Application of Design Failure Modes and Effect Analysis (DFMEA) to Vertical Roller Mill Gearbox

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Abstract: Design FMEA is structured method of identifying potential failure modes and providing corrective actions before first production run occurs. This paper aims to provide probable causes of failure, levels of effects of failure and corrective actions to be taken in the design phase for Bevel-Planetary Vertical Roller Mill Gearbox.

Keywords—DFMEA, Bevel-Planetary Gearbox, Vertical Roller Mill, Risk Priority Number

I. Introduction

1) Vertical Roller Mills:

Vertical roller mills (VRM) are well accepted as most effectual means for grinding raw material in cement and power generation industry. These mills are driven by heavy duty gearboxes with horizontal input shaft and vertical output shaft [1]. Generally, Bevel-Helical or Bevel-Planetary gearboxes are used for VRM. The gearbox is integral component of VRM as its output flange is rigidly connected with the mill grinding table. Fig. 1 shows the general arrangement of VRM with gearbox located at its bottom.

The output torque which is the foremost design criteria for the gearbox, has to be increased with increasing capacity of the mills [1]. This has put limitations on using Bevel-Helical gearboxes. Additionally, Bevel-Planetary gearboxes stand out with the following advantages over Bevel-Helical making them preferred choice for the application:

- Impervious to vertical impacts (grinding force) since the gears are isolated from the table or lower grinding bowl of the mill.
- Rigid because of round housing form.
- Precision machined because of the circular form.
- Easy to both assemble and disassemble because of the ease with which the thrust plates and the gears can be removed and due to the absence of gaskets necessary for sealing a split gear housing.
- Compact because the forces are being distributed in planetary stage.
- Quiet running because the high speed bevel stage being located deep within the gear unit.
- Efficient because of the loss –free coupling performance of planetary gear.

2) Design FMEA:

A failure mode can be defined as the way in which product, sub-assembly or component would fail to perform its intended function [ix]. DFMEA is a methodology to evaluate failure modes and their effects on the performance of a system in design phase. It is well defined approach to identify possible failure modes, estimate the effects of failure on operational condition of the system, prioritize the actions to reduce risk and evaluate design validation plan. DFMEA can be conducted when:

- New systems, products or processes are being designed
- Existing designs are being changed
- Carry over designs are used in new applications

Fig. 2 gives a simplified concept of DFMEA indicating required inputs and desired output.

Fig. 1: VRM with Bevel-Helical Gearbox (Left) and Bevel -Planetary Gearbox (Right)

Fig. 2: DFMEA Concept
The fact that the application of DFMEA to gearboxes by the manufacturers is irrefutable. However, there is no any published record of such application of DFMEA to a vertical roller mill gearbox. This paper documents the basic application of DFMEA to gearbox using the procedure adopted from Failure Modes and Effects Analysis (FMEA) for Wind Turbine, H. Arabian-Hoseynabadi, H. Oraee and P.J. Tanver [ii]. The procedure and analysis technique has been modified to make it appropriate for an industrial gearbox.

The flow chart in Fig. 3 explains the steps involved in DFMEA.

![Flow Chart](image)

**Fig. 3: DFMEA Procedure**

1. **Application Requirements and Gearbox function**: The requirements of application and gearbox function are explained in introduction Section of this paper.

2. **Gearbox Structure**: The taxonomy used to define gearbox structure can be in the form of block diagram, cross-sectional diagram of gearbox, flow chart or simply enlisting the components in their sub-assemblies. Enlisting the sub-assembly wise structure ensures that the every component has been taken into consideration. Fig. 4 shows the structure of Bevel-Planetary VRM gearbox.

![Gearbox Structure](image)

**Fig. 4: Gearbox Structure**

3. **Defining Criteria**:

   (a) **Severity**: Severity is the measure of importance of the effect of failure mode [viii]. Severity scale depends on the effect of failure on the performance of the gearbox. Severity rating can be defined using concept of Mean Time To Repair (MTTR). A Failure mode with low MTTR can be considered as less severe compared to that of with high MTTR. Table I shows the severity criteria used in this paper.

   ![Severity Table](image)

   **Table I: Severity Scale**

   (b) **Occurrence**: Occurrence is the frequency with which a particular cause occurs and creates failure [viii]. In other
words, it can be referred as probability of the cause of failure. The different levels of occurrence can be distinguished with the help of concept of Mean Time Between Failure. If time between failure due to particular cause is high then it will have less occurrence rating. Table II indicates the occurrence criteria.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Label</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inevitable</td>
<td>5</td>
<td>Failure will definitely occur</td>
<td></td>
</tr>
<tr>
<td>Frequent</td>
<td>4</td>
<td>Repeated failures with regular occurrence</td>
<td></td>
</tr>
<tr>
<td>Occasional</td>
<td>3</td>
<td>Occasional but not necessarily regular failures</td>
<td></td>
</tr>
<tr>
<td>Rare</td>
<td>2</td>
<td>Rare and irregular failures</td>
<td></td>
</tr>
<tr>
<td>Extremely Unlikely</td>
<td>1</td>
<td>Failure almost never occurs</td>
<td></td>
</tr>
</tbody>
</table>

Table II: Occurrence Scale

**4. Determining Failure Modes and Root Causes:** For this phase of DFMEA previous records of service reports of gearboxes have been studied. A brainstorming session was arranged involving design, manufacturing, assembly and service teams. In this session by utilizing application knowledge and data of previous failures, potential/probable failure modes and their possible root causes were determined. Table IV gives the general root causes of gearbox failure.

