Reliability analysis of cooling system of CNC grinding machine based on FTA analysis

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Abstract. In view of the lack of relevant research on CNC grinders in the field of reliability research of CNC machine tools at present, this research collected reliability data based on 19 MSK series grinder machine tools of a machine tool factory, found out the crucial subsystem which is the most important component to the whole, and analyzed the reliability of the subsystem adopting FTA (Fault Tree Analysis). Statistical researched on 438 reliability data collected, combining with the actual production situation, the results shows that cooling system is the key to the reliability of the whole grinder machine tool. The 29 minimum cut sets obtained by FTA can be adjusted to improve the reliability of the cooling system, what is more, the reliability of grinder machine tool would be improved as well.

1. Introduction
CNC machine tool is the foundation of equipment manufacturing, found an increasingly wide utilization in various of modern large-scale industrial production automation. The reliability of CNC machine tool is of vital importance to the quality, efficiency, production cost and market competitiveness of modern production. Consequently, assessment of the reliability is of critical significance for trail-manufacturing the machine tools. Researchers could eliminate hidden trouble as well as get improvement and amendment with this approach.

There have already been a few researches in forecasting failure of a CNC machine tool to analyze the reliability of CNC containing condition characteristic index, computation of instantaneous reliability, and construction and application of the prediction model. Scientists and technicians of some universities in Britain start with collecting on-site reliability information of NC machine tools, establishing the database of reliability, analyzing and dealing with the data of reliability to find the contribution rule and the weak links. Ansell [1] has analyzed the field data collected in warranty period within three years to 35 CNC machine tools. He has designed a coding system to code of failure data. It is convenient to quantitative analysis of reliability methods [1]. Shen GX has evaluated the reliability of CNC machine tools by an entropy weight method for objectively empowering, overcoming the defects of subjectively determining weight in traditional weighted comprehensive evaluation method, calculating the weight of each index, evaluating comprehensively to the reliability of CNC machine tools [2]. L.C. Tang improved FMEA (Failure Mode and Effects Analysis) which is a traditional reliability analysis method, corned a different FMEA technology based on fuzzy logic and Prototype evaluation expert system. The advantages about the technology are as following. Firstly, it is able to reflect the real-time situation more...
truly and flexibly, own to that the failure messages in FMEA are described as fuzzy variable. Secondly, due to discussing various relationships between the failure models and the effects, the reasoning model is able to react to most serious effect of the failure model at the stage of reasoning. Lastly, the expert evaluation system Integrating the expertise of engineers adequately during the whole analysis process, so that it could complete quantitative analysis to save cost [3].

Nevertheless, few researchers have addressed the field about CNC grinder. what’s more, almost all of the researchers concentrate on researching of the complete machine, so that absence the separate study of subsytems whose failure data is superb than any other systems, and then, it is insufficient to reduce the frequency of failures fundamentally and improve the reliability of CNC grinder, owing to without redefining the group of the faults.

In this study, we collected fault data of a series CNC grinder for one and a half years, found out the weak link, and got key subsystems before analysis. Then, analyzed the key subsystem (cooling system)’s reliability adopted Fault Tree Analysis (FTA), which is a convenient method to trace parts with frequent faults. Last but not least, took steps to improve the problematic components by the fault data analyzing upon.

2. Collection and classification of fault data

2.1. Principles of data acquisition
It is necessary to collect enough fault data to increase the credibility of the statistics. Timing truncation reliability test is usually used in this process. The principles are as following[4]:
1) The fault is defined the event that could not accomplish the wanted function under prescribed conditions and time, owing to quality defects of CNC grinding machine tool.
2) Early failure before user use exclude faults since that it is outside the prescribed interception range.
3) Local minor faults that are not related to the function of the whole machine temporarily or have little influence on it ,like damage of machine tool lighting, exclude faults as no downtime loss caused.
4)Other faults caused by an associated fault are counted as only one fault, for example, if hydrostatic spindle is damaged due to hydraulic system failure, only one fault of "hydraulic system failure" is recorded.

2.2. Data grouping and processing
Dividing subsystems rationally is crucial to follow-up reliability analysis, modeling and optimum design, it need to take comprehensive factors into consideration, like the feature of its structure, consensus of industry enterprises, as well as function division in NC grinding machine design, manufacturing and outsourcing. Above all, the research divide the grinder machine tool into 11 subsystems[5], as shown in Fig.1.
There are two parts of source in this research. One part is obtained by grinder manufacturers from grinder users, another part is collected by the project team at the production site of the enterprise. There are 438 pieces of fault data totally collected by tracking and statistics of 19 MKS series CNC mills. Statistical information of fault location of collected data is shown in table 1.

