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Reliability Study of Elevator Rotor Manufacturing Unit Based on FMECA

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Abstract: *The elevator rotor manufacturing unit, as a core equipment of the elevator traction machine, has extremely high requirements for processing stability, necessitating reliability analysis. After confirming the hierarchical division and fault criteria of the rotor manufacturing unit, fault analysis was conducted on ten functional subsystems, and corresponding FMECA (Failure Modes, Effects, and Criticality Analysis) results were obtained. Finally, the prominent fault issues of the rotor manufacturing unit were summarized, and appropriate improvement measures were proposed. This study provides a strong basis for the reliability management and improvement of the rotor manufacturing unit. It identifies the main sources of failure, and based on the characteristics of the failure sources and related fault results, suggestions for design, manufacturing, and maintenance are provided.*

Keywords: *Elevator Rotor Manufacturing Unit, Reliability, Failure Modes, Effects, Criticality Analysis (FMECA)*

1. Introduction

In the context of "Made in China 2025," improving the reliability of manufacturing units has become an inevitable requirement. Although some achievements have been made in the study of domestic machine tool reliability under national support, the focus has been mainly on individual machines, with limited research on the reliability of manufacturing units. To meet market demand, small and medium-sized enterprises widely adopt flexible manufacturing units, which calls for in-depth research into their reliability. The reliability of manufacturing units is a key indicator of manufacturing system performance, directly affecting order delivery, product quality, and production costs. High-reliability manufacturing units can enhance system flexibility and shorten fault repair time, ensuring the orderly conduct of production.

Adamyan and He[1] studied the reliability and safety evaluation of continuous-fault manufacturing systems, using Petri nets for modeling and constructing reachability trees to determine the fault occurrence sequence and probabilities. Loganathan and Gandhi[2] constructed a general hierarchical structure tree and functional tree based on graph theory, using directed graphs to describe the functional implementation process and determining the importance of each function by processing the functional connection matrix, thus proposing measures to enhance system reliability. Xu Yiru et al.[3] built an FMC failure tree model and proposed methods to improve unit reliability. Feng Hutian et al.[4] proposed a reliable stochastic model for FMC composed of machine tools, robots, and transport systems, analyzing its productivity by solving closed equations. Sinha and Steel[5] improved the traditional FMECA method to enhance the accuracy and efficiency in analyzing the UK offshore wind farms. Carpitella et al.[6] integrated reliability analysis and MCDM (Multi-Criteria Decision-Making) methods to optimize complex system maintenance activities, first conducting FMECA and then applying fuzzy ideal solutions to rank failure modes. Sun Shuguang et al.[7] proposed a combined method of Interpretative Structural Model (ISM) and FMECA for fault analysis of machining centers.

The elevator rotor, as a key component of the elevator traction machine, has extremely high safety requirements. Any failure may lead to severe consequences, making reliability design and evaluation crucial. This paper uses the FMECA analysis method, first identifying the key equipment of the elevator rotor manufacturing unit, then performing detailed analysis on these devices, identifying the most threatening failures, and proposing corresponding improvement measures. This process is significant for ensuring the safety and reliability of the manufacturing unit's operation.

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2. Introduction to Elevator Rotor Manufacturing Unit

The traction machine rotor component is a core part of the elevator traction machine. When the elevator starts, the motor applies rotational force to the rotor, causing it to continue rotating. The magnetic energy is converted into electrical energy, and the electrical energy from the rotor is transferred to the elevator drive wheel, thereby driving the elevator's ascent and descent. Due to the demands of actual production, an automated unit for processing the traction machine rotor is equipped in the processing workshop (as shown in Figure 1).

