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Scaled Testing for Wind Turbine Drivetrains: State of the art and recent developments

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Abstract. As wind turbine drivetrains grow in scale and complexity, the practice of full-scale testing has become expensive and logistically demanding. These challenges are inducing a significant shift in the wind energy industry, potentially propelling scaled testing from a specialized academic pursuit into a widely adopted method. While scaled testing has a well-established history in the analysis of the structural integrity of wind turbine components and the aerodynamic performance, its application to drivetrain systems is a recent but expanding field. This paper reviews state-of-the-art scaled testing methods for wind turbine drivetrain components. It addresses recent developments, and the ongoing efforts of standardized scaled testing methods for wind turbine drivetrains. Considering the research and case studies presented in this paper, it is projected that scaled testing will become an integral and essential part of the design, validation, and optimization processes for future wind turbine drivetrain systems.

1. Introduction

In the competitive sector of wind turbine (WT) technology, manufacturers strive for rapid prototype testing to achieve faster time to market while ensuring product reliability. As a result, significant advances have been made towards the development of full-scale nacelle testing facilities worldwide, which are now a fundamental part of the development process for many WT manufacturers [1]. However, with the ever-increasing size and power ratings of modern wind turbines, full-scale testing is becoming expensive and challenging. There has been a trend of establishing larger test benches with increased load application capabilities to accommodate the demands of larger WTs as shown in **Figure 1**. However, this continuous trend of constructing bigger nacelle test benches for larger WTs might not be a sustainable solution as the escalating capital investment required for such massive infrastructure creates a significant barrier to entry. Accessing established nacelle test facilities is already financially challenging for smaller WT manufacturers or suppliers and the construction of larger test benches, with potentially higher cost, may further limit the number of manufacturers financially strong enough to utilize these facilities in their development process [2]. Consequently, the existing testing methods need to adapt with the evolving WT technology.

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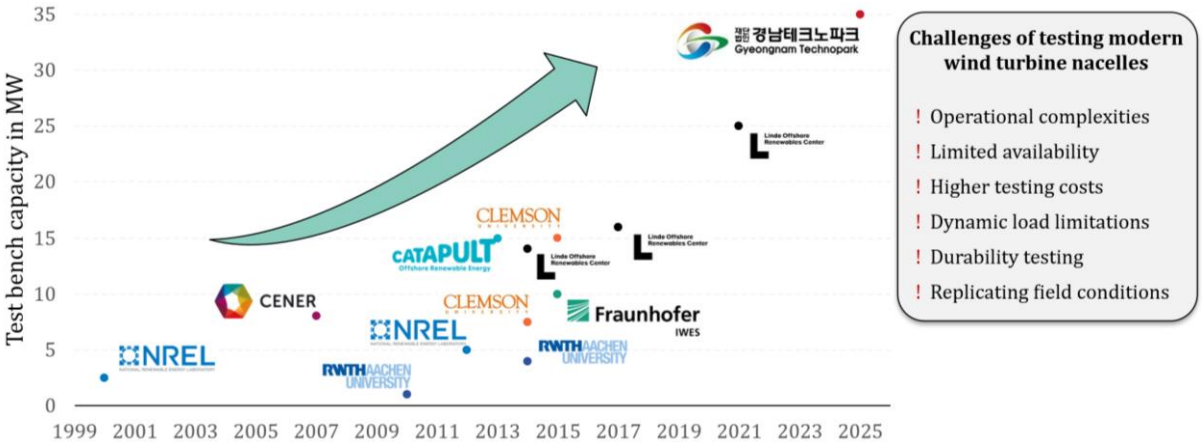


Figure 1. Development trend of world-wide nacelle testing facilities over the years and the challenges of testing modern wind turbine nacelles [1].

This paper explores alternative solutions for testing WT drivetrains, with a specific focus on state-of-the-art scaled testing methods. The paper begins by comparing various alternative methods of testing WT drivetrains as compared to ground based nacelle testing. It then focuses on scaled testing and introduces principles of scaling, followed by reviewing the existing scaled testing methods for key drivetrain subsystems and components. By exploring recent developments in scaled testing methods for WT drivetrains, the paper concludes with a comprehensive outlook on the future of drivetrain testing.

