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Reliability Test Tailoring for Reducers Validation in E-Drive Systems

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Abstract

In the rapidly evolving landscape of electrified powertrains, Valeo Power division has emerged as a key supplier of eDrive systems for pure electric and hybrid vehicles. A critical challenge in this domain is translating customer-defined reliability targets and extensive operational duty cycles into efficient and representative validation tests. These duty cycles, encompassing diverse driving conditions and driver severities over a vehicle's lifetime, necessitate a robust methodology for identifying and addressing potential failure mechanisms within the mechanical transmission systems (reducer or gearbox).

This paper outlines Valeo's approach to tailoring reliability tests for reducers, aiming to achieve customer specifications with a limited number of test devices and optimized test durations. The methodology involves several key steps: condensation of real-world drive cycle into a synthetic drive cycle with a reduced duration, test acceleration, stress-strength interference analysis, and statistical assessment using cumulative binomial law.

A crucial aspect of this process is the Physics-of-Failure approach: identification of relevant failure modes and the application of appropriate condensation techniques. For reducer fatigue failure mechanism, particular attention is given to two primary loading types: absolute torque/speed loading (surface damage) and torque inversion cycles (alternate damage). The application of materials fatigue modelling (the Wohler inverse power law and its coefficients), which quantify the relationship between load level and component lifetime, is fundamental to both the condensation process and the overall reliability analysis. This comprehensive approach ensures that the derived test definitions are not only effective for physical validation but also provide valuable insights for advanced simulation and design optimization.

Keywords: reliability, reducer, duty cycle, failure mechanism, condensation, stress-strength, binomial law, test acceleration, simulation

1. Introduction

In the rapidly evolving landscape of electrified powertrains, customer reliability requirements have become increasingly demanding in recent years.

In this context and as a key developing supplier of e-drive systems, Valeo must comply strictly with these requirements, and propose a complete methodology that involves analyzing and elaborating the requirements, and finally demonstrating the achievement of objectives through both simulation and testing.

A rigorous methodology is proposed for tailoring reducer reliability tests to meet specifications with minimal devices and optimized duration. The process includes: identifying all components subject to fatigue degradation and associated failure mechanisms, processing customer real-world duty cycles and defining equivalent and easy-to-manage cycles, developing reliability tools for tailoring a reliability test plan (stress-strength approach, statistical assessment with cumulative binomial law).

2. Reducer architecture

2.1. *The role of a reducer*

In e-Drive systems, the reducer serves as a mechanical device positioned between the electric motor (input) and the output shafts connected to the wheels (Fig. 1). Its primary function is to transmit power from the e-machine to the wheels, simultaneously increasing the torque level (to achieve the required vehicle torque for extreme loads like maximum weight and steep slopes) and decreasing the speed level (to match the vehicle's typical speed range). This conversion is achieved through an internal assembly of gears, shafts, and bearings. Additionally, the reducer incorporates a differential, which is essential for allowing a speed difference between the left and right wheels, thereby preventing slippage and abnormal wear during turning or bending conditions.

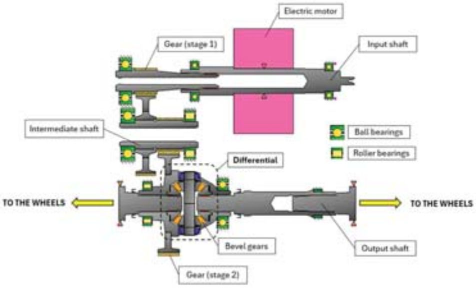


Fig. 1: Architecture of a reducer

2.2. *Reliability breakdown*

A crucial initial step in this methodology involves identifying and listing all components subject to fatigue loadings, and subsequently linking a failure mechanism to each one. This critical identification process can be greatly supported by reviewing the Design Failure Mode and Effects Analysis (DFMEA) or by leveraging insights gained from previous failure experiences.

In the reducer scope, main identified components and failure mechanisms are:

- Bearing pitting
- Gear pitting (teeth contact)
- Gear bending (root teeth breakage)
- All components loaded with alternate torque cycling (shafts, screws or welding joints, housings, splines).
- Differential fatigue (bevel gears pitting, bending, cups wear-out)

Based on the series block-diagram approach for a system composed of multiple components, the reducer's overall reliability is determined by multiplying the individual reliability of each of its constituent components.

