Advances in Machinery, Materials Science and Engineering Application IX
M. Chen et al. (Eds.)

doi:10.3233/ATDE230473

Reliability Analysis of Reducer Gears Based on FTA

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Abstract. As a common power transmission component in the heavy industry field, reducers are widely used in wind turbines, lifting mechanisms, rail travel mechanisms, and many other occasions. If the transmission gear fails during operation, it will lead to serious consequences. Therefore, it is necessary to conduct reliability analysis on them to reduce the number of failures. This paper presents an analysis of the operating environment for a specific level of gears in a gearbox, taking into account potential gear failures and the impact of failures in other components. The reliability of the gear's operating environment is modeled using the fault tree analysis method. By collecting relevant event failure rate data and failure time data for seal failures in gearboxes obtained from the company, parameter estimation of the failure distribution for seal failures is performed using the maximum likelihood estimation method. The data obtained from the calculation of the distribution functions for each event failure is used to conduct quantitative analysis of the fault tree. Based on the results of the quantitative analysis of the fault tree, the weak links in the system, which are important failure factors affecting the normal operation of the gear, are identified. Guiding improvement suggestions are provided to enhance the reliability of gearbox gear operations.

Keywords. Reducer gear, operating environment, fault tree analysis, weak link

1. Introduction

As a commonly used power transmission device for large equipment products, reducers are widely used in the energy field. For example, in the pitch system of wind turbines, the motor drives the reducer to maintain the rotation of the blades according to a specific wind direction [1], and in the yaw system, the reducer is used to regulate the rotation of the cabin; The lifting process of an offshore operating platform using the meshing of gear teeth and racks of a gearbox [2]; The movement of various cranes and lifting of heavy objects at the shipping dock. Due to the frequent involvement in the safe operation of major equipment, it is self-evident that the reliability requirements of the gearbox are high. Once a malfunction occurs, it can cause power transmission to stop, and in severe cases, it can lead to device damage and casualties. As shown in figure 1, according to relevant research conducted by enterprises, it is known that the transmission gear of the reducer often malfunctions during actual use, which affects the progress of engineering projects. Therefore, it is imperative to study the reliability of the reducer gear.

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This paper takes a model reducer of a well-known reducer manufacturing enterprise as an example, analyzes the functional principle of its gear, collects the corresponding fault types and uses Fault tree analysis to model the reliability of the reducer gear [3]. Considering the integrity and wide application of the fault tree, the operation environment of the reducer gear is considered, and the fault Tree model based on the overall operation environment of the gear is established; Then, the distribution of each bottom event will be solved through the collected relevant data, and the probability data of the bottom event will be obtained before the quantitative analysis of the fault tree [4]. Based on the results of the Fault tree analysis, the key faults that affect the normal operation of the gear, namely the weak links, will be identified and suggestions for improvement will be put forward.

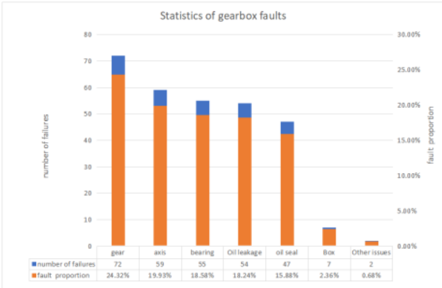

Figure 1. Classification and statistics of gearbox faults.

2. Reliability Modeling of Reducer Gears

2.1. Fault Tree Analysis

By comprehensively grasping the structural and functional failures of the system, taking the least desirable event in the system as the top event, identify all the causal events that cause the event to occur, and treat them as intermediate events. Then, analyze each intermediate event in detail, identify all the next level events that cause the intermediate event to occur, and so on, until the lowest level causal event is found, and treat it as the bottom event [5], The upper and lower level events are connected together by means of logic gates to form a pyramid like inverted Tree structure, which is called fault tree.

2.2. Establishment of Fault Tree for Reducer Gears

2.2.1. Introduction to the Operating Environment of the Reducer Gear

Due to the need to establish a fault tree graph about the gear operating environment, the situation of the gear operating environment can be understood through the description of structural functional principles. The direct contact includes the shaft and lubricating oil parts, and the indirect contact includes the bearing components. However, the specific fault tree establishment process still needs to be carried out through common fault situations. Through the description of the operating environment of the gear and the collection of common fault conditions, a fault Tree model of gear failure of the reducer can be established. The internal structure and function diagram of the reducer is shown in figure 2:

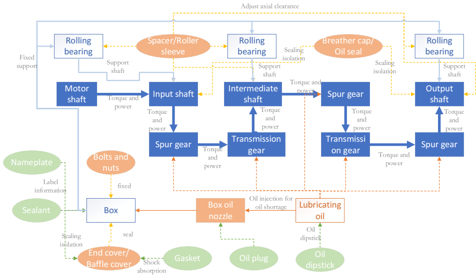

Figure 2. Structural and functional block diagram of a certain type of reducer.

