IMPROVED QUALITY OF ROTOR BALANCING MEASUREMENTS THROUGH CRITERIA FROM THE GUIDELINE VDI-3834-1:2015

Anke Grunwald, Christoph Heilmann, Michael Melsheimer
grunwald@berlinwind.com, melsheimer@berlinwind.com, heilmann@berlinwind.com
BerlinWind GmbH, Bundesallee 67, 12161 Berlin, Germany,
Tel: +49 30 688 333 7-40, Fax: -69

Summary

Harvesting the high yield expected from wind turbines (WT) requires high availability and efficiency. An intolerable blade angle deviation (BAD) deteriorates aerodynamics and rotor efficiency. The annual energy production (AEP) is lowered by several percent and service life by some years. Harmful vibration, damage costs and down times increase.

Independent statistics on BAD and rotor mass imbalance (MI) at WT rotors reveal that three quarters of the operating WT exceed the related design limits, which have been mandatory for decades in the WT design standards IEC 61400-1 and -3. For 383 WTs (average 2.2 MW), investigated for BAD with and without suspicion, 76% or 25% exceeded the limit by a factor 2 or 6. The mean BAD is 1.5°. For 57% of the 1149 blades, the absolute deviation from the design blade angle exceeded 0.9° (3 x limit of 0.3°). Twice the MI limit is exceeded at 27% of the WT with intolerable MI.

This proves that the typical balancing procedures - static blade balancing for MI prevention and BA adjustment by 0°-marking or templates - fail to prevent these issues. Quality criteria for identifying reliable BAD and RI measurement procedures are derived from the guideline VDI3834:2015 and the balancing standard ISO 21940-13:2012. Suitable balancing procedures for life-long periodical BAD and MI verification are well-proven for years and include quality control measures in all its steps. They prevent a negative impact on the AEP and OPEX, which is by a factor 3.5 to 70 higher than the measurement costs.

Key words:
Wind turbine, rotor balancing, quality criteria, blade angle deviation, mass imbalance, fatigue, design limits

1. INTRODUCTION

For wind turbines (WT) high availability and efficiency are required to harvest the high yield expected. An intolerable blade angle deviation (BAD) deteriorates aerodynamics and rotor efficiency, fig. 1. The annual energy production (AEP) may be lowered by several percent. BAD causes an aerodynamic imbalance (AI) which increases harmful vibration, fatigue, damage costs, down times and lifetime consumption. A mass imbalance (MI) has the same consequences, fig. 1. However, AI increases nois emission, especially for stall, and falsifies the determination of MI For a BAD exceeding 1.5°, already detected at WT, service life may be reduced below 10 years. Moreover, BAD falsifies the measurements performed to eliminate MI.

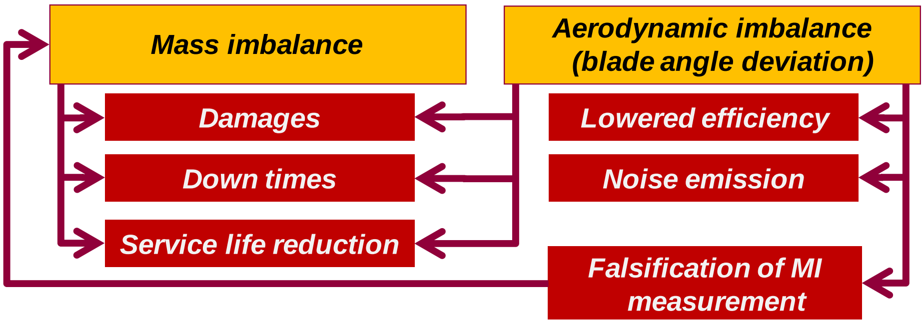


Figure 1: Negative impacts of intolerable deviation from rotor design parameters blade angle deviation and mass imbalance

Independent statistics on AI due to BAD and MI at onshore WT rotors, fig. 2, reveal that three quarters of the operating WT exceed the related design limits from certification which have been mandatory for decades in the On- and Offshore WT design standards IEC 61400-1, -3 and guidelines [1-4]. They have to be included in the operational fatigue analysis for the entire lifetime. The two types of rotor imbalance (RI) cause increased inertia (from MI) and aerodynamic forces (AI) which are related to the rotor's rotational frequency. So inevitably, they act every revolution and produce millions of load cycles in the lifetime, thus increasing fatigue.
For BAD, it has to be distinguished between the two types:

- absolute blade angle deviation (ABAD) with respect to the design blade angle, affecting yield and vibration and
- relative BAD (RBAD) between the blades of a rotor mainly causing increase vibration.