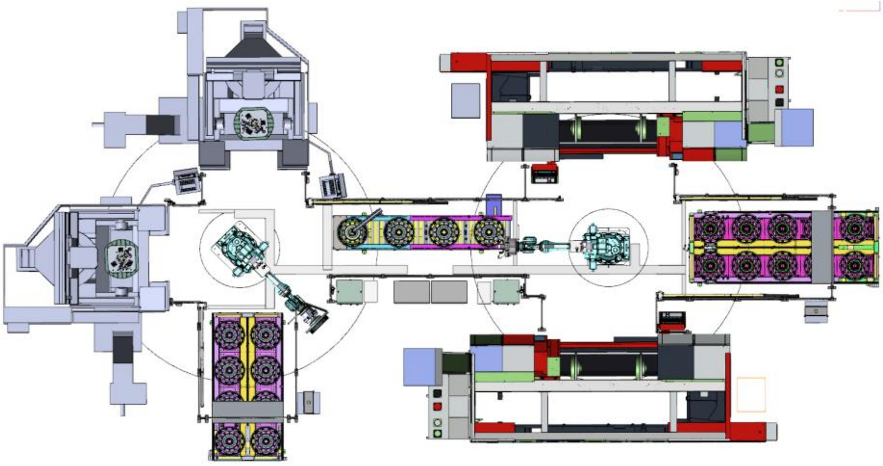

Figure 1 Layout of manufacturing cell

The entire manufacturing unit is also equipped with two robots for handling and processing rotor components, as well as three roller conveyors for transporting and moving parts. In addition, there is one camera recognition system used for phase recognition of the parts. With such a layout and equipment configuration, the traction machine rotor manufacturing unit can meet large-scale market demands and possesses a certain degree of flexibility. It can reorganize processes or switch to single-machine production in the event of equipment failure or the need for reduced production, ensuring the continuous operation of production.

In the study of the elevator rotor manufacturing unit, the entire manufacturing unit is subdivided into ten main functional subsystems. These subsystems include cutting, clamping, control, electrical, hydraulic and pneumatic, servo drive, photography, transmission, robots, and protective systems. As shown in Figure 2.

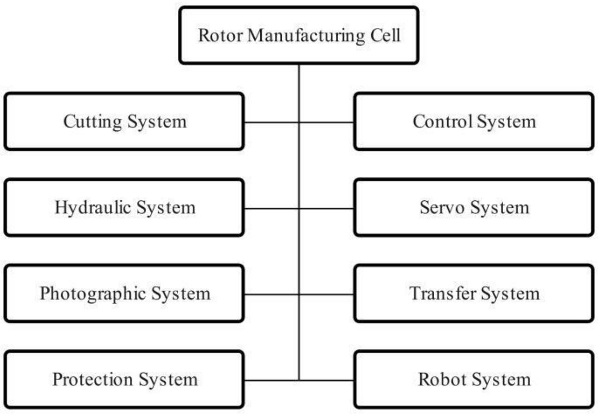

Figure 2 Functional structure diagram

This division aims to comprehensively cover all aspects required for the manufacturing unit to achieve its functional objectives, thus providing a structured framework for a deeper understanding of how each subsystem contributes to the overall performance. In addition, it lays the foundation for detailed comparative analysis of potential failures in each subsystem, to identify the specific sources and causes of the failures.

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3. Introduction to FMECA Method

Failure Modes, Effects, and Criticality Analysis (FMECA) is a systematic and comprehensive method used to evaluate the potential failure modes of equipment, components, or processes. FMECA analyzes the functional impacts that these failure modes may cause and assesses their potential effects on system reliability, safety, and performance. Its aim is to identify and prioritize potential issues. The ultimate goal is to optimize designs, improve preventive maintenance plans, and develop effective detection and corrective measures to enhance the system's stability and long-term reliability.

Hazard analysis can be conducted using both qualitative and quantitative methods. When failure data for a product is unavailable, the qualitative analysis method should be used, when more accurate failure data is available, the quantitative analysis method should be employed. This study is based on a previously established rotor manufacturing unit failure database and adopts a quantitative hazard analysis method. Specifically, we calculate the criticality (CRij) of each failure mode and the component's criticality (CRi) to the system using a specific formula, and then rank the obtained CRi values. This method helps to accurately assess and rank the level of hazard each failure mode poses to the system.

If a failure mode j occurs in the failure location of subsystem i, the hazard level of this failure mode to the processing center can be expressed as CRij, with the following calculation formula [8]:

$$CR_{ij}=\alpha_{ij}\beta_{ij}\lambda_i \tag{1}$$

The criticality of all failures occurring in subsystem i to the processing center is CRi, and the calculation formula is as follows:

$$CR_i=\sum_{j=1}^{n}CR_{ij} \tag{2}$$

Substituting equation (1) into equation (2), we get:

$$CR_i=\sum_{j=1}^{n}\alpha_{ij}\beta_{ij}\lambda_i \tag{3}$$

In equations (1), (2), and (3), n represents the number of different failure modes occurring in subsystem i, Pj is the probability that failure mode j causes a failure in the rotor manufacturing unit subsystem i, with its calculation formula shown in (4), Pi is the probability of damage caused to the rotor manufacturing unit when subsystem i fails due to failure mode j, λi is the basic failure rate of subsystem i, which can be equal to the average failure rate, with its calculation formula shown in (5). In equation (4), Nj represents the number of occurrences of failure mode j in subsystem i, Ni is the total number of failures that have occurred in subsystem i. In equation (5), Ni_total represents the total number of failures in subsystem i over the total time, T_total represents the accumulated operating time, which, through statistical calculation, is found to be 5280 hours.

$$\alpha_{ij}=\frac{n_j}{n_i} \tag{4}$$

$$\overline{\lambda}=\frac{N_i}{\sum t} \tag{5}$$

According to the GB7826 standard, there are four possible values for damage probability: when P = 0, it indicates that the failure mode poses no possibility of causing any damage to the system, when P = 0.1, it indicates a very low probability of causing damage, when P = 0.5, it indicates a moderate probability of causing some level of damage, and when P = 1, it indicates that the failure mode will definitely cause damage to the system.

