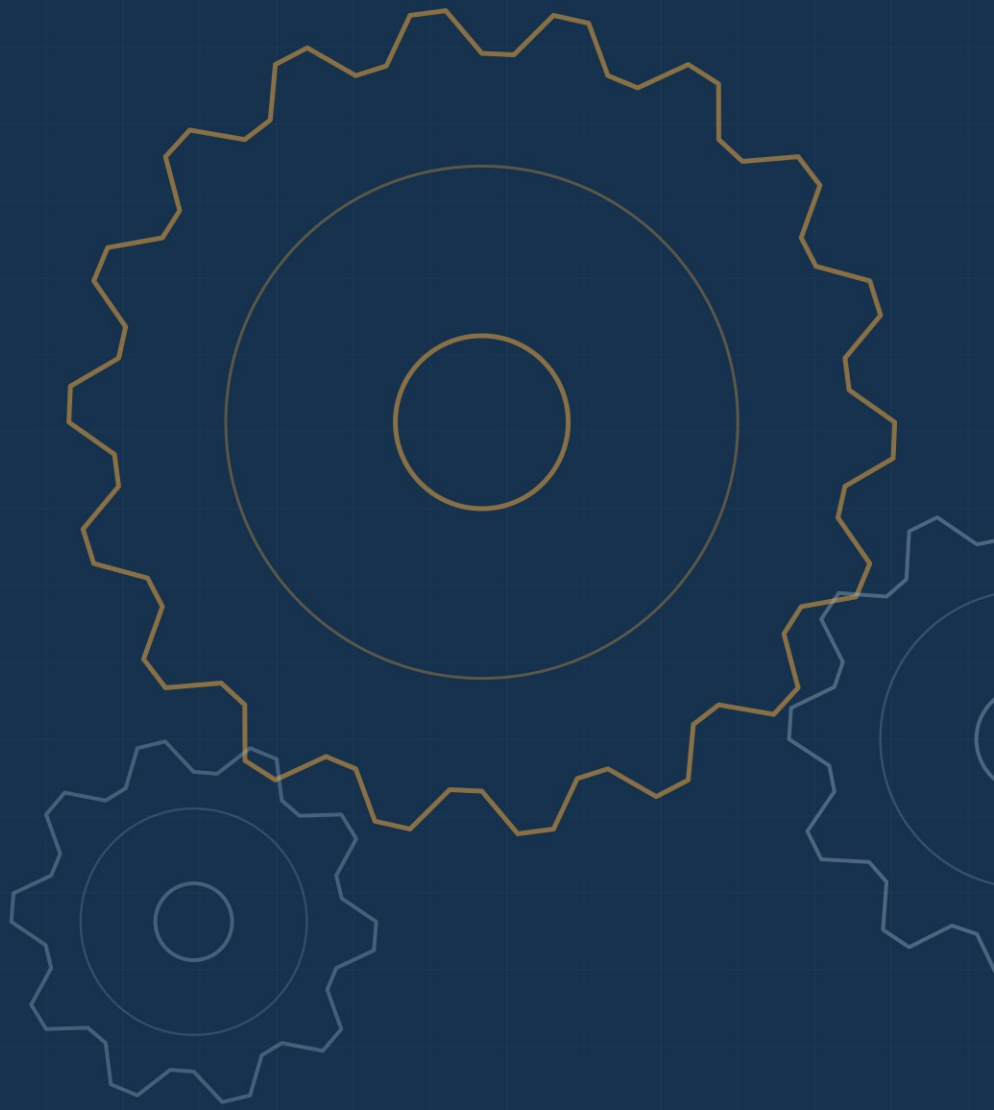
BASICS OF MACHINE OPERATION

Block 3 · Lecture 5 · 20 Jan 2027

Condition Monitoring Techniques; Reliability Fundamentals

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Course plan

L1 Block 1 · 2 Dec 2026

Introduction to machine operation · Machines as technical means

L2 Block 1 · 2 Dec 2026

Systems approach · Maintenance organisation and strategies

L3 Block 2 · 9 Dec 2026

Modern maintenance · Availability, durability and wear

L4 Block 2 · 9 Dec 2026

Tribology and lubrication · Fundamentals of diagnostics

L5 Block 3 · 20 Jan 2027

Condition monitoring · Reliability fundamentals

L6 Block 3 · 20 Jan 2027

System reliability · Failure analysis and improvement

L7 Block 4 · 27 Jan 2027

Life data and maintenance logistics · Industry 4.0 · Review

Today: L5. Condition Monitoring Techniques; Reliability Fundamentals

RECAP

Before Christmas – six points

- Friction and wear are properties of the **tribological system**.
- **Stribeck curve**: boundary → mixed → full-film lubrication.
- Wear mechanisms: **adhesion, abrasion, fatigue, tribochemical**.
- Lubrication: the **five rights** + contamination control.
- Diagnostics: diagnosing, monitoring, genesis, prognosis; **m ≥ n**.
- **Trends and thresholds**; false alarms vs missed faults.

TODAY

Plan for today

PART A

Condition monitoring techniques

1. Overview and the CM programme
2. Vibration analysis
3. Thermography and oil analysis
4. Ultrasound, electrical tests, NDT, IIoT

PART B

Reliability fundamentals

5. Basic reliability measures
6. The exponential distribution
7. The Weibull distribution
8. Bearing life and reliability data

01

Condition monitoring – an overview

Methods, their strengths, and how to build a monitoring programme



Main condition monitoring methods

Vibration analysis
unbalance, misalignment, looseness, bearing and gear faults – the most universal method for rotating machines.

Thermography
contact-free temperature images – electrical connections, bearings, insulation, heat exchangers.

Oil and wear debris analysis
condition of the lubricant, contamination and wear metals – gearboxes, engines, hydraulics.

Ultrasound and acoustic emission
leaks, early bearing damage, lubrication, electrical discharges, crack growth.

Electrical tests (MCSA, insulation)
motor current signature, insulation resistance – motors, drives and cables.

Non-destructive testing (NDT)
visual, penetrant, magnetic, ultrasonic, eddy current – cracks and wall thickness.

Which method detects which fault?

Fault	Vibration	Thermography	Oil analysis	Ultrasound	Electrical
Unbalance	●				
Misalignment	●	○			
Bearing damage	●	○	○	●	
Gear wear	●		●	○	
Lubrication problem	○	●	●	●	
Electrical fault (motor, connection)	○	●		○	●
Leaks (air, steam, gas)		○		●	
Cracks	○			○	

● very suitable ○ suitable in some cases · Cracks: NDT methods (penetrant, magnetic, ultrasonic)

Building a condition monitoring programme (ISO 17359)

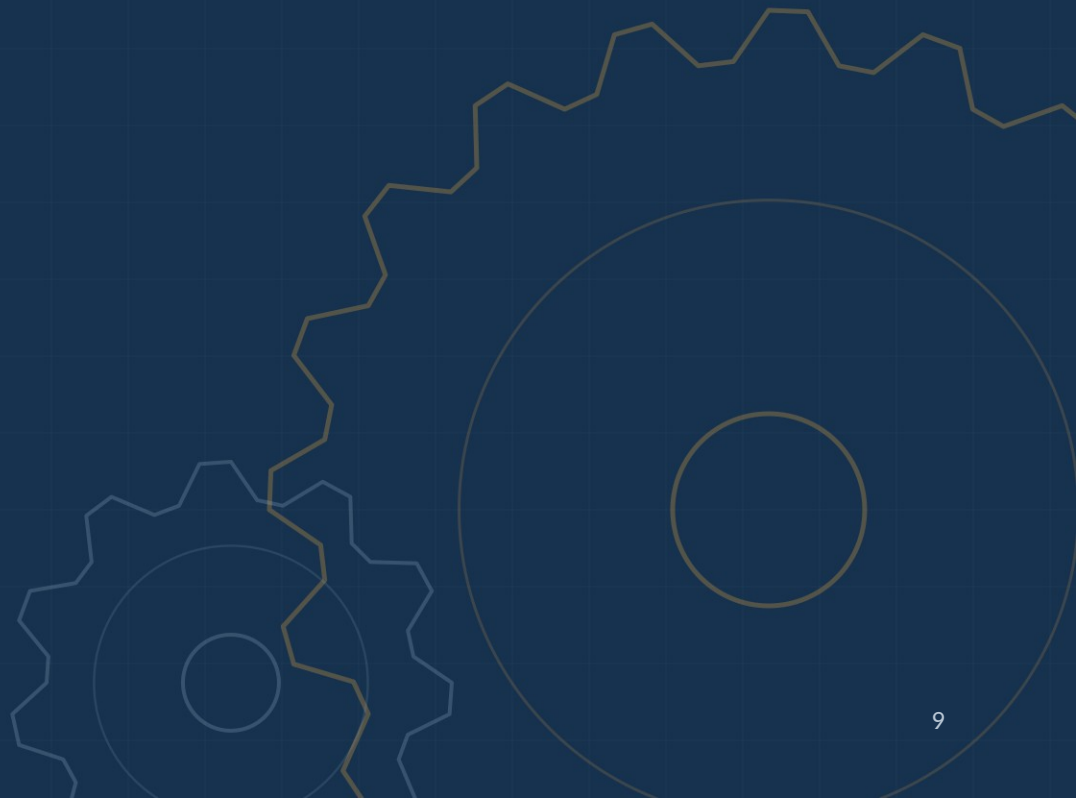
1. **Equipment audit – list of machines**
2. **Criticality analysis**
3. **Failure modes and symptoms (FMEA)**
4. **Select methods and measurement points**
5. **Set intervals and alarm limits**
6. **Measure, analyse, trend**
7. **Diagnosis and prognosis**
8. **Maintenance action and feedback**

A continuous cycle: results feed back into step 1. Start with the most critical machines.

