How Reliable is a Reliability Calculation?

Hanspeter Dinner

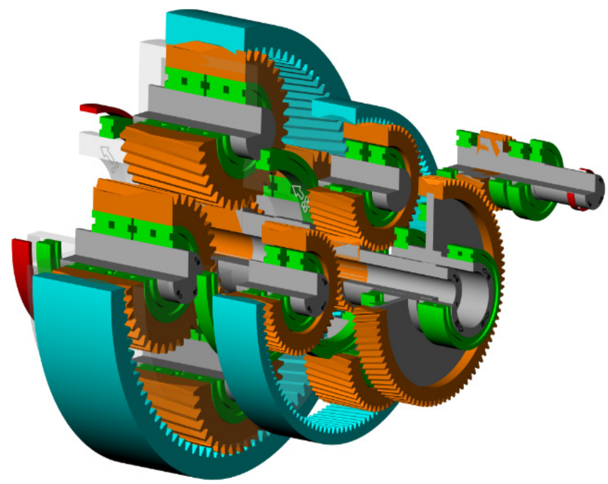


Figure 1 KISSsoft model used for calculation. Planetary carrier not shown; housing not shown.

Objective of the Study

Bearing failures are a major concern in wind turbine main gearboxes. The risk of bearing failure $F(t)$ is calculated from the bearing life L. If this is done for all bearings in a gearbox, then, the bearing subsystem reliability for the required life $R(H_{req})=1-F(H_{req})$ may be calculated. Methods used for such calculations for wind gearboxes are well established and have been widely used in other fields, (Refs. 5–11).

A calculated failure risk will not necessarily reflect the failure rate experienced in the field. The reason for this is, e.g., that only a few failure modes are open to a reliability calculation. Here, another, sometimes overlooked reason, is addressed: The calculated reliability will change with any small variation of input parameters or calculation method.

Reliability as a Design Requirement for Wind Turbine Gearboxes

ISO 81400-4, (Ref. 1), states "…The required design life shall be specified for each of the major subsystems of the gearbox including gears, bearings, housings, shafts and seals.…" In this statement, attention is directed to the underlying reliability of the material data or load capacity numbers associated with the life calculation of components. For the bearing rating, design rules (Refs. 1–3) usually stipulate a bearing failure probability of 10%. If in a gearbox each bearing reaches the required life H_{req} (e.g. 175,200 $h=20$ y, using L_{nmrh} along (Ref. 4)) at a probability of failure of $F=10\%$, the reliability of the bearing subsystem is less than 90%. The reliability of the bearing subsystem is the product of all bearing reliabilities.

Single bearing reliability calculation. In B20 revision of AGMA 6006, (Ref. 2)), bearing reliability $R(t)$ as a function of time t is calculated with a three parameter Weibull distribution:

$$R(t)=e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \quad \text{where } \eta=\frac{L-\gamma}{\sqrt[\beta]{-\ln(R_0)}}$$

L = Modified reference rating L_{nmrh},
γ = Location parameter $= C\gamma * L$; $C\gamma = 0.05$
β = Shape parameter = 1.500
η = Scale parameter
R_0 = Reference reliability, reliability used to calculate L_{nmrh}, $R_0=90\%$

Bearing Subsystem Life and Reliability

Base line model and reference conditions. The bearing subsystem of a 3MW class main gearbox is investigated. The rotor shaft is supported by two bearings; planet carrier bearing life is assumed as "infinite."

Different effects are considered in the calculations. From a reference condition listed below, small changes are introduced to study how they affect the reliability of the bearing subsystem.

Results, reference calculation. With settings per DNV GL guideline (Ref. 3) and above, calculations are done using *KISSsoft* software (Ref. 1), giving:

For all 32 bearings, the reliability function $R(t)$ is plotted (see figure 2 in grey). Bearing subsystem reliability (blue) is calculated therefrom. The intersection of subsystem life H_{req} at 175,200 hours (vertical, red) and the time dependent subsystem reliability (blue) results in a subsystem reliability value of about 0.59 (blue, dashed, horizontal line).

