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Main bearings in large offshore wind turbines: development trends, design and analysis requirements

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Abstract. This paper discusses analysis requirements for design and operation of main bearings in modern multi-megawatt offshore wind turbines, motivated by the industry's search for reliable and cost effective main bearing solutions that limit the effects of non-torque loads, and the need for effective bearing health monitoring. Gearboxes historically received attention on the grounds of reliability, sparking significant interest in drivetrain dynamics. However, design trends in modern, large turbines, influencing choices for a future 10+ MW generation, indicate that more attention to main bearings or rotor support bearings is needed as part of a more holistic approach to flexural dynamics. Through a survey of existing research, offshore wind turbine design trends, design codes, industry practices and standards, we look at how main bearings are treated in a life cycle perspective, considered design features, modeling and simulation approaches, interaction and interfaces between industry stakeholders, as well as re-use of simulation models for predictive analytics in operation. We conclude that flexible main bearing representation is important in dynamic analyses and that industry practices are needed that enable sufficient model exchange or interfaces and thus effective exploitation of the benefits of a simulation model throughout the turbine life cycle.

1. Introduction

Offshore wind power plays a central role in meeting Europe's Energy Policy Objectives for 2020 and beyond, as cited by the European Commission [1] and echoed by Wind Europe[2]. Objectives include reducing CO₂ emissions, ensuring security of supply and improving EU competitiveness. Offshore wind not only accounts for a significant share of the wind power development potential, but also represents a number of advantages such as stable and strong winds, fewer space-related conflicts and restraints on turbine size. Cost models encourage increasing turbine size in order to harvest wind energy at greater heights and give fewer unit operations and access points. A separate development path for offshore wind turbines branched off early in this millennium, giving turbines with up to 9.5 MW rating [3] currently available to the market, and expectations that a 10+ MW generation of turbines will become available over the next decade.

If the increase in turbine size has been faster than predicted, it hardly measures up to the pace at which European bottom fixed offshore wind developments approached grid parity. As fierce competition in offshore wind farm auctions sported zero subsidies bids since 2016, the industry put tremendous pressure on itself, further sharpening the demand for technological advances and bigger turbines at minimum expense of increased specific weight and cost. Added general



enhancement factors such as maximal design utilization and higher degree of adaptation to site-specific conditions, as well as consistent reliability and controllable wear and fatigue reserves, the industry rely more than ever on engineering tools and methods capable of supporting high perfection in both turbine design and operation. Successful application of such tools and methods certainly adds to the competitive advantage of the user.

As designs evolve, changes in turbine size and drivetrain layout affects the premises for modeling and simulation of main bearings or rotor support bearings. On one hand, numerical models represent the bearing influence on overall structural dynamic behavior and non-torque loads on the drivetrain. Earlier studies have well documented the importance of main bearing performance on the life of gearboxes. It is equally important for the airgap in direct drive generators. On the other hand, models provide the basis for estimation of bearing operating parameters, which is essential for designing a reliable bearing arrangement and opens up for model based prediction during service. Designing and operating a main bearing arrangement for a 10+ MW turbine is a walk into unknown territory, with limited backing in current industry-specific standards and practices. Hence, analysis methods need to be established, both in form of modelling practices properly addressing reciprocal effects between turbine flexural dynamics and bearing internal dynamics, and methods for linking and exchanging models enabling effective use throughout the turbine life cycle, the latter illustrated in Figure 1.

