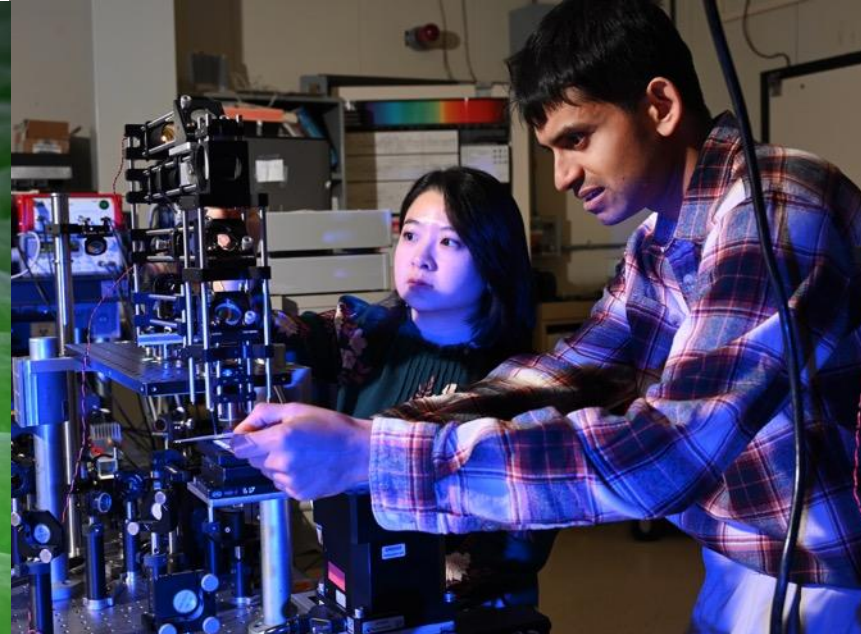




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An FMEA-Informed Reliability Framework for Infinitely Variable Transmissions in Tidal Energy Systems

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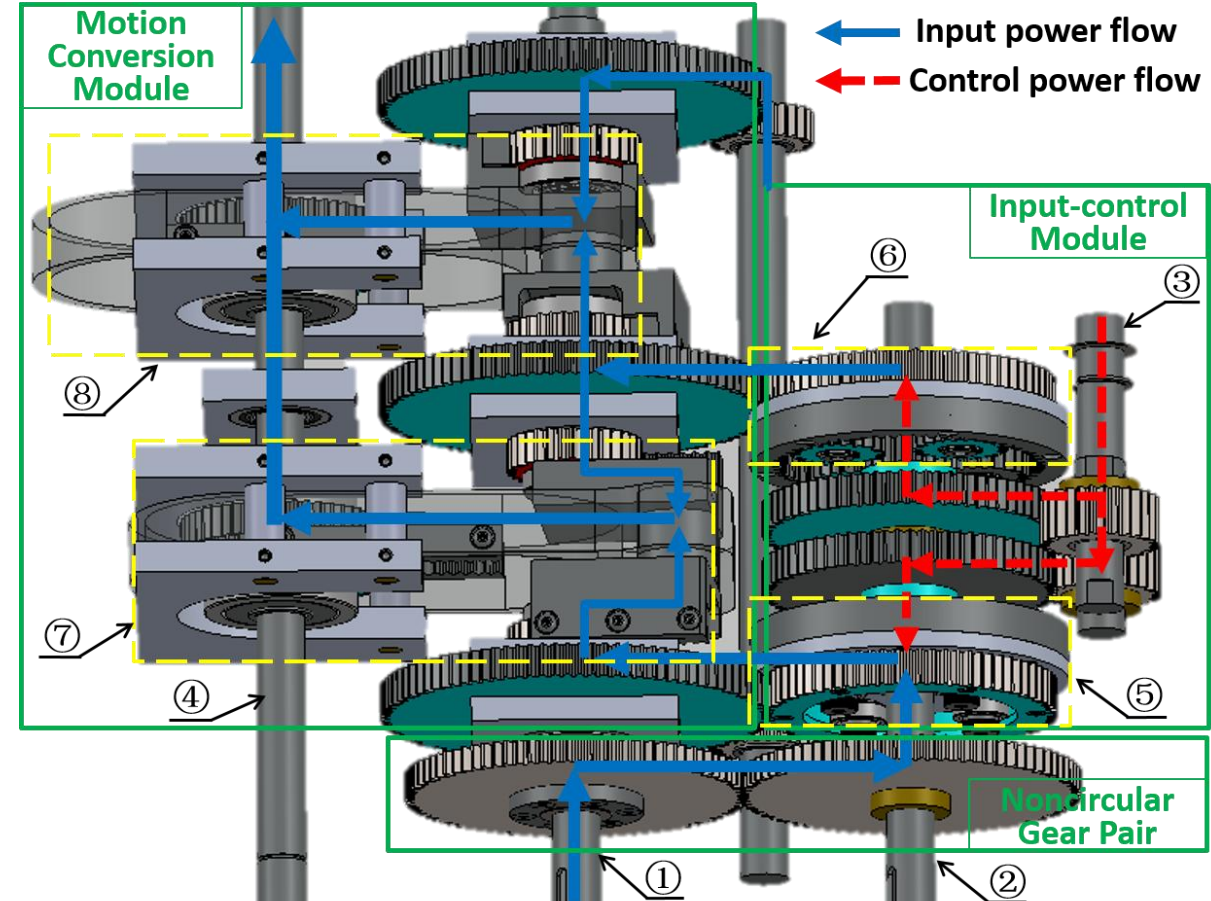
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Acknowledgement

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Research Objective and Tasks