02

Vibration analysis

Quantities, spectra, fault frequencies and severity



Vibration quantities

Displacement [µm]

how far the surface moves. Best for **low frequencies** (below ~10 Hz) and shaft movement in plain bearings.

Velocity [mm/s]

how fast it moves. Best measure of **overall severity** of machine vibration (10 Hz – 1 kHz). Used in ISO 20816.

Acceleration [m/s² or g]

how fast the velocity changes. Best for **high frequencies** – early bearing and gear damage (impacts).

We usually describe vibration by its **RMS** (root mean square) value – a measure of energy – and sometimes by **peak** values. For a pure sine wave: peak = √2 × RMS ≈ 1.414 × RMS.

EXAMPLE

Converting vibration quantities

For a sine wave at frequency f:

$$v = 2\pi f \cdot x$$

$$a = 2\pi f \cdot v$$

$$peak = \sqrt{2} \cdot RMS$$

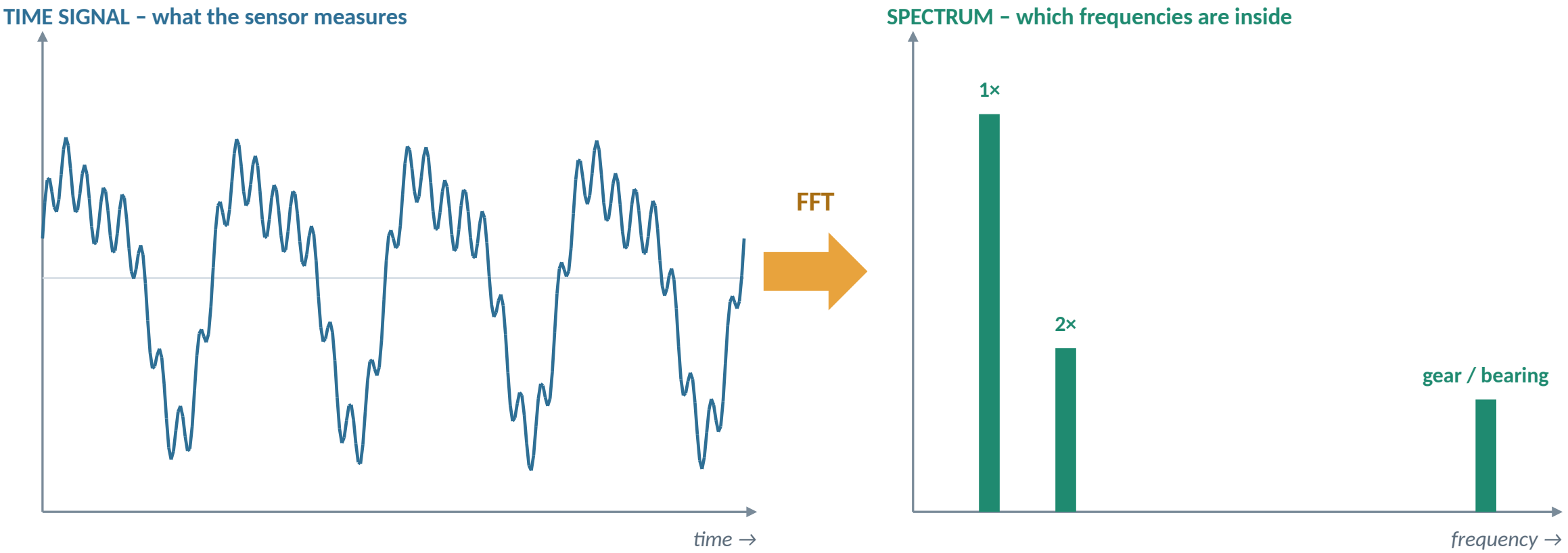
Higher frequency → acceleration grows, displacement falls. That is why we choose the quantity by the frequency range.

DATA: a fan at 3000 rpm → f = 50 Hz; measured v RMS = 4.5 mm/s

Peak velocity	$4.5 \times 1.414 \approx 6.36\ \mathrm{mm/s}$
2π f	$2 \times 3.14 \times 50 \approx 314\ 1/\mathrm{s}$
Peak displacement	$6.36\ /\ 314 \approx 0.020\ \mathrm{mm} = 20\ \mu\mathrm{m}$
Peak acceleration	$314 \times 6.36 \approx 2\,000\ \mathrm{mm/s^2} = 2.0\ \mathrm{m/s^2}$

$2.0\ m/s^2 \approx 0.2\ g$ ($g = 9.81\ m/s^2$)

Time signal and spectrum (FFT)



The spectrum separates the sources – each fault has its typical frequency.

Typical fault frequencies

Fault	Typical frequency	Other features
Unbalance	1× running speed	radial, sinusoidal, phase stable
Misalignment	1× and 2× (sometimes 3×)	high axial vibration
Mechanical looseness	many harmonics 1×, 2×, 3×…	sometimes ½× sub-harmonics
Gear faults	gear mesh frequency = z × f (+ sidebands)	z – number of teeth
Rolling bearing faults	BPFO, BPFI, BSF, FTF (non-integer)	early stage: high-frequency impacts (envelope)
Electrical (motor)	2 × line frequency (100 Hz in EU)	disappears when power is switched off

f – shaft rotational frequency [Hz] = rpm / 60. Running speed is often written as "1×".

EXAMPLE

Bearing defect frequencies

$$BPFO = (n/2) \cdot f \cdot (1 - d/D \cdot \cos \varphi)$$

$$BPFI = (n/2) \cdot f \cdot (1 + d/D \cdot \cos \varphi)$$

BPFO – ball pass frequency, outer race; **BPFI** – inner race

n – number of rolling elements, **f** – shaft frequency [Hz]

d – ball diameter, **D** – pitch diameter, **φ** – contact angle

Also: **BSF** (ball spin), **FTF** (cage) – from catalogues or software.

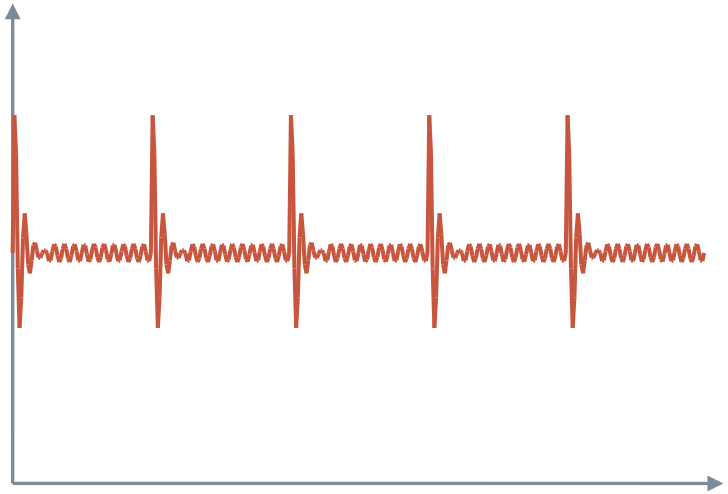
DATA: n = 9, d = 7.9 mm, D = 39 mm, φ = 0°, 1500 rpm → f = 25 Hz

d/D	$7.9 / 39 \approx 0.20$
BPFO	$4.5 \times 25 \times 0.80 \approx 90$ Hz
BPFI	$4.5 \times 25 \times 1.20 \approx 135$ Hz

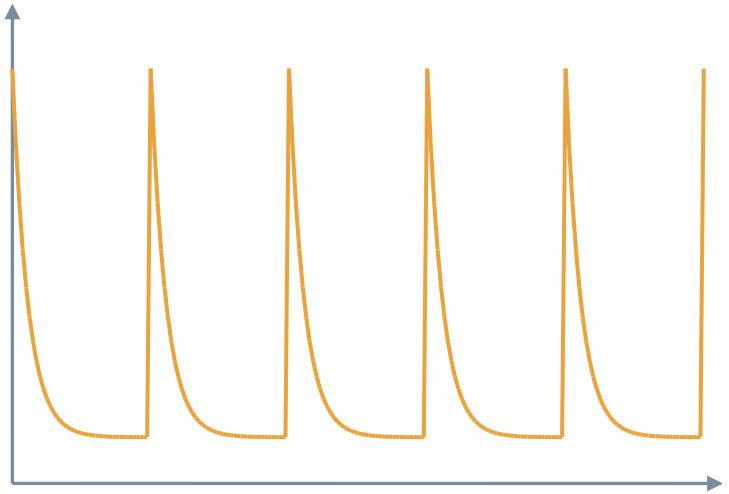
A peak at **90 Hz** (3.6 × running speed) in the envelope spectrum → **outer race damage**.

Envelope analysis – finding early bearing damage

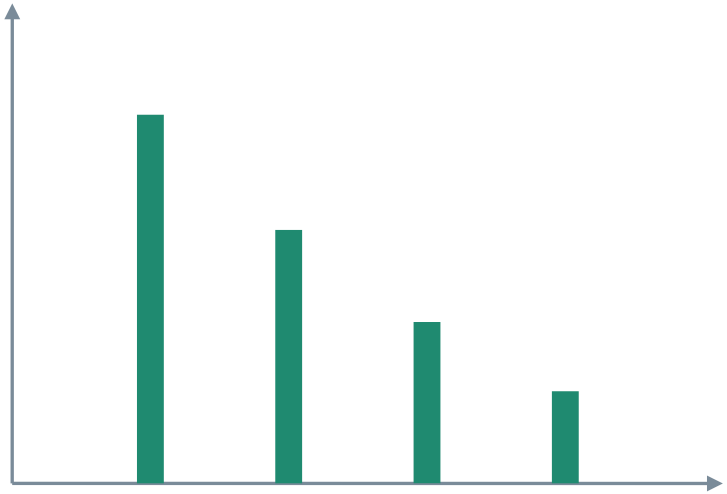
1. Impacts excite high frequencies



2. Filter + demodulate → envelope



3. Spectrum of the envelope



BPFO and harmonics

Each time a ball hits a small defect, it makes a short **impact** that “rings” the structure at high frequency. The envelope method extracts the **repetition rate** of these impacts – the bearing defect frequency – **long before** the overall vibration level increases.