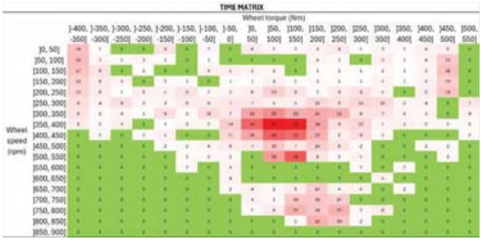
$$R = \prod_i R_i \tag{1}$$

R: Reducer's overall reliability
R_i: Component "i" reliability

3. Duty cycles processing

The critical subsequent step involves analyzing and processing duty cycles to link specific damaging loads to each potential failure mechanism.

Customer-provided duty cycles are typically supplied as time-based matrices (Table 1) or vectors detailing time spent at various torque, speed, and temperature conditions.



TIME MATRIX

Wheel torque (Nm):]-400, -350]]-350, -300]]-300, -250]]-250, -200]]-200, -150]]-150, -100]]-100, -50]]-50, 0]]0, 50]]50, 100]]100, 150]]150, 200]]200, 250]]250, 300]]300, 350]]350, 400]]400, 450]]450, 500]]500, 550]

Wheel speed (rpm):]0, 50]]50, 100]]100, 150]]150, 200]]200, 250]]250, 300]]300, 350]]350, 400]]400, 450]]450, 500]]500, 550]]550, 600]]600, 650]]650, 700]]700, 750]]750, 800]]800, 850]]850, 900]

Table 1: Time-based matrix

For alternating torque scenarios, these duty cycles are often specifically presented as Rainflow counting matrices (Table 2), which describe the number of occurrences (or cycles) from an initial torque to a final one.

OUTPUTSHAFT TORQUE RAINFLOW MATRIX

To (Nm) ---->:]-1100, -900]]-900, -700]]-700, -500]]-500, -300]]-300, -100]]-100, 100]]100, 300]]300, 500]]500, 700]]700, 900]]900, 1100]]1100, 1300]]1300, 1500]]1500, 1700]]1700, 1900]]1900, 2100]]2100, 2300]

<---- From (Nm):]-1100, -900]]-900, -700]]-700, -500]]-500, -300]]-300, -100]]-100, 100]]100, 300]]300, 500]]500, 700]]700, 900]]900, 1100]]1100, 1300]]1300, 1500]]1500, 1700]

Table 2: Torque Rainflow-counting matrix

Reliability assessment mandates the input of duty cycle severity (e.g., average customer, severe customer 90%, 99%, …). To facilitate the reliability processing steps described in Section four, this data must be consolidated into a single value.

The so-called condensation involves different calculation steps, depending on the type of component and/or failure mechanism to be studied. Following paragraphs detail the condensation for bearings & gears, alternating torque and differential.

3.1. Bearings and gears

A damaging load is determined for both bearings and gears by combining the number of revolutions and the torque level elevated by a Wohler coefficient (Basquin b). The Wohler coefficient, which characterizes life-damaging behavior, is specific to the particular failure mechanism under consideration, such as gear pitting, gear bending, or bearing failure.

A relation exists between applied torque and lifetime (Wohler curve, Fig. 2), which can be modelized through Wohler Inverse Power law:

$$N.T^b = A \tag{2}$$

N: Component lifetime (revolutions, cycles, hours, …)
T: Applied torque
b: Wohler coefficient
A: Constant value

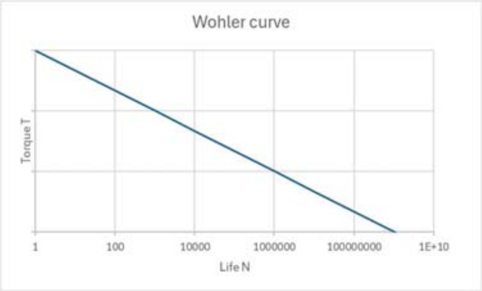


Fig. 2: Wohler curve (Relation between torque and lifetime)

Applying this model, the damaging load is determined by the following formula:

$$d = rev \times |T|^b \tag{3}$$

d: Damaging load
rev: Number of revolutions at the output shaft
T: Applied torque at the output shaft
b: Wohler coefficient

3.2. Alternating torque

For alternating torque scenarios (Fig. 3), the Rainflow matrix mentioned in Section two needs to be condensed into one "accelerated" number of alternate torque cycles.

Every cycle from an initial torque T_i to a final torque T_j is converted into one equivalent alternate cycle $T_{i,j}^{alt}$ through the Smith-Goodman projection method (Fig. 4).