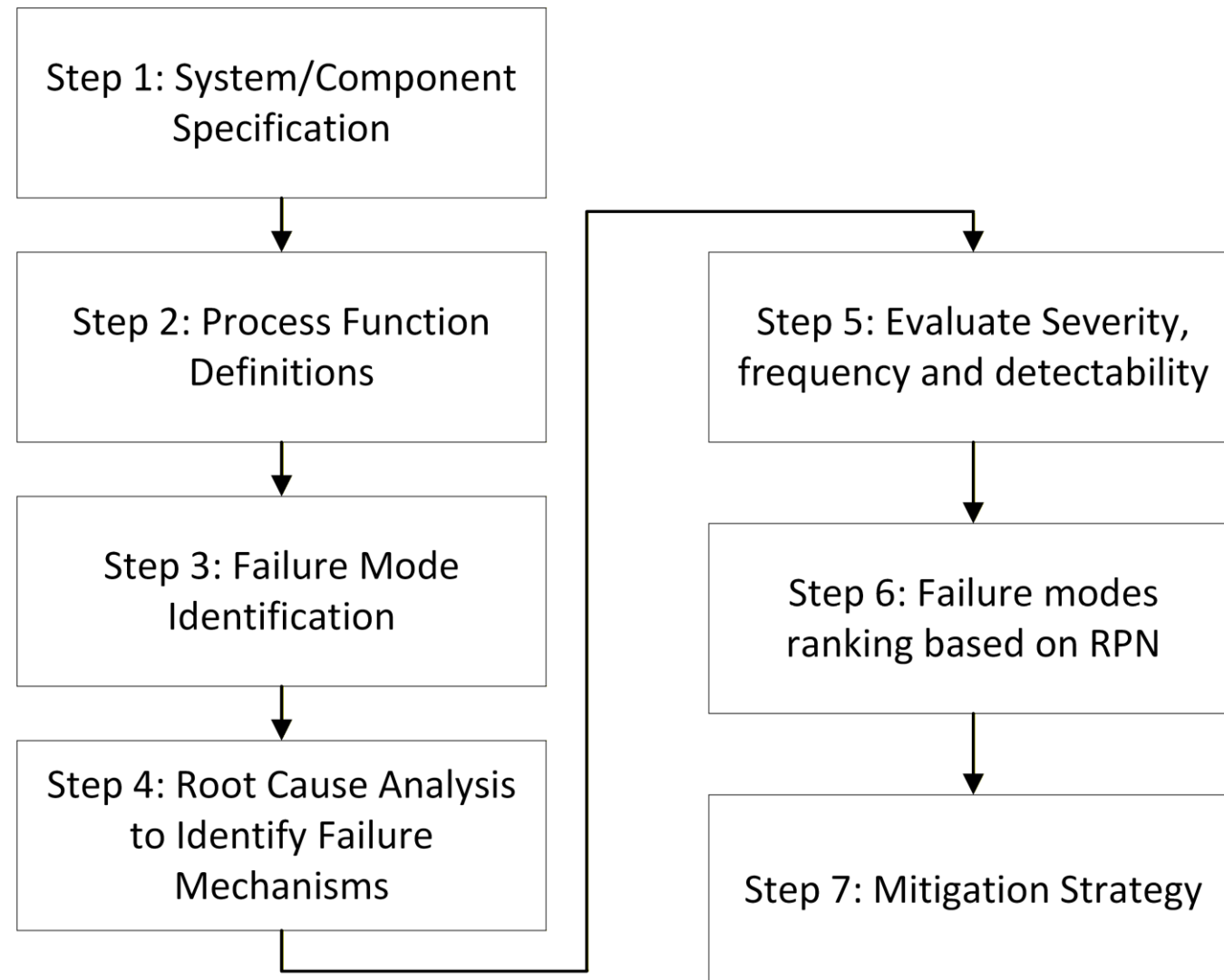
- **Objective:** Perform the following tasks to support New Technology Qualification (NTQ) process for infinitely variable transmission (IVT) design in tidal energy converter.
 - Task 1: Failure modes and effects analysis (FMEA) on the gear box
 - both the root bending fatigue in non-circular gear pair and planet gear sets were identified as the dominant failure mechanisms (WE336)
 - Task 2: Probabilistic Physics-of-Failure (PPOF) based reliability assessment-stress-strength analysis (WE206)



Task-1: Failure Mode and Effect Analysis-Driven Reliability and Reliability Assessment for IVT

- Methodological Steps developed for Failure Mode and Effect Analysis (FMEA)
- Different failure modes were identified and characterized for different gear types in IVT based on the publicly available gear failure database.
- As part of the FMEA, failure modes are ranked based on the Risk Priority Number (RPN).
- The most important failure modes is loss of torque transmission, mainly caused by root bending fatigue
- A reliability assessment equation is developed for the IVT gearbox
- Literature-based failure rate were obtained by relevant fields including wind turbine gears to support the reliability assessment
- Sensitivity study was performed to analyze the uncertain parameters

Failure Mode and Effect Analysis (FMEA)



FMEA-Step 1: Target system: IVT Gearbox in Tidal Current Energy Converter (TCEC)

