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Simplified equivalent model for seismic centrifuge testing of offshore wind turbine jacket foundations

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ABSTRACT: As offshore wind farms expand into seismically active regions, understanding the behavior of offshore wind turbine (OWT) foundations under seismic loading conditions by physical modeling is crucial. This study addresses the complexities of centrifuge modeling for prototype-scale OWT by developing a practical, simplified framework to represent a four-legged jacket structure for testing. A four-legged OWT jacket structure is simplified into an idealized cylindrical model with adjusted dimensions and mass distribution to maintain a similar natural frequency to the original. The model's accuracy was validated through analytical calculations and finite element analysis using SAP2000. Results show that the natural frequency of the simplified model closely matches, with a difference of around 0.03 Hz, that of the original structure in both analytical and numerical assessments. This approach ensures dynamic consistency while meeting centrifuge constraints, providing a reliable basis for future physical testing and offering insights for seismic-resistant OWT design.

Keywords: Offshore wind turbines; Jacket foundation; Centrifuge test; Simplified model; Natural frequency

1 INTRODUCTION

The global focus on green energy, particularly offshore wind farms, has been increasing significantly. Countries such as the USA, China, India, and several others in Southeast Asia are strategically planning to expand their offshore wind infrastructure. However, many of these countries are located along seismic belts and frequently experience earthquakes, making offshore wind farms in these regions particularly vulnerable to seismic hazards. Consequently, the demand for seismic-resistant designs for offshore wind turbines (OWTs) has been growing.

To assess the behavior of OWT foundations under seismic loading, two primary methods are commonly used: numerical and physical modeling techniques. Numerical modeling utilizes advanced computational tools to simulate interactions between OWT foundations and surrounding soil (e.g., Khodakarami and Lashgari 2018; De Risi et al., 2018; Farahani and Barari 2023). Physical modeling is significant for exploring the complex dynamics of soil-structure interactions through scaled-down prototypes (Haddad et al., 2022).. Geotechnical centrifuge modeling is particularly valuable as it replicates field stress conditions, allowing researchers to measure and observe how offshore foundations respond to seismic forces. This form of physical modeling is crucial for validating numerical models and providing real-world insights into OWT designs, especially in regions with complex geotechnical and seismic profiles.

Recent years have seen several centrifuge modeling studies focused on OWT foundations (e.g., Yu et al., 2015; Wang et al., 2017; Seong et al., 2019; Natarajan and Madabhushi, 2022). However, centrifuge modeling presents challenges due to the considerable size, weight, and details of these structures. For instance, a 5 MW OWT with a jacket structure has a mass of around 2000 tons and a height of approximately 134 meters, making small-scale laboratory modeling difficult. Moreover, centrifuge facilities have limitations based on scaling factor rules, such as container dimensions, that restrict the feasible scaling of different OWT models. For example, Yu et al. (2015) tested the seismic behaviour of monopile with a solid cylinder, and a smaller diameter cylinder representing the wind tower. Seong et al. (2019) modeled a prototype wind turbine with monopile foundation, applying a two-stage scaling law to scale down the structure into a hollow cylinder with a constant diameter. Natarajan and Madabhushi (2022) conducted seismic tests on an equivalent pile supported jacket structure with 2 x 2 pile foundations rigidly attached to a brass plate, onto which the hollow cylinder tower was mounted.

The natural frequency of OWTs is a key factor in their seismic response, making it essential to maintain the prototype's natural frequency within physical models to ensure predictive accuracy. This alignment enables efficient and reliable testing, allowing insights from small-scale models to be confidently applied to full-scale prototypes. The primary objective of this simplified model is to replicate the dynamic behavior of the original jacket structure, focusing on its natural frequency while simplifying joints and connections. It is specifically intended for investigating the dynamic response of pile-supported jacket structures rather than for analyzing axial or lateral loading effects on the piles. However, achieving the same dynamic conditions at a reduced scale poses significant challenges in centrifuge modeling, specifically for jacket structures with numerous details. Accordingly, flexural stiffness was used in developing the simplified model. However, achieving the same dynamic conditions at a reduced scale poses significant challenges in centrifuge modeling, specifically for jacket structures with numerous details.