2. Alternative methods for testing wind turbine drivetrains

Alternative solutions for testing WT drivetrains include virtual testing, hybrid testing, and scaled testing, each one with unique strengths and challenges, as summarized in **Figure 2**. Virtual testing exclusively relies on high-fidelity computational models, often in a co-simulation environment [3]. This approach offers substantial advantages in terms of cost-effectiveness, flexibility, and repeatability, allowing for numerous and safe exploration of tests without physical risk. However, it is fundamentally model-dependent as the accuracy of the results is inherently limited by the fidelity and underlying assumptions of the system models. Consequently, the results necessitate rigorous external validation which requires test data, either through component tests or tests of a similar reference system.

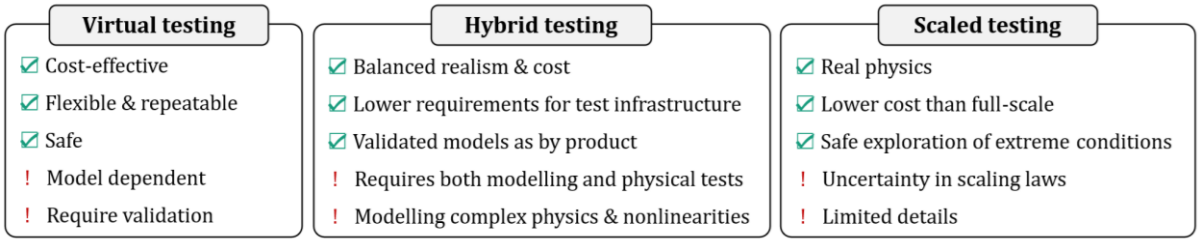


Figure 2. Comparison of various testing concepts for wind turbine drivetrains.

Hybrid testing can resolve these issues as it combines the advantages of physical tests and simulations [4]. This method leverages partial load tests conducted on a physical test bench to develop and validate a high-fidelity simulation model which is subsequently used to predict the full-load behavior of the WT drivetrain, enabling the investigation of load ranges beyond the physical test bench's capabilities. This can be a good trade-off between abstraction from the full-scale

and testing cost, effectively reducing the requirements for full-load system tests. Furthermore, the measured partial load tests allow model tuning and validation as a by-product. Primary challenges in implementing hybrid testing include the intrinsic requirement of both modeling and physical tests, and the difficulty associated with accurately modeling complex physics and nonlinear responses [5].

Scaled testing involves the design and deployment of geometrically or physically downscaled prototypes to analyse full-scale behavior. The core benefit of this technique is the ability to examine the real physics of critical phenomena at a lower cost than full-scale tests. It also allows for the safe exploration of extreme conditions that might lead to failure in a full-scale prototype. Successful implementation depends heavily upon correct definition of interfaces and the accurate application of scaling laws [6]. However, these laws are subject to inherent uncertainty and may not adequately capture localized phenomena that do not scale linearly [7]. The remainder of the paper will focus on scaled testing methods specifically for WT drivetrains.

3. Scaled Testing for Wind Turbine Drivetrains

The goal of scaled testing is to replicate the behavior of a full-scale system in a smaller, more manageable specimen by implementing a certain scaling method. Scaling methods are commonly based on the laws of similitude [8], which dictate that a scaled specimen accurately represents the full-scale prototype if the phenomena governing their behavior are physically similar. A scaled model is said to have achieved similitude with the actual system if the two systems share the same geometric, kinematic, and dynamic similarities. In general, geometric similarity focuses on the scaling of dimensions, kinematic similarity on the scaling of displacements and velocities, and dynamic similarity on the scaling of integrated values such as forces. The requirements for dynamic similarity are the most restrictive and the existence of dynamic similarity implies that the conditions for geometric and kinematic similarities already exist [9]. Dimensional analysis, such as the Buckingham Pi-Theorem [10], is applied to derive scaling factors. By formulating dimensionless groups, this technique condenses numerous physical variables into a manageable set of parameters. This allows for straightforward analysis of scaled-model data and its extrapolation to the design and performance prediction of full-size prototypes.