How severe is it? – ISO 20816 zones

		*v RMS [mm/s]**
A	newly commissioned machines	**≤ 1.4**
B	acceptable for unrestricted long-term operation	**1.4 – 2.8**
C	unsatisfactory – limited operation; plan action	**2.8 – 4.5**
D	vibration severe enough to cause damage	**> 4.5**

Measured on bearing housings, broadband velocity RMS.

Limits depend on machine **group, power and foundation**.

Also watch the **trend** – a jump inside zone B is a warning.

** example: medium-size machines on a rigid foundation – check the standard for your machine group*

Sensors and measurement points

Accelerometers

piezoelectric (wide frequency range, industry standard) or MEMS (cheap, used in wireless sensors).

Mounting

stud mounting – best; adhesive – good; magnet – practical for routes; hand-held probe – only low frequencies.

Where?

on bearing housings, as close as possible to the load zone – not on thin covers or guards.

Directions

horizontal (H), vertical (V) and axial (A) – axial is important for misalignment.

Always measure in the **same point, same direction and same operating conditions** – otherwise trends are meaningless. Mark the points on the machine.

GROUP EXERCISE

ACTIVITY

Read the spectrum: what is the fault?

Work in pairs for **6 minutes**. A motor-driven machine runs at **1 500 rpm (25 Hz)**. Name the most likely fault for each finding:

1. High peak at 25 Hz, mainly radial; phase is stable
2. Peaks at 25 Hz and 50 Hz; high axial vibration
3. Many harmonics: 25, 50, 75, 100, 125 Hz…
4. Envelope spectrum shows peaks at 90, 180, 270 Hz
5. Peak at 100 Hz that disappears immediately when power is switched off
6. Peak at 25 × 31 = 775 Hz with sidebands ±25 Hz (gear with 31 teeth)

GROUP EXERCISE

ANSWERS

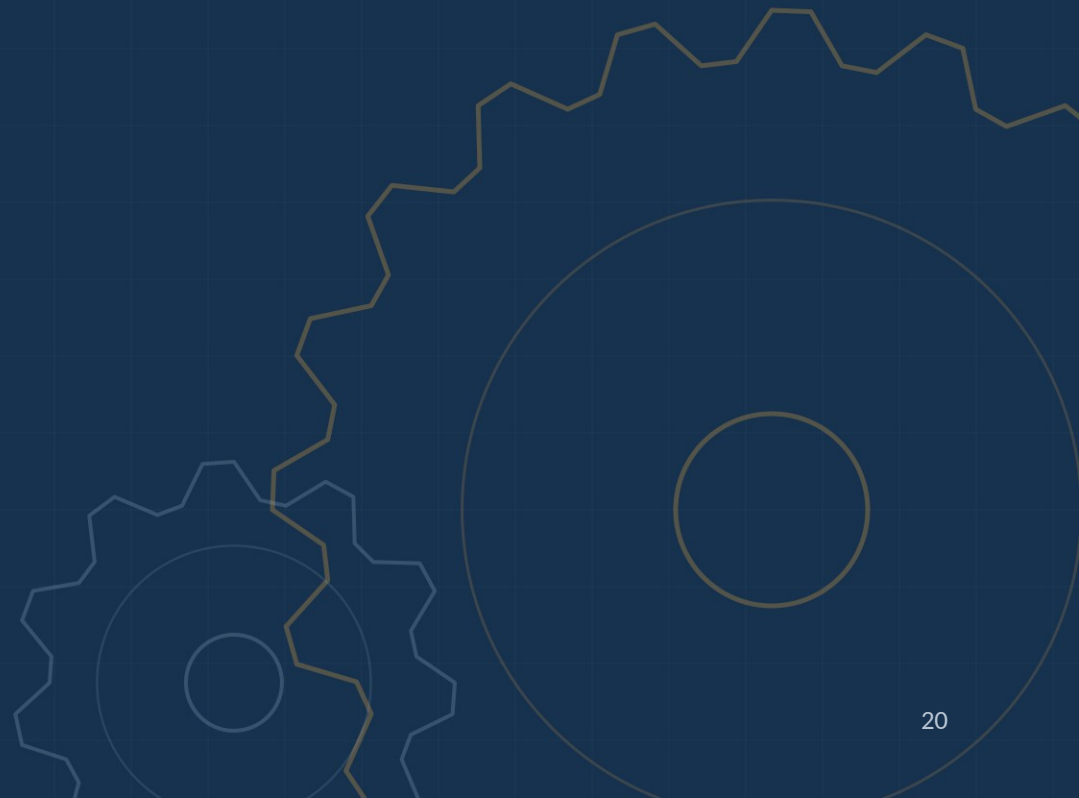
Read the spectrum – solution

Finding	Most likely fault	Next step
1. 25 Hz radial, stable phase	unbalance	balancing on site
2. 25 + 50 Hz, high axial	misalignment	laser shaft alignment
3. many harmonics of 25 Hz	mechanical looseness	check bolts, foundation, fits
4. envelope 90, 180, 270 Hz	bearing outer race damage (BPFO)	plan bearing replacement; trend weekly
5. 100 Hz, disappears without power	electrical cause (2 × line frequency)	electrical tests: air gap, windings, supply
6. 775 Hz with ±25 Hz sidebands	gear wear / damage on the 25 Hz shaft	oil analysis, inspection of the gear

03

Thermography and oil analysis

Seeing heat – and reading the “blood test” of a machine



Infrared thermography – principles

Every object above absolute zero emits **infrared radiation**. An infrared camera converts it into a temperature image – **without contact** and **during operation**. Guidelines: ISO 18434-1.

Applications

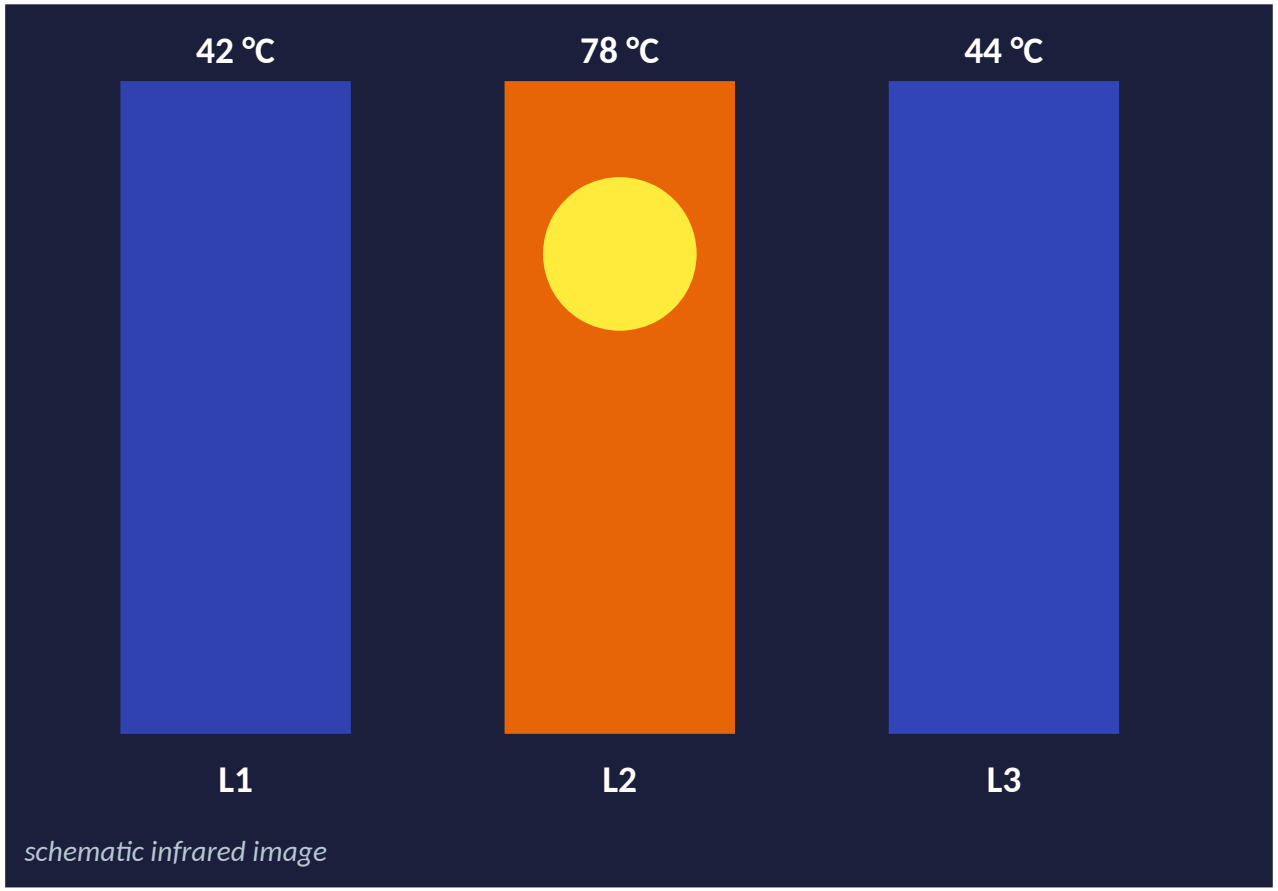
electrical connections and switchgear, motors, bearings, couplings (misalignment), steam traps, refractory linings, insulation, heat exchangers.

