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Advancements in continuous learning for tonality free turbine design

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Summary

Wind turbine noise tonality is a phenomenon where a frequency component sticks out from the overall frequency spectrum shape of the noise emitted from the turbine. This is a concern for turbine manufacturers as such tonal noise could be annoying for neighbors. The various international standards and guidelines define methods for assessing tonality and based on the meta-data regarding turbine components and operation it is possible to identify the source of such tonalities.

Turbine design for good tonal noise performance requires thorough understanding of the involved phenomena and system integration capability of the highest order as it is a complicated subject and the realm of possibilities is huge. Therefore, it is important to have a focused and simplified communicable approach to find solutions where most optimal.

This paper describes the framework developed by Vestas Wind Systems to ensure integration of all the complex systems from multiple suppliers that enables our turbines to operate compliant with tonality requirements. Multiple simulation models, measurements and consistency in performance are evaluated for the complete (value) chain, starting from component suppliers to a full turbine assembly under operational conditions.

1. Introduction

Wind turbines keep expanding their role in a world with rapidly increasing demand for clean energy and therefore the individual turbines are optimized for providing more energy production to lower the cost and utilize the wind resources to a maximum - also in more densely populated areas. This together drives bigger turbines, larger rotors to capture the wind and potentially more noise emission from the individual turbine.

As overall wind turbine noise is for 90 % emitted as aerodynamic noise from the rotor and to a wide extend governed by tip speed the larger rotors challenges the entire load carrying system by the need of operation of the large rotors at very low rotational speeds and at high torques through the drive system. In addition to lowering the rotor speed overall noise improvement is gained by advanced noise optimized airfoil/blade shapes and application of noise reduction

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addons to the blades (serrated trailing edges). Bringing it all together and finding the optimal balance in design it has been possible to even lower the overall noise emission while improving energy production as illustrated in Figure 1.

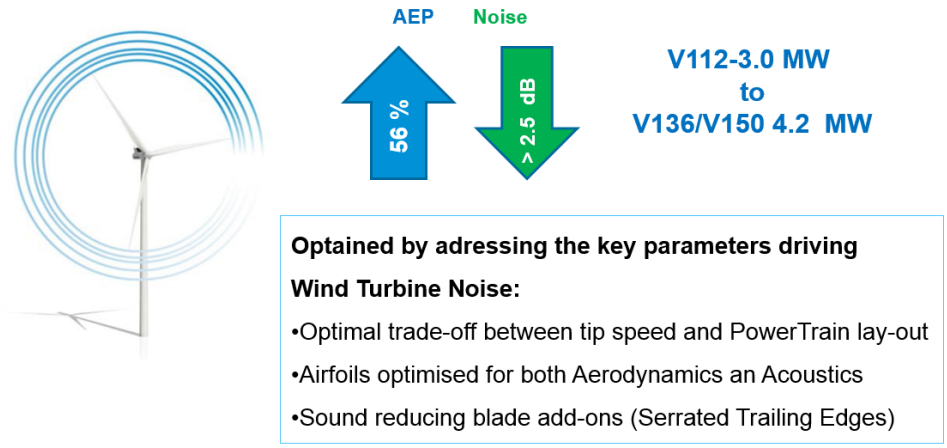

Figure 1: Balancing annual energy production (AEP) and noise emission for Vestas 4 MW platform

Although the large design effort in reducing overall noise emission from the turbines do pay of, the side effect is that less rotor noise emission at lower rotational speeds has reduced the masking energy for tones and potentially making them more audible as illustrated in Figure 2 as evaluated according to IEC 61400-11 ed.3 [1].

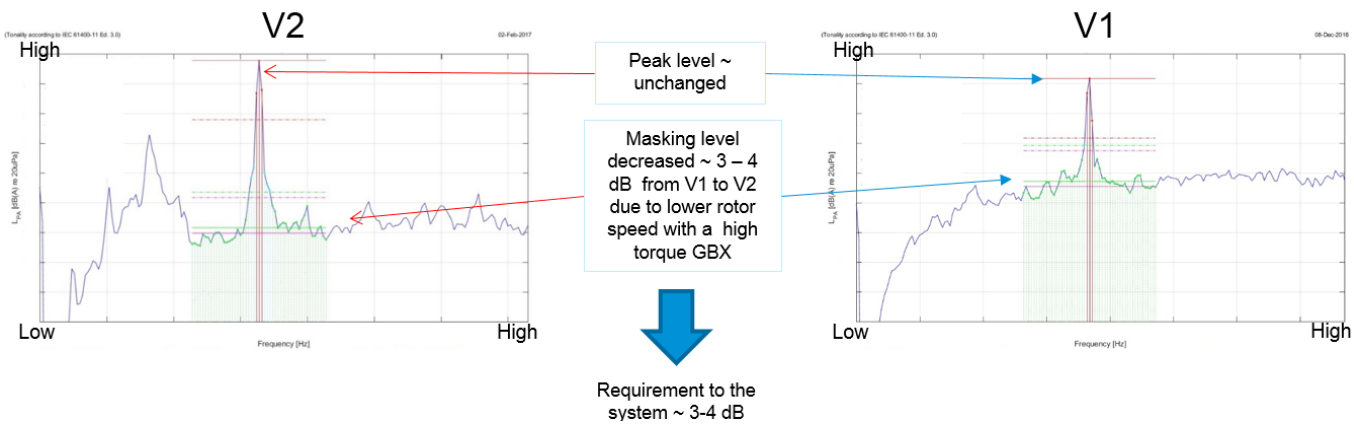

Figure 2: Challenge on tonal audibility when reducing masking noise as effect of rotor noise reduction

The optimization of noise performance for turbines therefore links heavily across both rotor noise optimization as well as optimization of the so-called mechanical noise sources normally responsible for any tonal noise emission and calls for a thorough and systematic approach.

This paper will describe the framework developed by Vestas Wind Systems focussing on tonal noise optimization with the link to aerodynamic noise models.

2. Background

When considering tonal noise emission from wind turbines a quick separation into airborne noise sources as fans, pumps etc. and structure borne (vibration) noise sources as gearbox or generator can normally be made.

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For airborne tonal noise sources, it is rather straight forward to set up requirements on individual components and have that verified already on component level before assembling into the turbine.

For structure borne tonal noise sources it is more complex and calls for a good understanding of the source, the transmission path and the noise radiator as illustrated in Figure 3 to the left.