Table 1. Statistics of fault location of CNC grinding machine.

| Subsystem code | Subsystem                        | Frequency number | Frequency    |
|----------------|----------------------------------|------------------|--------------|
| BS             | basic system                     | 29               | 0.0388       |
| NC             | NC system                        | 77               | 0.1029       |
| SD             | spindle system                   | 63               | 0.0842       |
| FD             | feed system                      | 23               | 0.0321       |
| SV             | servo system                     | 14               | 0.0187       |
| EC             | electronic control system        | 141              | 0.1885       |
| HY             | hydraulic system                 | 44               | 0.0588       |
| CL             | cooling system                   | 94               | 0.1257       |
| LB             | lubrication system               | 55               | 0.0735       |
| HS             | headstock system                 | 148              | 0.1965       |
| MI             | measuring instrument system      | 60               | 0.0802       |

Figure 1. Subsystem division of CNC grinding machine.
As can be seen from the figure, it is obvious that headstock system, electronic system and cooling system are the three system with the highest failure frequency in working process. In this research, CNC grinder machine with double grinding wheels were adopted. The cooling system play a crucial role in this kind of CNC grinder machine, while, the system is used in cooling workpiece and grinding wheel in case that the temperature is too high to cause faults, rinsing the debris embedded in the gap of the grinding wheel and on the bed to make sure machine tool clear. Owing to the importance upon, this article choose cooling system to analyse the reliability.

3. FTA of cooling system

FTA is a design analysis method, that could reduce probability of failure, improve the reliability of a system. In the process of analysis, the factors (such as hardware, software, environment, human factors)\[6\]to be taken into account are whose breaking could fault the whole system. In this way, researchers are supposed to analyze the faulting factors, and paint logic block diagrams, which are the Fault Tree models, to determine possible combinations that cause the fault of system and the occurrence possibilities. Then the fault possibility of the system would be calculate, engineers could take corresponding measurements to deal with these mistakes.

FTA consists of qualitative and quantitative analysis\[7\]. The purpose of the qualitative analysis is to find out the causes and combination causes leading arises of the top event, as well as identify all failure modes that cause top events to occur. By this means, the potential faults would be identified to optimum design, what’s more, it is helpful to guide fault diagnosis, improve the plan of operation and maintenance. When it comes to quantitative of FTA, the task is that find all of the minimal cut sets of the fault tree. It is useful to calculate and estimate the probability that the top event occurs. In this way, engineers would be more easily to make decision in maintenance, design, etc. While, the probability of the top event occurring could be solved by minimal cut sets in the process of quantitative computation.

Above all, FTA is a method whose ability of analysis, logic and solving route is intuitive, strong and clear, resulting in its capability of qualitative and quantitative analysis. The reliability of designated system would be dramatically improved. The procedure of FTA is as follow: Choose a reasonable top event; Build up a fault tree according to the reasons of fault occurring and the events at each level are represented in their own codes. Determine the minimal cut sets by qualitative analysis. Find out the weak links and solve them.

3.1. Establishment of fault tree for cooling system of CNC grinding machine

A fault tree represents the logical relationship between the basic event and the defined top event. Its establishing is the key to FTA. The specific steps are as follows:
1) Select and choose appropriate top events, which denote the most undesirable events or the failure in the process of logic analysis.

2) Analyse top events, that means, find out the direct, necessary and sufficient cause of top events. Then, define top events and all direct causes as output events and input events, while, according to the logical relationships of all of upon events, link output events and input events with logic gates.

3) Analyse the input events directly connecting to the top event. If a event is able to be further decomposed, it would be the output event of the next level, then, turn to step2.

4) Repeat. A fault tree is accomplished, when all of the input events couldn’t decompose any more.

In this research, the key subsystem to the reliability of double grinding wheels CNC grinder machine tool is cooling system. Extract the data of cooling system from all of the data collected in the field timing truncation test, define events and codes at each level according to the data of cooling system, as shown in table 4-7 and establish the fault tree of cooling system, as shown in fig 4, which combine with actual faults and guidance of technicians.