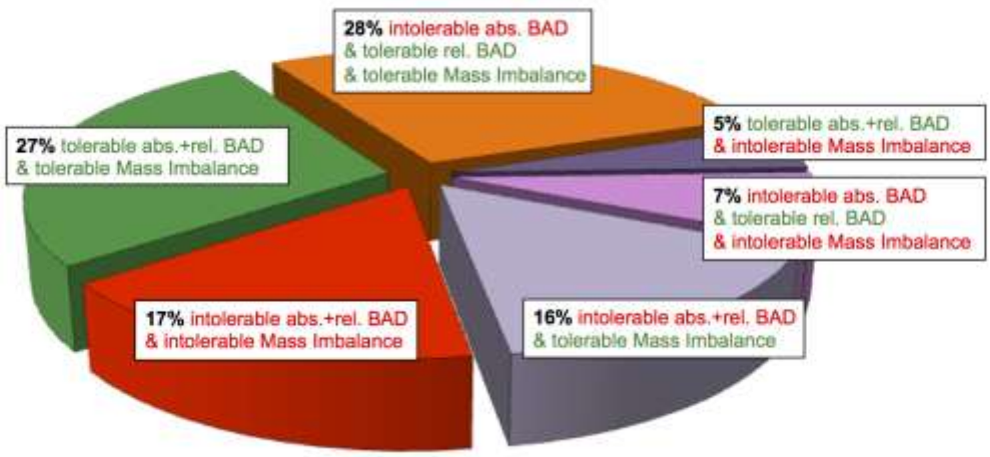


Figure 2: Shares of wind turbines affected by blade angle deviation and/ or mass imbalance (combination of case studies with and without known BAD and/or imbalance issues)

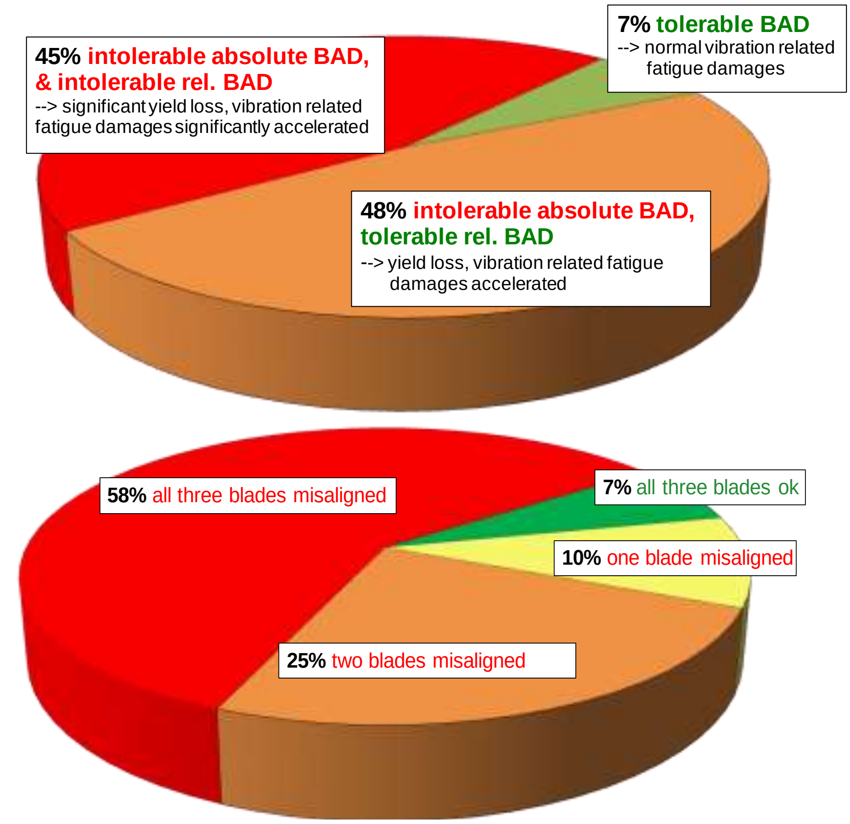


Figure 3: Case study on absolute blade angle deviation at 383 WT rotors (with and without suspicion), top: shares of WT affected by ABAD and RBAD
bottom: Shares by the number of affected blades per rotor (total 1143 blades)

In [3, 4] an ABAD limit of +/- 0.3° is proposed and widely applied in the wind industry. Consequently, the derived RBAD limit is 0.6°. The production tolerance for the twist between maximum chord radius and reference radius close to blade tip is often in the range of 1.0°. The unfavourable rotor setting with ABAD has to be included in the 20 years' design life fatigue load analysis. This implies that a real WT matches only with the type certificate or approval if its ABAD is below the limit during the entire service life. Whenever blade angle measurements detect an intolerable RBAD, there is automatically at least for one blade an intolerable ABAD as well.

For 383 WTs (average 2.2 MW), investigated for ABAD with and without suspicion, only 7% had a tolerable BAD, fig 3, (here, ABAD is named collective BAD) and at most WT, more than one blade was affected. 76% or 25% exceeded the limit for ABAD by a factor 2 or 6. The mean ABAD is 1.5°. For 57% of the 1149 blades, the ABAD from the design blade angle exceeded 0.9° (3 x limit of 0.3°). Twice the MI limit is exceeded at 27% of the WT with intolerable MI. Every year, there are WTs with mass imbalance in the range between 2000 and 5000 kg*m, not only in cases where a blade is exchanged after a severe damage where the need for balancing is obvious.

This proves that the typical balancing procedures - static blade balancing for MI prevention and BA adjustment by 0°-marking or templates - fail to prevent these issues.

Moreover, statistic evaluation of balancing measurements revealed that the root-mean-square based method proposed in the guideline VDI 3834-1:2015 [5] for vibration evaluation at wind turbines is insensitive even to severe MI and AI.