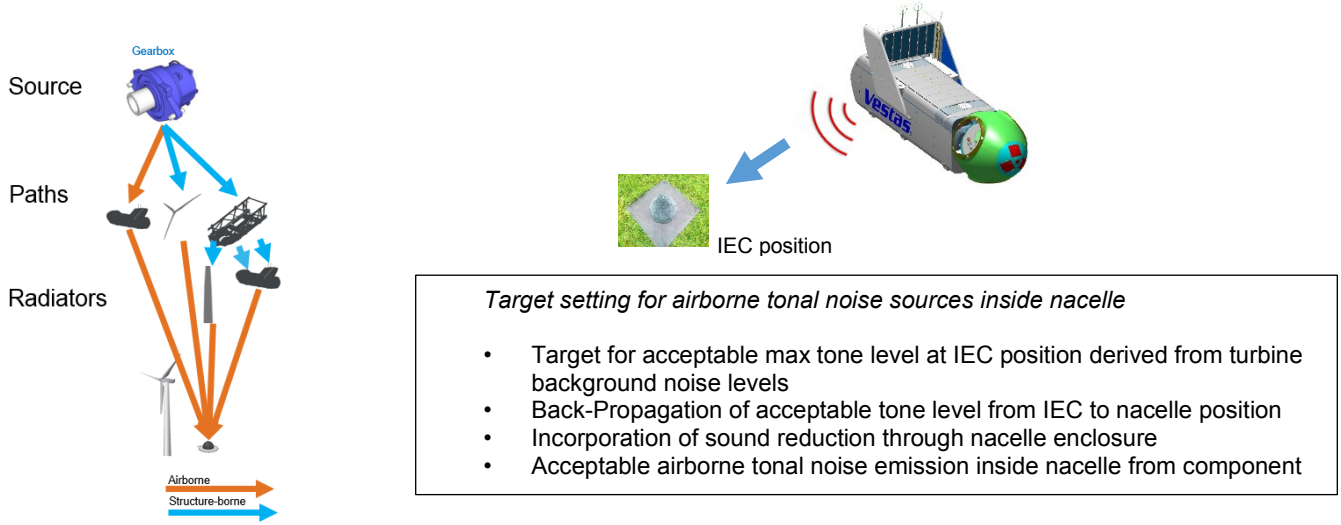

Figure 3: Structure borne noise split into source, path and radiator and target setting example for airborne sources

Also, in Figure 3 (to the right) the systematic approach for setting tonality target on component level is listed with the airborne tonal noise emission from the Gearbox taken as an example. Based on predicted masking noise levels a “back-propagated” tonality target can be derived for the different noise sources depending on frequency and turbine operation.

In Figure 4 an example of masking noise predicted for the actual turbine rotor is shown for a given gearbox order for different turbines. The masking noise is calculated based on the aerodynamic rotor noise model according to the relevant critical bands for a given gearbox order and used as described for target setting. As a conservative approach, only rotor noise masking is considered but different levels of ambient noise from surrounding vegetations etc. could be considered as well. This masking energy prediction approach is validated, and an example shown in Figure 5 plotting the simulated and measured masking energy. As can be observed, the trends and levels are quite comparable.

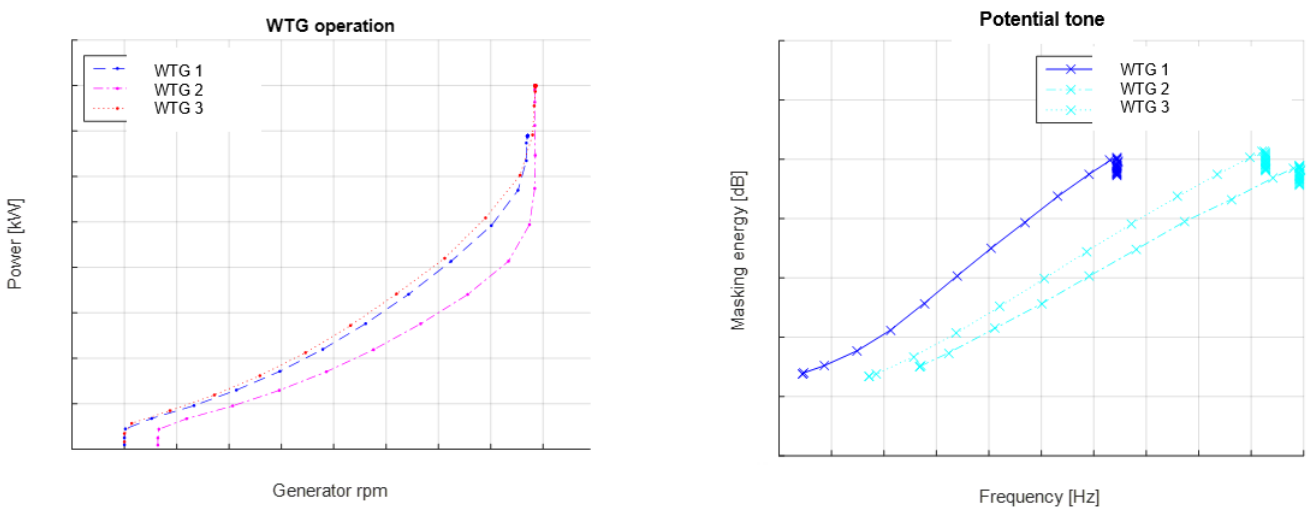

Figure 4: Predicted masking noise levels for different turbines for a given tone source order with reference to IEC 61400-11 ed.3

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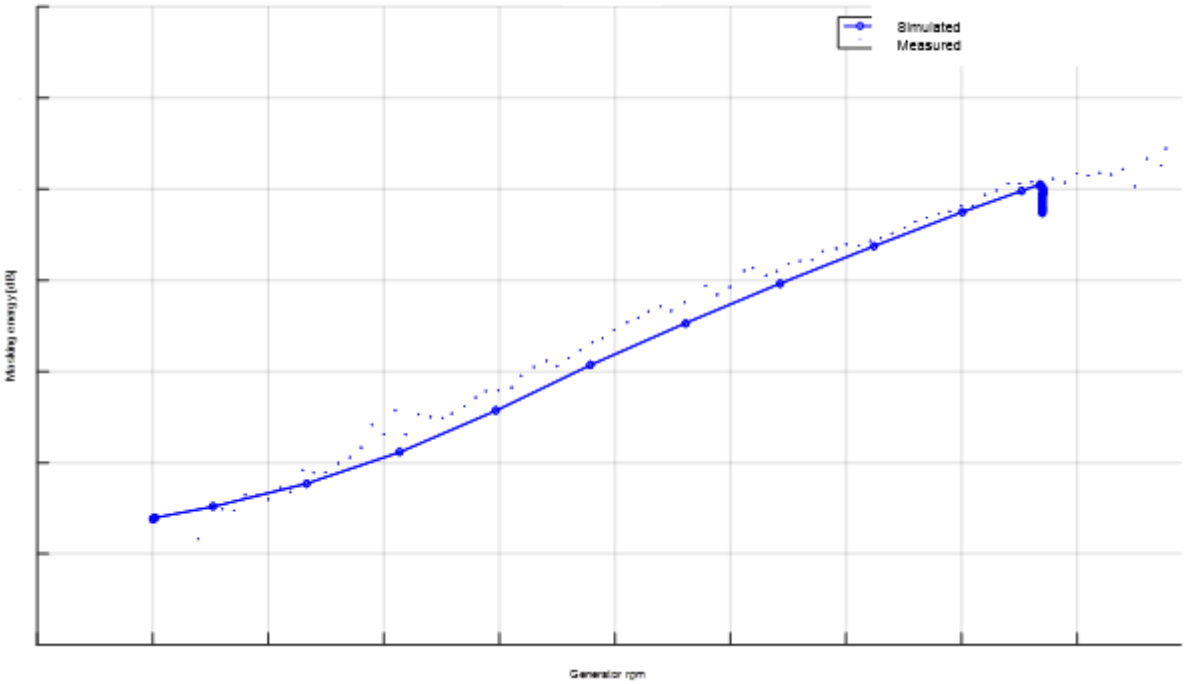

Figure 5: Validation of masking energy prediction

For structure borne tonality noise sources the approach is the same as for airborne noise sources although quite more complex and includes, as the remainder of this paper will describe, the approach taken by Vestas to support this.