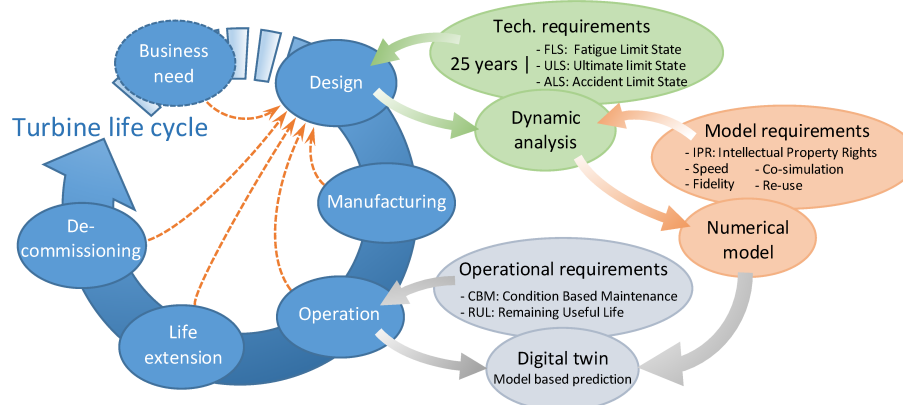


Figure 1. Requirements in a life cycle perspective

2. Design and analysis

2.1. Drivetrain flexibility and dynamic analysis

The inherently fluctuating nature of wind and wave loads, and the resulting vibratory response of wind turbines and foundations, necessitates global dynamic analyses for assessing loads and performance. Rotation of the blades and hub introduces gyroscopic and centrifugal forces and moments in addition to the dynamic forces and moments from energy conversion and control actions. Gravitation pulls on the blades and the overhung rotor. Floating wind turbine operation introduces additional forces from active floater motion control. A number of industry-standard design codes have been developed for overall turbine analysis, for example SIMA, FAST, FLEX5, BLADED and HAWC2, described in Vorpahl et. al [4]. Sometimes referred to as integrated codes, aero-elastic codes or even aero-servo-hydro-elastic codes, depending on the included functionality, these codes offer little but the most basic representation of main bearings and drivetrain.

Increased interest in more detailed dynamic analyses of drivetrains came with the gearbox reliability issues experienced more frequently as turbine development pace picked up. Although

due to several factors, general lack of understanding of dynamic load effects was commonly acknowledged as the underlying problem [5]. Numerous studies on drivetrain dynamics have followed. Early examples include those by Peeters et. al [6] and Schlecht et. al [7, 8], the latter pointing to structural flexibility as the reason why gears and bearings that work well in other industries fail in offshore wind, and advocating flexible modelling. Incremental contributions have since provided insight in the effect of drivetrain flexibility and layout, and established flexible Multi-Body Simulation (MBS) as state of the art in drivetrain modelling and analysis. These studies commonly use the de-coupled approach, whereby spectra or time series of forces and moments at the main shaft are generated by an aeroelastic design code and supplied as input to a separate drivetrain MBS model.

Guo et. al [9] presents a study on internal and external measures to a gearbox, to reduce the effect of non-torque loads on gear alignment. The external solution involves transferring torque from the hub to the gearbox by a quill shaft. The internal solution involves replacing the bearings supporting the first stage planet carrier, from cylindrical roller bearings to preloaded tapered roller bearings, in order to increase system stiffness. Redirecting forces from the shaft to the gearbox housing significantly reduces gear misalignment. Detailed modeling of the front carrier bearing shows how a minimum radial force is secured through 360 degrees for nominal torque and bending in the tapered roller bearing as opposed to the cylindrical roller bearing, and thus reduces the risk of roller slip. Dynamic load effects and interfaces of the detailed bearing model are not discussed. The study concludes that preload and consequently tight manufacturing tolerances are essential to meet design objectives.

Helsen et. al [10] presents a study on natural frequencies of a gearbox in free boundary conditions, considered flexible versus rigid multi-body modelling approaches. Flexible bodies are obtained by Component Mode Synthesis (CMS) model reduction techniques from Finite Element (FE) models. From a methodological view, the importance of defining appropriate multi-point coupling structures at body interfaces is emphasized. Simulation results show that introducing flexible bearings for supporting a flexible planet carrier body largely impacts natural frequencies, thus the bearing should be represented as accurately as possible. Helsen et. al [11, 12] present further results on the effects of including flexibility in gearbox modelling, and consider the effects of turbine upscaling, observing that gearbox housing is the most influential flexibility in the system.

Helsen et. al [13] extends studies on gearbox flexibility to include a main shaft, main bearings and gearbox supports in a comparison between drivetrain configurations. A three-point suspension, where the gearbox supports the main shaft rear end, is compared with an arrangement featuring two main bearings and an overhung gearbox, the latter with either resilient or hydraulically equalised torque reaction supports. Idealisations include a rigid bedplate. The two-bearing arrangement is shown to reduce the gearbox response amplitudes. It is concluded that main bearing stiffness in itself has little influence on the result, whereas the distance between main bearings has some influence. An elaboration on this result should have considered the relative stiffness and geometric aspects of the whole shaft-bearing assembly.

Nejad et. al [14] presents a complete 5 MW reference gearbox for offshore wind turbines, based on a well-defined design basis and developed using systematic methods. The present MBS model contains both rigid and flexible elements, and model fidelity follows recommendations by Guo et al. [9] in order to strike a balance between characteristics and simulation time. The model is used by Nejad et. al [15] for comparing drivetrain loads in a land based turbine with a offshore spar-type floating turbine, showing that the axial load carrying main bearing sustain more fatigue damage accumulation in the floating turbine application.