Drive train or structural monitoring systems may presently only be used for indicating the presence of MI and/or AI, if they are equipped with suitable sensors and evaluation software for even this task, which is mostly not the case. Hence, to diagnose MI and AI exactly, mobile in-situ measurements by experts are a must.

Therefore, the guideline's revision VDI 3834-1:2015 [5] was extended by an annex on in-situ rotor balancing at WT. This complements the in-situ balancing standard DIN ISO 21940-13 [6] with WT-related aspects and balancing experience.

The quality criteria derived there from and described below help to identify WT reliable rotor balancing methods meeting the field challenges: complex WT dynamics, potential falsification by AI and non-linear aerodynamics, individuality of WT types, wind fluctuations and the manifold root causes for WT rotor imbalance.

2. QUALITY CRITERIA FOR WIND TURBINE ROTOR BALANCING

2.1 NEED FOR IN-SITU BALANCING

According to ISO 21940-13:2012: "Criteria and safeguards for the in-situ balancing of medium and large rotors" [6], in-situ balancing is imperative

- if the final rotor assembly is on site and
- if RI changes obviously during operation (wear, erosion, loss of parts, repair, etc.).

Both is the fact for WT rotors. Therefore, in-situ rotor balancing is the only appropriate method, static blade balancing is not sufficient.

2.2 QUALITY CRITERIA

2.2 (a) Working safety

A safe work procedure is imperative and includes a careful risk assessment of all steps of access, installation, measurement and de-installation. An important aspect is the prevention of unwanted excess vibration through knowledge about resonance effects, etc., Fig. 4.

2.2 (b) Suitable procedure

A correct logical step-wise order, fig. 5, considering the various root causes for AI and MI is required to prevent the falsification of the MI measurement and assure the reliability of the measurement. This includes root cause oriented elimination /repair of issues falsifying MI

measurements, e.g. erosion, blade angle deviation, temporal imbalance from blocked drainage holes, etc.
Onshore, a photometric blade angle measurement is very reliable, with a high quality digital camera mounted on a tripod below the rotor at a careful chosen camera position. A series of photos per blade allows statistical evaluation, fig. 5, and determination of the absolute blade angles with an accuracy of 0.1°. This method is not applicable Offshore due to the lack of a stable ground. Therefore, a laser-based measurement method has been developed and applied successfully with the same measurement accuracy for relative blade angle measurements.
The laser-based blade surface scanning system is located on the heli deck and scans the profile contour of the locked blade at several radial sections. Then, the relative angles are determined. Currently there exists no method for measuring absolute blade angles Offshore, but this is under development.

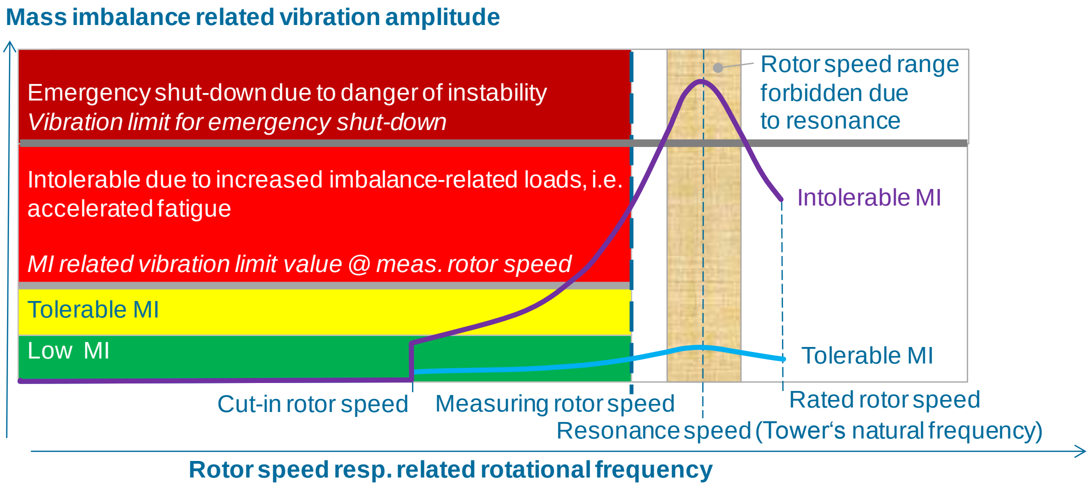


Figure 4: Rotor speed impact on imbalance related measuring amplitude due to resonance and therefore necessary definition of an MI related vibration limit value valid for the measuring rotor speed