3. Process for structure borne tonality free design

Turbine design for good tonal performance requires significant insight to module integration and co-ordination in a turbine development process. The phenomena that result in tonality are complex and thus without thorough understanding it is easy to oversee some potential pitfalls. However, if everything is considered at once then the process ends up being too complicated and impedes progress. While presenting a lot of challenges, tonality also manifests lots of opportunities once properly considered. There is also a need to communicate with the modules and components building the turbine in a manner that is understandable since their primary functions cannot be compromised.

3.1 Design for tonality

Keeping the above in mind, a process has been designed which paves the way for successful design. The process relies heavily on the experience and past developments. The turbine is broken down to the needed level through a combination of full FEM models and super elements. On this *reduced* model excitations from potential tonality sources are applied. The location of the excitations is chosen to fit with the actual design. As an example, for potential powertrain tones, excitation from multibody simulations are applied at the interfaces to the turbine. Based on the input loads, the transfer characteristics of the components and radiation from the blades and tower, the tonal noise radiation is simulated, as shown in Figure 6.

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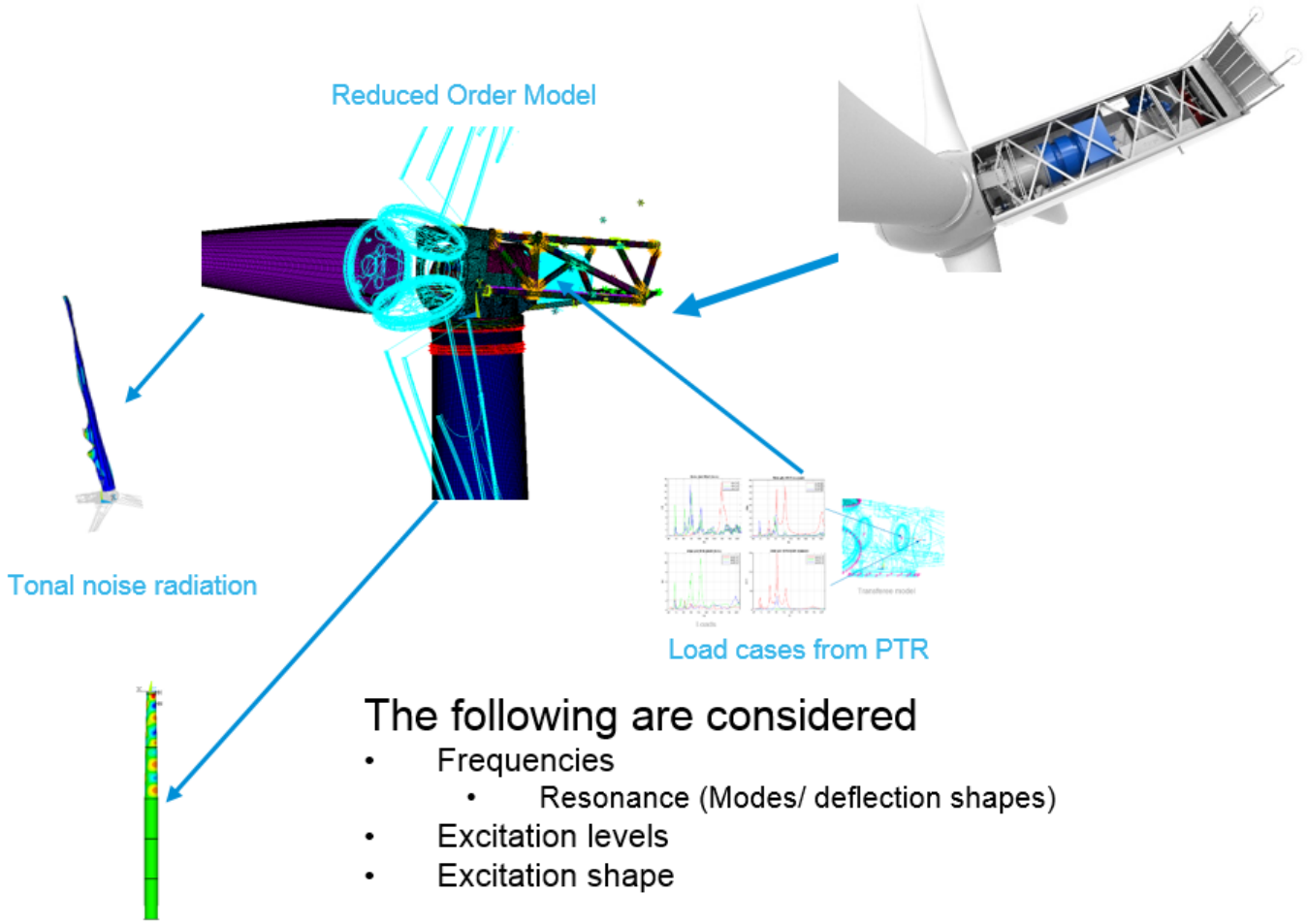

Figure 6: Workflow for tonal noise radiation simulations

This is then used to back propagate requirements to the modules building the turbine, keeping in mind the expected masking. The requirement breakdown and balancing with regards to both compliance and cost is done for the excitation source, transfer path and the radiators, with the knowledge of past experiences within the realm of possibilities. The approach is a significant development over past simulation approaches, in the sense that together with resonance frequencies and excitation levels, excitation shape is also considered. The accuracy of the prediction depends on the combination of excitation inputs, transfer path component models and the radiation simulations. The excitation shape inputs are achieved via loading the model at the interfaces.

To get to the requirements for the modules building the turbine, inputs are also taken from the masking simulations. This sets up the criteria for allowable tonal radiation for the different operational regimes for the turbine before physical turbine set-up is measured.

The tonal noise radiation simulations and masking energy simulations are performed during different stages of any project. The need and extent for simulations for a turbine type is evaluated on case by case basis. Tonal noise radiation is simulated for each load case, which might arise out of different tonal sources or changes in the source or turbine design. The simulations are also performed for sensitivity analysis of components to tonal radiation.
The masking energy simulations are needed for the excitation source only if the frequency changes as a function of speed. As an example, for a generator if the number of pole pairs is changed the slot passage frequency at the same generator speed would change and this would require a re-calculation for the expected masking.

