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DISCUSSIONS

Interactive comment on "Constructing Fast and Representative Analytical Models of Wind Turbine Main-Bearings" *by* James Stirling et al.

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Dear Reviewer,

Thank you for taking the time to study this paper and provide valuable constructive criticism which we believe has helped develop and strengthen this work. I have laid out all of your comments below and responded each of them in turn. Some comments touch upon the overall goal of this work and so the opening of the response has been written to clarify the main goals and overall narrative of the paper. Having received feedback on the paper we now realise that this was not outlined clearly enough in the original manuscript and so we will also be making this clearer in the updated paper.

If more information is required or we have misinterpreted any of your comments, then

please don't hesitate to get in contact and we will be happy to provide extra information to remedy this.

Best regards,

James Stirling (Lead author)

Review Comments and Author Response

Opening:

Recent work which has demonstrated important and unusual load behaviours in wind turbine main bearings has used simplified analytical representations of the drivetrain. Such simple representations will be necessary if this type of analysis is to be performed for large numbers of load cases, incorporated into fleet wide wind turbine digital twin models, used in wind farm simulation software or as part of industry standard BEM programs such as Bladed or FAST. Analytical models of these type are therefore important and already utilised in some instances. However, to date a detailed assessment of how effectively these models represent wind turbine drivetrain load reaction at the main bearing (including different bearing types) has not yet been carried out and it is therefore important to scrutinise the validity of these models and where they might apply.

As you have quite rightly pointed out, wind turbine drivetrains and main bearings in particular are specific to individual turbine designs, as such we are looking to understand in as much generality as possible how these types of analytical models may be used to represent main bearing load characteristics, without focussing on any one design case (since this would reduce the generality and applicability of results). In order to move in this direction, we have identified a need to work up through the available levels of complexity of modelling, understanding at each stage how one model represents the next in the chain. The benefit of such an approach being that at each stage, whenever a lack of agreement is found (such as in the TRB case of the present paper) small additions to the model can be sought to bring the quality of outputs back towards something which is accurate enough to be useful, while also developing knowledge about which effects can and can't be captured at each level.

In the current paper we are starting with the existing 2-dimensional, orthogonally independent, simply supported models and looking to compare with something closer to representing a real world main bearing in a wind turbine drivetrain. Since the strongest assumptions in the initial models are independence of horizontal and vertical planes (from a load perspective) and simply supported load reactions (no moment reaction, only force), we wish to compare their performance against more realistic models that don't necessarily make these assumptions. A 3-dimensional FE model avoids the orthogonality assumption. With respect to simple vs other support types we want to give the 3D model force reaction capabilities which are closer to those of real main bearings in order to assess when the simple support assumption is valid (and to consider how the simple model might be extended to compensate when it's not valid). Main bearings for wind turbines are known to have two force reaction 'types' in general. Bearings that support forces only and not moments (double row SRBs), and bearings that support both forces and moments (double row TRBs) and so simplified bearing representations are created for the 3D FE model which have these general support behaviours (without being exact models for a specific bearings).

Hence, the overarching research goal of this paper is to answer: Can analytical models be used to effectively evaluate load reaction behaviours for 3-dimensional support configurations with either moment reacting or non-moment reacting behaviours at the main support point? Tackling this question in the current paper demonstrates the validity of existing models for force reactions on the bearing as a 'unit' while also setting the stage for further work with more detailed analytical and FE model comparisons which, for example, could start evaluating internal load distributions etc.

Review comment:

The authors present a manuscript that deals with the calculation of main bearing reaction forces, based on previous work. They show in a very qualified way how simple approaches can also be used in the wind community. As in previous publications of the authors, the realistic wind conditions, which are used for the calculations, should be emphasized. The manuscript is well organized and written but needs major revisions in both the theoretical and practical areas.

Response:

We agree that a better description of the simulated wind files would help strengthen this paper. We will therefore include this in the updated manuscript and also add extra comments throughout the body of work emphasizing that the outcomes are related to realistic wind conditions and that the models remain effective over a wind turbines full operational range.

Review comment:

The presented results are not repeatable. Concerns arise about the used stiffness values and the practical relevance of the paper. For the FE-models, stiffness values from ROMAX are used, but not named. The authors should give all numbers (including stiffness's, L1 and L2). Furthermore, the dimensions of the used bearing design are interesting for the reader. Since the main shaft will affect the FE-simulations as well, more details are needed.

Response:

We agree that disclosing all dimensions and parameters of the models will help the reader gain a better understanding of the work, as well as improve reproducibility. We have spoken to industry partners and they have given the go-ahead to disclose all parameters in the paper so these will be included in the updated manuscript. A table will also be included to the paper which provides specific input forces and output results for all of the models, further helping the reader to gain an understanding of the behaviour of the models and also to aid in repeatability.

Review comment:

The paper compares a single main bearing system with a SRB and a TRB. It is needless to say, that different bearings need different design of the system and will have different stiffness values. The authors choose an equal design and equal values for SRB and TRB. More and detailed information are needed and a better visualization would be beneficial. The system in Figure 1 shows an axial spring, what does this spring represent?

Response:

This comment is mainly addressed in the introduction of the response and centres around the goals of the study. The main purpose of the study was to compare the accuracy of the analytical models previously published by comparison with more realistic 3-dimensional models, and also test the performance when a different force reaction behaviour is present (i.e. in the case of a TRB). The models are, therefore, deliberately general and do not seek to represent any particular bearing specifically, but rather the global behaviour of different bearing types. Likewise, the rest of the drivetrain system such as the shaft and gearbox connections remain both general and similar for the two different bearing types to create a like for like study on how the bearing behaviours affect the reaction forces seen and our ability to reproduce them with simple analytical models.