Watch out

emissivity – shiny metal surfaces reflect heat and give wrong readings; **reflections**, distance, wind, sun; electrical inspections need **sufficient load** (ideally > 40% of rated).

EXAMPLE

Example: a three-phase connection



Three phases with **the same load**. Phase L2 is about **35 °C hotter** than the others.

Most likely: a **loose or corroded connection** – high contact resistance → heat ($P = I^2R$).

Action: plan re-tightening/cleaning at the next shutdown; if ΔT keeps growing – act sooner.

Compare **similar components under similar load** – the ΔT tells more than the absolute value.

Oil analysis – the “blood test” of a machine

Oil condition

viscosity, oxidation, acid number (TAN), additive depletion – is the oil still good?

Contamination

particle count (ISO 4406), water content, silicon (dust), coolant – is the oil clean?

Wear

wear metals (spectrometry), ferrous density / PQ index, ferrography – is the machine wearing?

One sample answers three questions: change the oil? improve filtration or sealing? inspect the machine?

Where do the particles come from?

Element	Typical source	What it may indicate
Iron (Fe)	gears, shafts, rolling bearings, cylinders	general wear of steel parts
Copper (Cu), Tin (Sn), Lead (Pb)	bronze bushings, bearing cages, plain bearings	wear of bushings or plain bearings
Chromium (Cr)	piston rings, bearing steels	ring or bearing wear
Aluminium (Al)	pistons, housings, pumps	wear or rubbing of alloy parts
Silicon (Si)	dust, sand	dirt entry – check air filters and seals
Sodium (Na), Potassium (K)	coolant (glycol)	coolant leak into oil

Trends matter more than single values – compare with previous samples from the same machine.

EXAMPLE

Reading an ISO 4406 cleanliness code

19 / 17 / 14

19 code for particles ≥ 4 µm per mL

17 code for particles ≥ 6 µm per mL

14 code for particles ≥ 14 µm per mL

Each number is a **range code**. One step up = about **twice as many** particles.

DATA: hydraulic system, target 16/14/11, measured 19/17/14

Difference	3 code steps
Factor	$2 \times 2 \times 2 \approx 8\times$

The oil is about **8 times dirtier** than the target. Hard particles cause **abrasive wear** in pumps and valves.

Action: check filters and breathers, use offline filtration, find the source.

Good oil sampling practice

Same point

a permanent sampling valve in a live zone – after the pump, before the filter

Running machine

at normal temperature, or within 30 min after stop – particles are suspended

Clean bottle

certified clean, flushed, closed immediately

Never from the drain

the bottom of the tank collects sludge and water – not representative

Label it

machine, point, date, operating hours, oil hours, oil type

Regular interval

e.g. every 250–500 h for critical machines – trends need regular data

04

Ultrasound, electrical tests, NDT and IIoT

More tools in the box – and how sensors go online



Airborne ultrasound and acoustic emission

Ultrasound (above ~20 kHz) is not audible – an instrument converts it into sound and a dB value. It is directional, so we can find the exact source even in a noisy plant.

Compressed air and gas leaks

turbulent flow through a leak produces ultrasound – fast leak surveys.

Bearing condition and lubrication

friction level rises when grease is missing; drops when greased correctly – “grease by ultrasound”.

Electrical discharges

arcing, tracking and corona in switchgear – safe detection from a distance.

Acoustic emission (AE)

stress waves from growing cracks – pressure vessels, structures, slow-speed bearings.

EXAMPLE

What does a compressed air leak cost?

DATA (illustrative)

- an ultrasound survey finds **20 leaks**
- together they need **8 kW** of compressor power
- operation: **6 000 h** per year
- electricity: **0.15 €/kWh**
- repair: **2 technician days** + parts ≈ **1 000 €**

Energy per year	$8 \times 6\,000 = 48\,000$ kWh
Cost per year	$48\,000 \times 0.15 = 7\,200$ €
Payback	$1\,000 / 7\,200 \approx 0.14$ year ≈ 7 weeks

Leaks are invisible and silent in a noisy plant – but they cost real money and energy. Condition monitoring is not only about failures – it also saves **energy**.

Electrical condition monitoring of motors

Motor current signature analysis (MCSA)

spectrum of the supply current: broken rotor bars (sidebands around line frequency), eccentricity, load problems – measured in the cabinet.

Insulation resistance

megohmmeter test of windings and cables; polarisation index – moisture and ageing of insulation.

Power quality

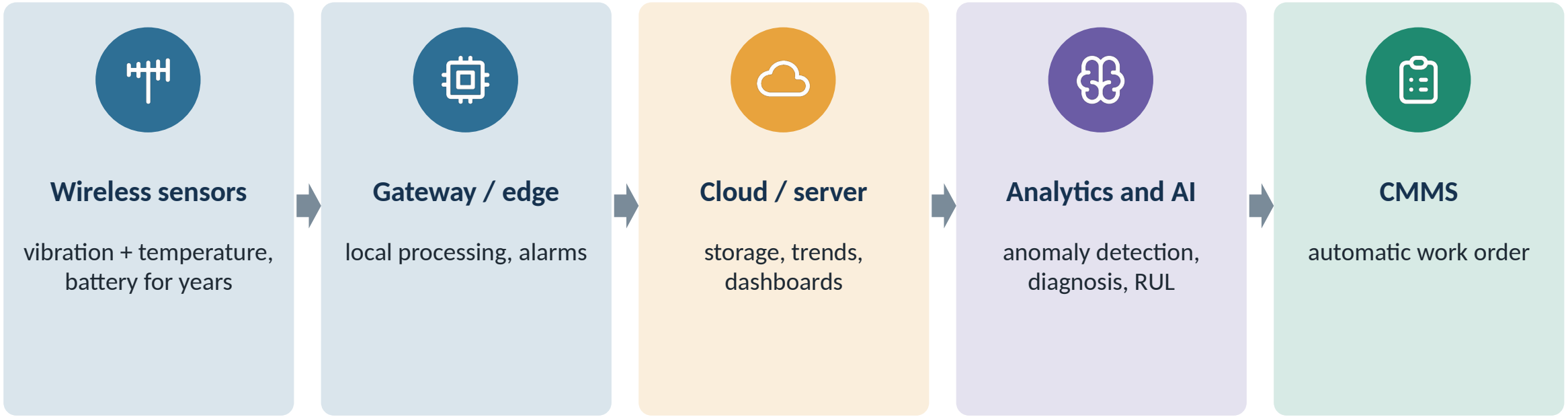
voltage unbalance, harmonics, inverter effects – causes of overheating and bearing currents.

Non-destructive testing (NDT) – overview

Method	Principle	Typical use
VT – visual testing	eye, magnifier, endoscope, camera	first and cheapest check; inside engines and turbines
PT – penetrant testing	coloured liquid enters surface cracks	surface cracks in any non-porous material
MT – magnetic particle testing	magnetic field leaks at cracks; particles show them	surface and near-surface cracks in steel
UT – ultrasonic testing	sound waves reflect from flaws and back walls	internal flaws, welds, wall thickness (corrosion)
ET – eddy current testing	induced currents change near flaws	tubes of heat exchangers, aircraft structures
RT – radiographic testing	X-rays or gamma rays through the part	welds, castings – needs radiation safety

NDT personnel are certified (e.g. ISO 9712). NDT is often required by law for pressure equipment and lifting devices.

Online monitoring and the Industrial Internet of Things



Cheaper sensors make **continuous monitoring** possible also for “standard” machines. Challenges: **alarm fatigue** (too many alarms), **cybersecurity**, battery and network management – and people who can act on the data.

CASE STUDY

Case study: catching a fan bearing in time

Month 0	Wireless sensor installed on a critical exhaust fan. Baseline: 1.8 mm/s, envelope quiet.
Month 7	Envelope spectrum shows BPFO peaks; overall level still 2.0 mm/s (zone B). Warning sent.
Month 8	Envelope rising, grease added – short improvement only. Bearing ordered, replacement planned.
Month 9	Bearing replaced during a planned 4-hour stop. Outer race shows spalling.

Without monitoring: sudden failure, fan housing damaged, production stopped for 2 days, emergency costs.

With monitoring: 4-hour planned stop, one bearing.

The P-F interval here was about **2 months** – plenty of time to plan.

QUIZ

Quiz 1 – condition monitoring

1 **Which vibration quantity is best for early bearing damage (high frequencies)?**

A) displacement | B) velocity | C) acceleration | D) temperature

2 **A high peak at 1× running speed, mainly radial, usually means...**

A) unbalance | B) misalignment | C) looseness | D) bearing damage

3 **Thermography of electrical connections needs...**

A) a stopped machine | B) sufficient electrical load | C) oil samples | D) an endoscope

4 **ISO 4406 code 19/17/14 vs target 16/14/11 means the oil is about...**

A) the same | B) 2× dirtier | C) 8× dirtier | D) 100× cleaner

5 **Silicon (Si) in an oil sample usually indicates...**

A) bronze wear | B) dirt / dust entry | C) coolant leak | D) new oil

ANSWERS

Quiz 1 – answers

1 Which vibration quantity is best for early bearing damage (high frequencies)?

- A) displacement
- B) velocity
- **C) acceleration**
- D) temperature

2 A high peak at 1× running speed, mainly radial, usually means...

- **A) unbalance**
- B) misalignment
- C) looseness
- D) bearing damage

3 Thermography of electrical connections needs...

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- **C) 8× dirtier**
- D) 100× cleaner