With a drivetrain representation limited to a single joint providing continuous rotation against a drivetrain torque, and a stiffness matrix for the remaining 5 DOF, the aeroelastic codes provide for coupled approaches elaborating on the mechatronic aspects associated with drivetrain

torsional dynamics, energy conversion in the generator and control functions. Examples of such studies include those by Gallego-Calderon et. al [16, 17]. Coupled analyses can be based on model extensions, for example in the form of dynamic link libraries, or on co-simulation. The choice between coupled and de-coupled approaches rests on several factors, namely:

- The computational expense involved in running through the load cases in IEC 61400-1 [18]. A very detailed model might be neither necessary nor very expedient for every load case.
- The criticality of the load case for the drivetrain, and whether control strategies and transient phenomena need consideration. IEC 61400-4 [19] states that time domain analysis is suitable for analyzing transient load effects in the gearbox. Nejad et. al [20, 14] investigates the importance of load effects from blade pitch actuation failure and emergency shutdown in a bottom-fixed wind turbine. Results show that considerable force is imposed on the main bearings, causing significant damage accumulation.
- The prevailing of the industry-standard aeroelastic codes, due to availability and backing by a wide user base, including both manufacturers and project developers.
- The separability of the ranges of natural frequencies involved on the structural side and the drivetrain side, respectively. Helsen et. al [12] show that this holds to a lesser degree for typical geared designs as turbine size increases.
- Whether drivetrain affect the overall structural dynamics, i.e. the reciprocity between levels. For example, the flexibility surrounding a bearing can affect fundamental global modes, and thus be rendered important in a high level analysis, whereas inertial forces on individual bearing rollers are dismissible in the same context on grounds of energy content.
- The availability of well-defined interfaces between models.
- The sharing of information between parties. Argyriadis et. al [21] problematizes this aspect. Proprietary analyses might prohibit exchange of anything but condensed results, for example stiffness matrices.

The PROTEST project [22] was launched in response to lack of clear definitions of load cases and load interfaces for pitch systems, yaw systems, drivetrains and main bearings, aiming to provide input to standardisation work. Based on input from project partners, geared drivetrains with high-speed generators was set as base case. Argyriadis et. al [21] delivered a state-of-the-art report on current turbine solutions as well as analysis practices and tools. Pitfalls are identified as finding the maximum stress response, transferring data between parties, determining load cases and processing the numerous simulation cases. Holierhoek et. al [23] dealt with Design Load Cases (DLCs), pointing to misalignment, resonance analysis and Low Voltage Ride Through (LVRT) as important, the first two items not representing load cases, but rather design features not readily modelled in current tools. Lekou et. al [24] dealt with load interfaces, considering forces and moments at main bearings, gearbox input and output shafts, and gearbox supports. Recommendations for standardisation work are given in [25]. Aeroelastic code-level fidelity is implicitly accepted on grounds of the prohibitively long simulation times associated with more detailed analyses.

2.2. Design diversity, trends and subsupplier influence

Discussions over wind turbine solutions are frequently reliability-oriented, thus often concerned with conceptual choices, for example between geared or directly driven generators. Significant diversity is seen in drivetrain design, by virtue of different origins, assumptions, analyses, experiences and priorities. Whilst initially the most viable approach, drivetrains are to a lesser degree than before based on standard components transferred from other industries. Bespoke solutions at some point proves a better compromise between cost and performance, for example medium and low speed speed generators which help bring down gear ratios to manageable levels

and also debunk the myth that direct drive turbines need be substantially bulkier and heavier. Supplier influence plays a role in this respect, with drivetrain component manufacturers actively targeting solutions towards the wind power industry. This development is also reflected in main bearing solutions [26, 27].

The actual differences in geometry and flexural characteristics between various main bearing arrangements generally receive little attention. Some of the measures used and proposed by the industry to decouple the drivetrain from the rotor well illustrates the difficulty of the task at hand for the designer. Palliatives like flexible couplings and mechanical load equalization can reduce non-torque load effects, and ease the analysis task by shifting interfaces and allowing decoupled analyses. It is thus tempting to pose the rhetorical question if modelling and simulation options, and the challenge of treating structural flexibility in a consistent manner, ultimately influences design choices. Main bearings have a difficult place in that they are implicitly considered a part of the drivetrain unless dissociated by decoupling devices or simply gearless designs; then they seem somewhat ignored, a point well illustrated in Van Kuik et. al [28].