Table 2. Layer 1 Events and Codes.

| Event name          | Event code |
|---------------------|------------|
| Cooling system      | A          |

Table 3. Layer 2 Events and Codes.

| Event name                                      | Event code |
|------------------------------------------------|------------|
| Turning Accuracy Exceeding Standard            | B01        |
| Machining Accuracy Exceeding Standard          | B02        |
| Detecting Component Failure                    | B03        |
| Data Transmission Anomaly                      | B04        |
| Component Redundancy                           | B05        |
| Executing Element Accident Stop Failure        | B06        |
| No Speed or Low Actuator                       | B07        |
| Impulse of Actuator                            | B08        |

Table 4. Layer 3 Events and Codes.

| Event name                                      | Event code |
|------------------------------------------------|------------|
| Loosening of Transmission Components           | C01        |
| Damage of Transmission Components              | C02        |
| Damage of Electrical Components                | C03        |
| Insufficient Stiffness                         | C04        |
| Parts Failure                                  | C05        |
| Poor Accuracy of Parts and Components           | C06        |
| Parts Interfere with Each Other                | C07        |
| Damage of Supporting Parts                     | C08        |
Table 5. Layer 4 Events and Codes.

| Event name                  | Event code | Event name                  | Event code |
|-----------------------------|------------|-----------------------------|------------|
| Belt Damage                 | D01        | Belt Fracture               | D16        |
| Parameter Error             | D02        | Belt Wear                   | D17        |
| Improper Operation          | D03        | Belt Loosening              | D18        |
| Low Precision of Baffle Ring| D04        | Ungrounding line            | D19        |
| Tip Wear                    | D05        | Signal Line Break           | D20        |
| Bad Dynamic Balance         | D06        | Signal Line Loosening       | D21        |
| Insufficient Clamping Force | D07        | Too High Modification Speed | D22        |
| Contactor Damage            | D08        | Improper Selection          | D23        |
| Bearing Deformation         | D09        | Component Loosening         | D24        |
| Claw Damage                 | D10        | Stent Damage                | D25        |
| Switch Damage               | D11        | Bearing Cover Damage        | D26        |
| Switch link break           | D12        | Bearing Loosening           | D27        |
| Deformation of Joint        | D13        | Bearing Damage              | D28        |
| Surface of Parts            | D14        | Unreasonable Assembly       | D29        |
| Low Nut Precision           | D15        | Low Bearing Accuracy        | D30        |

In cooling system of the CNC grinder machine tool, as can be seen in Fig. 4, the main causes of breaking of cooling system are: coolant unclean cleaning, fault of magnetic roller, belt damage, motor damage, damage to pipes and joints, poor sealing, fault of hydraulic pump, compressor damage, radiator damage, etc. Magnetic sticks, belts, motors, pipes, joints, cooling pumps, compressors, radiators, etc., as external purchases, are supposed to enhance quality assessment of partners in the process of purchasing to improve the quality of outsourcing parts. It is also supposed to clean up debris and iron powder filtered out of coolant in regular to make sure the cleanliness of coolant and reduce damage frequency of cooling system. What is more, degree of damage to pipes and joints should be checked periodically, replace in time if the component damaged, make sure the reliability of cooling system, and improve the reliability of the CNC grinder machine tool.

Figure 3. Fault tree of cooling system.

3.2. Qualitative analysis of fault tree

After the establishment of fault tree, the image description of the relationship between failure events was provided, and the role of different failure modes in the occurrence of top events was drawn. Based on this, qualitative analysis of fault tree is carried out, it analyse the rules and characteristics of a certain type of faults, find a feasible way to control events, and analyse basic cause events from the fault tree structure to take measures to solve the problem of faults fundamentally.

In this research, Semanderes algorithm was used to solving minimum cut sets of cooling system fault tree, it is developed by Semanderes in 1972[8]. Its basic principle is that it could utilize gate structural functions to the lowest intermediate event of the fault tree, if intermediate events were linked by logic
to the underlying events. While, if an intermediate event was a logical OR gate associated with the underlying event, choose the OR gate structural function formula. Then, calculate till the top. Results would be simplified by Boolean algebra if their bottom events are the same. Simplify by set operating rules step by step till get the minimum cut sets.