Figure 7 presents a simplified overview of the simulation process to ensure design for tonality from kick-off. Tonal radiation simulations are performed on the turbine concept design utilizing

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concept loads for potential sources. This supports selection of the right concept. Once the concept is chosen more matured loads are applied on a further detailed turbine model to identify potential risks. For the risks identified, design iterations are performed to evaluate the effectiveness of mitigations. The pro-active approach is essential to ensure preparedness for identified risks, should they materialize.

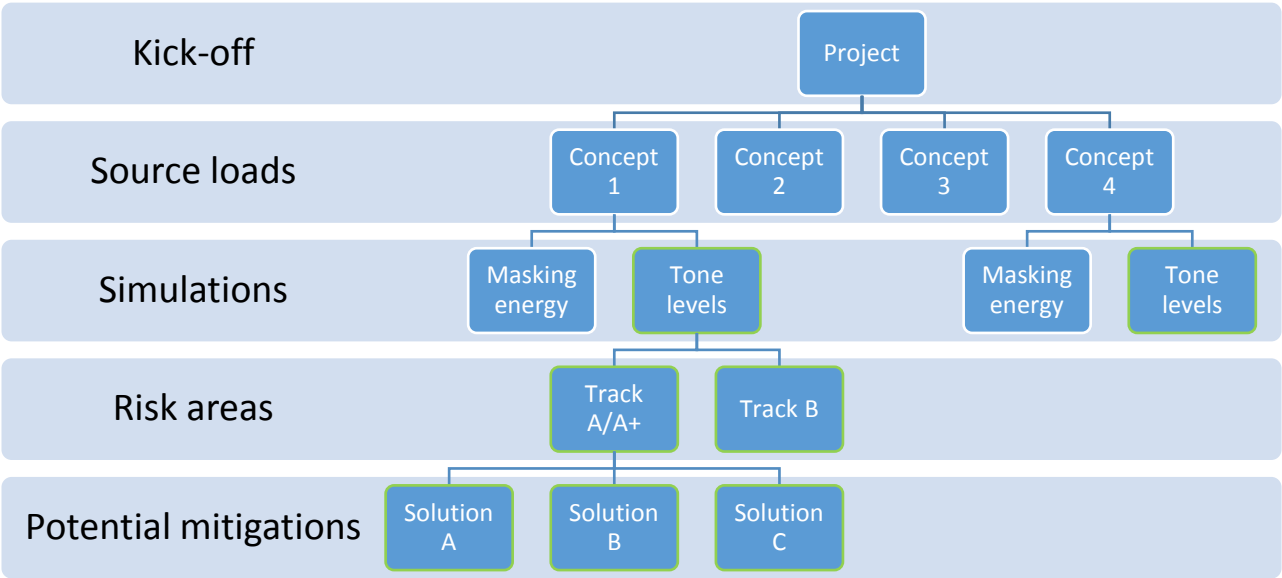

Figure 7: Schematic of the approach for tonality simulation during different stages

In Figure 8 an example is given where loads from a potential tonal source are applied on the turbine model and tonal noise radiation is estimated and compared to the relevant target. The estimate includes breakdown of the contribution from potential radiators.

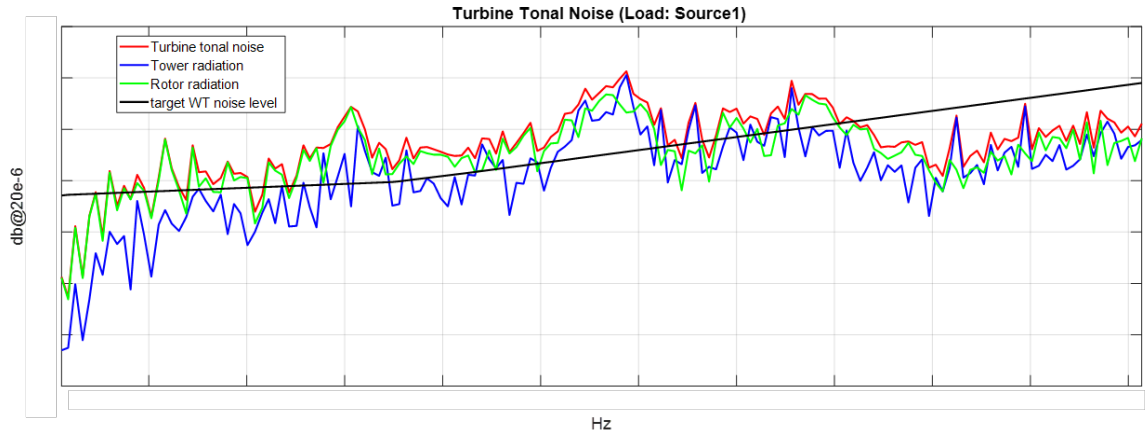

Figure 8: Tonal noise radiation from the turbine, including contribution from radiators and compared to target

The overall turbine requirements are broken down for modules from source to transfer path and radiators. The tonality models are used to set guidance in the form of needed reduction as scaling factors. This is done to preserve the excitation shape since the loading is known to influence the tonal noise radiation significantly.

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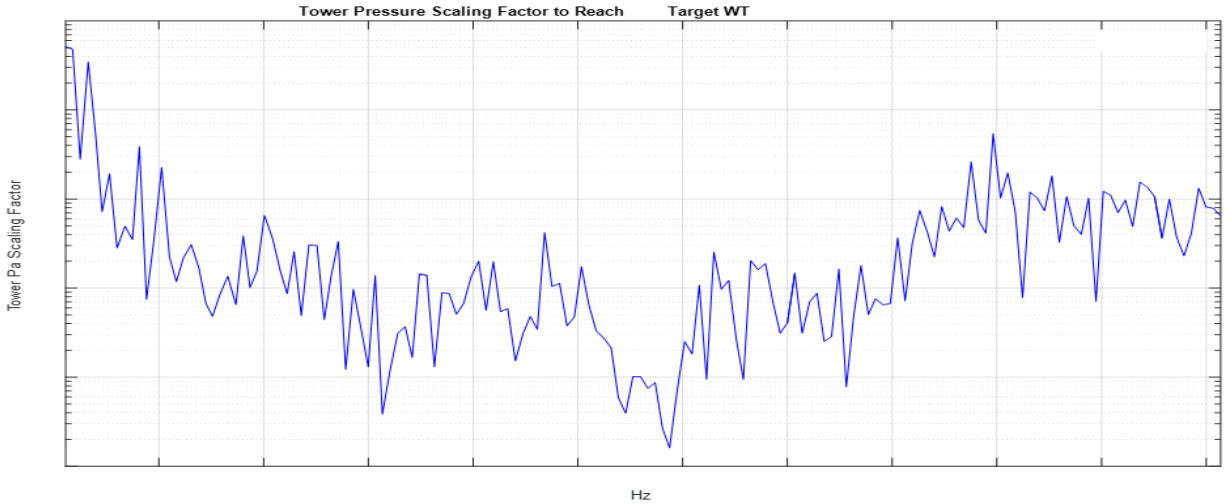

Figure 9: Tower noise radiation scaling factor to meet the target turbine tonal radiation for Source1

Setting of limits for systems and balancing requirements between them is an iterative process, even though the target limit line for tonal noise radiation from the turbine itself doesn't change much. Figure 9 illustrates the requirements that are set on tower noise radiation to be compliant.

