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Research Article

Failure Modes and Effect Analysis of Gear Pair

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Abstract

In the present study, the failure mode and effect analysis (FMEA) process has been used to determine the probable failure mechanisms of gear pairs and their implications on the performance, availability, and cost. The risk priority number (RPN) is calculated to rank the failure modes and identify high-risk failures. The methods are proposed to minimize high-risk failure modes.

Keywords: *RPN, FMEA, faults in the gearbox*

1. Introduction

The gears are the most efficient way to transmit the power[1]. It is found that most gears are failed 74% of time due to the service-related causes and 23% due to design and manufacturing errors[2]. The services-related failures are due to consistent overloading, torque fluctuations, improper installation, improper lubrication, contamination of foreign particles, operational errors and so on. The failure of gears is classified as lubricated and non-lubricated failures. According to the American Gear Manufacturing Association (AGMA), the failure of the gears is classified into seven categories. The terminology and the definition of the expected gear failures are provided in the ANSI/AGMA 1010-F14 [3] and ISO 10825:1995 [4]. The failure of the gears is the primary reason for the transmission of the helicopter (19.1%) and wind turbine system (9.8%) and also results in the loss of human lives[2]. The modification in the gear profile and improper alignment leads to the stress concentration, increased vibration and noise, and the connecting system's failure [5–7]. FMEA is a widely accepted method to identify the failure and its effect on the system performance. It facilitates the designer in generating the ideas for obtaining solutions to prevent failure [8,9].

An FMEA is a strategy for systematically detecting and avoiding product and process issues before developing. As the requirement for availability rises, the design engineer focuses on defect prevention, safety enhancement, and availability enhancement. The FMEA is performed both during the design phase and on existing products. FMEA is the endeavour to avoid failure before it occurs.

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The whole of the industry's quality improvement program incorporates the FMEA, which reduces failure costs and increases industry savings. The FMEA is the most time-consuming and resource-intensive procedure since it is team-based and requires the participation of several individuals[8,9].

The primary purpose of the FMEA procedure is to identify all possible failures and their occurrence frequency, severity, and detection. A product is considered to have failed if it fails to provide the expected performance. In the design phase, the designer ensures that the product functions properly, yet failure may still occur despite these safeguards. Failure mode refers to any recognizable and distinguishing method through which a product may fail. The failure modes impact the product's performance, safety, and availability and may lead to catastrophic failure. The following variables influence the relative probability of failure and its consequences: Severity is the result of a failure. Occurrence — The possibility/frequency that the failure will occur. Detection - The possibility of a failure being identified before it has an effect. In the FMEA process, the following fundamental phases are carried out:

- Start

a. Define the scale table for severity, occurrence, and detection.

b. Divide the product into significant and sub-components.

c. Identify all probable failures of each component.

d. Identify the consequences of each failure mode.

e. Determine each failure mode's root cause.

f. List each failure's preventive and control.

g. Calculate the risk priority number (RPN) (Severity ranking × Occurrence ranking × Detection ranking).

h. If adjustment is necessary, repeat the procedure

- Stop

In literature many tribological studies are carried out for the failure of machine components like bearings [9,10,19–28,11,29–38,12,39–48,13,49–58,14,59,60,15–18]and gear[32,61–66]. Failures of gears are classed as lubrication-related and non-lubrication-related[1,67]. The primary design criteria for gear are load-bearing capacity, vibration, noise, operational life, reliability, size, and initial and running expenses[1]. To study the effect of gear tooth failure on gear performance, it is necessary to understand how the failure occurred.

This study has studied several conceivable failure types of gear pairs and their severity. The projected risk priority number for each failure scenario was then used to rate the failure. Elimination or reduction of high-risk failure modes discussed and proposed.

2. FMEA method for a pair of gears

In the FMEA, it is necessary to identify the numerous failure modes of the gear pair, their severity, detection technique, and impact on performance. The gear pair consists of several components; thus, it is necessary to establish the failure mechanism of each component and the interaction between component failures. FMEA is an excellent technique that provides a methodical approach for identifying and categorizing the different failure modes and enables the designer to avoid them during actual operational usage. FMEA includes the following steps:

2.1 Examine the product

Using 3D models and technical drawings, the product is evaluated. It is necessary to examine the interdependence between the system's many components. The gearbox system, as seen in Figure 1, comprises single-stage spur gears made of EN24 steel, bearings to support the gear-containing shafts, and a lubrication system to oil the gears.