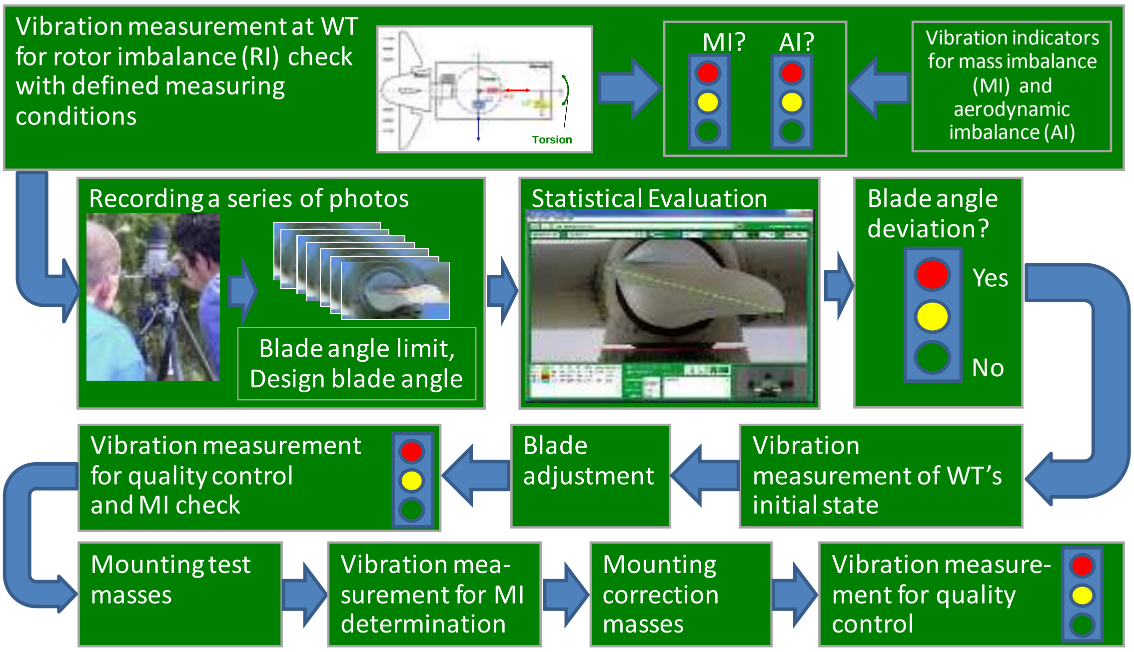


Figure 5: Scheme of high quality WT balancing procedure preventing falsified results with photometric blade angle measurement and mass imbalance calibration

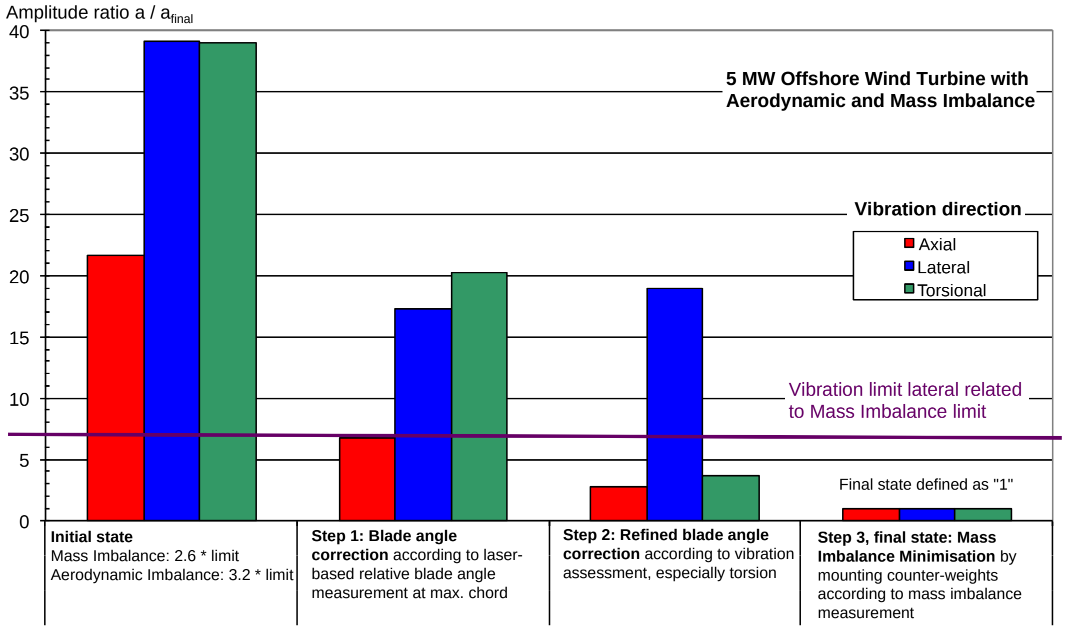


Figure 6: Significant reduction of the imbalance-related vibration amplitude by blade angle correction and mass balancing of a 5 MW Offshore WT