In the field of wind turbine technology, scaled tests for global WT aerodynamics [11], the rotor system [7] and offshore floater dynamics [12] has been researched for many years. To align with the objectives of this paper, a literature review focusing on the scaled testing of the mechanical drivetrain was conducted. **Table 1** lists the state-of-the-art scaled testing methods and case studies specifically focusing on the mechanical components of a WT drivetrain. Scaled testing for the WT gearbox has been demonstrated across three focus areas. First, a 1:4-scale similarity model has been used to evaluate parameters like gear load capacity and tooth bending strength by comparing tooth stresses [13]. Secondly, for gear pitting safety and contact fatigue, numerical optimization has been employed to determine scaling factors for gear safety and normalized natural frequencies, using variable scaling factors for shaft geometry and inertia [6]. Finally, the dynamic response of a gearbox has been addressed and demonstrated by scaling down the rated power from 3000 kW to 20 kW, utilizing the tip speed ratio and a relationship between angular velocity and blade radius as scaling considerations [14].

Most critical failure modes for the remaining drivetrain components such as the main bearing, mechanical brake, and high-speed coupling still lack documented, dedicated scaling approaches in the state of the art. This lack is likely to be a symptom of an incomplete understanding of the underlying failure mechanisms. Without having complete understanding of the relevant

mechanisms that cause the failure, it is not possible to correctly derive the required scaling methods. For the case of main bearings, design standards are based on rolling contact fatigue and no publicly available models or validated methods exist for further failure modes like smearing, micro-pitting and white etching cracks. Many failure modes are governed by factors that do not scale linearly with size. For example, bearing smearing is highly dependent on the speed, load, and internal geometry [15], all of which change fundamentally as the bearing size increases. If the physics governing this failure are not fully mapped out across different scales, a scaling method cannot be developed.

Table 1. State-of-the-art scaled testing for the mechanical components of wind turbine drivetrain.

Subsystem	Test purpose	Scaling method	Source
Gearbox	Gear load capacity Tooth bending strength Surface durability	▪ Comparison of tooth stresses ▪ 1:4-scale similarity model	[13]
	Dynamic response	▪ Similarity in the inertia time constant, tip speed ratio and a relationship of angular velocity and blade radius. ▪ Rated power scaled from 3000 kW to 20 kW.	[14]
	Pitting safety factors, gear contact stress & fatigue	▪ Scaling factors determined using numerical optimization and objective functions for the safety factors of the gears and for the normalized natural frequencies. ▪ Variable scaling factors for shaft diameter, length, system mass moment of inertia and gear stage.	[6]
	Smearing Abrasion Micro-pitting Corrosion Rolling contact fatigue White etching	No published approaches	
Main bearing	Ring creep Smearing Rolling contact fatigue Micro-pitting Abrasive wear Fretting Brinelling Cage failure	No published approaches (Tests for rolling contact fatigue may be transferred from other applications.)	
Mechanical brake	Wear of brake disc Disc cracks	No published approaches (Similar applications are available in other industrial sectors.)	
High speed coupling	Coupling slippage Bolt failure	No published approaches	

4. Recent Developments

Section 3 introduced the theoretical framework of scaling laws and identified significant knowledge gaps, demonstrating that many drivetrain components still lack validated scaling procedures. These identified gaps now provide the context for a shift in research priorities.

Specifically, the focus has moved away from universal theories towards component-specific validation and functional scaling. This evolution is evidenced by a notable surge in specialized research and industrial projects over the last five years targeting previously unexplored areas. Many of these efforts emphasize the industry-driven validation of specific drivetrain components. The following subsections categorize these recent developments by their primary technical focus.

4.1 Scaled tests for a novel main bearing concept

Recently, novel concepts of plain bearings as main bearings for WTs are being introduced. Downsized prototypes are being used to test the functionality of such novel plain bearing designs. The FlexPad project [16] introduced a design methodology for utilizing plain bearings as main bearings. To reduce test bench costs, this method was developed using a scaled reference bearing (see **Figure 3**). The reference geometry was scaled down with a constant Sommerfeld number, reducing the outer diameter from 926 mm to 500 mm. The geometry of the scaled bearing was optimized using simulations [17].