Step 1: System/Component Specification

Step 2: Process Function Definitions

Step 3: Failure Mode Identification

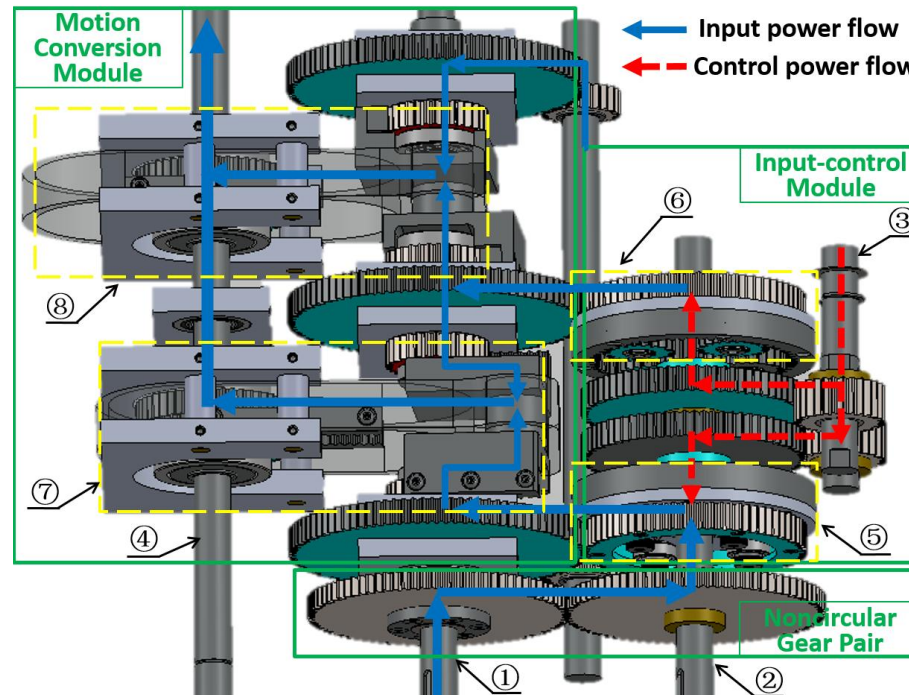
Step 4: Root Cause Analysis to Identify Failure Mechanisms

Step 5: Evaluate Severity, frequency and detectability

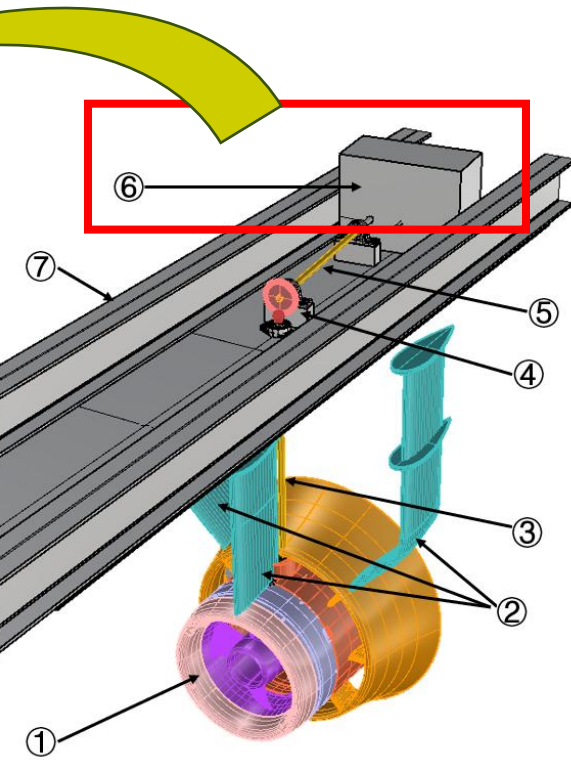
Step 6: Failure modes ranking based on RPN

Step 7: Mitigation Strategy

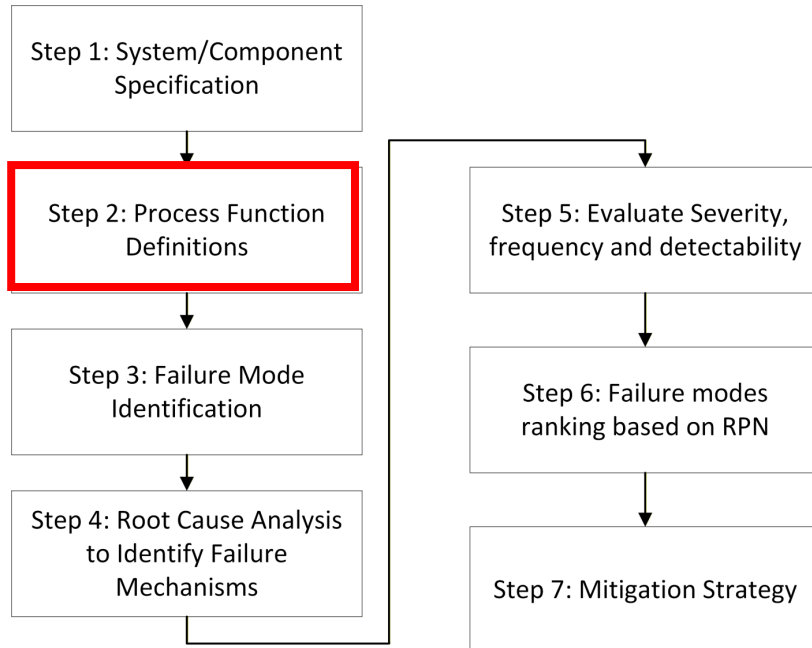
- A. Noncircular gear pair
- B. Planetary gear sets *2 (ICM)
- C. Rack–pinion sets (MCM)
- D. Output gears (MCM)
- E. Gearbox seal



- ①: Tidal turbine
- ②: Holding arms
- ③: Primary drive shaft
- ④: Bevel gear pair
- ⑤: Secondary drive shaft
- ⑥: IVT
- ⑦: Mounting platform