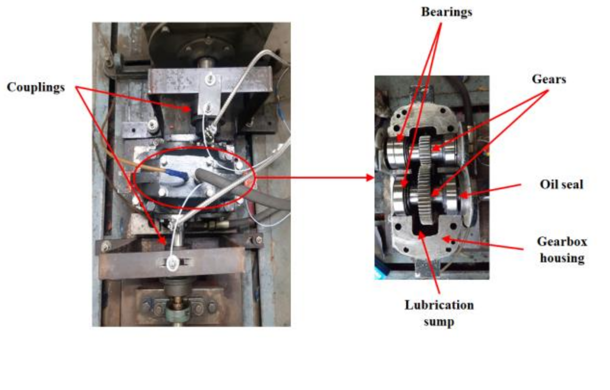

Fig.1 Gearbox system

Power and motion are transmitted via the gears. The driving motor turns the pinion by connection, and the pinion rotates the gear through direct contact, the output gear being subjected to stresses such as torque, etc. The gears are the primary component of the current system, including shafts, bearings, and lubrication systems as auxiliary components.

2.2 List the possible failure modes

Identify the failure modes that might impair the performance of the product. Let's divide the system into smaller subsystems and concentrate on one component at a time to identify probable failure mechanisms. Multiple failure mechanisms exist for each component. In the case of a gearbox, gear, shaft, bearing, lubrication system, lubricant, and oil seal failures are considered.

The American Gear Manufacturing Association (AGMA) classified 36 failure mechanisms of gears into seven categories: wear, scuffing, surface fatigue, plastic flow, cracking, bending fatigue, and breakage. The gear failure is classified into two categories: lubricated and non-lubricated[2,67–70]. Sliding wear, scoring, plastic flow, surface fatigue, cracking, fracture, and bending fatigue are the most common causes of gear failure. Figures 2 (a-i) exhibit a failed gear.

The bearing may fail due to manufacturing errors, abrasive wear, the embedding of hard foreign particles, spalling, plastic deformation, indentation, surface fatigue, etc. [8].

The shaft might fail due to a fracture, bow, breakage, etc. The lubrication system may fail to owe to lubricant leakage, low levels of lubricant, the absence of wear debris filtering, foreign pollutants, etc. The lubrication may fail because of moisture contamination, oxidation, depletion of lubricant additives, change in viscosity/inappropriate viscosity, and unfavourable operating temperature [62,71].

Due to wear, incorrect installation, chemical incompatibility, compression set, etc., oil seals fail [6]. In addition to the failures mentioned above, coupled components might fail due to unbalanced rotation, misalignment, slackness, overload, coupling failure, etc.

2.3 List the possible outcomes for each failure mode

After identifying all the gearbox system's failure modes, each failure mode's performance impact is assessed. Therefore, it is necessary to assess the severity of each failure scenario and its possible impact. It applies to the if-then statement. If this failure has happened, what are the repercussions?