However, these values have significant gaps between them, and the system’s complexity and the diversity of failure modes make such categorization insufficient. When multiple failure modes potentially cause system damage, assigning P = 0.5 alone cannot distinguish between varying levels of severity. To better reflect these differences, the damage probability for failure modes that may cause system damage can be set to any value between 0.1 and 0.9. The higher the value, the greater the likelihood that the failure mode will cause damage to the system.

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In actual system operation, ensuring the safety of operators is of paramount importance. Therefore, for failure modes that may pose risks to personnel, relatively higher values should be selected.

4. FMECA Analysis of Functional Subsystems

The research object of this study is the rotor manufacturing unit of an elevator production company. The production cycle of this unit is 30 minutes per piece, with an annual output of 50,000 units. The production operation follows a three-shift system, with a daily effective working time of 20 hours and an annual effective working day count of 260 days.

With the close cooperation and guidance of the workers, this study identifies the locations of failures, failure modes, and their causes. A detailed FMECA (Failure Modes, Effects, and Criticality Analysis) is conducted on the five functional subsystems of the rotor manufacturing unit that experience frequent failures. Through this analysis, high-criticality failure modes within each system are identified, and corresponding improvement suggestions and measures are proposed to enhance the overall reliability of the equipment and improve production efficiency.

4.1 FMECA Analysis of the Cutting System

The cutting system is a key functional system for the machining of workpieces, with its primary objective being the transformation of cast blanks into final products. The cutting system mainly consists of two key components: the machine tool's cutting tool and spindle. As shown in Table 1, the FMECA analysis results for the cutting system of the rotor manufacturing unit are provided.

Table 1 FMECA Analysis of the Cutting System

Failure Part	Equipment	Failure Mode	Cause of Failure	Effect of Failure	Severity Level	Failure Rate(10^{-4}/h)	Criticality (10^{-5}/h)
Tool Holder	Lathe	No Action	Switching Solenoid Valve Wire Break	Cannot Process	3	7.576	1.457
	Lathe	No Action	Mechanical Jamming	Cannot Process	3	15.153	5.828
	Lathe	Cannot Reach Position	Control Signal Interference	Cannot Move	3	30.303	23.315
	Lathe	Cannot Return to Origin	Belt Fracture	Tool Cannot Be Used	3	11.362	5.245
	Lathe	False Alarm	Tool Wear	Cannot Cut	2	18.924	9.105
	Machining Center	Broken Tool	Excessive Feed	Cannot Rotate	6	5.682	0.492
	Machining Center	Stuck	False Power Off	Cannot Rotate	2	7.576	1.457
	Machining Center	Fallen Off	Tool Magazine Jamming	Collision Alarm	3	1.894	0.146
Tool Magazine	Machining Center	Cannot Rotate	No Control Output from PLC	Tool Magazine No Action	2	22.733	7.867
	Machining Center	Cannot Rotate	Over-tight Mechanical Connection	Tool Magazine No Action	2	9.470	1.366
	Machining Center	Cannot Reach Position	Motor Rotation Failure	Tool Magazine Alarm	2	3.788	0.437

4.2 FMECA Analysis of the Hydraulic System

The hydraulic system is a device that uses liquid as a transmission medium, designed to perform functions such as lifting and moving the worktable, clamping and releasing the workpiece, and enabling rapid forward and backward movement of the tool during the machining process. Its main components include the hydraulic pump, valves, cylinders, oil tank, and pipelines. Most of the equipment in the rotor manufacturing unit contains hydraulic components. As shown in Table 2, the FMECA analysis results for the hydraulic system of the rotor manufacturing unit are provided.