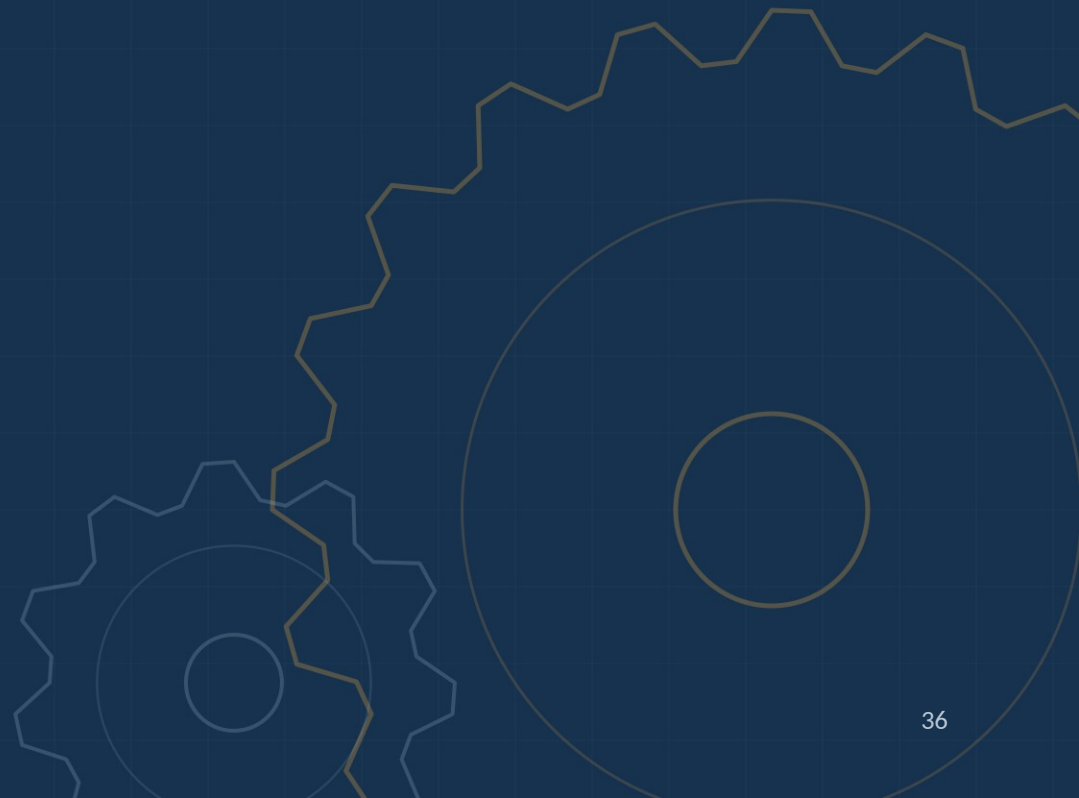
5 Silicon (Si) in an oil sample usually indicates...

- A) bronze wear
- **B) dirt / dust entry**
- C) coolant leak
- D) new oil

05

Basic reliability measures

Reliability function, failure rate and mean time to failure



What is reliability?

Reliability (IEC 60050-192): the ability to perform as required, **without failure**, for a **given time interval**, under **given conditions**.

Three elements are always needed: a clear definition of **failure** (what does “as required” mean?), a **time** (or cycles, km), and **conditions** (load, environment, maintenance).

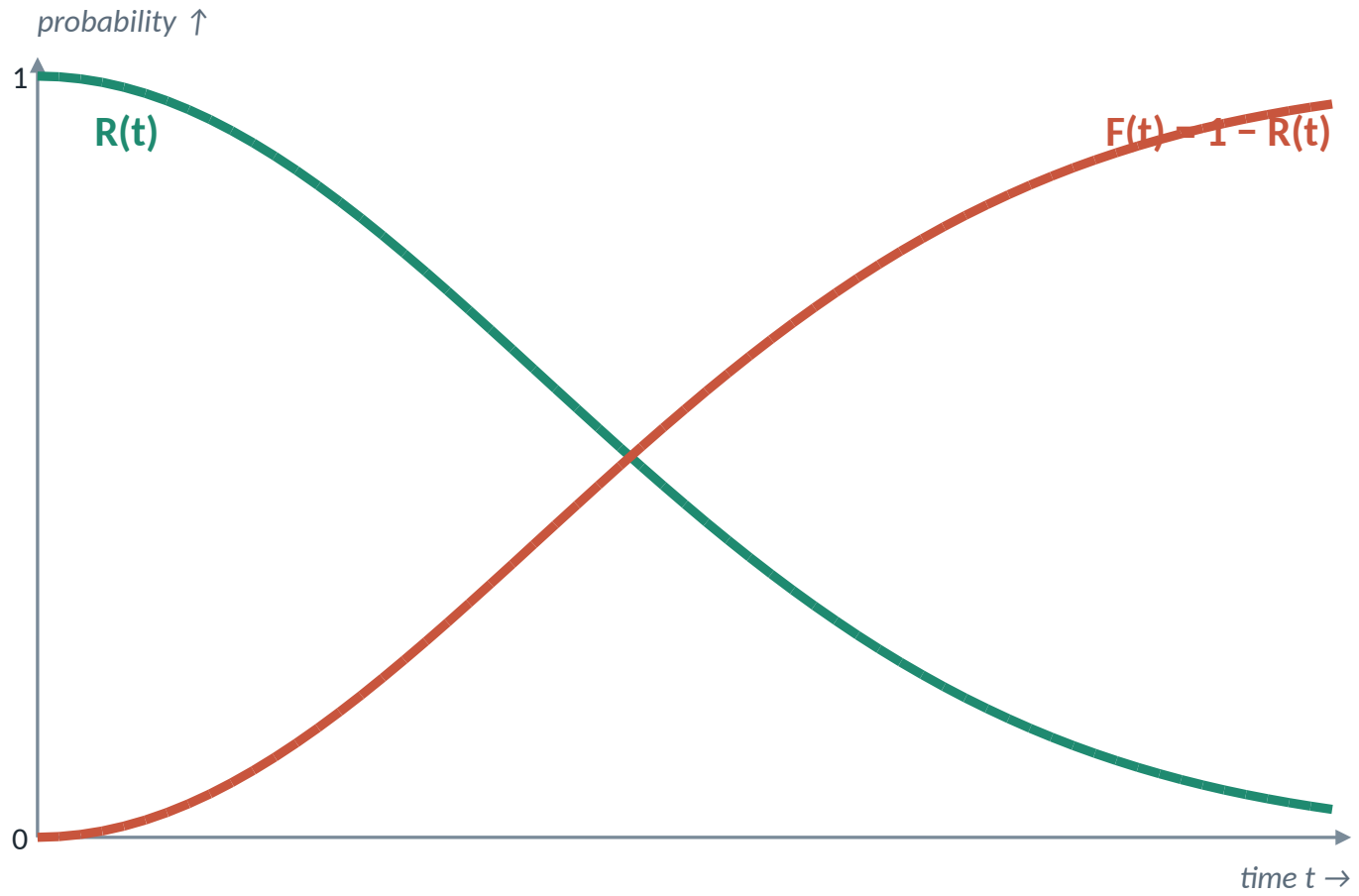
Reliability is a **probability** – it describes a **population** of objects, not one specific machine. “The reliability of this pump for one year is 0.9” means: about 90% of such pumps work one year without failure.



KEY TAKEAWAY

Reliability = **probability** of no failure, for a **time**, under **conditions**.

Reliability function R(t) and unreliability F(t)



R(t) – probability that an object works **without failure** until time t. Starts at 1 and falls.

F(t) – probability that it **fails before** t (unreliability, cumulative distribution). Starts at 0 and rises.

Always: **R(t) + F(t) = 1**.

EXAMPLE

Estimating R(t) from test data

100 identical pumps start at t = 0. We count how many still work: **$R(t) \approx N_s(t) / N_0$**, **$F(t) = 1 - R(t)$**

Time t [h]	Working $N_s(t)$	Failed in interval	R(t)	F(t)
0	100	–	1.00	0.00
1 000	92	8	0.92	0.08
2 000	81	11	0.81	0.19
3 000	65	16	0.65	0.35
4 000	46	19	0.46	0.54

Question: what is the probability that a pump survives **2 000 h**? → **R = 0.81**. And fails before 4 000 h? → **F = 0.54**.

Failure density f(t) and failure rate λ(t)

$$f(t) = dF(t) \,/\, dt$$

$$\lambda(t) = \frac{f(t)}{R(t)}$$

f(t) – failure density: how failures are distributed in time (for the whole population).

λ(t) – failure rate (hazard rate): the probability that an object that **has survived until t** fails in the next small time interval, per unit time.

λ(t) is the curve we know from the **bathtub** and from **Nowlan & Heap** patterns. Units: 1/h, or failures per hour.

Empirical estimate from the pump data, interval 2 000–3 000 h:

λ ≈ failures / (survivors at start × interval)

λ ≈ 16 / (81 × 1 000 h) ≈ **$2.0 \cdot 10^{-4}$ 1/h**

Mean time to failure – MTTF and MTBF

$$MTTF = \int_0^\infty R(t)\,dt$$

= the area under the R(t) curve

MTTF – **Mean Time To Failure** – for **non-repairable** objects – average life until the (first) failure

MTBF – **Mean Time Between Failures** – for **repairable** objects – average operating time between failures

MTTR – **Mean Time To Restore** – average time to restore after a failure – used with MTBF for availability

MTTF is an **average** – it does **not** mean that most objects survive until MTTF.