<table>
<thead>
<tr>
<th>Root Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Error</td>
</tr>
<tr>
<td>Mechanical Overload</td>
</tr>
<tr>
<td>Presence of debris/Contamination</td>
</tr>
<tr>
<td>Connection Failure</td>
</tr>
<tr>
<td>Insufficient Input from Site</td>
</tr>
<tr>
<td>Raw Material Quality/Heat Treatment</td>
</tr>
<tr>
<td>Manufacturing or assembly Error</td>
</tr>
<tr>
<td>Insufficient Lubrication</td>
</tr>
</tbody>
</table>

Table IV: General Root Causes

The potential failure modes of gearbox are tabulated in Table V.

**5. Conducting DFMEA:** Fig. 5 shows the matrix used to carry out DFMEA of Bevel-Planetary gearbox.
The function of each component of sub-assembly has defined in the matrix. The failure mode for each component has been determined. The effects of failure were then categorised as Local effect, Next effect and End effect. This categorisation helps in identifying the root cause(s) easily and applying severity rating accurately. The relationship between failure mode and root cause may not be always one to one. A single failure mode may have more than one root cause. A Risk Priority Number is calculated using formula,

\[ RPN = \text{Severity} \times \text{Occurrence} \times \text{Detection} \]

After calculating the RPN for every component, next step is to identify critical components viz. components with high RPN. By comparing the RPN values of components, the components with RPN equal to or more than 40 had been considered as critical components.

![Root Cause Vs RPN and Root Cause Vs Occurrence No.](image)

Fig. 6: Root Cause Vs RPN and Root Cause Vs Occurrence No.

From Fig.6 it is clear that occurrence of design error is highest and it is main cause of failure. Hence, corrective actions were taken to reduce risk of design error for critical components. Fig. 7 shows contribution of design error RPN in total RPN of critical components.

![Critical Component vs RPN and Critical Component vs Occurrence](image)

Fig. 7: Design Error RPN for Critical Components

The corrective actions to reduce design errors for critical components are tabulated in Table VI.

### Table VI: Corrective Actions

<table>
<thead>
<tr>
<th>Critical Component</th>
<th>Corrective Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ribs</td>
<td>Static and modal analysis on casing is done through FEA. Casing is reinforced with adequate ribs providing more stiffness to casing</td>
</tr>
<tr>
<td>Spiral Bevel/Flank</td>
<td>Tooth stresses are checked in KISSggs for required service lactor. Shaft is analyzed for fatigue stresses through FEA and design is found to be safe. Drawing checklist reviewed</td>
</tr>
<tr>
<td>Coupling End TRD</td>
<td>Drawing selection is verified in KISSggs for required service life and found to be safe. Adequate lubrication and cooling is provided to the bearing</td>
</tr>
<tr>
<td>Bevel Wheel/Shaft</td>
<td>Static analysis of shaft is carried out with different load cases and peak stresses through FEA and design is found to be safe</td>
</tr>
<tr>
<td>Spur Wheel</td>
<td>Tooth stresses are checked in KISSggs for required service lactor. Shaft is analyzed for fatigue stresses through FEA and design is found to be safe. Drawing checklist reviewed</td>
</tr>
<tr>
<td>Bevel Wheel/Shaft Top</td>
<td>Tooth stresses are checked in KISSggs for required service lactor. Shaft is analyzed for fatigue stresses through FEA and design is found to be safe. Drawing checklist reviewed.</td>
</tr>
<tr>
<td>Sun Pinion</td>
<td>Tooth stresses are checked in KISSggs for required service lactor. Shaft is analyzed for fatigue stresses through FEA and design is found to be safe. Adequate lubrication and cooling is provided to the bearing</td>
</tr>
<tr>
<td>Planets</td>
<td>Tooth stresses are checked in KISSggs for required service lactor. Shaft is analyzed for fatigue stresses through FEA and design is found to be safe. Drawing checklist reviewed</td>
</tr>
<tr>
<td>Planet Bearing SBF</td>
<td>Drawing selection is verified in KISSggs for required service life and found to be safe. Adequate lubrication and cooling is provided to the bearing.</td>
</tr>
<tr>
<td>Axonisc</td>
<td>Tooth stresses are checked in KISSggs for required service lactor. Shaft is analyzed for fatigue stresses through FEA and design is found to be safe. Drawing checklist reviewed</td>
</tr>
<tr>
<td>Thrust Pad Bearing</td>
<td>Bearing set is analyzed for static and dynamic axial thrust load in FEA. The static and dynamic axial load on the pads are found to be within the allowable value.</td>
</tr>
</tbody>
</table>

### III. Results and Tables

After implementing corrective actions for critical components, once again RPN was calculated. The design error RPN was found to be decreased more than 50% for each critical component.

Fig. 8 shows the comparison of design error RPN before and after implementing corrective actions. The decrease in design error RPN values has also decreased the overall RPN for critical components. Thus ensuring the robustness of design of gearbox. Fig. 9 shows the comparison of RPN for critical components before and after implementation of corrective actions.
Occurrence number can be used effectively to identify highest contributing root cause to failure. Similar RPN for bevel pinion shaft and bevel wheel before and after implementation of corrective actions indicates that failure of any one of them will result in failure/replacement of other. Results obtained from design tools like FEA, KISSSys, can be compiled and used efficiently in DFMEA to decrease risk of failure and bring robustness in design of gearbox.

IV. Conclusion

References

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