Table 1 Reference conditions for the calculation of the bearing life

Property	Reference value	Affects
Clearance, position in tolerance field	Mean value in tolerance field	Operating clearance, load distribution in bearing
Inner and outer race temperature	Temperature differences per Table 4, ISO 81400-4, [1]	Operating clearance, load distribution in bearing
Load application position	Load in center of gear face width	Load distribution, planet bearings
Planet load distribution (Kγ)	Kγ = 1.10 for LSS, Kγ = 1.05 for ISS	Load on planet bearings LSS, ISS
Nominal torque	100% nominal load	Load level on bearings
Lubricant temperature	65°C	Lubricant viscosity, aISO factor
Lubricant contamination	- / 17 / 14, beta25 = 75	Life rating
Bearing clearance variation, planet bearings	All bearings have same bearing clearance	Load distribution among planet bearings,
Pressure angle, gears	Operating pressure angle αwt is used	Bearing forces

Variation of Calculation Settings

Parameters varied. Thirteen experiments are set up. Only one parameter is changed compared to the reference calculation.

Resulting reliability curves. For each experiment, for all bearings, life and reliability curve are calculated. Bearing subsystem reliability and failure probability curve is plotted in (Figure 3). The resulting reliability values for the required life H_{req} are determined as intersection of the reliability curves with the vertical line at $x = H_{req}$. Experiment 1 and 12 gave highest reliability, highlighted (green). Experiment 8 gave second highest reliability (cyan). Experiment 2, 6 and 7 gave second-lowest reliability, (pink). Experiment 11 gave lowest reliability (grey, solid line).

Calculated reliability values $R(H_{req})$ range from 38% to 70%. If we accept that experiment 11 is extreme and omit it, we still find a range of 19%-points.

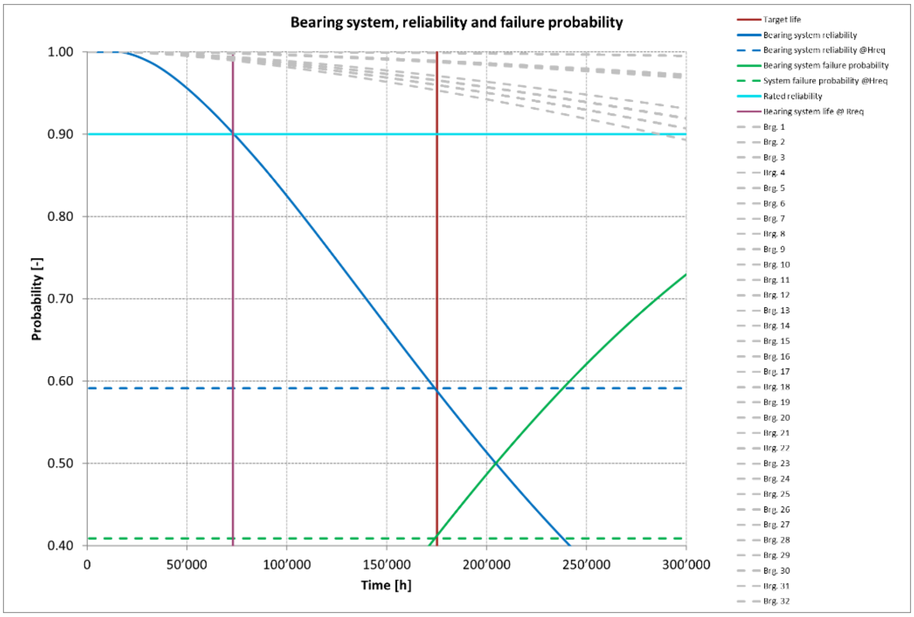


Figure 2 Bearings reliability (grey), subsystems reliability (blue), required subsystems life Hreq (vertical, red), rated reliability (horizontal, cyan), subsystem reliability at required life (horizontal, dashed blue), subsystem life at rated reliability (vertical, pink).