In the follow-up project NextMBU [18], the bearing was scaled up for use in an 8.5 MW WT and examined using elasto-hydrodynamic (EHD) simulations. It was found that the disproportionate increase in breakaway torque with rotor size poses a key challenge to using the scaled bearing as a main bearing [19]. The aim of the ongoing research project is the development of a plain bearing main bearing unit in a market relevant size.

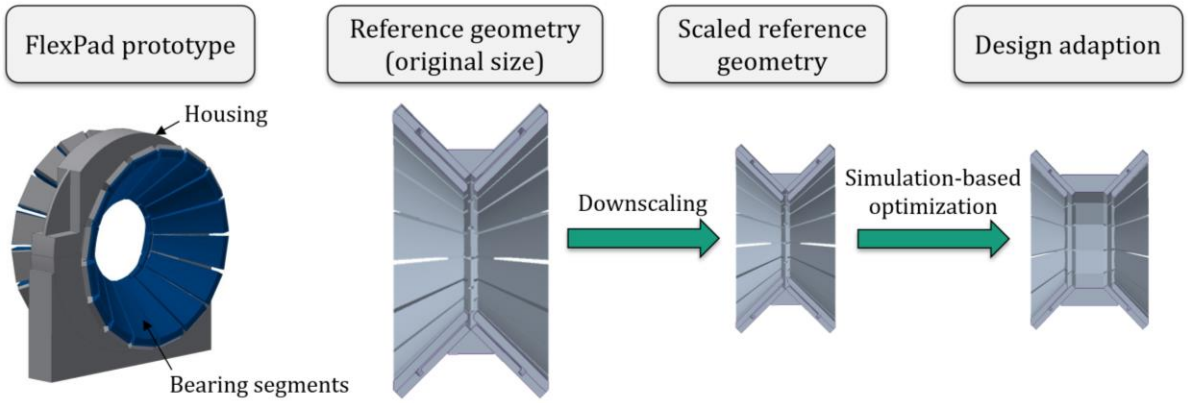


Figure 3. Design process of a scaled and optimized plain bearing as main bearing [17].

4.2 Scaled tests for main bearing condition monitoring

A novel laboratory-scale test bench prototype has been recently developed for full characterization and condition monitoring of WT main bearing faults [20]. WT scaling laws have been employed, which adjust essential parameters, such as rotor radius, blade mass, and angular velocity, to ensure geometric, kinematic, and dynamic similarity between the test bench and a full-scale WT rotor-bearing system. The test setup utilized three spherical roller bearings (SKF 22206 E/C3) as test specimens, each artificially faulted, running on a 30 mm main shaft with a speed range of 100–300 RPM and a maximum aerodynamic thrust load of 1500 N. The test bench's effectiveness was confirmed by preliminary evaluation, which showed discriminative variations in vibration signals across different bearing health states. Moreover, a Bayesian-optimized LSTM model developed with the collected data demonstrated successful main bearing fault diagnosis. The study proposes that the method's insights can be extended to other WT bearings.

4.3 Scaling in combination with virtual testing

The traditional testing pyramid culminates in the most expensive and time-consuming stage: testing the full structure against fixed loads. The recent EU project INNTERESTING [21] aimed

towards integrating scaling methods with virtual testing to overcome the limitations of conventional large-scale physical tests. The project proposed a novel hybrid method (as depicted in **Figure 4**) that combines simplified, smaller-scale physical tests with advanced virtual testing [22]. These results were then combined using a smart fusion process and upscaling techniques to robustly predict the reliability, lifetime, and failure modes of the full-scale components without requiring massive, costly test benches.