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Table 2 FMECA Analysis of the Hydraulic System

Failure Part	Equipment	Failure Mode	Cause of Failure	Effect of Failure	Severity Level	Failure Rate(10^{-4}/h)	Criticality (10^{-5}/h)
Pump	Lathe	Abnormal Noise	Oil Filter Clogging	Excessive Pressure	3	9.470	5.919
	Machining Center	Abnormal Vibration	Oil Contamination with Chips	Abnormal Noise	3	22.732	28.413
	Lathe	Leak	Insufficient Oil in Tank, Air Intake	Hydraulic Oil Leak	3	13.264	5.800
	Lathe	Seepage	Oil Line Blockage	Guide Rail Lubrication Alarm	4	7.576	3.157
	Machining Center	Leak	Loose Piping	Cooling Pump Not Working	3	5.682	1.776
Hydraulic Valve	Lathe	Cannot Operate	Valve Core Stuck	Spool Valve Stuck	4	5.682	1.776
	Lathe	Cannot Operate	Clogging	Control Oil Line Failure	4	13.262	9.667

4.3 Control System FMECA Analysis

The control system is the "intelligent core" of the manufacturing unit, formulating and inputting operational programs for the actuating components. The system consists of multiple modules, coordinating the synergistic actions of the manufacturing unit processes to ensure that the machining process proceeds in an orderly manner. The FMECA analysis results for the rotor manufacturing unit control system are shown in Table 3:

Table 3 FMECA Analysis of the Control System

Faulty Component	Equipment	Failure Mode	Cause of Failure	Effect of Failure	Severity Level	Failure Rate(10^{-4}/h)	Hazard Level(10^{-5}/h)
Power Supply Module	Lathe	Unable to Start Normally	Module Fault	Unable to Power On the Machine	3	3.788	0.484
	Machining Center	Unable to Start Normally	CNC Parameter Error	Unable to Power On the Machine	2	11.363	4.352
Program Module	Lathe	Not Running	CNC Parameter Error	Operation Interrupted	3	15.154	10.323
	Lathe	Program Alarm	CNC Parameter Error	Operation Interrupted	3	28.412	27.205
	Machining Center	False Alarm	CNC Parameter Error	Operation Interrupted	2	22.733	17.414
Encoder Module	Lathe	Program Not Running	Signal Conversion Fault	X11 Axis Alarm	2	7.576	1.934

4.4 Transmission System FMECA Analysis

The main task of the transmission system is the material transfer between the manufacturing unit's equipment, which includes rolling guides. The FMECA analysis results for the rotor manufacturing unit's transmission system are shown in Table 4:

Table 4 FMECA Analysis of the Transmission System

Faulty Component	Equipment	Failure Mode	Cause of Failure	Effect of Failure	Severity Level	Failure Rate(10^{-4}/h)	Hazard Level(10^{-5}/h)
Sensor	Loading and Unloading Roller Conveyor	Stuck	Sensor Contaminated	Roller Conveyor Not Moving	2	30.301	21.083
		Damaged	Sensor Damaged	Roller Conveyor Not Moving	3	15.154	7.905
Positioning Block		Damaged	Fixing Screw Detached	Feeding Failure	4	3.788	0.659
Motor		Stuck	Motor Bearing Stuck	Roller Conveyor Not Moving	4	7.576	2.635
Sensor	Buffer Zone Roller Conveyor	Stuck	Sensor Contaminated	Roller Conveyor Not Moving	2	26.523	16.143
Material Stop Block		Damaged	Material Stop Block Shape Deformed	Workpiece Surface May Be Damaged	4	3.788	0.659

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4.5 Camera System FMECA Analysis

The camera system is a machine vision technology that, through the use of cameras or other image sensors, captures image information from the external environment to perform operations such as object recognition, positioning, and tracking in the scene. This system is of great significance in assisting robots to complete tasks and improve operational precision and autonomy. The FMECA analysis results for the rotor manufacturing unit's camera system are shown in Table 5:

Table 5 FMECA Analysis of the Camera System

Faulty Component	Equipment	Failure Mode	Cause of Failure	Effect of Failure	Severity Level	Failure Rate(10^{-3}/h)	Hazard Level(10^{-3}/h)
Camera	Camera System	Poor Image Quality	Lens Contaminated with Oil	Unable to Capture Workpiece	2	1.693	5.713
		Image Loss	Optical Sensor Damaged	Unable to Capture Workpiece	5	0.287	0.397
		Unable to Operate	Camera Circuit Fault	Unable to Capture Image	4	0.564	1.270
Image Processing Module		Software Failure	Calculation Error or Infinite Loop	Unable to Capture Image	5	6.480	20.952
		Hardware Failure	Processor Overheating	Unable to Capture Image	3	0.425	0.536

4.6 Summary of Major Causes

Through the FMECA analysis of the above key functional subsystems, the following prominent failure issues were identified:

(1) During the workpiece handling process, due to unreasonable robot movement sequencing, the air tube cover on the actuator frequently detaches, interrupting the production flow. Repairing and debugging the robot usually takes a long time, which impacts overall production efficiency.