This study focuses on developing a simplified approach for modeling OWTs with jacket structure for a robust centrifuge modeling. This is the first phase of manufacturing a model to conduct a series of dynamic centrifuge tests at the Taiwan Geotechnical Centrifuge Facility. The study is divided into three parts: first, presenting the properties of an OWT foundation; second, detailing the simplified modeling approach; third, performing a modal analysis to estimate natural frequencies; and finally, comparing the results of the proposed approach with numerical and analytical methods.

2 OFFSHORE WIND TURBINE PROPERTIES

Offshore wind turbine towers are typically constructed as tapered tubular sections with wall thickness that varies along their height, as detailed in (Vorpahl et al., 2011). Additionally, three-point masses at different tower heights representing the flanges, bolts, and other equipments should be included in the model to accurately reflect the tower's mass distribution.

In this study, a 5MW jacket foundation-supported OWT was selected for investigation. This type of structure consists of a wind turbine tower, a concrete transition piece (TP) and a four-legged jacket structure as shown in Figure 1. The jacket structure legs are mounted on four pile foundations by using grouted connections at each jacket corner detailed based on "NREL-5MW Offshore Baseline Turbine (Jonkman et al., 2009)". The general properties of OC4 jacket are presented in Table 1.

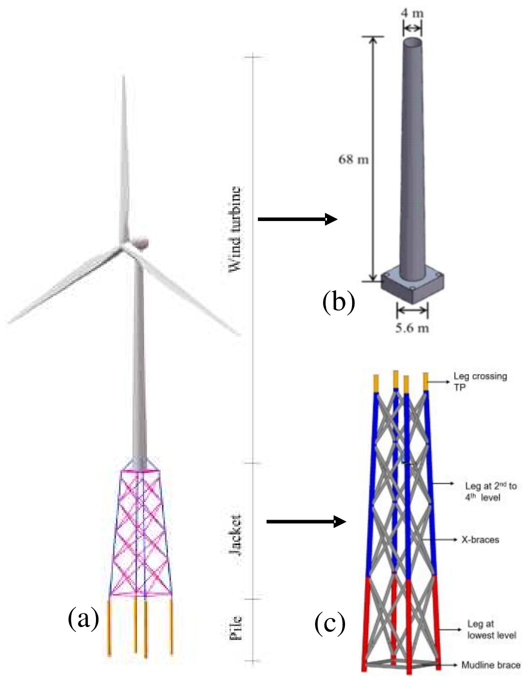

Figure 1. Illustration of jacket structure (a) full OWT jacket structure with pile foundations (Zheng et al., 2023) (b) wind turbine tower (Lai et al., 2016) (c) jacket structure components (Vorpahl et al., 2011)

Table 2 shows the properties of jacket structure components, which were marked with different colours in Figure 1(c). In centrifuge modeling, accurately replicating the complex geometry of jacket structures can be prohibitively expensive and time-consuming, especially with various components like K-joints, X-joints, braces, and jacket legs.

Table 1. General properties for OC4 jacket (Vorpahl et al., 2009)

	Parameter	Value
M_R (ton)	Rotor mass	110
M_N (ton)	Nacelle mass	240
M_{TP}(ton)	Transition piece mass	666
D_{top} (m)	Tower top diameter	4.0
D_{bottom} (m)	Tower bottom diameter	5.6
t_T (mm)	Tower thickness	22-32
L_{top} (m)	Jacket top leg spacing	8
L_{bottom} (m)	Jacket bottom leg spacing	12
h_T (m)	Height of tower	68
h_J (m)	Height of jacket	61.65

To overcome these challenges, an effective approach is to simplify the structure into an idealized and equivalent model. This model should closely match the dynamic behavior of the actual jacket structure by carefully adjusting both flexural stiffness and mass distribution. This alignment is achieved through eigenvalue analysis, allowing for a comparison of the natural frequencies between the original jacket model and the simplified equivalent model.