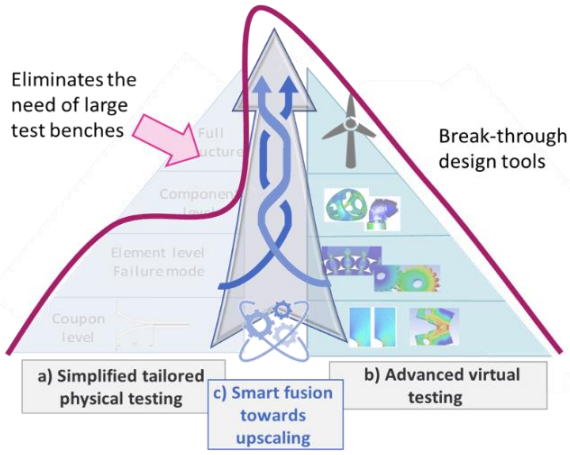


Figure 4. INNTERESTING smart fusion concept to eliminate the need of large test benches [23].

This project pursued the validation of the developments through three different case studies for an innovative pitch bearing concept, a gearbox concept for next generation WTs, and an innovative repair solution for lifetime extension of existing pitch bearings.

4.4 Scaled tests for cast iron components

As part of the LeKoGussWEA project, a WT's cast iron components were scaled down and tested. These tests were performed to assess the fatigue strength of cast iron components in WTs. For this purpose, a planet carrier was scaled down by a length scaling factor of 1:4 and modified for use on a test bench (**Figure 5**). Then, the transferability of the results to the full-size test specimen was verified.

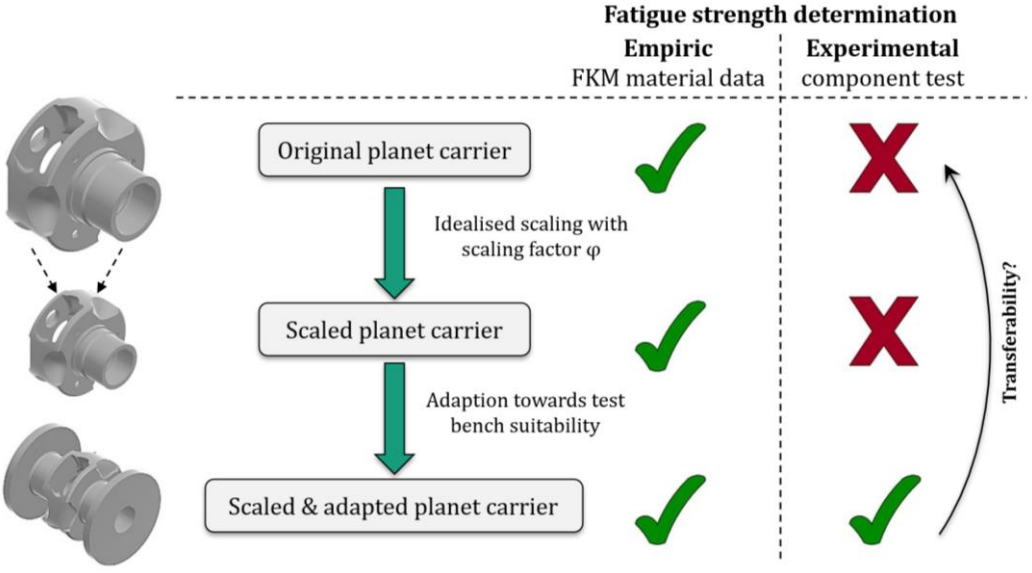


Figure 5. Scaling process for the determination of fatigue strength of a planet carrier [24].

These tests enabled a reduction in the required material by approximately 95 %, and the torque under which the tests were performed was reduced by 99 %. However, using the same material composition and heat treatment for the scaled test specimen as for the full-size test specimen was insufficient. The scaled test specimen is therefore more susceptible to shrink holes and consequently has reduced fatigue strength [24].

4.5 Scaled multi axis test bench for main bearing testing

Scaled testing, like full-scale testing, requires customized test benches. One example is a scaled multi-axis test bench installed at DTU Wind and Energy Systems, which was developed by R&D Test Systems. The test bench was originally developed as a scaled platform to support the development and verification of the control system and actuators for a full-scale Wind Load Unit (WLU) [25]. Following updates and modifications, it is now being reused as a scaled main bearing test bench to support ongoing research activities at DTU.