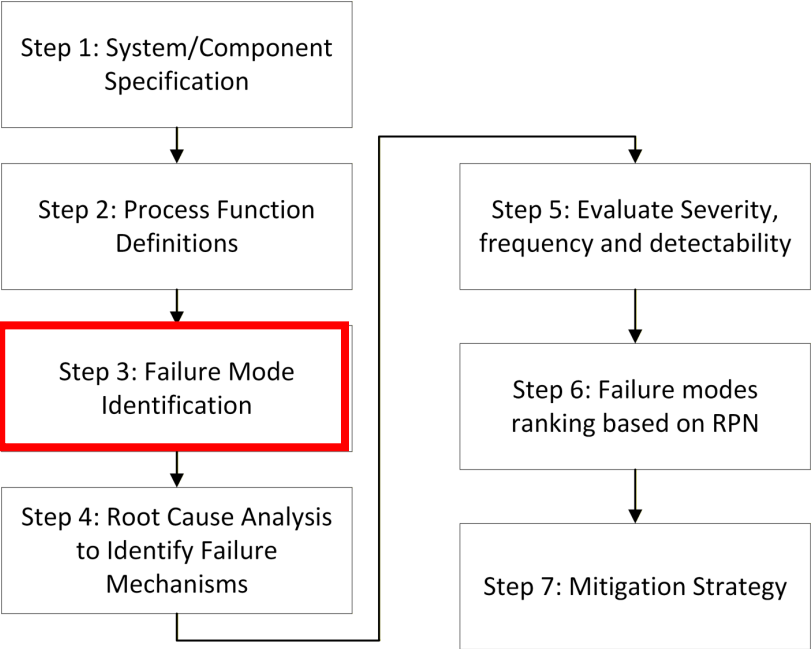


FMEA-Step 2: Process Function Definitions



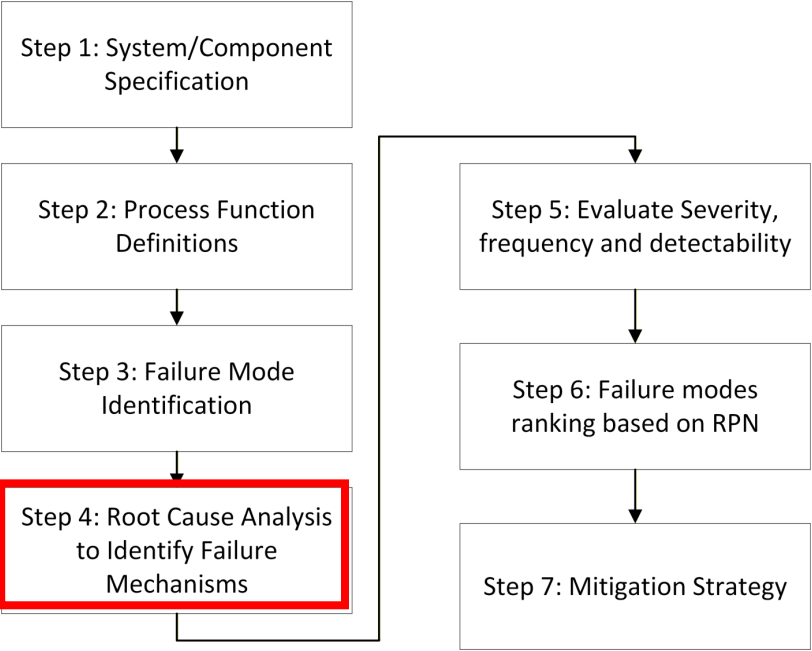
Gear/System Type	Process Functions
A. Noncircular gear pair	Transmit input torque and create modulated Speed
B. Planetary gear sets	Combine control speed & modulated speed
C. Rack–pinion sets	Convert translation to rotation
D. Output gears	Provide rotational outputs
E. Gearbox seal	Isolate sea water from equipment

FMEA-Step 3: Failure Modes Identification



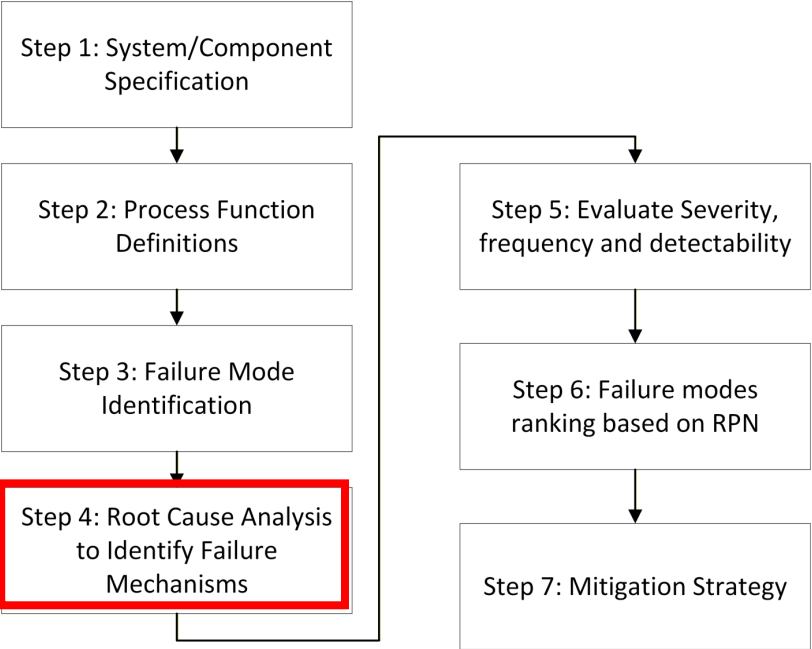
Gear/Syst em Type	Process Functions	Failure Mode
A. Noncircul ar gear pair	Transmit input torque and create modulated Speed	Loss of torque Transmission; Excessive vibration/noise; Loss of modulation Accuracy
B. Planetary gear sets	Combine control speed & modulated speed	Loss of combined speed Accuracy; Loss of torque Transmission; Excessive vibration/noise; Overheating; Locked rotation
C. Rack– pinion sets	Convert translation (yoke) to rotation	Excess backlash; Fail-to-run; Tooth chipping; Overheating; Corrosion-driven degradation
D. Output gears	Provide rotational outputs	Loss of output torque contribution; Excessive vibration/noise; Efficiency loss
E. Gearbox seal	Isolate sea water from equipment	Water ingress beyond limit