Table 2. Properties of jacket structure components (Vorpahl et al., 2009)

Component	Outer diameter (m)	Thickness (m)
x- and mud braces (grey)	0.8	0.02
Leg at lowest level (red)	1.2	0.05
Leg 2nd to 4th level (blue)	1.2	0.035
Leg crossing TP	1.2	0.04

3 DESIGN OF SIMPLIFIED MODEL OF JACKET STRUCTURE

The jacket structure and wind turbine tower are assumed as Euler-Bernoulli beams to analytically calculate the stiffness and natural frequency. This assumption can provide a simplified effective approach to capture the dynamic behavior of the system. The concept of a simplified model is shown in Figure 2. Figure 2 shows that the tapered tubular sections and jacket structure were initially simplified into two cylinders of different diameters, each with a uniformly distributed mass, given by m_T and m_J, respectively. These were then further idealized into a single equivalent section representing the tower-jacket system. The leg spacing varies with height in a four-legged jacket structure. Accordingly, the equivalent stiffness can be estimated by a function of the ratio between the top and bottom leg spacing as follows:

$$b = \frac{L_{bottom}}{L_{top}} \quad (1)$$

$$I_{J-top} = \frac{A_C \cdot L_{top}^2}{2} \quad (2)$$

where m is the ratio between the jacket bottom and top leg spacing, L_{bottom} is the jacket bottom leg spacing, L_{top} is the jacket top leg spacing, and A_c is the cross-sectional area of the jacket leg. The m parameter provides a basis for calculating stiffness adjustments needed to accurately represent the structural behavior at different heights in an equivalent model.

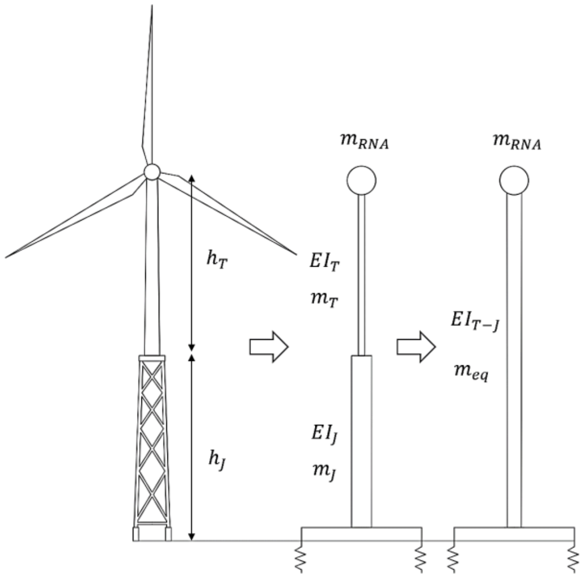

Figure 2. Simplification of jacket-tower system

Accordingly, the stiffness of the jacket structure can be expressed as follows:

$$f(b) = \frac{1}{3} \cdot \frac{b(b-1)^3}{b^2 - 2b\ln(b) - 1} \quad (3)$$

$$EI_J = EI_{J-top} \cdot f(b) = 3200\ GNm^2 \quad (4)$$

where EI_J is the stiffness of the jacket structure, I_{J-top} is the moment of inertia at the top of the jacket structure.

The wind turbine tower with varying diameter and thickness can be simplified into a constant diameter cylinder as shown in Figure 2(b). The average thickness of the wind turbine tower is calculated as

$$t_T = \frac{m_T}{\rho_s h_T D_T \pi} \quad (5)$$

$$D_T = \frac{D_{top}+D_{bottom}}{2} \quad (6)$$

where D_T is the average tower diameter, D_{top} and D_{bottom} is the tower top diameter and tower bottom diameter, respectively. The flexural stiffness of the equivalent constant diameter tower may be expressed as

$$a = \frac{D_{bottom}}{D_{top}} \quad (7)$$

$$f(a) = \frac{1}{3} \cdot \frac{2a^2(a-1)^3}{a^2(2lna-3)+4a-1} \quad (8)$$

$$I_{T-top} = \frac{\pi}{8} D_{top}^3 t_T \quad (9)$$

$$EI_T = EI_{T-top} \cdot f(a) = 305\ GNm^2 \quad (10)$$

where a is the ratio between the top outer diameter. Subsequently, the equivalent tower-jacket stiffness E_{T-J} is calculated as follows:

$$EI_{T-J} = E_T I_T \left(\frac{1}{1+(1+\psi)^3\chi-\chi}\right) \cdot \left(\frac{h_J+h_T}{h_T}\right)^3 \quad (11)$$

and

$$\chi = \frac{E_T I_T}{E_J I_J} = 0.01 \quad (12)$$

$$\psi = \frac{h_J}{h_T} = 0.97 \quad (13)$$

where $E_T I_T$ is the wind turbine tower stiffness, χ is the ratio between the tower and jacket stiffness, and ψ is the ratio between the height of jacket structure and tower.

3.1 Re-design based on natural frequency

The structure was simplified as a cylinder model that maintains the same height of the original jacket-tower system with a top lumped mass, and fixed on a rigid plate. However, the natural frequency as a critical parameter needs to be checked and the model re-designed accordingly. The natural frequency is essential because it governs how the structure responses to applied loads. The fixed-based frequency can be estimated based on Jalbi and Bhattacharya (2018) by using Eq. (14):

$$f_{fb} = \frac{1}{2\pi}\sqrt{\frac{3EI_{T-J}}{(0.243m_{eq}h_{total}+M_{RNA})(h_{total})^3}} \quad (14)$$

where f_{fb} is the fixed-base natural frequency, h_{total} is the total height of the jacket structure and the wind turbine tower, and M_{RNA} is the mass or rotor-nacelle assembly (RNA). Based on the equations above, the calculated tower-jacket structure stiffness (EI_{T-J}) is around 1423 GPa. The distributed mass (m_{eq}) is 4.2 tons/m. For the sake of brevity, the calculation of equivalent mass according to Jalbi and Bhattacharya (2018) is not presented here.

This paper aims to evaluate commonly used equations for estimating natural frequency. The Tempel/Molenaar equation is a simple and widely applied method in such cases. The equation proposed by Van Der Tempel and Molenaar (2002) serves as a verification step to cross-check the initial calculation of the fixed-based frequency, as suggested by Jalbi and Bhattacharya (2018). Furthermore, this equation is also utilized in redesigning the equivalent simplified model with a reduced height to preserve a natural frequency close to that of the original structure.

$$f_{fb} \cong \sqrt{\frac{3.04}{4\pi^2} \cdot \frac{EI_{T-J}}{(M+0.227\mu L)L^3}} \quad (15)$$

where M is top mass, μ is tower mass per meter and L is the tower height.

Figure 3. Constructed model based on the developed simplified model

Given that the primary objective of this paper is to develop an accurate and simplified model structure for centrifuge testing, it is crucial to ensure that the total vertical load acting on the pile foundations closely represents the original structure. The mass of the modeled RNA, tubular section, and rigid plate should be comparable to the combined mass of the RNA, tower, jacket structure, and transition piece (TP) in the full-scale structure. Due to size and height limitations, the full-scale prototype cannot be modeled directly in centrifuge tests. Therefore, the height of the structure is reduced while ensuring its natural frequency closely matches that of the original in accordance with Eq.(15). This frequency alignment was achieved by iteratively adjusting the outer diameter, the thickness of the cylinder, and the top lumped mass. Through this iterative process, a final design was developed that meets all required conditions. Figure 3 illustrates the constructed small-scaled model made from aluminum pipes modified by the obtained equivalent structure in Table 3.

Table 3. Properties of the simplified equivalent model with reduced height.