As shown in **Figure 6**, the test bench comprises a WLU implemented as a hydraulic hexapod, capable of applying static and dynamic loads to the device under test (DUT). In combination with an integrated drive system, the DUT can be loaded in all six degrees of freedom. In the configuration shown, the DUT consists of two main bearings mounted in a machine housing and supporting a main shaft, which is mechanically connected to both the hexapod and the drive unit. The DUT is mounted on a movable support structure, referred to as the Flexpod. Spring packages integrated into the Flexpod's support legs allow the emulation of different DUT stiffness characteristics. In combination with load transducers installed in these legs, the applied loads can be measured and validated in detail, thereby supporting the development and assessment of scaled testing methodologies in the future.

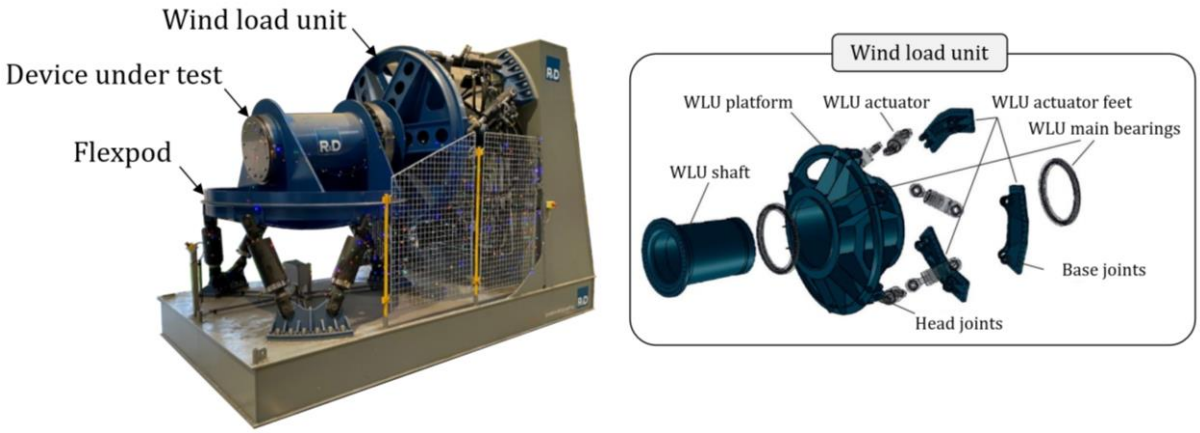


Figure 6. Hexapod bearing tester at DTU Wind and Energy Systems [25].

At DTU, the test bench will accommodate main bearing units of the Vestas V27 research turbine located on the same campus. The test bench will be commissioned in the coming years to analyse the operation of damage-induced main bearings under various operating conditions and to observe the performance of different lubricants and condition monitoring systems. For the comparison and transferability of the results of the scaled test bench with the full scale 25 MW test bench, scalability of key effects such as the roller contact pressures of the main bearings will be assessed.

4.6 Novel scaled component test bench for gearbox plain bearings

Conventional bearing test bench's apply radial loads directly via a load cylinder. This impedes the replication of several important effects such as the forces induced by the gearing and structural

deformation, planet ovalization, deformation of the planet carrier and tilting of the planet gears. Due to this abstraction, the contact conditions and temperature distributions in the plain bearing are not represented realistically. To reproduce realistic contact conditions and wear behavior of plain bearings in WT gearboxes, a novel test bench concept has been developed in close cooperation between the project partners CWD of RWTH Aachen University and RENK Test Systems GmbH [26]. **Figure 7** shows the schematics of the novel test bench design. This novel test bench allows the testing of a scaled planetary plain bearing with a diameter of 200 mm and up to a medium contact pressure of 43 MPa. This concept is based on a planetary gear dummy (a bushing) that rotates around a fixed pin via a belt drive. Load actuators apply the desired radial forces, the tilting moments due to the meshing of the teeth and the width load distribution and the forces for ovalizing the planetary wheel dummy.

