WHITE PAPER

Breaking the vicious cycle:

How real-time load sharing measurement transforms gearbox quality, warranty and design

Sensing360 GearUp | White Paper for New gearbox monitoring

Real-time measurement of per-planet load distribution quantifies manufacturing quality before shipment, provides deterministic evidence for warranty claims, and feeds the design optimization loop.

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The cycle that shortens life of every gearbox you ship

Every planetary gearbox you design and manufacture is subject to a self-reinforcing degradation process. It begins the moment the unit enters service, and often before that, at the factory gate.

Because of manufacturing and assembly tolerances (carrier pinhole position errors, gear tooth thickness variations, bearing clearance differences), the torque load is never perfectly distributed across the planet paths. When one planet carries more, others carry less and both conditions are dangerous. The physics of overloading and underloading are unforgiving Bearing and gear fatigue life scales with load to the power of approximately 3.3. A planet overloaded, i.e. carrying 20 percent more than its fair share sees its component life cut by roughly 50 percent. Did you know that significant underloading leads to severe operating conditions and failure modes (edge loading, bearing skidding, lubricant film starvation, white etching cracks etc..) that limit life even more.

> *Load sharing inequality drives wear, and wear feeds inequality, until failure.*

The deeper problem is what happens next, unequal loading accelerates wear. Wear changes the internal geometry: bearing clearances increase, stiffness in the parallel load paths shifts. These geometric changes increase the load sharing inequality further, which accelerates wear further. The cycle is self-reinforcing, and it runs silently, invisible to conventional end-of-line testing, invisible to vibration sensors on the housing, invisible until it becomes a failure as illustrated in figure 1.

This is not a rare edge case. It is the fundamental mechanism behind industry-wide failure of planetary gearboxes to reach their 20-year design life. NLR data shows 76.2 percent of gearbox failures originate in bearings and 17.3 percent in gears, totalling 93.5 percent of all failures. Most fail or require major intervention between years six and ten. The vicious cycle is the reason and planet load sharing is the leading indicator of failure before bearing or gear damage becomes visible or measurable.

To break the cycle, the loop must be interrupted by measurement and intervention. You cannot manage what you cannot see.

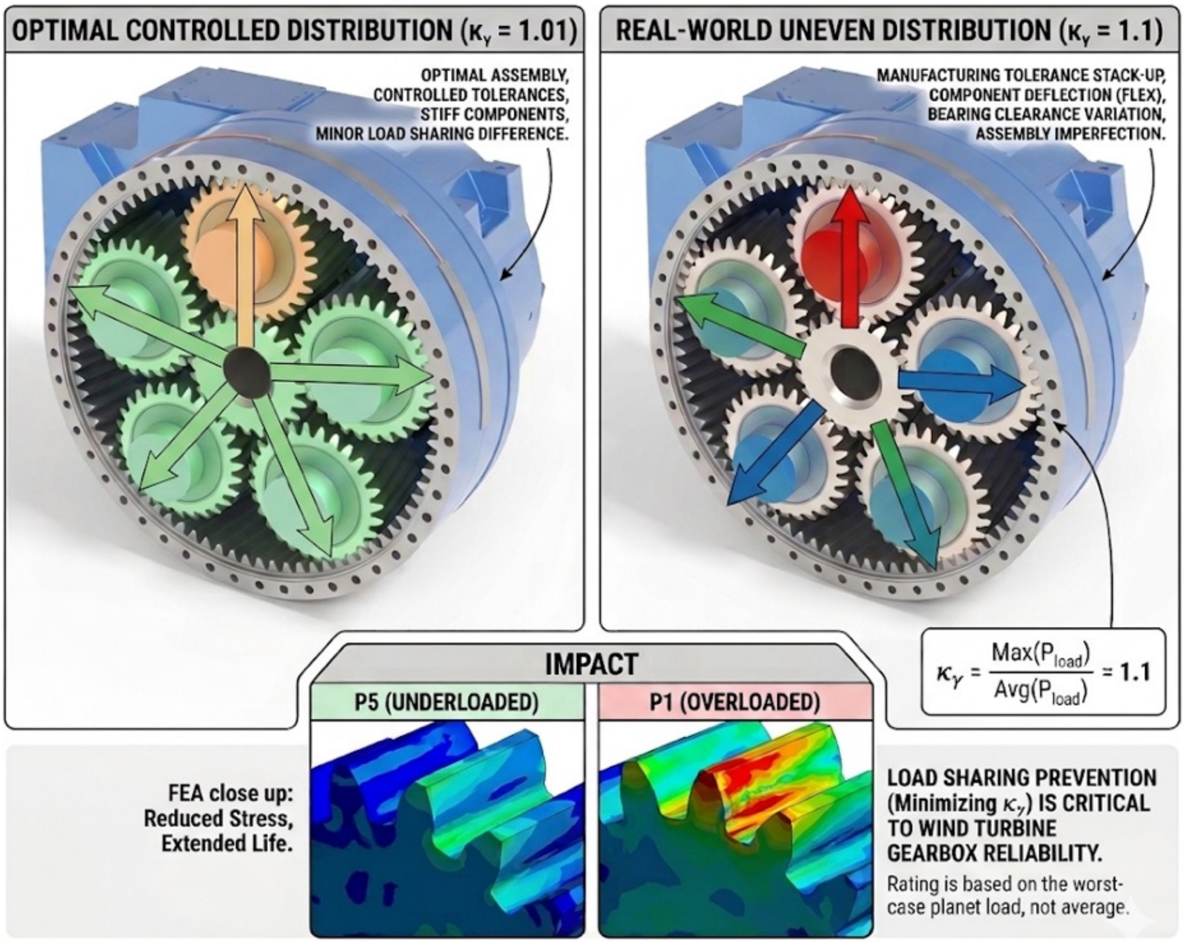


Figure 1: Optimal load sharing distribution versus non-optimal

What the standards require

IEC 61400-4 and ANSI/AGMA 6006-A03/B20 both require and assume that the mesh load factor (Kγ) remains within design limits throughout the gearbox service life. These standards are not optional guidance, they are the certification basis for every unit you ship.