(2) There is a significant lack of smoothness in the feeding process, and material roller jams frequently occur, leading to blockages in the feeding rollers. Additionally, the wear rate of the positioning pins is high, and the structural design is inadequate, all of which contribute to the instability of the feeding process.

(3) The Z3 axis belt on the lathe is prone to breakage, and severe tool wear or insufficient rigidity of the lathe tools can cause vibrations, leading to tool breakage. This not only increases tool usage costs but may also affect machining accuracy.

(4) In the machining center, the accumulation of metal chips between the tool holder and spindle can prevent proper tool clamping. Excessive feed rates, severe tool wear, or insufficient rigidity can also cause vibrations, leading to tool breakage. These issues negatively impact the machining process.

(5) In the hydraulic system, frequent jamming and clogging of the high-pressure pump and high-pressure filter are mainly due to contaminants entering the hydraulic oil, which affects the normal operation of the hydraulic system.

(6) In the electrical system, various switch failures are a major source of issues. These failures are mostly caused by loose switches and improper installation positions. Additionally, battery depletion without timely replacement is a common problem.

(7) In the pneumatic system, cylinder failures in the machining center tool changer occur frequently and are difficult to repair, mainly due to excessive moisture content in the compressed air. Furthermore, the machining center's inconvenient water-removal operation for the air source leads to water entering components such as the air valves.

(8) In the camera system, the camera software experiences calculation errors and freezing issues, which severely impact production cycle time and efficiency.

4.7 Main Improvement Measures

To improve the reliability of the rotor manufacturing unit in response to common failure issues, the following improvement measures can be implemented:

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(1) Robot Workpiece Handling

A replan and optimization of the robot's motion sequence are conducted to reduce the risk of tracheal hood detachment from the actuator.Specific measures include adjusting the sequence of workpiece gripping and placement to avoid excessive force on the air tube cover.In terms of structural optimization, the connection strength between the tracheal hood and the actuator has been increased, and a tracheal hood with an easy-locking design has been adopted.

(2) Feeding Process

The structural design of the feeding roller conveyor and positioning pin is optimized; wear-resistant materials are selected for the positioning pin, and an adjustable positioning pin structure is adopted. The roller conveyor is debugged to ensure smooth material transfer and to prevent stagnation. Where conditions allow, automated feeding equipment should be used to enhance the stability of the feeding process.

(3) Lathe Section

The risk of belt breakage can be reduced by selecting high-strength, wear-resistant belt materials. To address the issue of severe tool wear in the lathe, it is recommended to optimize tool material selection, such as using carbide or ceramic tools, to improve tool wear resistance. At the same time, the rigidity and stability of the tool are increased, and the risk of tool breakage caused by vibration is reduced by improving the tool structure and shank clamping method.

(4) Machining Center Spindle and Tool Holder

Equipment cleaning is enhanced, regular spindle cleaning and maintenance are performed, and cutting parameters are optimized to minimize tool wear and vibration, thereby reducing the risk of tool breakage.

(5) Hydraulic System

Engineers perform regular cleaning and maintenance of the hydraulic system to ensure stable operation, including adding filters, regularly replacing filter screens, and using system cleaners to remove oil residues. These measures will ensure normal operation of the hydraulic system and reduce the risk of jamming and clogging failures.

(6) Pneumatic System

The quality of compressed air is enhanced, additional air dryers and filters are installed, and regular air bleed operations are conducted to prevent water ingress into airway components. For cylinder failures in the machining center tool changer, it is recommended to use moisture-resistant cylinder materials to reduce the failure rate.

(7) Camera System

The parameters are reset, the number of consecutive photos is increased, a light source is added and its brightness is adjusted, and the software parameter settings are optimized to improve image quality.

(8) Operators

Operator skills training is enhanced to prevent misoperation, warning signs are arranged to remind operators of critical operations, and on-site supervision and guidance are reinforced to ensure proper operation.

5. Conclusion

This paper aims to systematically introduce the definition, classification, and main contents of Failure Modes, Effects, and Criticality Analysis (FMECA) methods, and explore their specific application in the failure analysis of the rotor manufacturing unit. By clearly defining the hierarchical structure and failure criteria of the rotor manufacturing unit, a thorough failure modes, effects, and criticality analysis was conducted on its five key functional subsystems, resulting in detailed FMECA analysis tables. Finally, the paper summarizes the most prominent failure issues in the rotor manufacturing unit and proposes a series of improvement measures, aiming to provide scientific evidence and technical support for the reliability management and optimization of the rotor manufacturing unit.

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