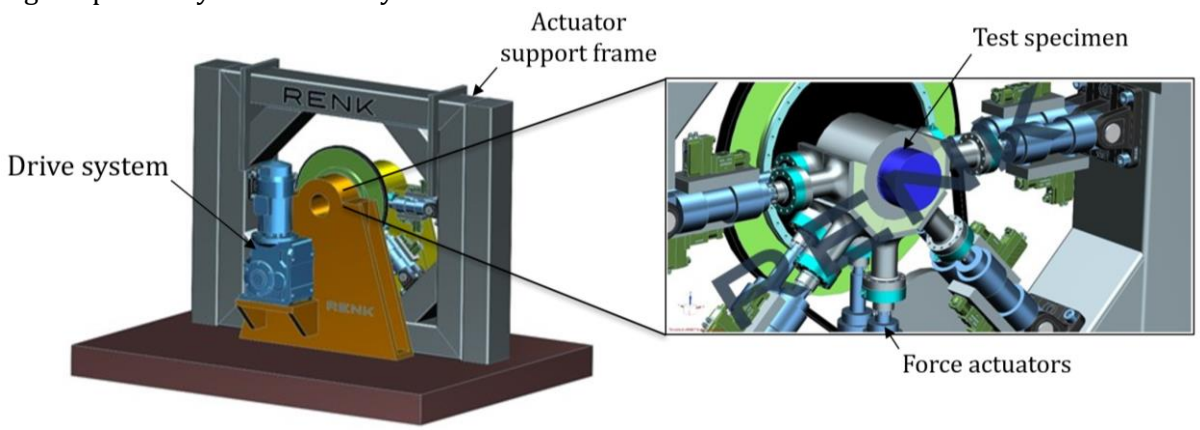


Figure 7. Design of the new planetary plain bearing test bench with multi-point load application [26].

Scaling of the cylindrical forces was carried out using FEM simulation and the validation of the contact conditions of the scaled test bench plain bearing was performed by comparing the contact conditions with those in the real size planetary gear plain bearing modeled in MBS/EHD. The applied loads of the previous step were downscaled to apply the contact pattern of the real size pin on the downscaled test bench. Geometric and kinematic scaling is performed with a factor till 0.65. The scaling factor is variable for this concept, depending on the sliding speed and contact loads of the planet pin. The resulting contact patterns in the scaled test bench were found to be almost identical to the real case. Furthermore, the simulation-based investigation recommended a total of 10 load cylinders to be installed, applying a maximum load of 226 kN to reproduce load conditions on a 200 mm scaled test plain bearing in similar manner as in the real size WT. Once finalized, this novel test bench will allow the qualification of the gearbox planet pins and lubricants.

4.7 Standardizing the methods for scaled testing

The growing importance of scaled testing for WTs is leading to a push for standardization. To counter the high costs and limited availability of massive full-scale test benches, the project SC4WT [27] aims to develop a simulation-verified, universally applicable guideline for designing scaled test specimens and conducting scaled tests of WT drivetrain systems and components. **Figure 8** illustrates the overall workflow of developing such a guideline within the scope of this research project. By utilizing an automated simulation toolchain (developed within the project), scaled test specimens are defined through a systematic optimization loop to evaluate their performance against target criteria relevant to a test purpose. If the scaled design fails to meet target criteria,

such as accurately replicating damage-equivalent loads or specific failure modes, design adjustments are made and the process is repeated until the target criteria are reached.

In the SC4WT project, the development of a comprehensive guideline serves as the primary mechanism for transferring academic research into standardized industrial practice. This guideline is designed as a practical, step-by-step manual that enables engineers to navigate the complexities of "scaling by design", ensuring that data gathered from smaller, cost-effective test specimens remains valid and transferable to full-scale multi-megawatt WT drivetrains. Furthermore, the guideline acts as a collaborative bridge between research institutions and the wind energy industry. It will be refined through continuous feedback loops with an industrial advisory board, including major wind turbine manufacturers and suppliers, to ensure its real-world applicability. This standardized framework not only aims to reduce the massive capital expenditure required for 15 MW+ test infrastructures but also establishes a common ground for manufacturers and suppliers. Ultimately, this document will provide the foundational methodology for the project's second phase, where the simulative findings will be validated through physical experiments.