FMEA-Step 4: Root Case Analysis (Part 1)



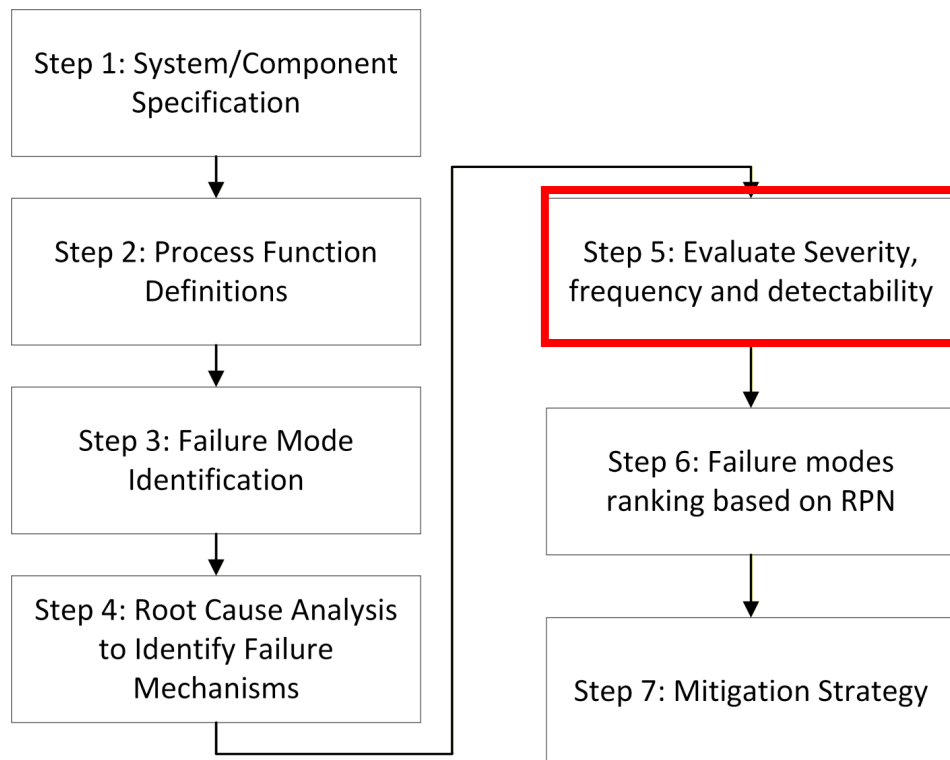
Category	Failure Mode	Failure Mechanism (Root Causes)
A.1	Loss of torque Transmission	Root bending fatigue
A.2	Excessive vibration/noise	Micro-pitting causing increased surface roughness and transmission error
A.3	Loss of modulation accuracy	Fretting wear at hub-shaft interface
B.1	Loss of combined speed accuracy	Sun gear tooth deflection under load
B.2	Loss of combined speed accuracy	Abrasive flank wear
B.3	Loss of torque Transmission	Excessive vibration/noise; Overheating; Locked rotation
B.4	Loss of torque Transmission	Ring gear rim/web cracking
B.5	Excessive vibration/noise	Subsurface fatigue leading to macro-pitting and debris formation
B.6	Excessive vibration/noise	Micropitting leading to macropitting progression
B.7	Overheating	Edge loading leading to localized heating
B.8	Overheating	Micropitting/scuffing increasing friction Coefficient
B.9	Locked rotation	Scuffing due to film collapse
B.10	Locked rotation	Debris-induced scuffing event

FMEA-Step 4: Root Case Analysis (Part 2)



