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# Semi-quantitative Risk Assessment Matrix for Rotating Equipment

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**Abstract.** In petrochemical, power generation, oil and gas industries and in variety of other sectors rotating equipments are in use to fulfill production requirements. Failure of rotating equipment, especially in such industries can result to risk related issues. A well implemented rotating equipment risk assessment strategy is most needed to achieve desired plant availability and efficiency. In this research semi-quantitative risk assessment approach is proposed to evaluate the risk of rotating equipment and categorize their associated failure risks. Borda ranking is adopted to evaluate the risk in order to minimize risk ties which exist in risk matrix. Compressor is taken as case study to show the applicability of the proposed method for rotating equipment. It was observed that risks of selected failure modes of gas turbine compressor fall in the categories of serious and medium levels based on risk matrix. Rotor bend distortion, blade failure or inlet guide vane failures needed more attention for treatment based on Borda ranking.

## Introduction

Rotating equipments are the general classification of mechanical equipments that are used to generate kinetic energy to a process [1]. The addition of kinetic energy may be needed to move material from one point to the next or to agitate the material. In rotating equipment solids, liquids or other materials shift through a mechanism of drivers like engines, turbines, motors, driven elements like pumps, compressors transmission elements and auxiliary equipments [2]. Rotating equipments are critical for many industries. Some examples are turbines, electric generators, pumps, compressors, electric motors and drives [1, 3]. Almost all rotating machinery have one general task; to efficiently transfer power to a rotating shaft induced by water, steam or gas flow, mechanical force and magnetic fields or vice versa.

To define a typical rotating equipment is quite difficult, because of broad range of rotating equipment present have various features like speeds, sizes, use etc [1]. Beside there are a wide variety of rotating equipment. In general any rotating equipment has three major components, which are rotor, bearings and last is supporting structure for rotor and bearings known as stator or foundation [4].

With the highly competitive nature of today's markets, industries cannot afford major rotating equipment failures [5]. Unexpected breakdowns of rotating equipment can result in unwanted downtime for plant, agreement deadlines, costly repair or replacement, also may affect safety and environmental issues, which may cost millions of dollars [6]. Organisations today are continually striving to source the most innovative technologies and practices to minimise those risks and improve their rotating machinery reliability. Rotating equipment incidents are most critical and need to be investigated since they can result in total loss of the facility.To decide what risk is for each critical piece of rotating equipment, a suitable technique is required.

Utilizing risked-based analysis tools can provide guidance. What and where the risks are located, how the risk levels for potential lost revenue can be reduced. Among the main concern is to prioritize maintenance decisions so that company resources can be properly used and applied for rotating equipment which have more risk [7, 8].

This study proposes semi-quantitative risk assessment matrix approach to assess the risk of rotating equipment. This approach is the combination of quantitative and qualitative measures. This approach is easier to perform because it does not need much data in comparison to quantitative risk assessment approach. Moreover, in comparison to qualitative approach this method provides more meaningful outcomes for decision making [9, 10]. Though the quantitative approach for the risk assessment is recommended, however it has many restrictions to carry out risk assessment of complex rotating systems [10].

## Methodology

In order to achieve the objective of the research, a suitable methodology is required. The following steps are defined to develop the semi-quantitative risk assessment matrix for rotating equipment.

**Analysis of Failures.** The good failure understanding leads to the real problem reasons which cause failures in rotating equipment. In this study to analyze the failures of the rotating equipment failure mode and effect analysis (FMEA) has been employed, as it is efficient tool to analyze equipment failures; for detail refer [11].

**Development of Risk Assessment Matrix.** To develop the semi-quantitative risk assessment matrix, the following rules are used [12];

- Risk matrix is based on definition of risk assessment, as it is combination of two basic parameters probability of failure P and its consequences C.
- Quantitative or qualitative assumptions are set to develop scales for consequences, probability and risk of failures.
- The matrix is developed based on the logic, if P is probability and C is severity of consequence, then the outcome is risk R [12].

**Development of Failure Probability Scale.** The occurrence of the particular system failure can be evaluated using real plant data, or from other available sources like engineering judgment etc. The failure rate range scale based on probability of failure are shown in Table 1, are adapted from MIL-STD 882.The scales could be further enhanced since various firms may have their own residual risk criterion [13].