Table 2 Calculated bearing life, reference values. For carrier bearings, a very high life is assumed

Stage	Position	Shaft	L10mrh in hours
LSS	RS-RS	Planet, same for all planets	314'820
LSS	RS-GS	Planet, same for all planets	9'889'777
LSS	GS-RS	Planet, same for all planets	10'504'562
LSS	GS-GS	Planet, same for all planets	345'866
LSS, ISS	RS, GS	Carrier	9'999'999
ISS	RS	Planet, same for all planets	646'878
ISS	GS	Planet, same for all planets	675'973
HSS	RS	Driving	344'247
HSS	GS-RS	Driving	9'999'999
HSS	GS-GS	Driving	622'918
HSS	RS	Driven	286'648
HSS	GS-RS	Driven	677'429
HSS	GS-GS	Driven	382'756

Table 3 Set up of the 14 experiments

Experiment	Parameter varied	Variation	Comments
1	Clearance, within tolerance field	Lower position	
2	Clearance, with in tolerance field	Upper position	
3	Inner, outer race temperature	Temperature difference between races reduced by 5K	Operating clearance but not oil viscosity
4	Inner, outer race temperature	Temperature difference between races increased by 5K	Operating clearance but not oil viscosity
5	Load position on gear face width	Offset 1 cm	
6	Load position on gear face width	Offset 2 cm	
7	Planet load distribution (Kγ)	Kγ values increased by 0.05	
8	Planet load distribution (Kγ)	Kγ values decreased by 0.05	
9	Nominal torque on gearbox input	Load decreased by 2.5 %	To consider e.g. site-specific loads
10	Nominal torque on gearbox input	Load increased by 2.5 %	To consider e.g. site-specific loads
11	Lubricant contamination	One class worse, - / 19 / 16, beta25 = 7	Reference class - / 17 / 14, beta25 = 75
11a	Lubricant contamination	One class better, -/15/12, beta12=200	Reference class - / 17 / 14, beta25 = 75
12	Pressure angle, gears	Nominal instead of operating pressure angle	
13	Bearing clearance variation in planet bearings	Outer bearing rows in LSS planets, clearance reduced by 10 µm, inner have a clearance increased by 10 µm	To simulate that bearings are not perfectly matched