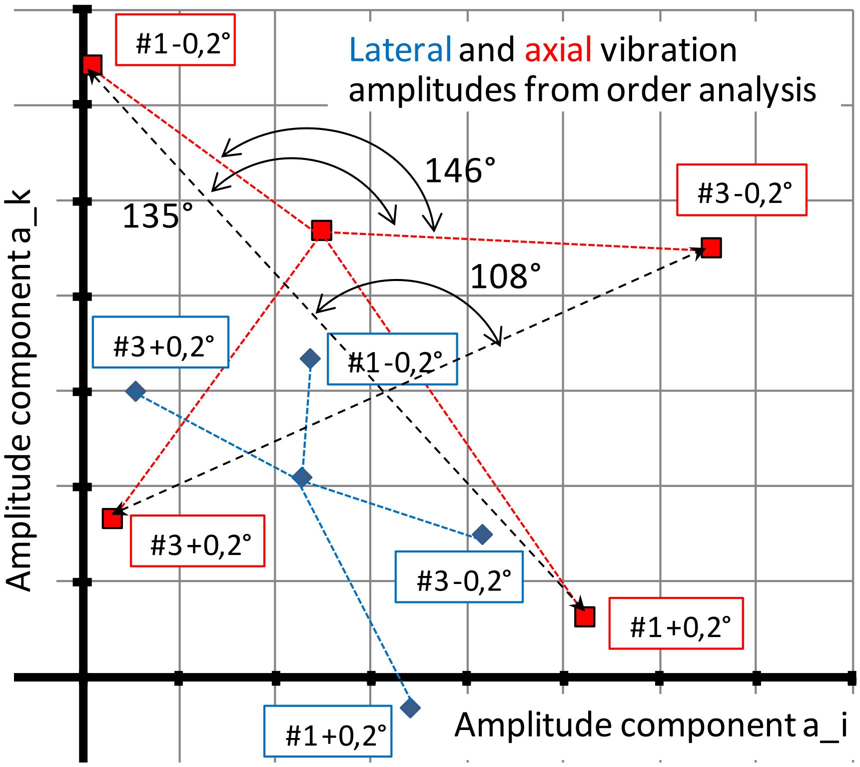


Figure 7: Strongly non-linear behaviour of the WT's vibrational response (amplitude and phase angle) to subsequent defined pitching of two blades by +/- 0.2° of a 2.5 MW WT

Fig. 6 shows the significant reduction of the imbalance-related vibration by subsequent blade angle correction and mass balancing. Load simulation by the OEM using the measurements results as input revealed that increased fatigue loads of the initial state would have reduced the WT's service life below 10 years.

Fig. 6 proves as well by the amplitude change from step 1 to 2 and 3, that blade angle adjustments need to be validated by vibration measurement to get a refined blade angle correction. The twist production tolerances of modern large blades have a strong vibrational impact. Without the refined blade angle correction based on vibration measurement, the axial and torsional vibration would have remained on a still inacceptable level.
Furthermore, the mass imbalance would have been under-estimated, as the lateral amplitude increases from step 1 to step 2.For modern Multi MW WT with large rotor diameters a blade angle change of 0.2° may cause an increase of the imbalance related acceleration amplitude equivalent to the MI limit related amplitude value. Therefore, in terms of the overall fatigue impact, it is not enough to adjust blades to be just within the BAD limits.
Furthermore, the twist tolerances between the blades cause that the aerodynamics get non-linear. Measurements shown in fig.7 reveal that for adjusting at one turbine two blades successively by the same blade angle change of + / -0.2° produces strongly differing, unequal changes of the related vibration amplitude and phase angle. This means that a step wise blade angle adjustment verification is recommendable, and that methods assuming a linear reaction of the vibration after one defined blade angle test pitch (in analogy to pure MI measurements with test mass) do not reflect real world experience. The defined measurement requirements assure reproducible results, fig. 4 and that results for similar WTs of the same type are comparable. This means that often, a load-free or load- reduced mode is required to allow that the turbine can better control the rotor speed to stay at the defined measurement rotor speed. Strict requirements for the sensor mounting position have to be considered because else the measurements are no longer comparable.

2.2 (c) Suitable measurement system and sensors

Due to the low rotor speed, the sensors have to be suitable for the frequency range below 0.5 Hz. The entire measurement chain including sensor and measuring device has to resolve very small imbalance related acceleration amplitudes below 5 mm/s² .The chosen sampling rate has to assure a sufficient number of data points per revolution for correct angular imbalance location and amplitude determination. A rotor speed sensor is required to monitor its fluctuation due to the wind variation.

2.2 (d) Suitable measurement period per test run

In order to assess and eliminate result falsification related to wind and rotor speed changes quite long measurement periods are required, for Multi-MW WT mostly more than 30 min. With shorter periods the uncertainty increases (e.g. by more than 30% for runs of 10 min length). Even with several test runs more it is then hardly possible to attain the same result for the MI minimisation.

2.2 (e) Reliable evaluation methods

The result from AI and MI measurement should be statistically safe and reproducible. For all the vibration measurements, order analysis is required to remove falsification from rotor speed fluctuation. Furthermore, the use of several indicators for cross-checks increases the reliability of the result, e.g. for AI evaluating axial and torsional vibration. The axial amplitude is influenced by wind shear, the torsional amplitude not. Therefore, torsional vibration is a very reliable second indicator for AI, see fig. 6. and 8.
Staff on site is always very positively astonished when after eliminating AI by correct blade angle adjustment, a WT with worn yaw brakes is no longer shaking excessively every revolution but stays calm despite the yaw brake pads are still worn.
For a rotor with a combined RI, i.e. with AI and MI simultaneously present, the AI and MI forces may be located at the same or different blades. A vibration measurement determines only the total sum of the force vectors, the shares are unknown beforehand. Hence, AI may cause an under- or over-estimation of the MI if it is not eliminated beforehand, as shown in fig. 9 for 15 WT of the same type. This is another reason that the procedure and the evaluation methods need to be as accurate as possible and the use of several indicators is wise.