Table 1. Failure rate range scale

| | |
|---|---|
| Frequent | >1f/year |
| Probable | 0.1-1 f/year |
| Occasional | 0.1-0.01 f/year |
| Remote | 0.01-0.001 f/year |
| Improbable | <0.001 f/year |

Table 2. Failure consequence scale

| | |
|---|---|
| Catastrophic | Plant shutdown, and may affect other system components and environment |
| Critical | Plant Shutdown, no other affect |
| Marginal | Degraded performance |
| Negligible | No affect to performance |

**Development of Failure Consequence Scale.** Failure consequences are categorized based on their impact. In this research only economic consequences of the failure are considered to rank the failures of rotating equipment. The consequences scales mentioned in Table 2, are adapted from MIL-STD 882 and are given consequences severity impacts for rotating equipment [13].

**Formulate Risk Matrix.** Risk matrix is developed after defining the risk parameter scales. The proposed risk assessment matrix is shown in Table 3. The cell which have number "1" is product of "Catastrophic" failure consequence and "Frquent" failure probability. The case is similar for all matrix cells from 1-20, each cell is product of probability P and consequence C.

**Risk Categorization.** In the risk assessment matrix in Table 3, each cell is assigned a value. This value helps to categorize the failures risk in such particular cell. Table 4, shows the different ranges of cell values to categorise failures based on combined effect of failure probability and its consequence. In this proposed risk assessment matrix, cell values from 1-5 show the High risk and this risk for the system is unacceptable. Similarly ranges are set from 1-20 and differet categories are presented as in Table 4.

Table 3. Semi-quantitative failure risk assessment matrix [13]

| Consequences / Probability | Catastrophic | Critical | Marginal | Negligible |
|---|---|---|---|---|
| **Frequent** | 1 | 3 | 7 | 13 |
| **Probable** | 2 | 5 | 9 | 16 |
| **Occasional** | 4 | 6 | 11 | 18 |
| **Remote** | 8 | 10 | 14 | 19 |
| **Improbable** | 12 | 15 | 17 | 20 |

Table 4. Semi-quantitative failure risk assessment matrix values [13]

| Failure risk assessment value | Failure risk category | |
|---|---|---|
| 1-5 | High | Not acceptable |
| 6-9 | Serious | Not desirable |
| 10-17 | Medium | Acceptable with review |
| 18-20 | Low | Acceptable without review |

**Borda Ranking.** Once risk matrix is developed, it is still not possible to decide which risk is most important. The risk matrix only separates the failure risks in four categories generally as High, Serious, Medium and Low. These four categories do not represent actual situation whereby there are many risk ties exist. In order to minimize risk ties Borda ranking method is adopted [14]. Borda ranking method uses the Eq. 1 to rank failure risks. Borda method needs certain number for each failure consequence and probability category to use in Eq. 1 to rank failure risks. The numbers are assigned for each consequence and probability category as shown in Table 5, and Table 6.

Table 5. Consequence of failure scale values

| Catastrophic | Critical | Marginal | Negligible |
|---|---|---|---|
| 4 | 3 | 2 | 1 |

Table 6. Failure rate range scale values

| Frequent | Probable | Occasional | Remote | Improbable |
|---|---|---|---|---|
| 5 | 4 | 3 | 2 | 1 |

$$b_i = \sum_k (N - r_{ik}) \tag{1}$$

where, $N$ represents total number of risks in risk matrix, $i$ is a particular risk, for criteria $k$. There are two conditions for risk matrix: $k=1$ is referring failure consequence (C), $k = 2$ represent to failure probability (P). If risk level is $r_{ik}$ and $i$ is within the criteria ($k$), then Eq. 1 provides Borda count of risk $i$. Later calculated $b_i$ values can be sorted with respect to the small to larger order, the Borda count of $b_i$ then will be the number of risk factors, which are larger than risk factor Borda count.

## Results and discussions

To demonstrate the use of proposed method for rotating equipment risk assessment, gas turbine (GT) compressor is taken as a case study. Failure probability and failure consequence are for various failure modes of gas turbine compressor are discussed and risk assessment is carried out in following steps.

**Failure Probability Analysis.** Failure modes of GT compressor adapted from [15] updated FMEA and failure ranges were assumed. GT compressor has 10 failure modes; occurrence of each failure mode causes the failure of compressor. As stated in MIL-STD 882 standard, scales for failure probability are flexible to change to fit the situation, GT compressor failure ranges were defined and categorized based on their occurrence rate as remote, probable, and occasional, as shown in Table 7.