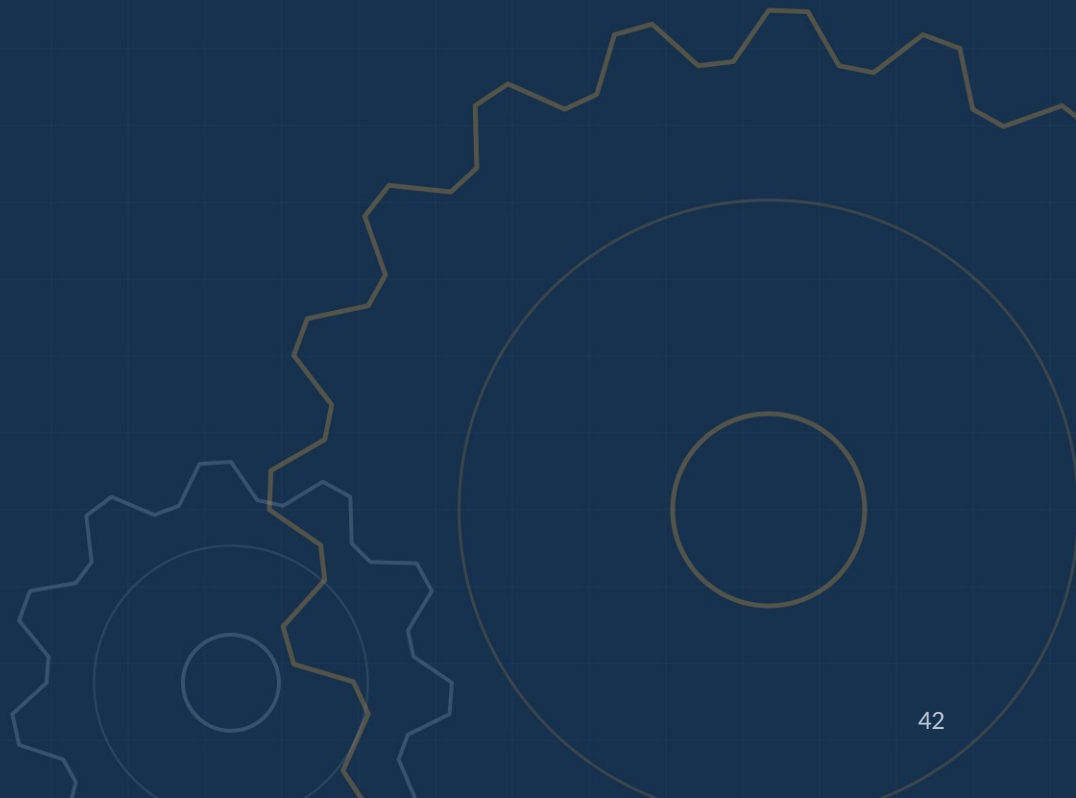
For random failures (exponential distribution), only about **37%** of objects survive until MTTF!

MTBF of 50 000 h does **not** mean that one machine works 50 000 h – it is a population average.

06

The exponential distribution

Constant failure rate – random failures



The exponential distribution – constant failure rate

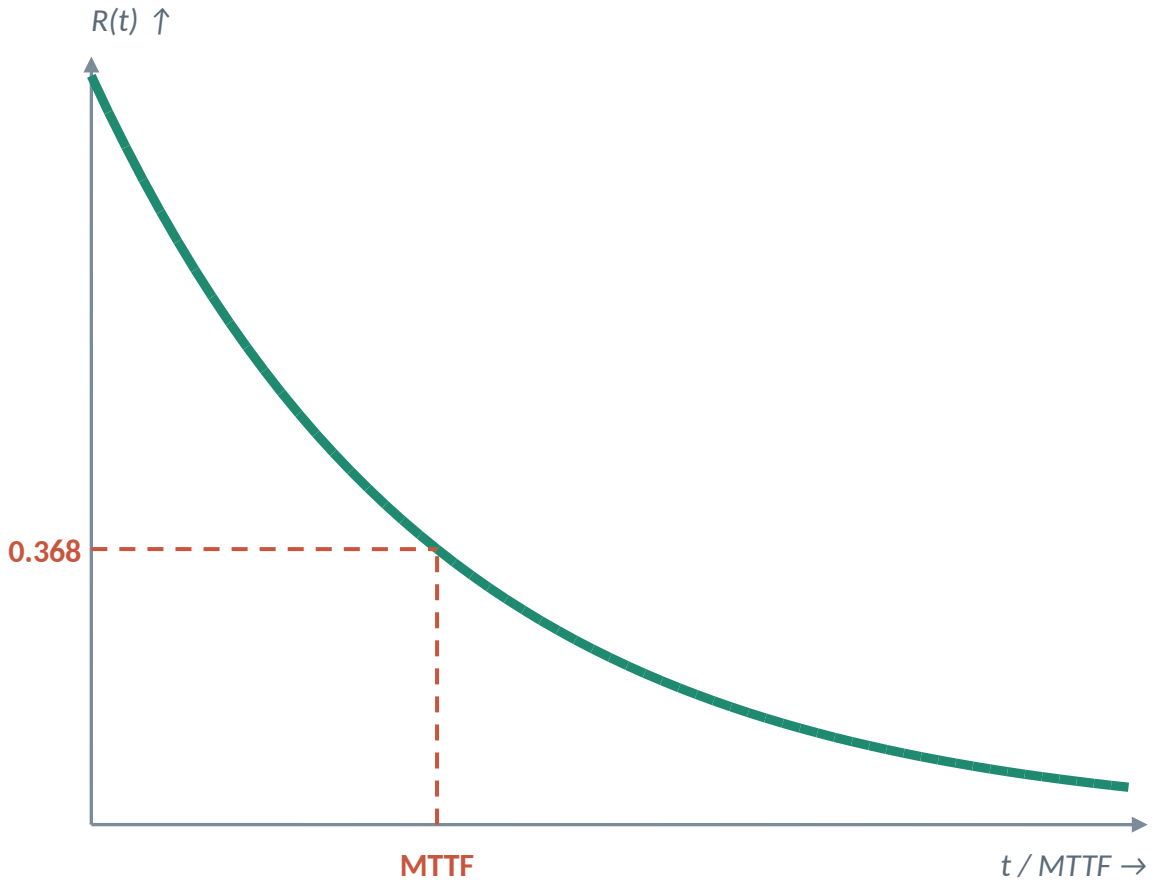
$$\lambda(t) = \lambda = const$$

$$R(t) = e^{-\lambda t}$$

$$MTTF = 1 / \lambda$$

Used for **random** failures – e.g. electronics, many complex systems in their useful life, the flat part of the bathtub.

Simple – one parameter λ.



WORKED EXAMPLE

EXAMPLE

Exponential distribution – a control unit

DATA: a control unit with $\lambda = 2 \cdot 10^{-4}$ 1/h (random failures)

MTTF	$1 / (2 \cdot 10^{-4}) = 5\,000$ h
R(1 000 h)	$e^{-0.2} \approx 0.819$
R(5 000 h) = R(MTTF)	$e^{-1} \approx 0.368$
Time for R = 0.9	$t = -\ln(0.9) / \lambda \approx 527$ h

After 1 000 h about **82%** still work.

Only **37%** reach the MTTF – many people expect 50%!

If we need 90% reliability, the unit can only be trusted for about **530 h**.

The memoryless property – and what it means for maintenance

Memoryless

with constant λ, an object that has worked 1 000 h has the **same** probability of failure in the next hour as a new one. Age does not matter – it is “as good as new”.

Consequence

preventive replacement by age makes no sense – a new part is not better than the old one. Better: condition monitoring, redundancy, fast repair (lower MTTR).

Electronic components are often specified in **FIT** – failures per 10^9 device-hours (e.g. 100 FIT = 10^{-7} 1/h).

EXERCISE

ACTIVITY

Your turn: electric motors in a plant

DATA

- a plant has **50 identical motors**
- failure rate $\lambda = 1 \cdot 10^{-5}$ **1/h** (constant)
- motors run **continuously, 8 760 h per year**



Calculate (5 minutes):

1. MTTF of one motor
2. R(1 year) for one motor
3. expected number of failed motors per year
4. how many spare motors would you keep?

EXERCISE

ANSWERS

Electric motors – solution

MTTF	$1 / 10^{-5} = 100\,000$ h ≈ 11.4 years
R(8 760 h)	$e^{-0.0876} \approx 0.916$
F(1 year)	$1 - 0.916 \approx 0.084$
Failures per year	$50 \times 0.084 \approx 4.2$ motors

Although MTTF is 11 years, we expect about **4 failures every year** in the plant.

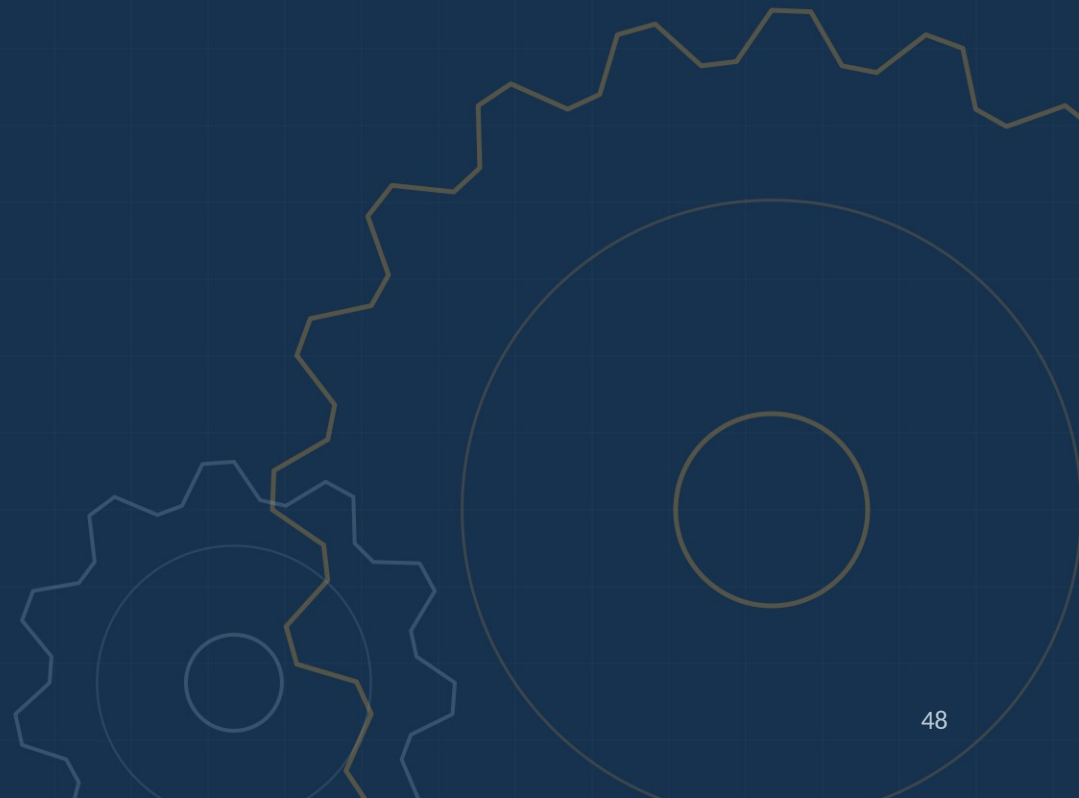
Spare parts: 1–2 motors in stock (plus fast delivery), depending on criticality and delivery time.