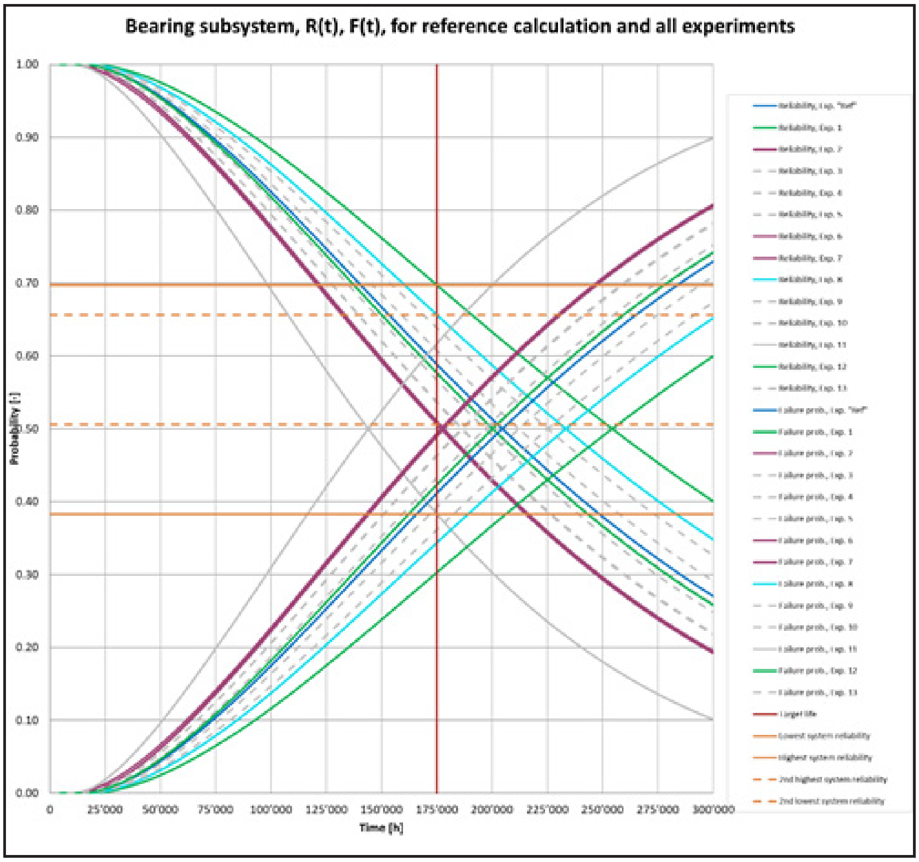
Conclusion

Governing effects. The reliability of the bearing subsystem is governed by the outer bearing rows in the LSS planet bearings and the output shaft bearings. We find that the biggest influence is from the lubricant cleanliness level. This is easy to understand as the lubricant cleanliness level itself affects the rated life of the LSS planet bearings the most, since those have the lowest lubricant film thickness and therefore a low aISO factor.

On the HSS bearings, a major influence is the pre-tension of paired TRBs and the influence of the bearing raceway temperature.

How reliable is the reliability calculation? We find that a calculated bearing subsystem reliability of a typical wind turbine gearbox has a typical error of ±10%-points.

If we are interested in comparing the total cost of ownership for several competing designs, based on bearing subsystem reliability numbers, this error of +/-10% is disappointing. The obvious solution is that all calculations must be done strictly with identical assumptions, calculation methods and tools. **PTE**



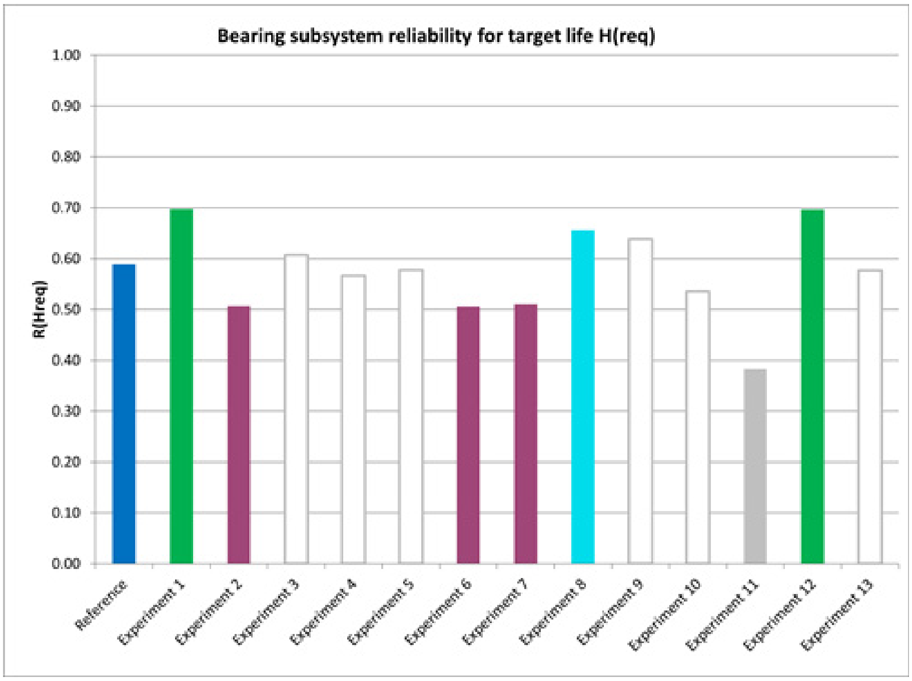


Figure 3 **Bearing subsystem reliability for different experiments (blue: reference calculation, green: highest result, pink: second lowest result, grey: lowest result, cyan: second highest results, white: other results). Upper image: reliability curves. Lower image: reliability levels at Hreq.**

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Hanspeter Dinner studied mechanical engineering at the Swiss Federal Institute of Technology, Zürich, Switzerland and the National University of Singapore. He first worked as FEM engineer with a Swiss consultancy and as lead stress engineer with a roller coaster developer. He joined KISSsoft AG as software support and project engineer. In 2008, he started the consultancy company EES KISSsoft GmbH, representing the KISSsoft company in China, Japan, Korea, Taiwan and India. He has conducted about a hundred FEM, gear, bearings and transmission projects serving the wind, tractor, industrial gearbox and fine pitch gear industry. Since August 2019, Dinner has been working in the function of Director Global Sales in the KISSsoft company.

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