We agree that the reader's understanding of the work and the FE models would be greatly improved by the inclusion of more detailed illustrations of the FE models and these will be included in the updated manuscript. We also agree that the paper would be improved through a more detailed description of the FE models and will, therefore, include information giving all dimensions, details of the mesh and how the mesh was obtained, connection types and contact conditions in the updated manuscript.

The axial spring is the stiffness equivalent of the gearbox connection in the axial direction and a description of this will be added to the paper explaining as such. This value was obtained by Onyx Insight through the use of a similar method used in this paper to obtain the equivalent spring stiffnesses in the full FE gearbox model within the Romax software.

Review comment:

The simulation model needs more explanations as well. It is not clear how the shaft affects the results. The description of the manuscript is not appropriate enough to understand the results in detail. Implementing a torsional stiffness for the TRB seems reasonable. Nevertheless, the new approach will only deliver satisfying results, when the stiffness values from FE-simulations are given. This raises the question of the benefits of the new approach, since a simulation model is needed anyhow. Here the authors should show the benefits of the approach more clearly. It would nice to see a few examples with varying stiffness's, to see the impact.

Response:

The descriptions of the FE models will be enhanced with more detail as stated above. A sensitivity analysis regarding shaft thickness is also being undertaken and included in the paper to illustrate the effect of the shaft on the results. Results of this sensitivity analysis obtained thus far indicate low sensitivity to this parameter, an important addition to the work. As stated in the introduction to the response, we are not claiming that our models directly represent a specific WT drivetrain assembly, however, all WTs have a shaft with a given stiffness and we have displayed the bearing reaction force results when this shaft stiffness is varied. Drive shafts tend to be a mostly solid piece of material, although a small hole will run throughout the shaft to allow for wiring to run through. Therefore, in our analysis we are using shaft thicknesses of 100%, 75% and 50% to conservatively cover realistic thickness (and hence stiffness) values.

The focus of this paper was not to deliver a complete and polished tool but to answer the question of “Can analytical models accurately represent the reaction force behaviour of wind turbine main bearings?”. The simple models tested and created in this body of work open the door to mass simulations and analysis in short periods of time and, thus, they could be effectively integrated into wind turbine loads simulation and monitoring at farm level during real-time operation. We agree that this could be made clearer in the paper and thus will improve the narrative in the updated manuscript.

With respect to the need for an existing FE model, during the design of WT drivetrains a detailed FE model is usually utilised. However, the company or people that do the detailed drivetrain design work, and hence have access to this FE model, will likely not share it with the wind farm operator who (for example) may be looking to develop digital twin models for their fleet. The benefit of our models is that the WF operator can request access to the non-proprietary values of equivalent stiffness values (determined using the FE model) without requiring access to the model itself. This allows for condensing of information into a form which is less commercially sensitive and allows it to be shared more widely. In addition, even where a full-blown FE model were available, it is not computationally viable to run it for each wind turbine across a wind farm where large scale studies or load/damage tracking during operation might be implemented. Furthermore, in existing certified aeroelastic codes (e.g. Bladed and FAST) structural and load analysis specifically requires for simple and fast running models of subcomponents. Models of the type developed here could therefore end up being integrated into these systems whereas FE models are simply not suitable in this context. As such we believe that there is a strong need for the models considered in this study even where an FE model (with low or high resolution) is available. You are quite right though that this discussion needs to appear in the paper in order to demonstrate the practical usefulness of its outcomes. As such this discussion will be added into the updated manuscript.

Review comment:

The authors use realistic load conditions, which makes the manuscript particularly in-

teresting for the wind community. However, since models are compared, simple load cases, which for example only consist of a moment or a certain load, should be additionally used. This provides information about the behaviour, which is not clearly explained in the current manuscript (this also increases repeatability).

Response:

A table of inputs for a particular time step and the corresponding output results for each will be included in the updated paper to help improve the reader’s understanding of the models behaviours and also improve the works reproducibility.

Review comment:

In general, the introduction uses grey literature and does not show the state of the art of wind turbine main bearings. The authors should heavily improve this part of the manuscript and should focus on peer-reviewed literature instead of grey literature. Especially, the statement in line 65-68 is not supported by the grey literature (YAGI and SMALLEY) and by the previous work (HART), and should be changed appropriate.

Response:

We also agree that more literature pertaining to wind turbine main bearings would strengthen this piece of work and this will be included in the updated manuscript. This will include [1-6], below, among others.

With respect to the second part of the comment, if there is a technical inconsistency at this stage we will be very happy to correct. However, we have struggled a little to understand the specific meaning of the comment relating to lines 65-68. It is of our understanding that the current bearing types used for main bearing in the field are most commonly double row SRBs and TRBs. We realise the bearings themselves are double rowed and we’d not added that detail before and hence have changed the sentence in the updated manuscript to include this distinction. Please feel free to respond with more details and we will endeavour to make sure our manuscript is correctly representing the bearings used for this component. We apologise for not understanding you first time round.

Review comment:

The Figures of the RMSE and Reaction Force are well organized. Nevertheless, in Figure 4 and 6 it is recommended to use equal values for the axis for a) and b).

Response:

This has been updated as requested.

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