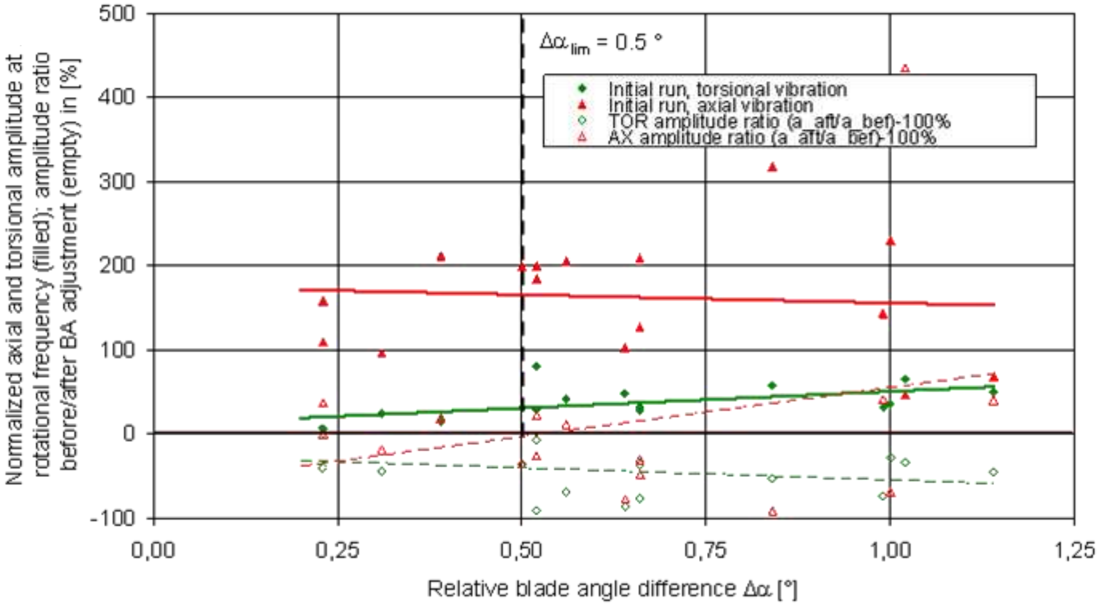


Figure 8: Irregular influence of BAD on axial vibration amplitude (and ratio) for 15 WT but suitability of torsional vibration amplitude (and ratio) as AI indicator

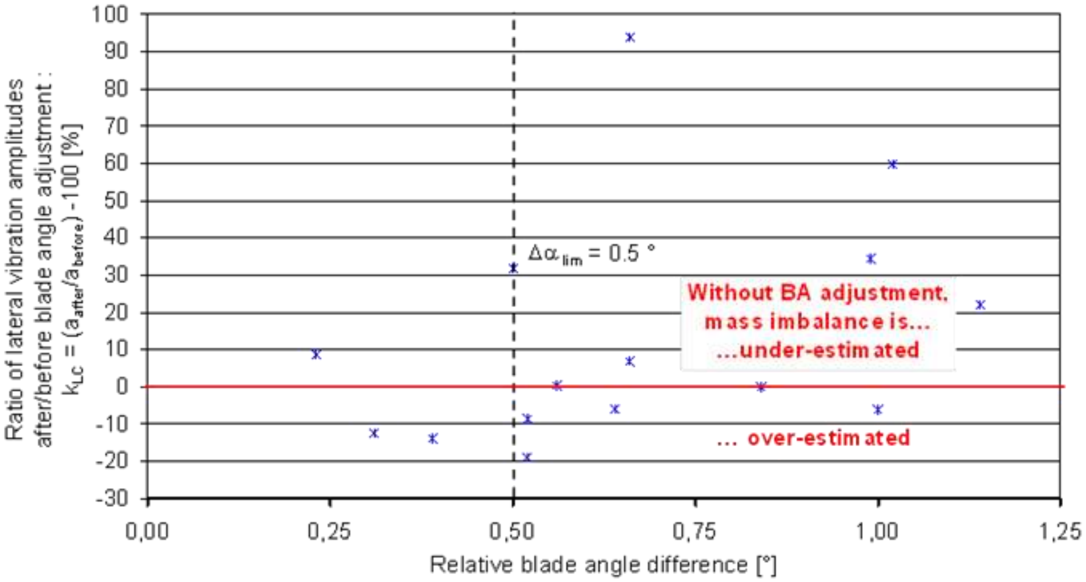


Figure 9: Irregular under- and over-estimation of MI determination (by lateral sensor) due to AI from blade angle difference for 15 WT of similar type, ratio of vibration amplitude after and before blade angle correction