The lowest level of a fault tree is:

C03=D08+D11
C02=D05+D16+D17+D128
C01=D01+D16+D18+D23+D24+D27+D29
C06=D04+D14+D26+D30
C04=D13+D15+D09+D29
C03=D11+D12
C05=D10+D28
C08=D25+D28+D29

The next level is:

B06=C03+C02=D05+D08+D11+D12+D16+D17+D28
B05=B05
D07=D07
B02=C01+D06+D29+C02=D05+D06+D16+D17+D18+D23+D24+D28+D29
D03=D03
B08=D29+C01+C08=D01+D16+D18+D23+D24+D25+D27+D28+D29
D22=D22
C07=D23+D29
B01=C06+C04+D04+D09+D14+D13+D15+D26+D29+D30
C03=D08+D11
B03=C03+C03+D29=D03+D11+D12+D29
B11=D20+D21
D19=D19
B07=C01+C02+C05+C08+D02
=B01+D05+D10+D16+D17+D18+D23+D24+D25+D27+D28+D29

The top level is:

A=B06+B05+D07+B02+D03+B08+D22+C07+B01+C03+B03+B04+D19+B07
=B05+D01+D03+D04+D05+D06+D07+D08+D09+D11+D12+D13+D14+D15+D16+D17
+D18+D19+D20+D21+D22+D23+D24+D25+D26+D27+D28+D29+D30
So, the minimal cut sets are: \{B05\} \{D01\} \{D03\} \{D04\} \{D05\} \{D06\} \{D07\} \{D08\} \{D09\} \{D11\} \{D12\} \{D13\} \{D14\} \{D15\} \{D16\} \{D17\} \{D18\} \{D19\} \{D20\} \{D21\} \{D22\} \{D23\} \{D24\} \{D25\} \{D26\} \{D27\} \{D28\} \{D29\} \{D30\}.

Represents the k minimal cut sets of the fault tree with C1, C2,……,Ck, the structure function of the fault tree is as follows:

$$\phi(X) = \bigcup_{j=1}^{k} C_j$$  \hspace{1cm} (1)

In the equation (1), k represents the number of minimal cut sets, Cj represents the j (j=1, 2, ……, k) minimum cut set in the fault tree.

It can be obtained by computation that there are 29 minimal cut sets in the fault tree of the cooling system of the CNC grinder machine tool. From the result, it is obvious that every bottom events would influence the top event. Actually, a fault tree could be described qualitatively by its structural function, and the reliability of the cooling system could be improved by solving the weak links finding out of the calculating minimal cut sets.
3.3. Quantitative analysis of fault tree

If all minimum cut sets ($C_1, C_2, \ldots, C_k$) and the probability of all bottom events ($x_1, x_2, \ldots, x_n$) occurrence of a fault tree were known, calculate the probability of the top event occurrence.

$$F = P(T) = \bigcup_{j=1}^{k} C_j$$  \hspace{1cm} (2)

In equation (2), $P$ denotes the probability of the top event occurrence, while $P(T)=F_i$, $F_i$ denotes the system failure probability. Then, the reliability, which is represented by $R$, of the system would be computed as equation (3).

$$R = 1 - F$$  \hspace{1cm} (3)

Finally, bring 29 unrelated minimal cut sets into equation (2), the failure probability and the reliability of the cooling system would be calculated, as shown in equation (4).

$$F = P(C_1) + P(C_2) + \cdots + P(C_j)$$  \hspace{1cm} (j=29)  \hspace{1cm} (4)

3.4. Results and measurements

Adopting above method, FTA, weak links of every subsystems would be checked out, and then, it would be better to correspond measures to the weak parts. For instance, analyze the problem that turning accuracy exceeded the standard whose frequently happening often lead to be broken. Then, adjust the bottom events Combining the minimum cut sets corresponding to B01 which are the causes of exceeding the standard of rotary accuracy, and Observing the change of fitting curve, shown in fig.7, of degraded track of rotation error to find the appropriate parameters of it to improve the reliability of the system.

![Fitting curve of rotation error degradation trajectory](image)

**Figure 4.** Fitting curve of rotation error degradation trajectory

4. Conclusion

The gap that the ignorance of reliability data collecting and analysis of CNC grinder machine tool, which require high accuracy has not been filled for a long time. In this research, viewing of this research situation, the research team entered the production workshop, accumulated 438 pieces of fault data by monitoring the working condition of 19 grinder machine tools of MSK series and found out the subsystem that have the greatest impact on the reliability of CNC machine tools, cooling system, by In-depth analysis of the distribution law of fault data. Then, Qualitative and quantitative analyze of cooling
system by FTA to find out the crucial components leading to frequency failure. Finally, proposed the solution to improve the reliability in term of ameliorating rotation error.

With this method, the reliability of the grinder machine tool improved obviously. One of the main evaluation indicators, MTBF (Mean Time Between Failure) increased to 2000. In the future, this analysis method would be applied to other types of machine tools and it will be of great importance in the field of machine tool reliability.

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