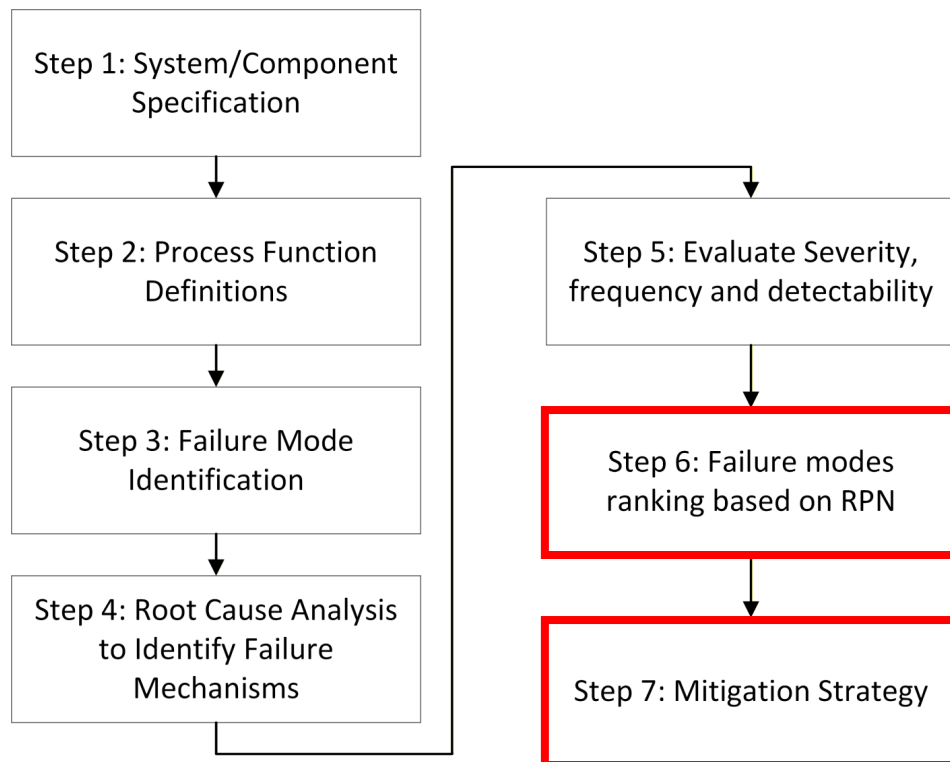
Fail ID	Failure Mode	Failure Mechanism (Root Causes)
C.1	Excess backlash	Abrasive wear of rack and pinion teeth
C.2	Fail-to-run	Debris wedging in engagement
C.3	Tooth chipping	Impact loading at reversal leading to stress Concentration
C.4	Overheating	Boundary lubrication loss
C.5	Corrosion-driven degradation	Corrosive wear
D.1	Loss of output torque contribution	Root bending fatigue of output gear Teeth
D.2	Excessive vibration/noise	Subsurface fatigue leading to spall formation
D.3	Efficiency loss	Profile wear increasing sliding losses
E.1	Water ingress beyond limit	Seal degradation (lip wear, elastomer aging, extrusion, pressure differential)

FMEA-Step 5: Evaluate severity, frequency, and detectability



Metric	Score	Definition
S	1–2	New and negligible impact on performance
	3–6	Degraded or minor impact on performance
	7–8	Derate or major impact on performance
	9–10	Forced Outage and catastrophic shutdown
F	1–2	Rare
	3–4	Occasional
	5–6	Moderate
	7–8	Frequent
	9–10	Very frequent
D	1–2	Very easy to detect early
	3–4	Easy to detect with common sensors
	5–6	Moderate detectability
	7–8	Hard to detect
	9–10	Extremely hard to detect

FMEA-Step 6 and 7: RPN and mitigation strategies



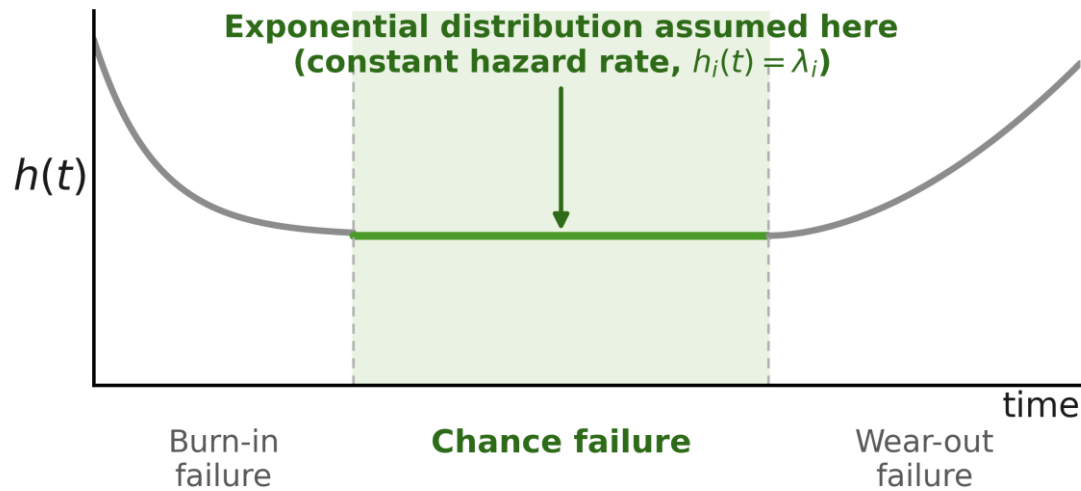
Fail. ID	RPN (S*F*D)	Mitigation Strategy
A.1	320 (10×4×8)	Increase root strength (fillet, case depth); reduce torque spikes; vibration monitoring for crack detection.
B.3	320 (10×4×8)	Strengthen planet tooth root; improve load sharing; limit transients; monitor vibration for crack initiation.
D.1	240 (10×3×8)	Increase root strength; limit shock loads; alignment control; crack monitoring with periodic NDE inspection.
B.1	216 (9×3×8)	Increase sun tooth stiffness; improve load sharing; manage transients; monitor transmission error trends.
C.1	210 (6×7×5)	Upgrade filtration; use wear-resistant coatings; maintain alignment; monitor backlash and particle counts.
A.3	200 (8×5×5)	Specify interference fits; apply anti-fretting coatings; limit micro-motion; monitor modulation accuracy.

Reliability Assessment (for non-repairable system)

$$Re_{IVT} = Re_{NGP} * Re_{PGS} * Re_{RPG} * Re_{OG} * Re_{GS}$$

$$Re_i = \exp\left(-\left(\frac{t}{\alpha_i}\right)^{\beta_i}\right), \quad i=NGP, PGS, RPG, OG, GS$$

Note: Exponential is the special case of Weibull with shape parameter $\beta = 1$
→ constant hazard rate, no shape parameter.