2.2 (f) Correct MI limit value for result assessment

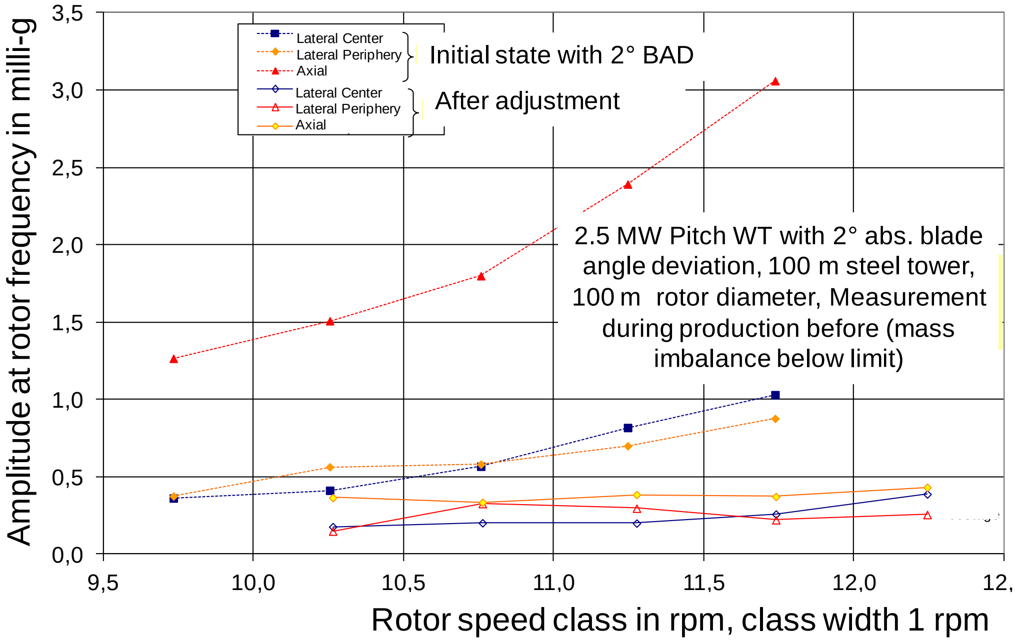
It has to be emphasized again that during design certification/type approval for each WT type an individual MI limit value (in the unit kg*m) is mandatory to be stated [1-4]. In contrast to that, for balancing many other machine types, a limit value for the vibration velocity amplitude (in mm/s) at rated rotational frequency as balancing quality grade is established [6]. This is not applicable for WT due to the standard's requirement to define per WT type an admissible imbalance limit and the WT's variable-speed operation. For the same MI, the vibration amplitude changes significantly with the rotor speed, fig. 4, so a MI related vibration limit value is valid only only for a defined measurement rotor speed. Furthermore, the hub height and the rotor diameter, as well as installed dampers, have an impact on the vibration response of the tower-nacelle system. Therefore, for WT of the same platform a MI related vibration limit value is valid only for a defined configu¬ration. For Offshore WT with individual total and foundation heights this mean that at every WT a separate in-situ calibration is a must. Onshore, it is possible to perform calibration measurements per WT type which then gives characteristic indicators values to assess already by the measurement of the initial WT's state, top in fig. 5, whether it is affected by MI and AI by RBAD or not. This provides a reduction of the measurement costs since the full balancing procedure is then performed only at affected WT.

2.2 (g) Suitable imbalance amplitude calibration

The test mass applied for calibration needs to be large enough for getting a proper signal change for in-situ calibration. So due to several tons rotor mass, often more than 100kg test mass is required. For WT the trend is to mount the test mass and counter weights inside the blade. If the test mass shall be installed at the beams inside the blade, this poses the problem that defined mounting spots are required which are durable enough. However, since in-situ balancing as design requirement is still often neglected, the mounting spots and procedures have to be developed and agreed later. This increases heavily the effort during preparation of WT balancing. If a WT manufacturer defines mounting spots during design and e.g. in a wind farm or in every WT these test masses would be pre-stored, the efficiency of performing in-situ balancing would drastically increase. This would safe a lot of costs for logistics and access for balancing.

2.2 (h) Reliable and repeated quality control

Repeated quality control during entire procedure, fig. 5, assures that there are no remaining AI and mistakes in the action taken. Vibration measurement before and after blade angle adjustment as well as validation runs after MI balancing, fig. 6 prove the load reduction by proper blade angle adjustment and balancing under the special measuring conditions. Fig. 10 shows for example the significant amplitude reduction during normal operation by a correct blade angle adjustment. For large mass imbalance, initial over-estimation is well known [6] and step wise balancing is recommended for fine tuning the counter weights. Another very recommendable measure is the application of the 4-eyes principle required of independent experts for WT [7], which assures that the results are not influenced by any party involved.



2.5 MW Pitch WT with 2° abs. blade angle deviation, 100 m steel tower, 100 m rotor diameter, Measurement during production before (mass imbalance below limit)

Figure 10: Reduction of rotor speed-related operational vibration through correct blade angle adjustment (1 milli-g = 9.81 mm/s²)

2.2 (i) Well trained and experienced staff

Due to the short periods with suitable weather for accessing WT for service, and further weather requirements for the rotor balancing, it is obvious that specialists are required to perform the task straightforward but careful because they are aware of the harmful effects of wrong recommendations causing increased instead of lowered vibration. Most manufacturers have as well only a few expert teams trained for their in-house methods for blade angle verification or balancing. Profound knowledge of WT dynamics is necessary to cope with unexpected WT behaviour on site, assure a high-quality result if there are stronger changes of the wind and to decide whether a measurement can be continued or has to be aborted. Prevention of hazard and long-term damages from wrong recommendations due to falsifications are further aspects. It is very costly if another measuring campaign is required.