The input excitations are known to have a dependence on the transfer path characteristics of the neighboring turbine system. Thus, a final simulation is done with the right set-up to verify the assumptions carried in previous simulations. This approach supports the modular products at Vestas by integrating standard modules into turbine variants.

3.2 Case study – tonality identification to solution and control

In addition to the simulation process, a structure borne noise model, SBN, is also employed which uses measured data to establish critical to tonality criteria, CTT. The two methods complement each other. After first IEC noise measurements are performed on a turbine, the data is thoroughly analysed using an inhouse tool with reference to the IEC analysis.

This is used to identify tonal or sound power issues. Once a tonal issue is identified the source can be easily pinpointed by means of an FFT waterfall, linking the turbine operation with the expected frequency from the source. Image digitalization software could also be used for this purpose, although this would introduce some uncertainty. The max tone levels and cause(s) for the issue are precisely extracted. Figure 10 below shows typical FFT waterfall from an internal noise measurement

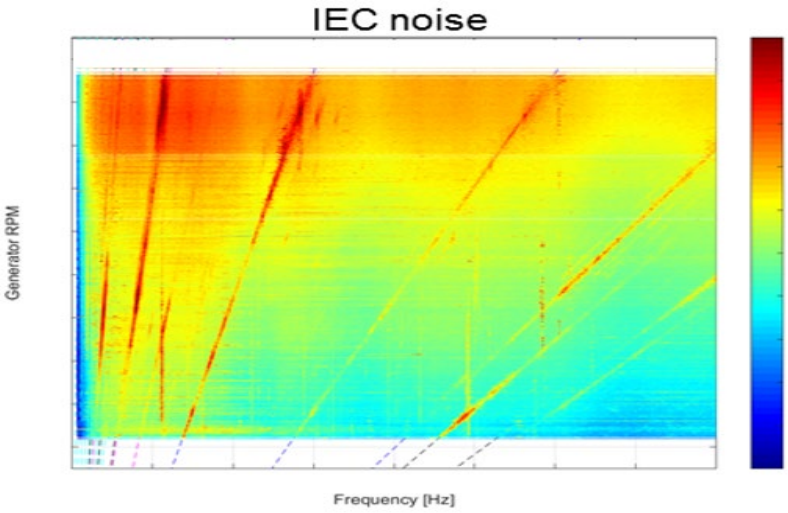

Figure 10: FFT waterfall from a typical internal noise measurement

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Utilizing the advanced analysis methods available, a problem statement is made towards the source. It is expected that the potential issue was already identified during the simulations. Figure 11 is provided as guidance for the module responsible for tonality with an indication for the needed reduction and margins available

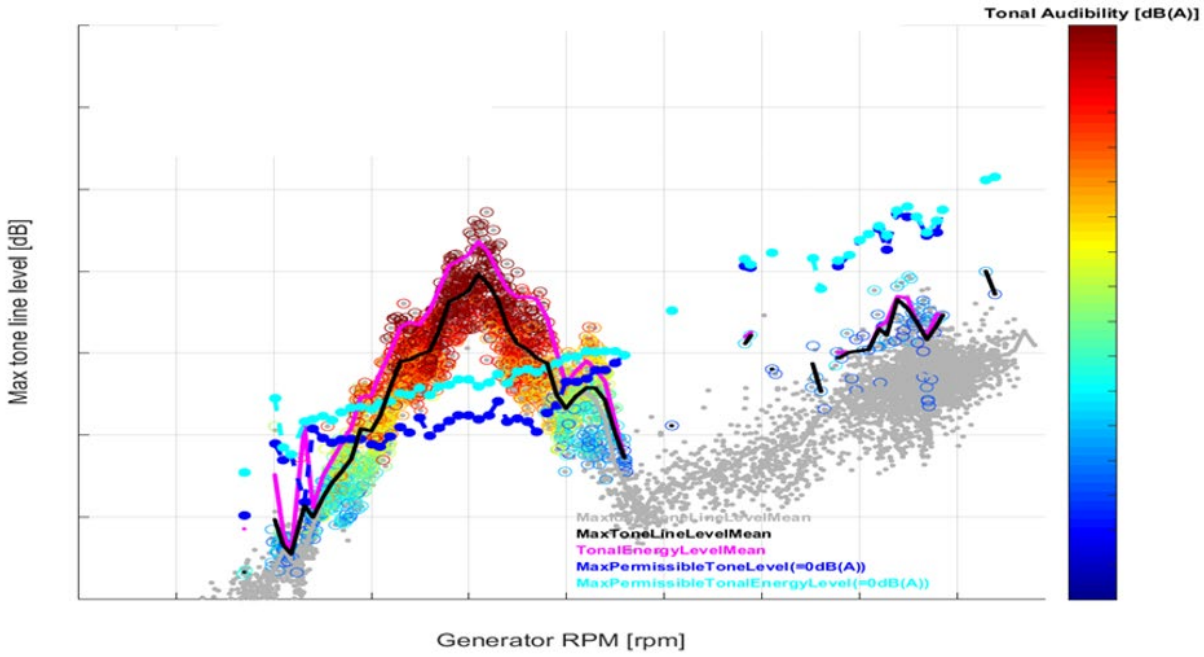

Figure 11: Problem statement towards source including exceedance and margins

This is one of the many figures that are generated to clearly pin point the source. Past measurement experience is extensively explored to set first guidance on turbine level limits. This is achieved by benchmarking against the previous measurements available in the database.

Supplementary vibration measurements are performed to identify drivers for tonality as shown in Figure 12.

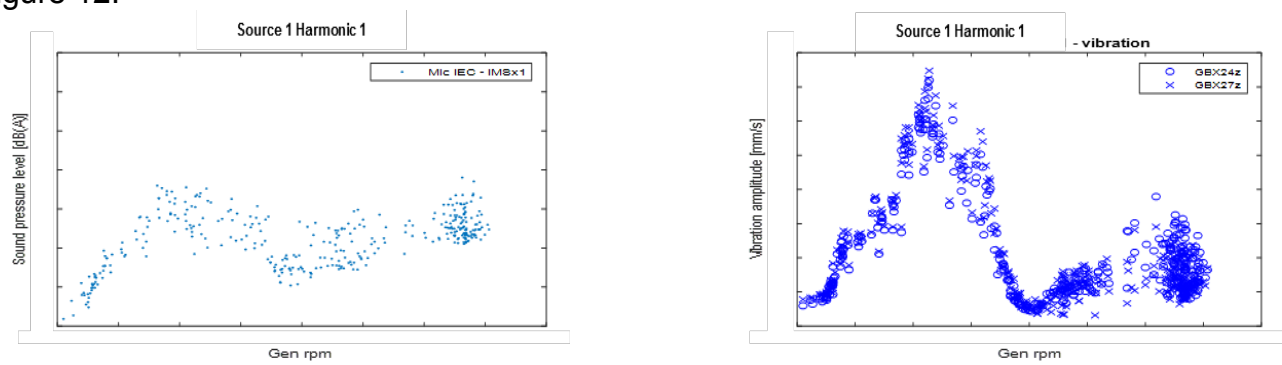

Figure 12: Supplementary vibration measurements linking noise performance with vibration levels

The operation deflection shapes around the hot-spots are animated and, if needed, modal analysis is also performed. This is done to provide inputs to the module causing the issue for mitigation design. If the issue has already been simulated, then it is used to confirm the hypothesis and validate models.