Re_{IVT} : Reliability of the entire infinitely variable transmission (IVT)

Re_{NGP} : Reliability of the Noncircular Gear Pairs (NGP)

Re_{PGS} : Reliability of the Planetary Gear Sets (PGS)

Re_{RPG} : Reliability of the Rack–Pinion Gears (RPG)

Re_{OG} : Reliability of the Output Gears (OG)

Re_{GS} : Reliability of the Gearbox Seal (GS)

Modarres, Mohammad, Mark P. Kaminskiy, and Vasiliy Krivtsov. *Reliability engineering and risk analysis: a practical guide*. CRC press, 2016.

Component Failure-Rate & Reliability Estimation

- Point estimates enable a first-pass model, with the baseline set using midpoint values
- Provides uncertainty bounds for sensitivity analysis

Component	λ Lower	λ Mid	λ Upper	R Upper (%)	R Mid (%)	R Lower (%)
Planetary Gear	0.000189	0.0500	0.1500	99.98	95.23	86.07
Non-Circular Gear	0.0200	0.0500	0.1452	97.15	92.88	86.49
Rack-Pinion Gear	0.0040	0.0080	0.0200	99.60	99.20	98.00
Output Gear	0.0020	0.0600	0.1000	98.00	94.18	90.50
Gearbox Seal	0.0300	0.0739	0.1892	97.00	92.88	82.76

Data provenance: Planetary, rack-pinion, output-gear and seal λ drawn from offshore wind-turbine gearbox / drivetrain reliability literature; the non-circular gear λ comes from a dedicated probabilistic physics-of-failure model (next presentation) for its bending-fatigue behavior.

Baseline One-Year System Reliability

Even with high individual-component reliability, the series configuration compounds risk — motivating the sensitivity analysis that follows.

76.75%

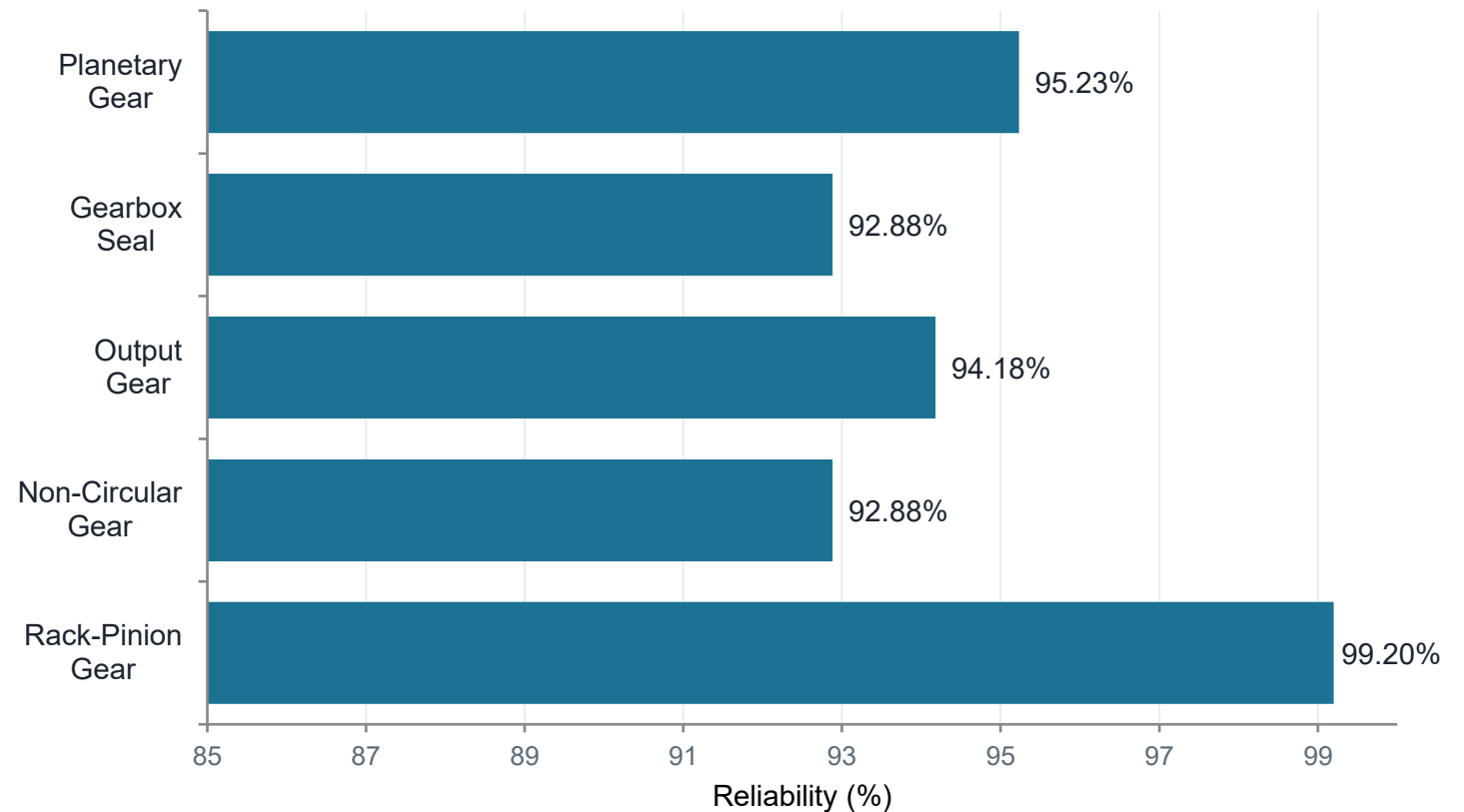
BASELINE $R(t=1 \text{ yr})$

Product of the five component midpoint reliabilities under the series-system assumption