Parameter	Value
Top lumped mass (ton)	280
Tower height (m)	60
Outer diameter (m)	2.0
Tower thickness (m)	0.22
Tower natural frequency (Hz)	0.315
Rigid plate thickness (m)	0.5
Rigid plate width (m)	15
Rigid plate length (m)	15

3.2 Verification of designed model with modal analysis

To verify the accuracy of the designed equivalent model, the analytically derived natural frequency was compared with results from a numerical analysis. A three-dimensional finite element model of the original and the simplified equivalent jacket structure was generated in the software SAP2000 to perform a modal analysis and determine the natural frequencies. The generated models in SAP2000 were shown in Figure 4. These frequencies were then used to validate and compare the FE model outcomes with those obtained from the analytical solution, ensuring accuracy and reliability in the dynamic assessment of the structure.

The original jacket structure components, wind turbine tower, and simplified equivalent model were constructed using beam elements, with their properties detailed in Tables 1-3. The material assumptions for steel include a density $\rho_s = 7850\ \text{kg/m}^3$, Young's modulus $E_s = 2.1 \times 10^{11}$ Pa and Poisson's ratio $\nu_s = 0.3$. The RNA was represented as a lumped mass at the top of the tower.

Table 4 shows that the fixed-base natural frequencies of the original jacket structure from SAP2000 closely match those calculated using analytical methods. Additionally, the simplified idealized model exhibits the dynamic properties similar to the original jacket structure. structure, although the natural frequency from SAP2000 is slightly higher than that determined from the analytical equations.

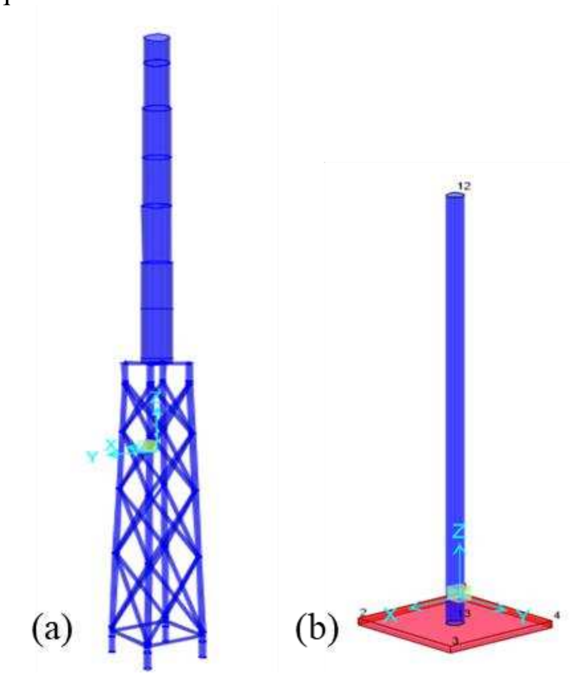

Figure 4. Generated models in SAP2000 (a)original jacket structure (b) simplified equivalent model

Table 4. Comparison between natural frequencies of original jacket and simplified equivalent model

Case	Numerical analysis	Analytical analysis	
		Eq. (14)	Eq.(15)
Original Jacket	0.305	0.304	0.312
Simplified model	0.336	-	0.287

4 CONCLUSIONS

As offshore wind farms expand into seismically active regions, understanding the behavior of offshore wind turbine (OWT) foundations under seismic loading conditions by physical modeling becomes increasingly crucial. This study addresses the complexities of full-scale OWT modeling by developing a practical, simplified framework to represent a four-legged jacket structure for centrifuge testing. Specifically, a four-legged OWT jacket structure mounted on pile foundations is simplified into a constant diameter and thickness cylinder rigidly fixed on a plate with a lumped top mass to represent the mass of the rotor-nacelle assembly RNA. Through adjusting parameters such as outer diameter, thickness, and top lumped mass, the height of the model structure is reduced to maintain a similar natural frequency to the original structure, with only a 0.03 Hz difference confirmed through both analytical calculations and finite element analysis in SAP2000. This method effectively replicates the dynamic characteristics of the full-scale structure while meeting the constraints of centrifuge modeling, providing a reliable foundation for further physical testing.

AUTHOR CONTRIBUTION STATEMENT

Yimo Wu: Methodology, Software, Writing- Original draft. **Ali Lashgari**: Methodology, Writing-Reviewing. **Amin Barari**: Writing-Reviewing, Supervision. **Lars Bo Ibsen**: Supervision

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