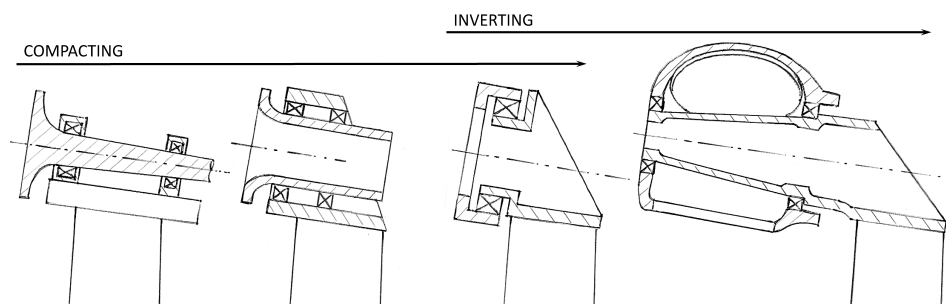


Figure 2. Main bearing arrangements

Figure 2 shows an array of drivetrain arrangements found in modern turbines, the one on the far left representing the most traditional variant. The relatively slender shaft can be supported by bearings able to accommodate some bending. Combined with an overhung gearbox, or direct drive generator, with resilient torque reaction support, this type of arrangement can be less affected by non-torque loads than a three-point support. Moving right in the figure, the arrangements represent compacting by the use of larger-diameter multi-row cylindrical roller bearings - or more commonly - opposing tapered roller bearings, ultimately the double-row tapered roller bearing in an inverted configuration, and to the far right an inverted design where the hub rotates around a spindle. Figure 2 helps illustrate that these drivetrains are not readily represented by the same model, simply by adjusting parameters. It is obvious that the arrangement on the far left is a good candidate for exchanging forces and moments for displacements in 6 DOF at the shaft ends.

2.3. Upscaling

Cost models encourage increasing turbine size in order to harvest wind energy at greater heights and give fewer unit operations and access points. Increased structural flexibility and lowered natural frequencies however pose significant design challenges, as cited by the UPWIND project [5]. The INNWIND project [29] investigates technologies for 10-20MW turbines and presents drivetrain arrangements that can accommodate both gearboxes and direct drive generators. Main bearings are shown as large-diameter rolling element bearings suspended in cylindrical shell-like structures, extrapolating current trends. Besides stating that Finite Element Analysis (FEA) is used for the designs, few bearing-related considerations are presented. Availability of bearings for the largest turbines are questioned, however not linked to specific size limitations in

manufacturing and transportation. The trade-offs between bearing arrangement, static bending moments from an overhung rotor, and also blade-tower clearance, are briefly considered. Active load reduction, e.g. cyclic blade pitching to counteract bending moments, is not discussed.

2.4. Bearing modelling

Non-linear bearing models including contact modelling are computationally expensive, but may prove relevant if dynamic load distribution is critical. Direct representation of rollers, cage, and contact models in a multi-body subsystem allow for studying of the internal dynamics and capturing of reciprocal effects between the complete rotor-dynamic system and the bearing subsystem. Such effects could include bearing failures and non-symmetric bearing characteristics. Rolling element bearings however span a very wide range of applications. Inertial forces on the bearing elements will typically be considered for normal-section bearings in high-speed applications. Treating the inner and - particularly - outer rings as rigid is common but not always a justifiable simplification. Wensing [30] and others have contributed to introducing flexible structures in rolling contact modelling. Very large thin-section bearings in low speed applications such as wind turbine main bearings find themselves on the far end of the scale in this respect; if inertial forces on the rolling elements can be rendered negligible, this is certainly not the case for bearing ring flexibility.

Kabus et. al [31] present a study on optimisation of housing flexibility and static load distribution in a large diameter low speed cylindrical roller element bearing, using an FE model. Due to the flexibility of the overall structure, the design force constraints are placed on each roller instead of directly optimising bearing fatigue as an objective function. This physically correct model representation gives the added benefit of enabling testing of different constraint models without excessive reprogramming, thus it is the primary choice for striking reasonable balance between spatial resolution and model complexity. Relatively simple spring models are used. Dabrowski et. al [32] presents a similar design optimisation study of a FE model of a main bearing spindle as used by Stehouwer et. al [29]. Bearing loads are applied as surface pressures, and no further considerations pertaining to the bearings are presented. Kirschneck et. al [33] study how magnetomechanical coupling modifies the natural modes of a direct drive generator supported by a single main bearing unit featuring cylindrical rollers in axial and radial direction. Also using an FE model for the analysis, bearing stiffness is recalculated as stiffness per unit area to be applied at the model boundary nodes.