**Failure Consequences Analysis.** Consequences severity categories are assigned for each failure mode of the GT compressor as shown in Table 7. Only single failure mode (over speed) of the GT compressor has catastrophic consequences. Remaining five failures found having critical consequences when they occur, three failures have negligible and one failure has marginal consequences level.

**Ranking Based on Risk Matrix and Borda Method.** Based on the estimated failure probability and consequence scales for GT compressor semi-quantitative risk matrix was developed using Table 3, results are shown in Table 7. Failure modes risks allocated in two risk categories which are serious and medium. Seven failure modes of GT compressor have medium risk, and three failure modes have serious risk levels. Based on risk categorization assumptions shown in Table 4, the failures have serious risk levels need urgent attention to minimize the risk levels because such failures are not desirable. The failure modes which have medium risk levels are required to set some preventive strategies to avoid their failure risk but they are in acceptable criteria.

Table 7. Risk ranking based on semi-quantitative risk matrix incorporating Borda method

| No: of risks | Failure mode | Probabilities of failure | | | Consequences of failure | | | Risk matrix ranking | Borda ranking |
|---|---|---|---|---|---|---|---|---|---|
| | | Failure ranges | Category | Scale | Impact | Category | Scale | | |
| 1 | Over speed | 0.01-0.001/year | Remote | 2 | Plant shutdown, and may affect other components and environment | Catastrophic | 4 | Serious | 2 |
| 2 | Rotor out of balance | 0.01-0.001/year | Remote | 2 | Plant Shutdown, no other affect | Critical | 3 | Medium | 3 |
| 3 | Rotor bend distortion | 0.01-0.1/year | Occasional | 3 | Plant Shutdown, no other affect | Critical | 3 | Serious | 0 |
| 4 | High temperature | 0.1-1.0/year | Probable | 4 | No affect on performance | Negligible | 1 | Medium | 3 |
| 5 | High vibration | 0.1-1.0/year | Probable | 4 | No affect on performance | Negligible | 1 | Medium | 3 |
| 6 | Tip rub | 0.01-0.001/year | Remote | 2 | Plant Shutdown, no other affect | Critical | 3 | Medium | 3 |
| 7 | Blade failure or inlet guide vane failure | 0.01-0.1/year | Occasional | 3 | Plant Shutdown, no other affect | Critical | 3 | Serious | 0 |
| 8 | Thrust bearing failure | 0.01-0.1/year | Occasional | 3 | Degraded performance | Marginal | 2 | Medium | 9 |
| 9 | Redial bearing failure | 0.1-1.0/year | Probable | 4 | No affect on performance | Negligible | 1 | Medium | 3 |
| 10 | Foreign object damage | 0.01-0.001/year | Remote | 2 | Plant Shutdown, no other affect | Critical | 3 | Medium | 3 |

Even if the different failure risks are categorized, still there was ambiguity due to the risk ties. As seven failure modes of GT compressor have medium risk, and three failure modes have serious risk levels. It is not possible to judge which risk from medium or serious risk categories is most important. Borda ranking is adopted to refine associated risks of the GT compressor failure modes. The value of $b_i$ was calculated using Eq. 1.

$b_i = \sum_k (N - r_{ik})$= (10-6) + (10-0) =14

The calculated $b_i$ values are 14, 13, 16, 13, 13, 13, 16, 11, 13, and 13. Based on these values Borda ranking performed as shown in Table 7. As failure mode three and seven have Borda ranking 0, which means these failure modes are most critical. Then, failure mode number one have Borda ranking 2 and requires second attention. The failure modes have similar ranking should be given equal attention. The last failure mode number eight has Borda ranking 9, and should be treated at last.

## Conclusion

Failure modes of GT compressor, their occurrence rate, consequence and associated risks were estimated and categorized using semi-quantitative risk matrix. The Borda ranking method was used to minimize the risk ties which exist in risk matrix ranking. Rotor bend distortion, blade failure/inlet guide vane and over speed were found having serious risk. Out of these three, rotor bend distortion and blade failure/inlet guide vane needed more attention for treatment based on Borda method evaluation. From medium risk failures modes except thrust bearing failure all require same attention. Thrust bearing failure mode should be treated last due to low risk. This study further can be extended to set maintenance actions to mitigate risk of GT compressor.

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