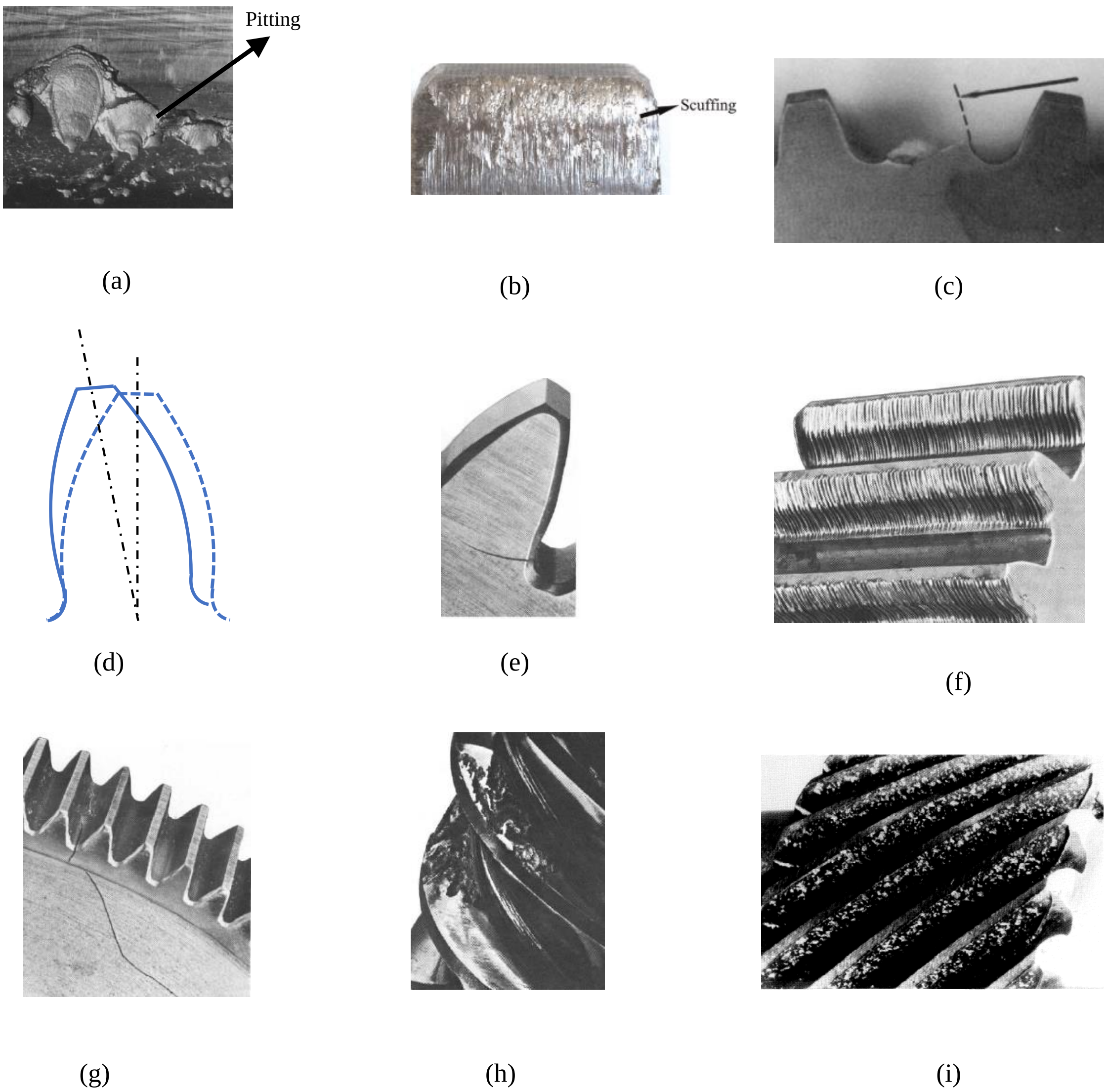

Fig. 2 (a) Pitting failure[67], (b) scuffing failure [72], (c) missing tooth [67], (d) tooth bending failure, (e) tooth crack failure, (f) abrasive wear failure, (g) rim or web failure, (h) spalling failure (e- h [73]), and (i) corrosion wear [4]

2.4 Assign a severity score to each effect

It is a grading based on the severity of the consequences should a failure occur. Occasionally, the severity of a situation is evident based on prior experience. However, it is necessary to determine the severity based on experience and prior understanding. The severity of the failure is quantified in Table (1) on a scale of 1 to 5, where 1 is the lowest severity, and 5 shows the highest severity.