Opposing tapered roller bearings can be axially preloaded to provide a stiff arrangement, and avoid spatial loss of preload due to structural deflection. Preloaded tapered roller bearings have become popular in wind turbines, both as main bearings and internally in gearboxes. In large-diameter double-row tapered roller bearings, maintaining preload is challenging due to the short distance between roller rows and the steep angle of attack. High preload is however imposed at the expense of capacity, thus the basic dynamic load rating factors bearing C and C_0 will give unrealistically long service lives and are not suitable for fatigue life calculation.

Reviewed publications are concerned with the effect of bearing mass-elastic properties on structural dynamics, less so on dynamic analysis as a premise for calculating bearing fatigue life with reasonable accuracy. This is also mostly the case with studies extending the simplest 6 DOF models by introducing multi-DOF bearing constraints. One exception is Kabus et. al [34, 31], acknowledging the need for time-domain simulation models considering non-Hertzian contact forces in arrangements representative of large offshore wind turbine drivetrains, and presenting a quasi-static approach. Simplifications include ignoring inertial effects on separate rollers. The study discusses simulation time versus number of interface nodes for the outer ring, and suggest that different models be used for different purposes. A 6 DOF model can be used for conceptual design, whereas a multi-DOF model can be used for bearing fatigue calculation, optimisation of preload and control studies.

MBS software allow for import of flexible bodies created by model reduction of FE models, or co-simulation with FE software. Dynamic behaviour of main bearings and required modeling detail can thus be explored with MBS software, e.g. Adams and Simpack, which both offer coupling with aeroelastic code. Use of extended MBS modeling for time series analysis of more complete turbine structures including drivetrain dynamics is investigated by Jassmann et. al [35], although the capabilities of MBS over aeroelastic codes is very moderately exploited.

De-coupled analyses for more complex drivetrain models can also be facilitated by shifting interfaces from main shaft to blade bearings, thus including the hub in the drivetrain.

2.5. Practises and interfaces

Standards open up for agreeable, non-standard methods for bearing life calculation, accommodating the use of specialty bearings where ISO/TS 16281 [36] has limited applicability. IEC 61400-1 [18] and DNVGL-ST-0361 [37] gives general recommendations and practices for dynamic simulation of drivetrains. IEC 61400-1 contains no specific mentioning of main bearings, but states in general that ISO 76 [38] and ISO 281 [39] shall be the basis for rating analysis for rolling element bearings, and that load distribution due to flexibility of connected parts shall be carefully considered using ISO 76 for slewing bearings. IEC 61400-4 [19] pertains specifically to gearboxes and gives bearing interface requirements, i.e. the information to be exchanged between gearbox manufacturer and bearing manufacturer. It opens up for the use of proprietary methods for calculating bearing rating life, provided that a comparison with ISO/TS 16281 [36] is made, and any differences are agreed upon between parties. Moreover, ISO 16281 recognises the possibility that some of its contents is subject to Intellectual Property Rights (IPR), but refuses responsibility on part of the publisher.

The turbine manufacturer has the total system responsibility, facing the challenge of ensuring consistent modelling and sufficient model integration. However, state of the art bearing software with advanced fatigue models, capable of treating preloaded bearings and special bearings supported in flexible structures, such as presented by Stacke et. al [40], are largely proprietary to bearing manufacturers and not freely licensed. The offshore wind industry has seen massive restructuring and consolidation on the manufacturer side, partly driven by the capital intensiveness, risk exposure, and generally resource- and knowledge-demanding process of bringing new products to the market. As time progresses, the value of mastering the increasingly specialized technologies involved is raising the bar in a self-reinforcing process, making new entries and competition technically more difficult and less economically attractive. In an industry not characterized by value chain integration, but rather open competition at each supplier tier, the question arises who benefits the most from a unique position. The turbine manufacturer has several options. Between avoiding the use of specialty rolling element bearings altogether and developing own advanced bearing analysis tools lie the possibility of model exchange or co-simulation using scalable interfaces, retaining at least some of the design characteristics in a black-box manner, e.g. under the Functional Mock-up Interface (FMI) framework.