Figure 13 is obtained utilizing another in house tool. Sensors of interest for tonality are identified and a critical to tonality criteria, CTT-criteria, is established or updated. Through this, source sensors with high vibrations are identified. The same exercise is also done for transfer path and radiators and requirements are accordingly distributed. Experience regarding vibration performance is kept in mind and serves as input guidance for the systems for assessing feasibility towards the requirements.

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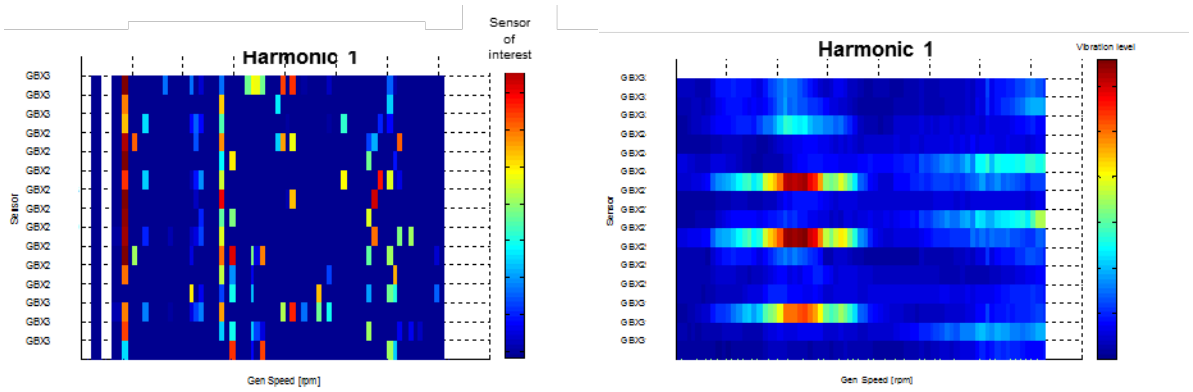

Figure 13: Sensors of interest identification

The requirements for needed reduction are even more precisely formulated and communicated to the responsible module owner or supplier. Design iterations are then measured on the test-rig for expected compliance as represented in Figure 14. Once an option provides acceptable results it is taken to the turbine and its performance verified.

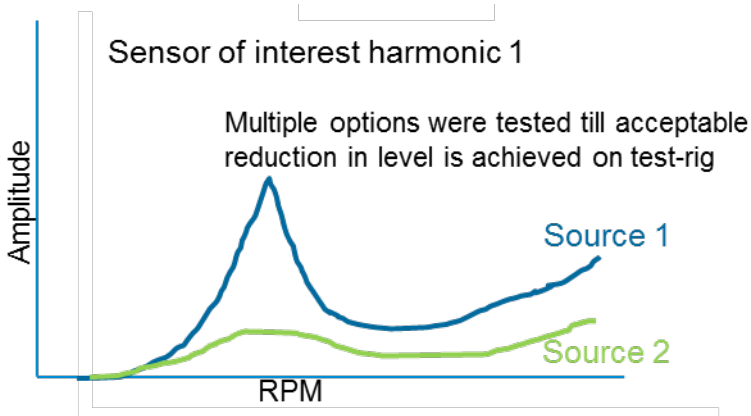

Figure 14: Design solution verification on the test-rig

Final verification is performed on the turbine. Sometimes intermediate add-on solutions representing the final design are also verified on the turbine before the final design, as indicated in Figure 15. Similar iterations are performed for the 2nd supplier, next Mk release, etc.

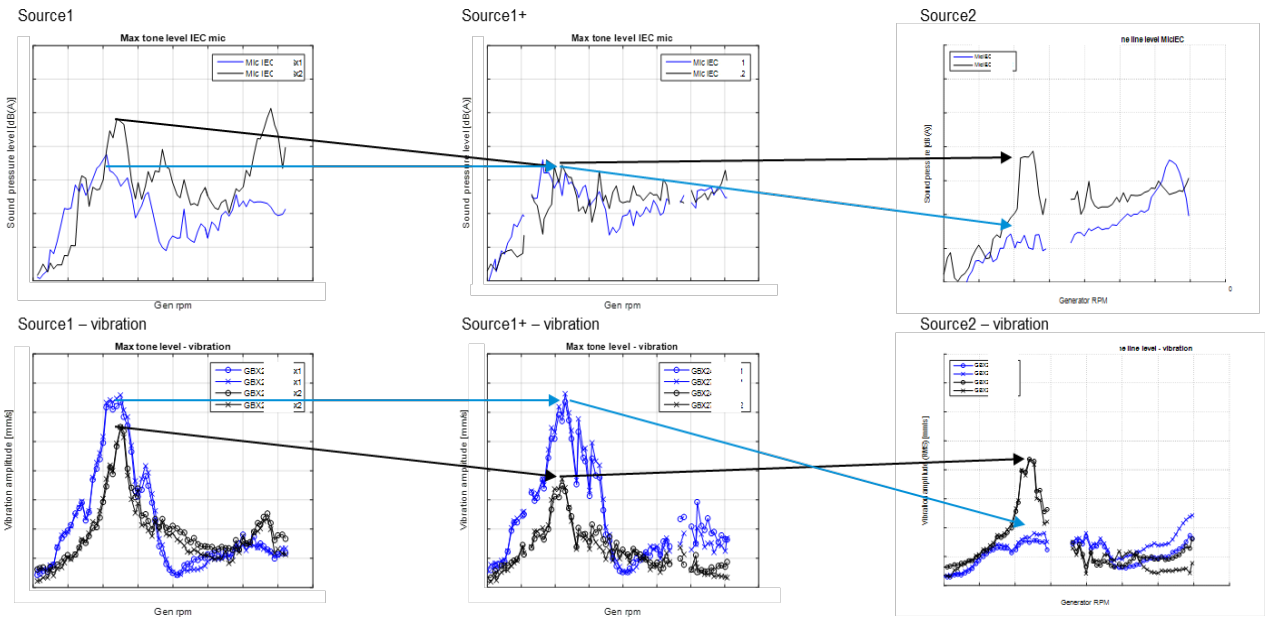

Figure 15: Turbine verification of compliance

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The tool is designed and validated for turbine vibrations. A wind turbine structure borne noise model through measured data is created and critical to tonality criteria established. Although the criterion is defined on turbine level it can be used to define the sensors and load cases of interest that should be monitored during factory acceptance testing of the components' serial production.

