^{st} digital twin		2^{nd} digital twin	
	N° cycles	Amplitude	N° cycles	Amplitude
z = 0m	167	$113\ 10^{-4}$ m	171	$111\ 10^{-4}$ m
z = -10m	219	$9.73\ 10^{-4}$ m	209	$8.02\ 10^{-4}$ m
z = -20m	262	$1.65\ 10^{-4}$ m	152	$1.27\ 10^{-4}$ m
z = -27.5m	207	$7.03\ 10^{-4}$ m	170	$5.16\ 10^{-4}$ m

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