3. Manufacturing, transportation and maintenance

The type of bearing used is strongly linked to achievable alignment and tolerances. Opposing tapered roller bearing arrangements are very sensitive to initial misalignment, and require well-defined shared shaft and housing structures providing for close manufacturing tolerances. Similarly, large, flexible housing structures are susceptible to deformation during machining and assembly, and fixtures, jigs and also orientation of the parts must be carefully considered. Misalignment is addressed as a modelling challenge by Argyriadis et. al [21], and is also treated by Kabus et. al [31]. Large drivetrain parts made from ductile cast iron are not uncommon, and the thickness of unmachined surfaces can vary slightly between specimens. Stiffness and damping of bolted connections are dependent on bolt tensioning and surface properties.

The aforementioned factors all affect the dynamic characteristics of the individual, assembled drivetrain. If not directly related to the physical properties of the design, the cleanliness in production is very important for rolling bearing life, and maintaining a clean environment around assembly of large bearings is challenging. Preloaded rolling bearings are also particularly susceptible to standstill damage through all stages including production, transportation and operation. Due to the high degree of integration into a complete structure, only a few arrangement types facilitate replacement of main bearings in situ without disassembling of the rotor-nacelle assembly. As can be seen from the above, the type of bearing arrangement require strong consideration of the effect of manufacturing, transportation and maintenance on the end result. These are also sensitivities that can be investigated by the use of simulation models.

4. Operation

Cost effective design translate into minimal conservatism and material usage. The best design is one that one knows exactly how and when will fail. The design task is however challenged with uncertainties due to simplifications, limitations and assumptions made in calculation of load response. Moreover, the real life loads can differ from assumptions made in the design basis. Applying measurements to turbines and foundations at the prototype stage or in particularly demanding sites, as part of design and analysis tool verification, is a natural way of closing the learning loop. However, the process of comparing analysis model output with real measured values from the physical system, given the same input, can be extended over the life of the turbine. Performed systematically, or even automated, such a process can help keep track of Remaining Useful Life (RUL), and thus:

- Support condition-based or risk-based maintenance strategies.
- Provide a basis for assessing alternative operational strategies, repowering and life extension.
- Highlight needs for software changes and revised or added control functions.

The concept of a digital twin encompasses such a process involving a real world physical system, a virtual system model and data linking the two [41]. A state space model, derived from first principles, is of course only one of many types of representations that can be included in the virtual space. The proposed type of model may however prove a valuable contribution to more direct measurement of spatial load effects in a main bearing. A model giving a more detailed view of a systems baseline dynamic behavior also provides the benefit of more precise fault diagnosing capability. Isermann [42, 43] treats model-based prediction based on parameter estimation, and Nejad [44] has presented a method for gearbox condition monitoring based on these principles. Measurements are primary available in the form of vibration monitoring almost exclusively fitted to all large wind turbines. Other types of measurements can however be considered based on technological advancements and lowered costs, such as localized strain [45], which would provide a valuable complement on large, flexible low-speed bearing subject to stochastic loads. With respect to load-reducing control strategies, Jassmann et. al [35] addresses the effects of increasing flexibility with size and points out that standard aeroelastic codes only to a very limited extent can be used to devise such strategies for the drivetrain.

Again, model and data exchange poses a challenge; predictive analytics widens the circle of stakeholders beyond the component and turbine manufacturers and the certifying body. A model contains information on the design, probably very explicit if used as an engineering tool. Manufacturers are reluctant to disclose such information, as they risk losing technological advantage. Operators might want to protect their capital investment through developing knowledge and operational strategies independently of the manufacturer. Between extensive commercial cooperation between the parties on one hand, and what the manufacturer would term reverse engineering on the other, exist the possibility of exchanging or linking models in an agreeable format. The MODRIO project pursue a framework [46] for this kind of cooperation.

5. Conclusion

Modeling and simulation of drivetrains in large, multi-MW offshore wind turbines should enable bearings being treated as flexible bodies, allowing proper analysis of dynamic load distribution in designs based on large-diameter rolling element bearings supported by cylindrical shell-like structures. Such provisions are not present or necessarily easily implemented in common aeroelastic codes. General-purpose MBS software is a possible alternative, used in aeroelastically coupled dynamic analyses for critical load cases. The resulting knowledge on dynamic load distribution forms a much-improved basis for any time-consuming higher-fidelity bearing analysis requiring decoupling. Unified practices across the industry are needed for defining model fidelity and interfaces, and for linking and exchange of models so that they can be effectively exploited in all stages of design and operation. A consistent treatment of flexibility in analysis of new designs reduces uncertainty and avoids conservatism, thus containing costs and improving feasibility for large offshore wind turbines.

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