This is how reliability data supports **spare parts planning** (Lecture 7).

07

The Weibull distribution

One model for early failures, random failures and wear-out



The Weibull distribution – two parameters

$$R(t) = exp[-(t/\eta)^{\beta}]$$

$$\lambda(t) = (\beta/\eta) \cdot (t/\eta)^{\beta-1}$$

β

shape parameter

tells us the failure pattern

η

scale parameter – characteristic life

at t = η, 63.2% of objects have failed

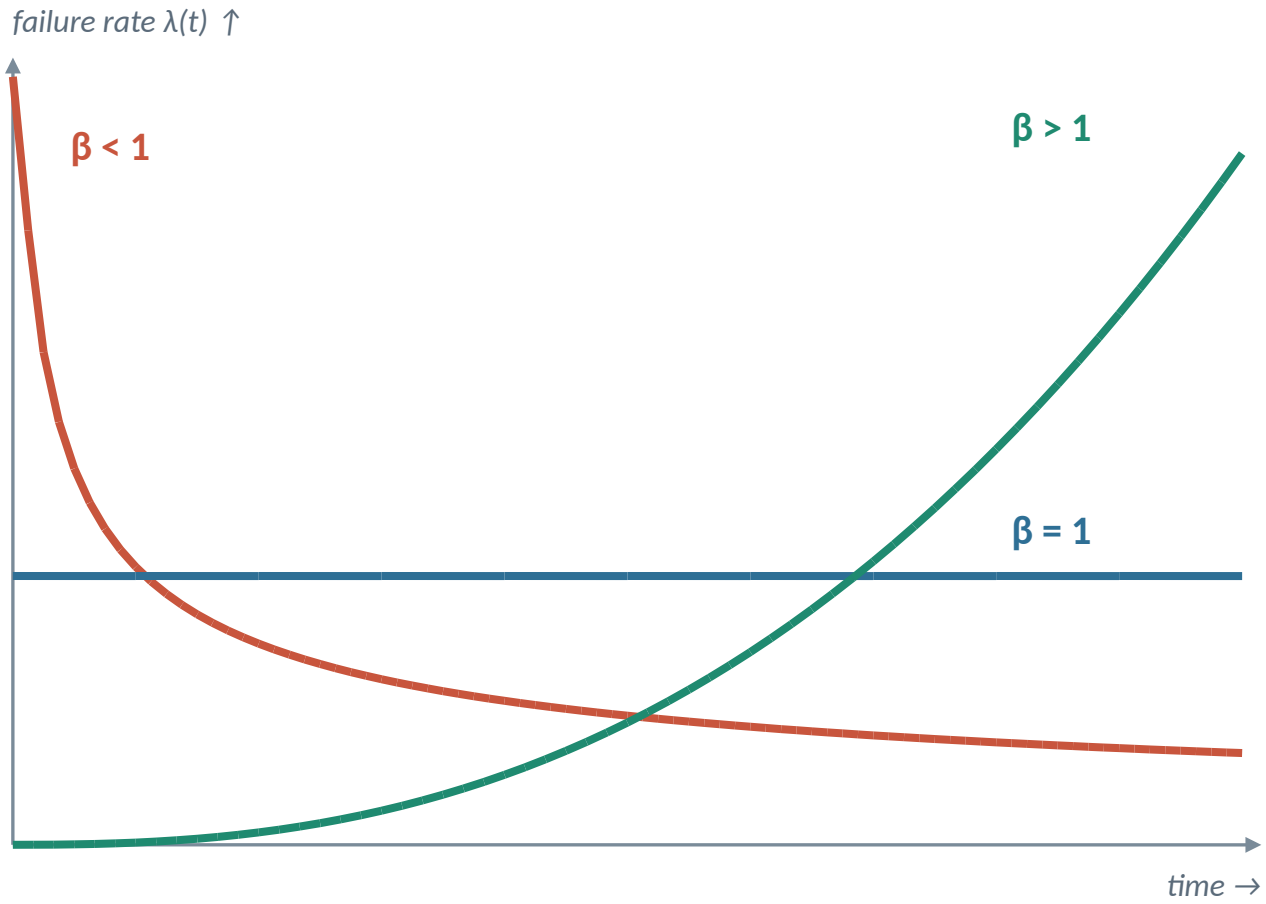
Developed by **Waloddi Weibull** (Sweden, 1951).

The most used distribution in mechanical reliability – bearings, gears, fatigue.

With **β = 1** it becomes the exponential distribution.

Parameters are estimated from failure data – e.g. on a Weibull plot.

What does β tell us?



β < 1

decreasing failure rate – **early failures** (infant mortality): assembly errors, defects

β = 1

constant failure rate – **random failures** (exponential)

β > 1

increasing failure rate – **wear-out**: fatigue (β ≈ 1.5–3), wear, corrosion; β ≈ 3.5 looks like a normal distribution

β and the maintenance strategy

Weibull β	Failure pattern	Preventive replacement by age?	Better approach
β < 1	early failures	NO – makes it worse (new parts fail early)	quality of assembly, burn-in, root cause analysis
β = 1	random	NO – no benefit	condition monitoring, redundancy, fast repair
β > 1	wear-out	YES – if the failure is expensive and the part is cheap	age-based replacement or condition monitoring

This is the mathematical background of **RCM** and of the Nowlan & Heap result from Lecture 3.

WORKED EXAMPLE

EXAMPLE

Weibull example: a gearbox bearing

DATA: β = 1.5, η = 20 000 h

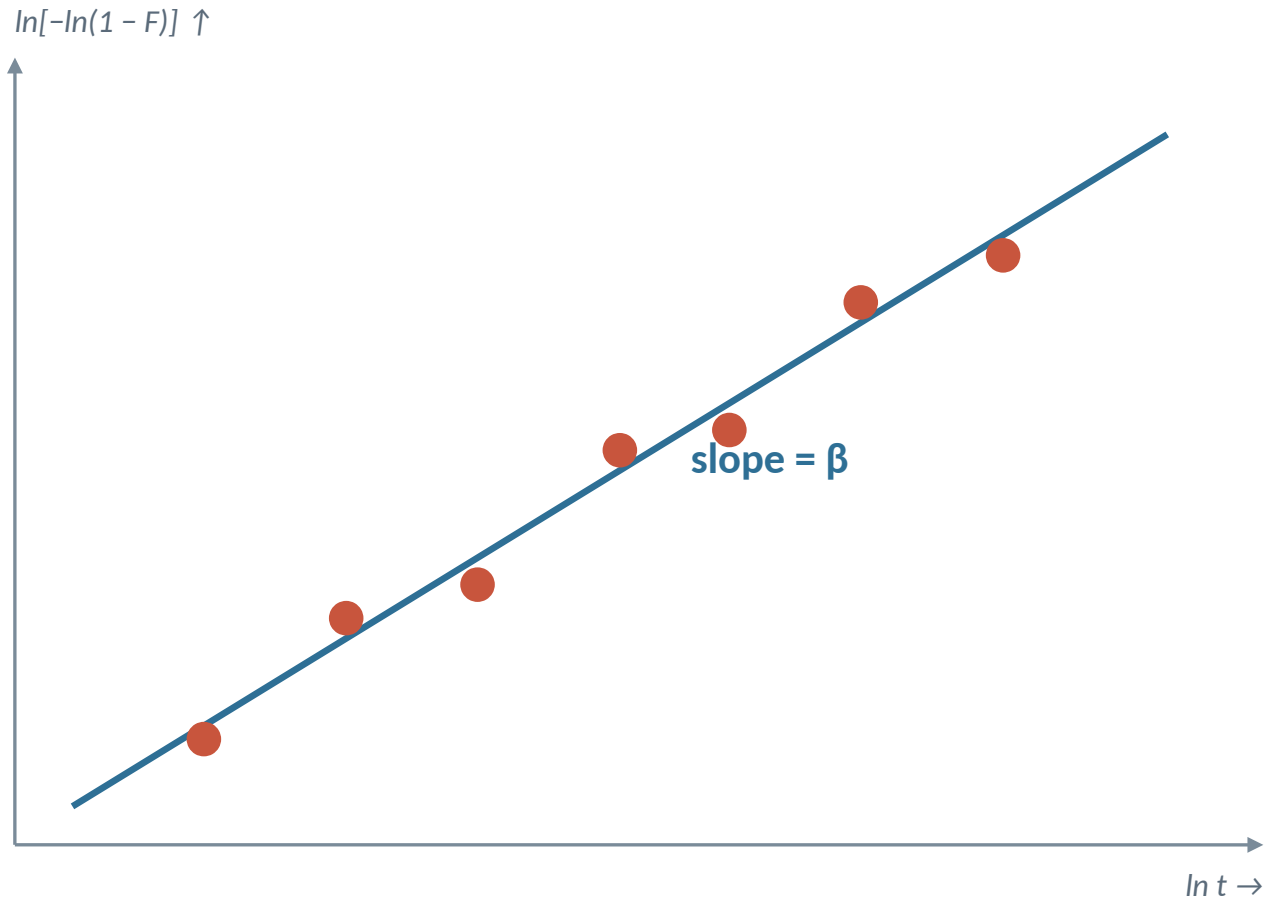
R(5 000 h)	$\exp[-(0.25)^{1.5}] = e^{-0.125} \approx 0.88$
R(20 000 h) = R(η)	$e^{-1} \approx 0.368$
B10 life (R = 0.9)	$t = \eta \cdot (-\ln 0.9)^{1/\beta}$
B10	$20\,000 \cdot (0.105)^{0.667} \approx 4\,460\ \text{h}$

B10 life – the time by which **10%** of the population has failed.