2.2. (j) Life-cycle-oriented approach for WT rotor balancing

According to [6] it is well known for other rotating machinery and turbines that the balancing state changes over time. Independent field experience with WT confirms this: Erosion, damages and repairs or even a blade exchange as well as changes in the WT control, pitch sensor failures, etc., are manifold reasons for the fact that balancing is required during commissioning and periodically throughout the entire WT service life to prevent accelerated fatigue and lifetime consumption, fig. 11. Therefore, a life-cycle-oriented approach for WT rotor balancing has to start with the design, i.e. consideration of in-situ balancing as a design criterion in terms of defining mounting positions for test masses and sensors. Then develop the related procedures and include it in the manuals as well as performing it in the field. Several procedures and tools developed and used by OEM for blade angle adjustment are not able to assure that an adjustment meets the design limits. This was confirmed already several times by independent parallel measurements and validation by vibration measurements.

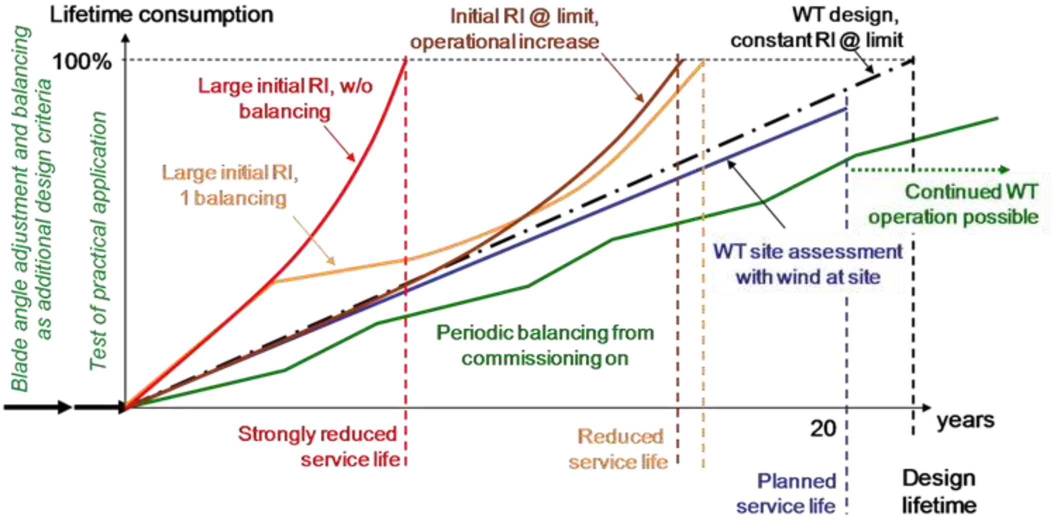


Figure 11: Positive impact of life cycle oriented WT balancing from the design stage on

The economic impact of MI and AI is far higher that the costs for the life long measurements. For an absolute blade angle deviation of 1.0° of all three blades, the AEP reduction is more than 7% [8]. Operational WT data, e.g. deviating power curves or data from WT structural monitoring is suitable to identify WT affected by RI. If for a WT type a certain number of similar WT has been measured for RI, it is possible to derive for defined measurement conditions a vibration limit value, fig. 4 as indicators to estimate the level of MI and AI without a complete balancing procedure. Research to determine MI and AI with tower top vibration measurement and a model-based approach showed that a very detailed and individually calibrated structural model of the WT and the rotor including aerodynamic model is required, and at least the axial, lateral and torsional vibration as input if the level of RI should be estimated from monitoring data.

Furthermore, due to the various possible root causes for MI and AI in-situ inspection and balancing, it is inevitable to determine the appropriate counter measures.

5. CONCLUSIONS

Available WT rotor balancing methods and procedures show a different level of complexity. The quality criteria derived from VDI 3834-1:2015 and DIN ISO 21940-13 help judging the overall suitability and benefit of a method. The criteria are as well useful to develop a life-cycle-oriented approach for WT rotor balancing, which reduces lifetime consumption, stand still and overall O&M costs.

The found high frequency of blade angle deviation at WT rotors and its negative effects on lifetime consumption and AEP show, that it is highly advisable to perform independent high-quality blade angle and imbalance measurements periodically from the commissioning onwards. The saved damage costs and the yield loss are by a factor 3 to 20 higher than the measurement costs. Furthermore, for one and the same site, a WT with a well adjusted and balanced rotor has a lower lifetime consumption and a higher potential for life time extension. Even for WT with a full-service contract, all parties involved benefit from balancing since the service provider has lower O&M costs and if there is an AEP-related gratification this will increase with the higher AEP from blade angle correction.

REFERENCES

1. DIN EN IEC 61400-1:2011: Wind Turbines- Part 1: Design requirements
2. IEC 61400-3:2009: Wind Turbines- Part 3: Design requirements for offshore wind turbines
3. Germanischer Lloyd, 2010: Guideline for the certification of wind turbines
4. Germanischer Lloyd, 2005: Guideline for the certification of Offshore wind turbines
5. Verein Deutscher Ingenieure (Association of German Engineers): Guideline VDI3834: Measurement and evaluation of the mechanical vibration of wind turbines and their components – Part 1: Onshore wind turbines with gearbox, 2015
6. DIN ISO 21940-13:2012 “Criteria and safeguards for the in-situ balancing of medium and large rotors“
7. BWE e.V. Grundsätze für Sachverständige (Basic principles for independent experts of the German Windenergy Association BWE) 2012
8. Donth A., Grunwald A. Heilmann C., Melsheimer M.: Payback Analysis of Different Rotor Balancing Strategies, EWEA 2013,Vienna, Austria, 4-7 February, 2013