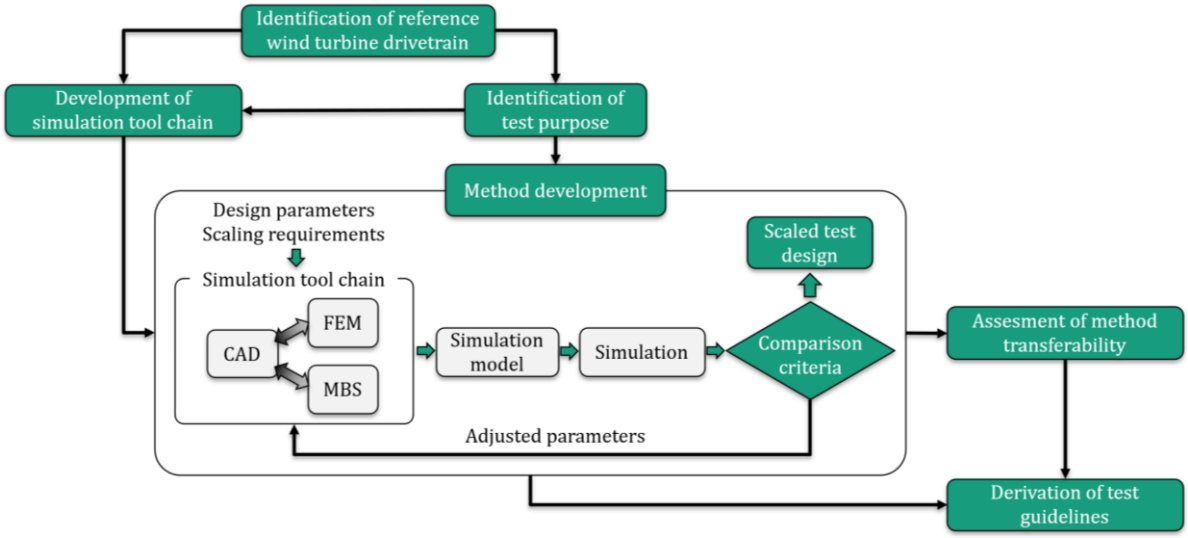


Figure 8. SC4WT project approach for developing standardized scaled tests for wind turbine drivetrains.

5. Concluding Remarks

The rapid growth in wind turbine size has made traditional full-scale drivetrain testing increasingly difficult and expensive. This economic and logistical pressure has propelled scaled testing from a niche research topic to a crucial and relevant method for the entire industry. While scaled testing has long been used for wind turbine structural and aerodynamic studies, its application to drivetrain subsystems remains a developing field with significant potential and notable hurdles. The widespread adoption of scaled testing for wind turbine drivetrains is currently hindered by distinct knowledge gaps. As highlighted in this review, a primary challenge lies in the incomplete understanding of underlying failure mechanisms for critical drivetrain components. The derivation of accurate scaling laws is further complicated by phenomena that do not scale linearly. Failure modes such as bearing smearing, micro-pitting, and white etching cracks are governed by various factors that change fundamentally as size increases. Without a comprehensive understanding of the physics governing such failures across different scales, developing valid scaling methods remains difficult. Material science presents an additional challenge, as seen in cast iron component

testing, identical material composition and heat treatment in scaled specimens can lead to disproportionate defects which compromise the transferability of fatigue strength results.

Nevertheless, the research and case studies presented in this paper reveal that scaled testing for wind turbine drivetrains is evolving from a supplementary technique into a dedicated field of study. The development of specialized test benches for scaled testing of drivetrain components demonstrates a trend towards capturing complex, multi-axis loading conditions that were previously only attainable on full-scale test benches. Furthermore, the exploration of "smart fusion" of simplified, cost-effective scaled tests with advanced virtual testing could also become a viable alternative to full-scale testing. Ensuring that scaled testing evolves into a reliable tool for the design, validation, and optimization of the next generation of wind turbine drivetrains requires the development of standardized scaled testing methods and guidelines, fostered by close collaboration between research institutions and the wind industry.

Acknowledgements

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