$$R_{IVT} = R_{PG} \times R_{NCG} \times R_{RPG} \times R_{OG} \times R_{GS}$$

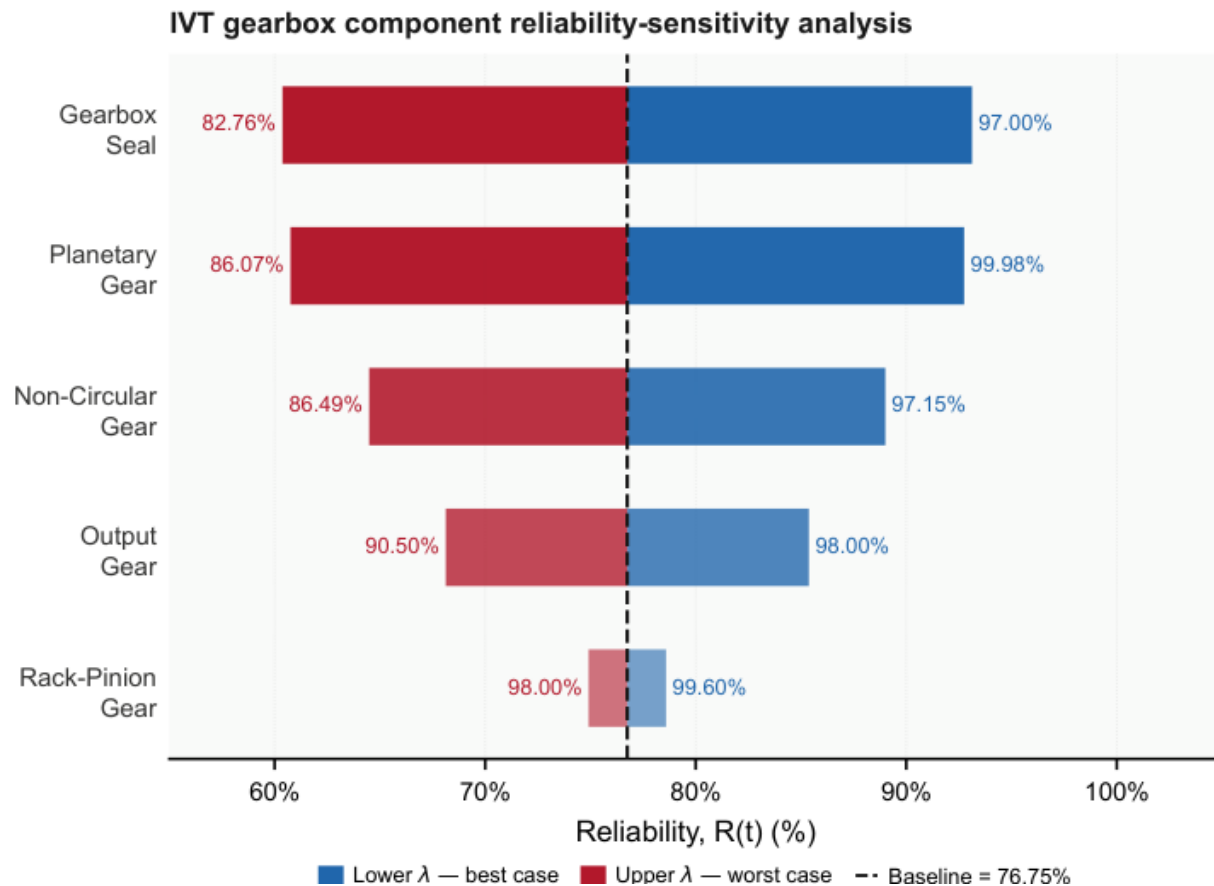
$$= 0.9523 \times 0.9288 \times 0.9920 \times 0.9418 \times 0.9288$$

Component Midpoint Reliability, $R(t = 1 \text{ yr})$



Sensitivity Analysis: What Moves the Reliability Result?

One-at-a-time sensitivity analysis over a one-year mission period



OAT variation reveals which component uncertainties matter most

1

Gearbox seal

Largest uncertainty range; governs water ingress, lubricant loss and contamination pathway.

2

Planetary gear

Second-largest lever; load sharing and tooth-root fatigue affect the system-level confidence.

3

Non-circular gear

Design-critical custom element; physics-of-failure data reduce uncertainty directly.

Conclusion & Future Work

CONCLUSIONS



A qualified reliability baseline

The IVT gearbox, modeled as a five-component non-repairable series system, has a baseline one-year reliability of 76.75%.



Root bending fatigue is design-critical

FMEA identified this as the dominant failure mechanism, driving the highest RPNs in the non-circular gear and planetary gear sets.



Three components dominate uncertainty

The gearbox seal, planetary gear, and non-circular gear are the leading contributors to reliability uncertainty.



A structured basis for qualification

Together, the FMEA and reliability model support technology qualification ahead of TCEC commercialization.

FUTURE WORK



Experimental IVT testing

Physical testing is needed to reduce uncertainty in component failure-rate estimates used in the reliability model.



Incorporate field failure data

Fit lifetime distributions from operational data in place of today's point-estimate failure rates.



Rigorous uncertainty quantification

Develop confidence intervals for failure rates, time-to-failure behavior, and reliability estimates.



Extend physics-of-failure modeling

Apply the non-circular-gear approach to other high-RPN components flagged by the FMEA.



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