Table 1 FMEA severity guideline (1 to 5 qualitative scale)

Effect	Rank	Criteria
No	1	No effect / Polishing
Slight	2	Mild wear / micropitting
Moderate	3	Adhesive wear/ abrasive wear
Major	4	Scuffing/ Pitting/ Bending/ Cracking
Serious	5	Tooth fracturing

2.5 Assign an occurrence rating to each failure mode

Actual process data is the most effective and acceptable way to establish the failure mechanism's occurrence frequency. The failure logs or other process records provide the data. In the absence of actual failure data, the team may estimate the frequency of potential failures. The occurrence rating is quantified on a scale of 1 to 5 in Table (2), where 1 is a minor occurrence, and 5 is an almost certain occurrence level.

Table 2 FMEA occurrence guideline (1 to 5 qualitative scale)

Effect	Rank	Criteria
Almost Never / Remote	1	Failure is unlikely or infrequent by nature
Slight	2	Few failures are probable
Moderate	3	Medium likelihood of failure likely
High	4	High likelihood of failure likely
Almost certain	5	Failure is nearly certain

2.6 Assign a detection score to each failure mode

The failure rating is assigned on a scale from lowest to highest. The detection is quantified on a scale of 1 to 5; as given in Table 3, 1 shows the highest or most proven detection technique, and 5 is the least or not available detection method.

Table 3 FMEA detectability guideline (1 to 5 qualitative scale)

Effect	Rank	Criteria
Almost certain	1	Proven detection techniques accessible during the idea stage
High	2	Proven computer analysis/simulation or modelling available during the early concept stage
Medium	3	Evaluations of early prototype system aspects
Slight / Remote	4	Proving durability tests on the product with the installed system and available procedures that are untested or unreliable
Almost impossible	5	There is no known method available

2.7 Determine the risk priority number for each failure

The calculation for the risk priority number (RPN) is as follows:

Risk Priority Number (RPN) = Severity ×Occurrence × Detection (1)

The total RPN is determined by adding all RPN together.

2.8 Prioritize the failure modes and remove or mitigate the high-risk failure modes

By RPN, the failure modes are graded from most significant importance to lowest. Identify and take strategies to eliminate or decrease the high-risk failure modes after prioritizing the failure mode. When a failure mechanism is removed, the new risk priority approaches zero as the occurrence ranking approaches one. While complete removal of failure modes is preferable, it may not always be possible. When this occurs, it is helpful to look back at the team's severity, incidence, and detection rankings for each item.

3. Result and discussion

The AGMA classification is used to classify the different failure modes of the gearbox and ranked based on RPN. The severity, occurrence and detection of these failures are decided based on historical data available in the literature. Tables 4, 5, 6 and 7 depict the possible failures of the gearbox, bearing, lubrication system and other components of the system and their potential effects on the gearbox's performance.

Table 4 FMEA worksheet for gears

Name of component: Gear						
SNo	Potential mode of failure	The possible impact of failure	Severity	Occurrence	Detection	RPN
1	Adhesive wear	Temperature rise, metal to metal contact, increased wear	4	4	2	24
2	Abrasive wear	Scratching of the active gear profile leads to scuffing, contamination of the lubricant, increased wear	4	4	2	24
3	Polishing	Remove minor imperfection, reduce accuracy of the gear profile	1	3	4	12
4	Corrosion	Lubrication contamination	3	2	3	18
5	Scuffing / Scoring	Increased temperature, metal to metal contact, rough surface	5	4	2	40
6	Plastic deformation	Profile modification, indentation	3	2	3	18
7	Root fillet yielding	Fracture, missing tooth	4	2	3	24
8	Tip to root interference	Undercutting, weak root	3	2	3	18
9	Subsurface fatigue	Formation of subsurface cracks, stress localization, reduce load carrying capacity, formation of pits	4	3	2	24
10	Micropitting	Rough surface, conversion to full scale pits,	4	4	2	32
11	Pitting	Increased stress concentration,	5	4	2	40
12	Spall	Increased stress concentration, decrease load carrying capacity	4	2	2	16
13	Fatigue cracks	Increase stress concentration, pitting, reduce load carrying capacity	4	3	3	36
14	Rim or web cracks	Increase stress concentration, reduce load carrying capacity	4	1	2	8
15	Root fillet cracks	Increase stress concentration, reduce load carrying capacity, progressive missing tooth	4	2	2	16
16	Fracture due to plastic deformation	Reduce load carrying capacity, missing tooth	4	2	2	16
17	Missing tooth	Increased noise and knocking	4	2	2	16