Characteristic life is 20 000 h, but 10% fail already before ~4 500 h.

β > 1 → wear-out → planned replacement or condition monitoring is justified.

The Weibull plot – estimating β and η from data



Sort failure times $t_1 \le t_2 \le \ldots \le t_n$.

Estimate F for each with **median ranks**: $F \approx (i - 0.3) / (n + 0.4)$.

Plot $\ln[-\ln(1 - F)]$ against $\ln t$ – Weibull data form a **straight line**.

Slope = β; η is the time where F = 63.2%.

Today: software or a spreadsheet does this in seconds.

EXERCISE

ACTIVITY

Your turn: Weibull wear-out of a seal

DATA – mechanical seals of a pump type

- shape **β = 3**
- characteristic life **η = 10 000 h**
- hint: (0.105)^(1/3) ≈ 0.472



Calculate (5 minutes):

1. R(5 000 h)
2. the B10 life
3. What failure pattern is it? Is age-based replacement reasonable?

EXERCISE

ANSWERS

Weibull seal – solution

R(5 000 h)	$\exp[-(0.5)^3] = e^{-0.125} \approx 0.88$
B10	$10\,000 \cdot (0.105)^{1/3} \approx 4\,720$ h

β = 3 → clear wear-out. Failures are concentrated around 7 000–12 000 h.

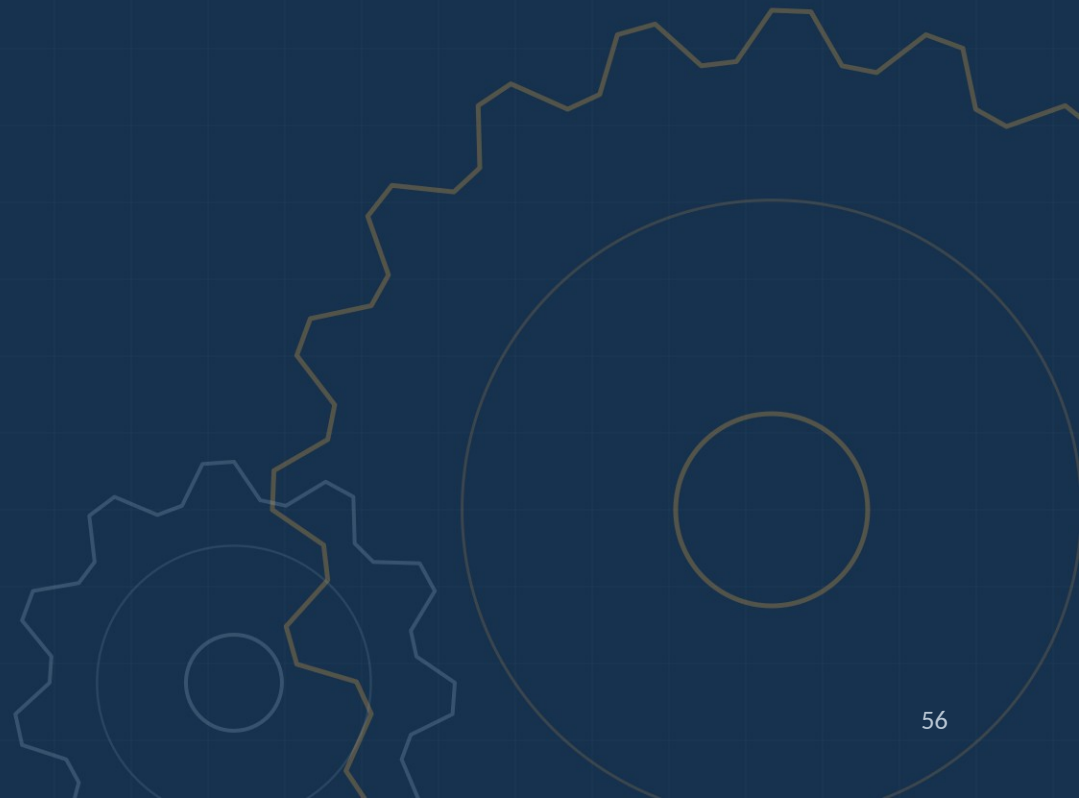
Age-based replacement at about **4 000–5 000 h** would prevent most failures – if a failure is expensive (leak, downtime).

Alternative: monitor leakage and replace on condition.

08

Bearing life and reliability data

From catalogue formulas to real failure data



EXAMPLE

Rolling bearing life L10 (ISO 281)

$$L_{10} = (C / P)^p \quad [10^6\ rev]$$

$$L_{10}h = 10^6 / (60 \cdot n) \cdot L_{10} \quad [h]$$

C – dynamic load rating, **P** – equivalent load, **p** = 3 (ball), 10/3 (roller), **n** – speed [rpm]. L_{10} = life reached by **90%** of bearings.

DATA: bearing 6310, C ≈ 61.8 kN, P = 6 kN, n = 1 500 rpm

C / P	$61.8 / 6 \approx 10.3$
L_{10}	$10.3^3 \approx 1\,093 \cdot 10^6$ rev
$L_{10}h$	$10^6 / 90\,000 \cdot 1\,093 \approx 12\,100$ h

Load matters a lot: if the load doubles to 12 kN, the life falls **8 times** (2^3) to about 1 500 h. This is why **misalignment, unbalance and overload** destroy bearings – and why reliability, tribology and diagnostics are connected. Modern ISO 281 adds factors for lubrication and contamination (a_ISO).

Where do reliability data come from?

Own operating data

CMMS history, failure codes, operating hours – the most relevant source, if the data quality is good (ISO 14224).

Manufacturer data

catalogue ratings (e.g. bearing C, L10), MTBF claims – check the assumed conditions.

Industry databases

e.g. **OREDA** (oil and gas equipment), handbooks for electronic components (e.g. IEC 61709).

Tests

laboratory life tests and accelerated tests – more in Lecture 7.

Reliability data are always **conditional**: the same pump has different reliability in clean water and in slurry.

QUIZ

Quiz 2 – reliability fundamentals

1 **R(t) = 0.85 means...**

A) 85% fail before t | B) 85% work without failure until t | C) MTTF = 0.85 t | D) the failure rate is 0.85

2 **For the exponential distribution, the share of objects surviving to MTTF is about...**

A) 50% | B) 37% | C) 63% | D) 90%

3 **$\lambda = 10^{-4}$ 1/h. MTTF equals...**

A) 100 h | B) 1 000 h | C) 10 000 h | D) 100 000 h

4 **Weibull $\beta > 1$ means...**

A) early failures | B) random failures | C) wear-out | D) no failures

5 **If the load on a ball bearing doubles, L10 life becomes...**

A) 2× shorter | B) 4× shorter | C) 8× shorter | D) unchanged

ANSWERS

Quiz 2 – answers

1 **R(t) = 0.85 means...**

A) 85% fail before t	**B) 85% work without failure until t**	C) MTTF = 0.85 t	D) the failure rate is 0.85

2 **For the exponential distribution, the share of objects surviving to MTTF is about...**

A) 50%	**B) 37%**	C) 63%	D) 90%

3 **$\lambda = 10^{-4}$ 1/h. MTTF equals...**

A) 100 h	B) 1 000 h	**C) 10 000 h**	D) 100 000 h

4 **Weibull $\beta > 1$ means...**

A) early failures	B) random failures	**C) wear-out**	D) no failures

5 **If the load on a ball bearing doubles, L10 life becomes...**

A) 2× shorter	B) 4× shorter	**C) 8× shorter**	D) unchanged

SUMMARY

Key takeaways from today

Vibration: **velocity** for severity, **acceleration/envelope** for early bearing damage; the **spectrum** identifies the fault.

Thermography: compare **ΔT** of similar parts under load; oil analysis: **condition, contamination, wear**.

Ultrasound finds leaks and lubrication problems – and saves **energy**.

R(t) + F(t) = 1; λ(t) is the failure rate; MTTF = area under R(t).

Exponential: **R = exp(−λt)**, MTTF = 1/λ, only 37% reach MTTF.

Weibull **β** tells the pattern: <1 early, =1 random, >1 wear-out.

REVIEW

Review questions



1. Compare displacement, velocity and acceleration as vibration quantities. When is each one used?
2. What are the typical spectrum features of unbalance, misalignment, looseness and bearing damage?
3. What can oil analysis tell us? Explain the ISO 4406 code.
4. Define reliability. Explain R(t), F(t), f(t) and λ(t).
5. For $\lambda = 2 \cdot 10^{-4}$ 1/h calculate MTTF and R(1 000 h). Why do only 37% survive to MTTF?
6. Explain the Weibull parameters β and η. How does β influence the maintenance strategy?

Thank you for your attention

Next: after the break – Lecture 6 · System Reliability; Failure Analysis and Reliability Improvement

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