3.2.1 Other investigations

Depending on the issue, other investigations are performed as needed, with clearly defined objectives for their usage. These include acoustic camera imaging, doppler shift analysis, etc. as shown in Figure 16. Their application is governed, or limited, by the need for identification of the radiator, quantification of contribution and the frequency of interest.

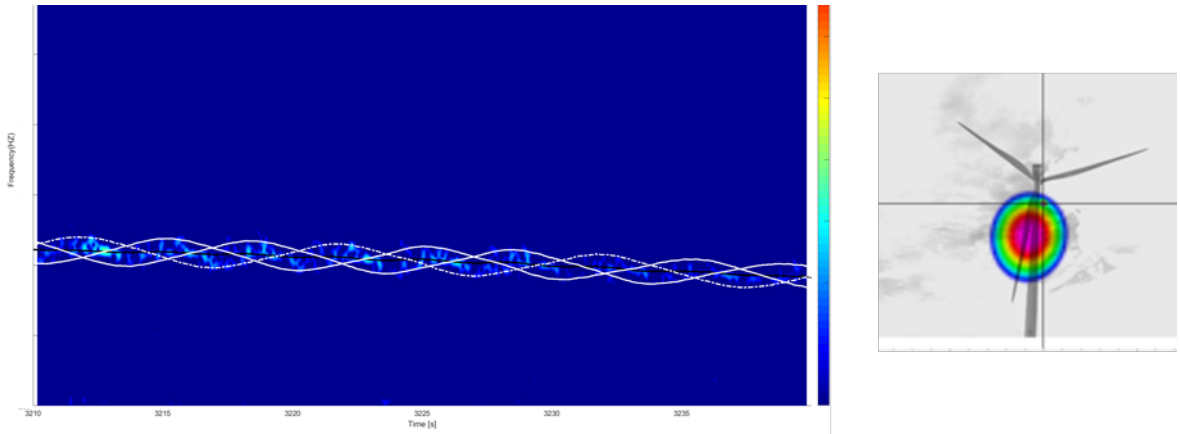

Figure 16: Doppler shift analysis and acoustic image to confirm radiating components

The investigations like in the figure above are performed on case by case basis with a line of sight towards a solution. The turbine blades and tower surfaces are known to be efficient radiators and could potentially be tonal if excited.

A parallel approach to identify the drivers for tonality from turbine operation, is usually maintained. This is done to investigate the driving factor for vibration levels leading to tonality and to understand if there could be potential intermediate control solutions that can be leveraged to reduce annoyance.

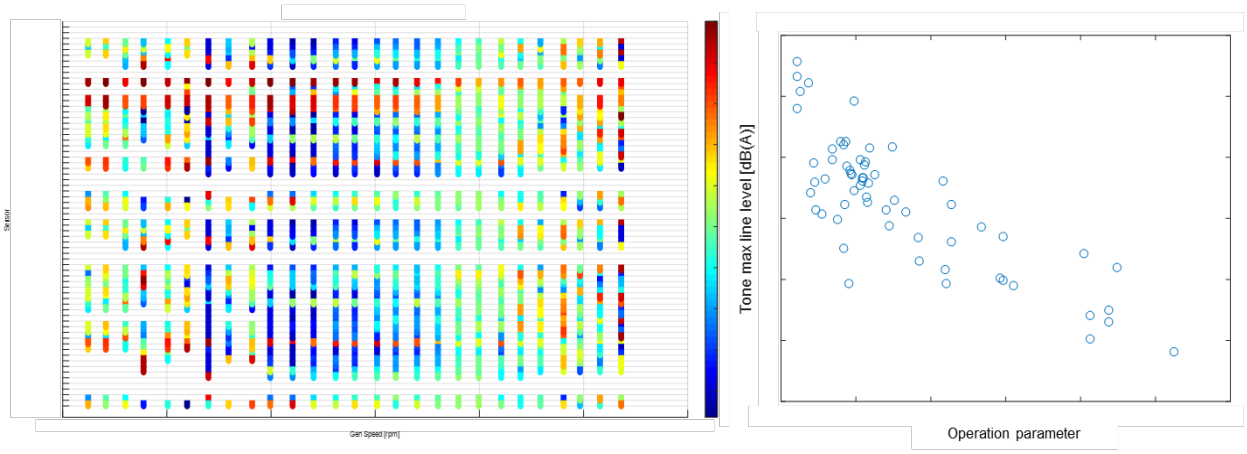

Figure 17: WTG operation parameters that could be drivers for tonality

A potential solution in Figure 17 is controlled operation parameter variation

3.3 Results and discussion

Achieving the objective of tonality free turbine design is not trivial. It requires understanding of noise and vibrations together with good module integration. Coordination and cooperation

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through simplified communicable targets distributed to modules facilitates design progress in the right direction. It also paves the way for needed developments.

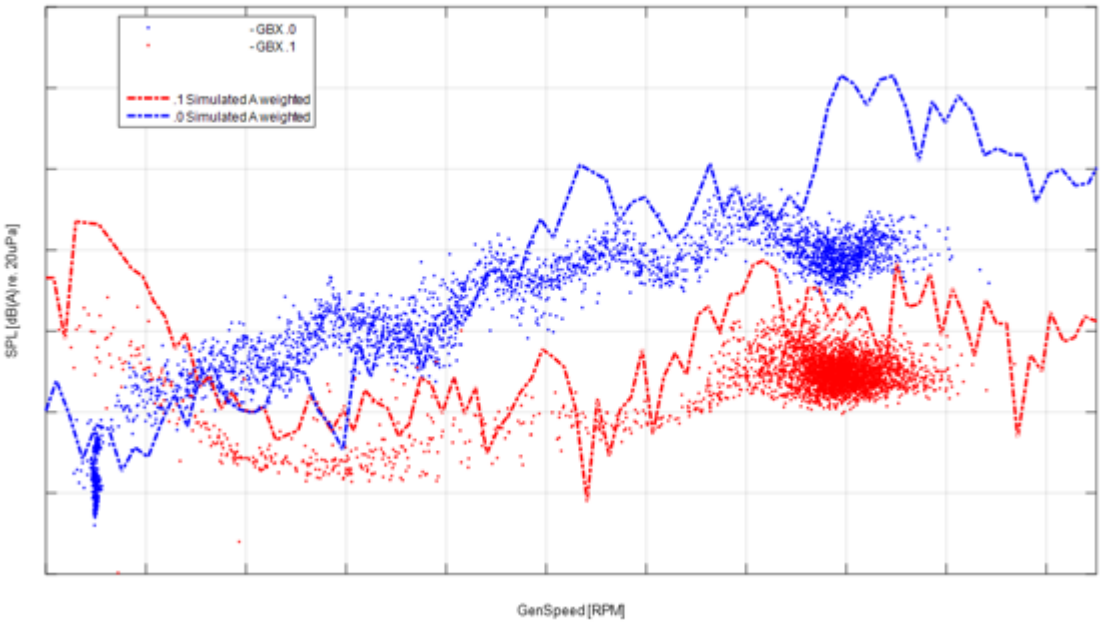

Figure 18: Simulated and measured tonal noise, arising from GBX tooth mesh frequency, for a full wind turbine

Figure 18 plots the expected turbine tonal noise from simulations of two gearbox variants with different excitation patterns and compares it with measurements. While the simulations were executed as constant torque speed run-up, the operation data was acquired when the turbine was following its power curve. The current model can capture the trends to an acceptable level. However, areas for improvements have been identified and are being worked upon. Some of these are further validation of the noise radiation model, input excitation loads validation, input loads discretization, input operational loads extraction, component damping, global model modal damping, radiation efficiency validation, etc.