Details for this methodology can be found in "Fatigue and Durability of Structural Materials" [1].

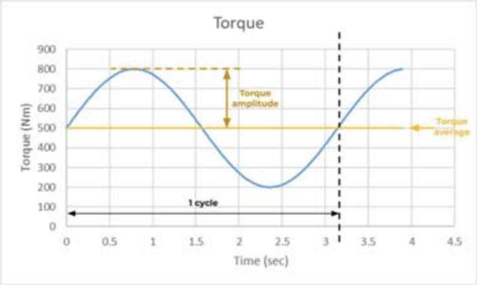


Fig. 3: Alternating torque cycle details

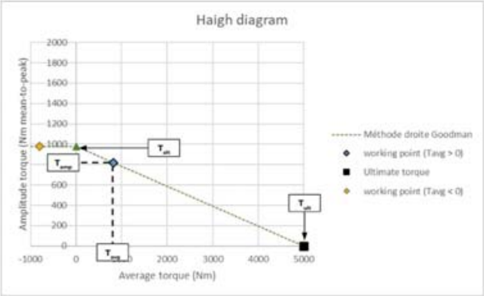


Fig. 4: Smith-Goodman projection

Similar to the approaches used for bearings and gears, a Wohler coefficient is then applied to "accelerate" the number of cycles. Ultimately, the Rainflow matrix is converted into a single equivalent torque cycle condition T_{eq}^{alt} with an associated number of occurrences N_{eq}, representing the same cumulative damage:

$$N_{eq} = \sum_{i,j} N_{i,j} \cdot \left(\frac{T_{i,j}^{alt}}{T_{eq}^{alt}} \right)^b \tag{4}$$

N_{eq}: Equivalent alternating torque cycles
$N_{i,j}$: Alternating torque cycles from a torque level T_i to a torque level T_j
$T_{i,j}^{alt}$: Alternating torque from a torque level T_i to a torque level T_j
T_{eq}^{alt}: Equivalent alternating torque
b: Wohler coefficient

3.3. Differential

For differential and more specifically for bevel gears fatigue, loading is expressed as the number of alternances between sun gear and differential casing (Fig. 5), at an equivalent torque level. Again, the number of alternances is "accelerated" with a specific Wohler coefficient.

Fig. 5: Differential architecture

$$N_{eq} = \sum_i t_{i,j}.\frac{W_i}{2}.\left(\frac{T_j}{T_{eq}}\right)^b \qquad (5)$$

N_{eq}: Equivalent number of alternances
$t_{i,j}$: Time spent at delta speed W_i and at torque level T_j
W_i: Delta speed (speed difference between right wheel and left wheel)
T_j: Torque level
T_{eq}: Equivalent torque level
b: Wohler coefficient

4. Reliability processing

4.1. Stress-strength interference

To evaluate the reliability for each defined failure mechanism, a comparison is necessary between the loading imposed by the duty cycle and the damage accumulated during the test. This comparison is the core principle of the stress-strength interference approach (Fig. 6).

Fig. 6: Stress-strength interference

The stress law characterizes the duty cycle distribution, representing how the product will be used in real-life. The strength law describes the product's lifetime distribution, indicating how long the product can operate before failure. A larger separation between the stress and strength distributions signifies a higher product reliability.

$$R = 1 - \int_0^\infty f_{strength}(x).\left(1 - F_{stress}(x)\right).dx \qquad (6)$$

R: Reliability of failure mechanism under study
$f_{strength}$: Failure density of strength law
F_{stress}: Distribution function of stress law

The challenge is to define (and demonstrate) a strength law that will allow reaching a targeted reliability level for each failure mechanism so that the reducer resulting reliability (product of each failure mechanism reliability) reaches the customer requirement.

Another application of the stress-strength interference approach is described in "Bayesian Network for Reliability Predictions of Automotive Battery Cooling System" [2].

4.2. Cumulative binomial law

In order to demonstrate the defined strength law with a limited number of parts to be tested, a statistical approach is necessary: the cumulative binomial law is therefore applied.

It proposes a relation between the number of DUTs (device under test), the confidence level, test time, Weibull shape parameter and reliability target.

$$ln(1 - C) = n\left(\frac{T}{t}\right)^\beta ln\left(R(t)\right) \qquad (7)$$

C: Confidence level
n: Number of DUTs
T: Test time
t: Time reached at reliability target
β: Weibull shape parameter
R(t): Reliability to be demonstrated at time t

At this stage of the process, a test plan is defined in terms of DUTs, test time and test conditions.