Table 5 FMEA worksheet for bearing

Name of component: Bearing						
SNo	Potential failure mode	The potential effect of the failure	Severity	Occurrence	Detection	RPN
1	Adhesive wear	Temperature rise, increased metal to metal contact, increased wear	4	4	2	32
2	Abrasive wear	Increased wear, scratching of the bearing surface	4	4	2	32
3	Spalling	Increased stress concentration, decrease load carrying capacity	4	3	2	24
4	Plastic deformation	Geometrical change in bearing, rolling elements, increase wear	4	3	3	36
5	Subsurface fatigue	Subsurface cracks formation, stress concentration, reduce load carrying capacity	4	2	2	16
6	Surface initiated fatigue	Pitting formation, increased wear and friction	5	2	2	20
7	Pitting of rolling elements	Increased wear and friction	5	3	2	30
8	Moisture corrosion	Lubricant contamination, increased friction	3	3	3	27

Table 6 FMEA worksheet for lubrication and lubrication system

Name of component: Lubrication and lubrication system						
SNo	Potential failure mode	The potential effect of the failure	Severity	Occurrence	Detection	RPN
1	No lubricant	Scuffing and thermal softening of the gear material	5	2	2	20
2	Lubricant supply without filtering the wear debris	Surface scratching and wear of the surface	4	3	3	36
3	Lubricant supply with other contaminants	Surface scratching and wear of the surface	4	2	3	24
4	Moisture contamination lubricant	Increased oxidation, undesirable viscosity of the lubricant	3	2	4	24
5	Improper viscosity of the lubricant	Undesirable friction increase, metal to metal contact	4	2	2	16
6	Depletion of lubricant additives	Increased wear	3	3	2	18

Table 7 FMEA worksheet for the other components

Name of component: Other						
SNo	Potential failure mode	Potential effect of the failure	Severity	Occurrence	Detection	RPN
1	Unbalance	Increased vibration, uneven wear	4	3	2	24
2	Cracked shaft	Shaft fracture and increased vibration and noise	5	1	4	20
3	Loose fitting of parts	Vibration and noise	4	2	2	16
4	Misalignment	Non-uniform wear	4	3	3	36
5	Seal leaks	Lubrication starvation, wear	4	2	2	16
6	Damaged coupling	Increased torsional vibration, reduce power transmission	5	2	2	20
7	Crack in gearbox casing	Vibration and noise	4	1	3	12
8	Excessive overload	Metal fatigue	4	2	2	16

Based on the FMEA document (Tables 4, 5, 6, and 7) for the gear pair, it is determined that wear and pitting are the leading causes of failure. The failure's detectability is its defining characteristic. Since it is challenging to take preventative actions against problems that are difficult to detect, the likelihood of failure rises. Lubrication and coupling failure are not significant concerns since they are readily identifiable, and preventative steps may be implemented as necessary. The gears are designed to transfer motion and power. The gear problem is complex due to changes in loads and velocities during meshing. The combination of sliding and rolling motion makes it further complicated. To minimise premature failure and improve the gear's service life, it is necessary to design the gear with the dominant failure mode in mind and to use lubricants with the proper viscosity.

4. Conclusions and recommendations

The FMEA for the gear pair was conducted for the gear pair. Over thirty-five potential mechanisms of failure of the gear system have been identified. These failure modes' severity, occurrence and detection are utilized in quantifying the RPN. The most critical failure modes identified in the basics of RPN are wear (adhesive and abrasive), pitting, scuffing and fatigue crack. All these failure mechanisms limit load capacity and increase stress concentration. The possible solution strategy to limit these failures is the use of a non-standard gear tooth profile design to increase the gear tooth resistance to overload and the wear (simulation study conducted in reference [74]), use of a proper filtration system to clean the lubricant oil, use of the suitable anti-wear lubricant additives, surface polishing, using proper manufacturing process to minimize the manufacturing errors and by minimizing the installation errors.

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