Based on the simulations, proactive mitigation design and testing for potential tonal sources is executed to enable shorter time to compliance. As this approach develops, a database is maintained for regular benchmarking and evaluation against past experiences, keeping in mind the complicated nature of the challenge, which implies the learnings may not always be directly transferable.

3.3.1 Validation

Validation follows the typical V-model. Simulations are used to set the target requirements. The requirements are cascaded down from turbine to system to component for verification on a test-rig. The validation of model follows. This is executed in the reverse order, since this is the order of testing. Component is verified on a test-rig first, hence that is the first model validation. This is followed by system testing and validation. Finally, extensive turbine testing and validation is performed.
The final step also includes establishment of a structure borne noise critical to tonality criteria, only in case a system is tonal.

The validation path necessitates updates for the different models and re-evaluation of the potential mitigation designs in scope for the various phases of the project. The results should be continually benchmarked.

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To obtain the maximum value from testing, it is important that the prototype components undergo extensive verification in the test rig at component and system level before the turbine. This is used to establish a proper specification for testing along the project lifecycle.

3.3.2 Control workflow

The control process is to ensure compliance to requirements. This is needed for all potentially tonal systems, for example, gearbox, generator, fans, etc.

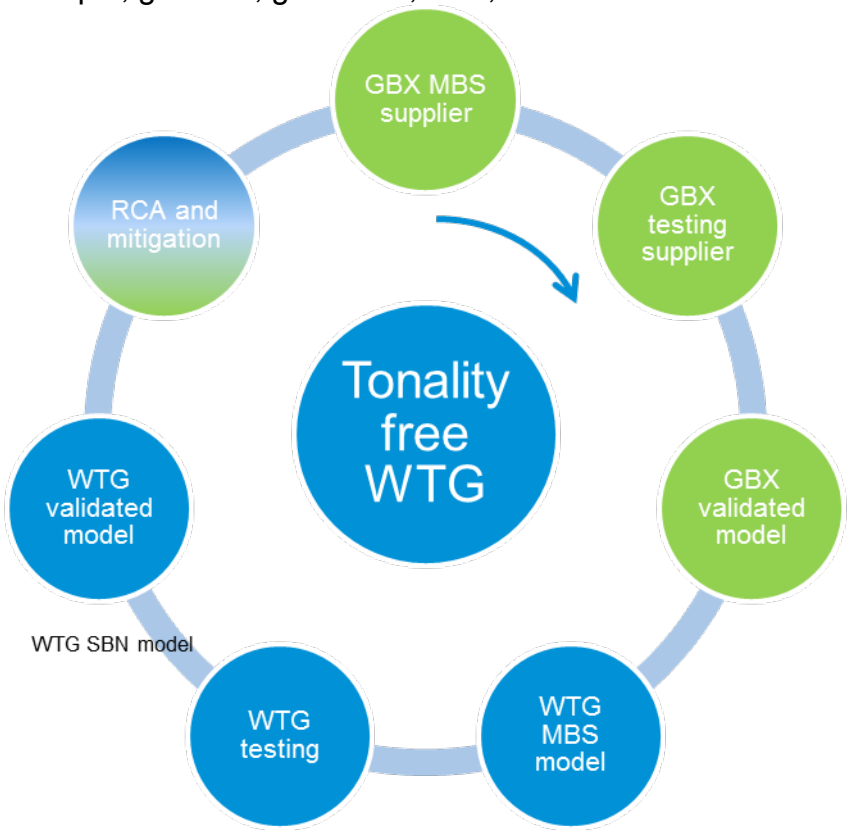

Figure 19: Workflow to be in control of SBN performance for a GBX

Figure 19 is a control workflow for root cause analysis, mitigation design and process control. After one complete cycle, from second test at supplier test rigs, we can come up with expected tone levels and evaluate for compliance. Once the expected levels are defined for the test-rig, quality follow-up keeps the serial production under control.

Ambition is to improve this even further with validated WTG acoustic simulation models using accurate excitation inputs from potential tone sources.

The explanation and understanding of reasons for tonality has evolved. The transition of focus to excitation levels from just resonance frequencies has been validated. The next step on the journey is the shape of excitations.

4. Conclusions

The advancements in continuous learning for tonality free design have been presented. The future is even more digital, with more simulations of potentially even bigger models and much more data from simulations and testing. Greater number of simulations will be performed for sensitivity studies to come up with ideal design and enable readiness for pro-active mitigation of potential issues. The simulations for probabilistic design will cover the intended component tolerances and their influence on tonality.

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Noise tonality is a concern as we care about neighbours, customers, regulations, etc. We have good understanding of our turbines and tonality, as we take it to be part of our core competence. Vestas has extensive experience from field noise measurements and simulations. Thus we are well positioned to leverage the potential out of the data we acquire from measurements using advanced analysis.

The uncertainty on tonality results is a combination of the entire chain on production tolerances, equipment assembly and measurements conditions, including but not limited to wind conditions, season, vegetation, etc. A good understanding of these at Vestas enables us to make the right conclusions that support decision making, by providing directions to have the right focus. Our ambition is for more accurate excitation inputs and better understanding of source excitations (frequencies, levels and shapes).

To support continued improvement of prediction accuracy early in the design phase further work is also needed to link the turbine vibrations with test-rig vibrations. Collaboration with module owners and suppliers is ongoing. Getting in control of part-to-part variance and its influence is relevant. Setting up of critical to tonality (CTT) criteria is taking us closer to our objective.

At Vestas, we ensure integration of all the complex modules (and components) from multiple suppliers to have turbine operation compliant with our tonality requirements, in addition to the components primary function. We also leverage the operation of the turbine to avoid tonality. We achieve this through a validated masking noise tool, turbine structure borne noise model based on measurements and are working on even more advanced turbine acoustic radiation model based on simulations which would enable design updates for source, transfer path and radiators. The approach would be used for setting up permissible excitations / loads, vibration transfer and tonal noise radiation for future products.

Tonality is a complicated subject. The realm of possibilities is huge. We aim to work in a focused and simplified communicable way to achieve desired objective of tonality free turbines without unnecessarily complicating or avoiding the issue but finding solutions where most optimal.

References

[1] IEC 61400-11. Edition 3.0 2012-11. INTERNATIONAL STANDARD. *Wind turbines – Part 11: Acoustic noise measurement techniques*

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