It is then essential to optimize it and to evaluate the risk of failure through simulation.

5. Test optimization

Reliance on a comprehensive list of all potential failure mechanisms often results in an overly ambitious and unrealistic test plan regarding the number of parts and the duration required to demonstrate reliability.

To shorten the test, two strategies can be employed: test acceleration and prioritizing failure mechanisms based on their criticality.

5.1. Test acceleration

It is useful to select severe test conditions (max torque, max speed, max temperature, max alternating torque). The first option is to play on torque parameter, through the calculation of equivalent condition, as described in Section three. The second option is to play on speed parameter, which will shorten the test as more revolutions are performed in the same amount of time. Specifically for bearings, the third option is to play on oil temperature and on pollution calibrated oil, which will lead to an acceleration (calculation details available in ISO281 standard [3]).

5.2. Failure mechanism criticality ranking

Thanks to simulation, a critical distinction can be made between high-risk and low-risk failure mechanisms (Fig. 7).

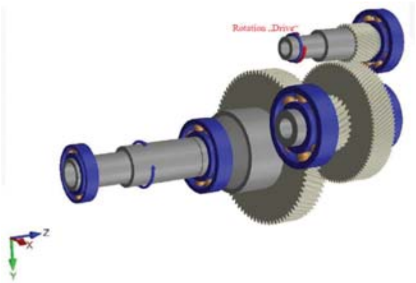


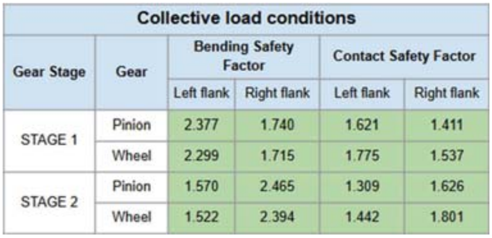
Fig. 7: 3D lifetime simulation of bearings and gears

If simulation indicates very low damage for specific failure mechanisms, these can be safely excluded from the required testing, leading to a reduction in overall test duration and cost.

In any case, simulation allows us to evaluate the remaining lifetime after test.

Bearings: lifetime is generally expressed as a damage percentage, indicating the remaining life relative to the theoretical time-to-failure at a given simulated time.

Gears (pitting and bending): lifetime is generally expressed as a safety factor, quantifying the stress margin between the applied stress and the theoretical stress-to-failure (Table 3).



Collective load conditions					
Gear Stage	Gear	Bending Safety Factor		Contact Safety Factor	
		Left flank	Right flank	Left flank	Right flank
STAGE 1	Pinion	2.377	1.740	1.621	1.411
	Wheel	2.299	1.715	1.775	1.537
STAGE 2	Pinion	1.570	2.465	1.309	1.626
	Wheel	1.522	2.394	1.442	1.801

Table 3: Example of gears lifetime simulation result (safety factor)

Damage percentage and safety factor are linked together as described in Fig. 8.

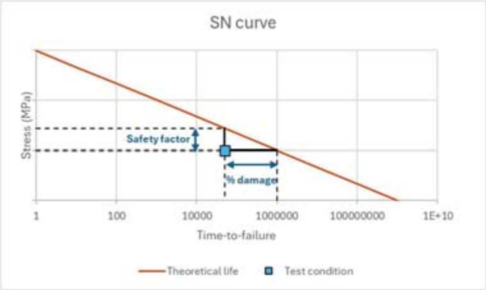


Fig. 8: Definition of life margins (% damage, safety factor)

6. Conclusion

A rigorous methodology has been developed for tailoring reliability tests, in order to meet more and more demanding customer reliability requirements.

The main steps are clearly detailed:

- **Reliability breakdown**, to identify all potential failure mechanisms
- **Duty cycle analysis and elaboration**, to establish the inputs necessary for test definition, and for simulation as well
- **Reliability process**, to propose an initial tailored test plan, including the required number of Devices Under Test (DUTs) and the total test time.
- **Test optimization** and failure risk assessment.

Although highly effective for reducers, this versatile methodology is also applicable to other eAxle sub-systems, such as the electric motor or the inverter.

Ultimately, this methodology underscores the importance and advantages of a collaborative approach, requiring the involvement of multiple disciplines such as system engineering, design, simulation, reliability, and testing.

References

[1] S.S. Manson, Gary R. Halford, "Fatigue and Durability of Structural Materials"

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[3] Rolling bearings - Dynamic load ratings and rating life ISO 281 standard