The practical implication is strict. To achieve the design life requirements that follow from the standard, Kγ must typically remain below approximately 1.10. Above this threshold but still below the conservative values reported in the standard, the conflicting demands of cost, lifetime, torque (density) and weight become practically irreconcilable.

The primary international standard for wind turbine gearboxes specifies that every production unit must undergo acceptance testing before leaving the factory. Conventional End-of-Line testing detects gross manufacturing and assembly errors, creates a 'birth certificate' of each and every gearbox but it does not measure and include per-planet load distribution. Planet load sharing is the most critical and currently unmeasured signal in planetary gearbox health.

There is no baseline load sharing fingerprint that survives into the field. When a warranty claim arrives two years after shipment, there is no factory evidence of the gearbox load sharing at the time it left your facility.

What GearUp measures at the factory

An easy to mount sensor strip,an array of Fiber Bragg Grating (FBG) sensors, is placed on the housing of the ring gear. The sensor is connected to a smart box that processes the sensor signals. As each planet passes, the strain pattern its mesh force creates, is captured at each sensor location, the S360smart e box processes these signals, extracting:

- Load Sharing Inequality Index (LSII). The maximum and minimum-to-mean planet load ratio across all planet paths and the Per-planet load sharing fractions Kγi, as a unique finger print of the delivered gearbox. Acts as a leading detector and diagnostic indicator of failure.
- Torque and speed, power. Measure the operating condition. Acts as a reference or input for the indicators.
- Spectral baseline. The healthy gear and bearing spectralfingerprint at known torque and speed. This is the cleanest spectrum this gearbox will ever produce, before field loading, wear or contamination alter the signal. Acts as a lagging detector and diagnostic indicator of failure.

- The Cumulative Damage Index (CDI) computed from factory test cycles per IEC 61400-4 and ANSI/AGMA 6006, which extends standard Weibull reliability theory to varying operating conditions via the concept of "used capacity." The complete variable operating history of a used gearbox is summarised by one scalar. This allows to compare design life assumptions with life calculated of a used gearbox with known operating history.

These four KPIs combine into a Diagnostic Passport, a signed, standards-referenced document stored in the Sensing360 cloud and accessible to the Gearbox or Turbine OEM and operator from factory or commissioning onwards. One set of KPIs for the entire lifecycle.

From quality gate to warranty to design feedback

The passport serves three functions simultaneously.

As a quality gate

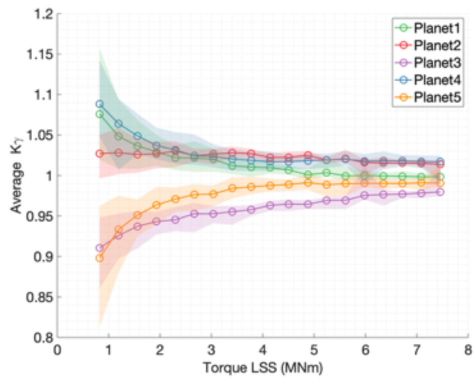
It provides an automated pass/hold/rework decision at the factory gate, based on actual measured $K\gamma$, not inferred from vibration or noise. Assembly defects that pass conventional testing (pinhole position errors, irregular planet spacing, bearing clearance batches) are caught before shipment. Systematic production line improvement points become visible across batches, closing the manufacturing feedback loop.

As a warranty shield

It proves the gearbox left your factory with documented $K\gamma$ within design limits. When a field failure occurs and the claim arrives, the question of whether the fault originated at manufacture, during transport, or through operational misuse is answered by data. The factory passport compared against the field baseline at commissioning separates these causes definitively. Warranty provisions can be reduced when you have deterministic proof of how the gearbox was operating.

As a design feedback loop

The load sharing signatures measured across a production run reveal which tolerance choices are consuming fatigue life in the field. Which bearing clearance specifications drive Kγ above 1.10 during curtailment? This is the data that moves future designs from conservative ignorance margins toward optimised architectures, lighter, cheaper, more torque-dense, because the uncertainty in load distribution has been removed.



Kγ values of a gearbox

How to start: low level entry point

The system consists of a easy-to-install sensor strip wired to the S360 smart box with a single fibre cable. The system can be installed by your or our team within a few hours. This can be done in the factory or up tower, the S360 smart box can be configured remotely.

To start we offer a the 3-unit pilot (three passports, three units, no commitment beyond the pilot) at a fixed feeand is typically initiated by a quality or reliability engineer who wants to understand what Kγ actually looks like across their production run. The answer is almost always illuminating.

Example GearUp strip installation up-tower