2.2.2. Fault Tree of Gearbox Gears

Based on the analysis of the operating environment of the reducer gear in the previous text and the collected relevant fault modes, a fault tree diagram can be established as shown in figure 3. The main events mainly include gear tooth fracture, tooth surface damage, wheel body cracks, and other fault modes and mechanisms related to the gear itself, as well as other components such as shafts, bearings, and lubrication systems that may affect the normal operation of the gear [6-8], It is necessary to consider the many factors that may affect the operation of gears in order to better determine the important reasons for gear failure.

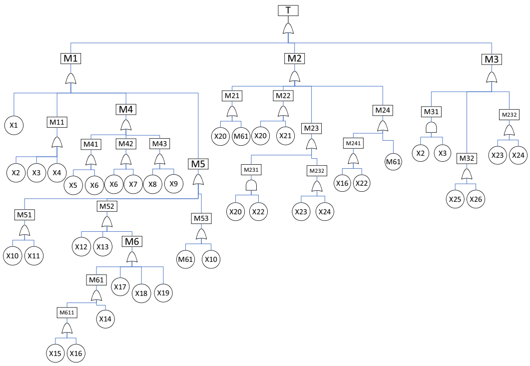

Figure 3. Fault tree of gearbox gears.

3. Quantitative Analysis of Fault Trees

3.1. Bottom Event Related Data and Distribution Solution

3.1.1. Obtaining Fault Data

Considering that it is difficult to obtain data on the failure rate of some bottom events, one method is to search for data on the intermediate events above it, and the other method is to process fault data of similar products for components with the same name [9-11]; The bottom event failure distribution with fixed failure rate is described by

Exponential distribution. The failure rate data sorted out comprehensively is shown in table 1 below:

Table 1. Failure rate of each event.

Fault Code	Event Name	λ/10^(-6) $\boldsymbol{times}$ ·h^(-1)	Fault Code	Event Name	λ/10^(-6) $\boldsymbol{times}$ ·h^(-1)
X1	Fatigue fracture	2	X14	Insufficient oil injection in the box	0.001
M11	Overload fracture	1.2	X15	Deterioration of lubricating oil	2
X5	Poor shaft material	1.4	X16	Impurities in lubricating oil	2
X6	Serious shaft overload	0.5	X17	Fault of electric oil pump	37.3
X7	Insufficient shaft processing accuracy	0.4	X18	Magnetic failure of drain plug	0.0221
X8	Improper shaft assembly	2	X20	Heavy-duty operation	5
X9	Shaft fatigue damage	1.2	X21	Rupture of lubricating oil film	1.5
X10	Serious bearing overload	1.2	X22	Foreign object intrusion between meshing teeth	0.5
X11	Poor bearing quality	0.02	X23	Improper gear assembly	0.8
X12	Variation of bearing clearance	0.5	X24	Inadequate pre-tightening force of important bolts	0.12
X13	Improper bearing installation	1.1	M32	Gear manufacturing problem	0.4

For the important bottom event of sealing failure, considering the many fault factors involved, it is simplified as one event for calculation. According to literature reading and considering engineering practice, sealing failure generally follows a Weibull distribution [12]. This article will use a two-parameter Weibull distribution to present the failure distribution function of sealing failure.

When the distribution is known, it is necessary to solve the distribution parameters. In this paper, maximum likelihood estimation is used to calculate the Weibull distribution parameters [13]. Through data collection, analysis, and integration by enterprises, the required small sample data of sealing failure is shown in table 2.

Table 2. Sealing failure time.

Number	Fault time t/h	Number	Fault time t/h
1	4584	11	13584
2	5328	12	15096
3	5712	13	15336
4	7416	14	15360
5	8064	15	15432
6	9960	16	18864
7	11088	17	18984
8	11688	18	23064
9	12192	19	32352
10	13488	20	38928

3.1.2. Maximum Likelihood Estimation

3.1.2.1. Solving the Fault Distribution of Sealing Failure

To solve parameters using the maximum likelihood method, it is necessary to know the failure probability density function of the specified distribution [14]. The failure probability density function of the two-parameter Weibull distribution is shown in equation (1):

$$f(t) = \frac{m}{\eta}\left(\frac{t}{\eta}\right)^{m-1} \exp\left[-\left(\frac{t}{\eta}\right)^{m}\right] \ (m,\eta > 0, t \geq 0) \tag{1}$$

Make$L = \prod_{i=1}^{n} f(t_i; m, \eta)$, this is the likelihood function. When L is maximum, the required parameter m,η estimation value are obtained. Obviously, it is necessary to derive the function, but it is troublesome to directly calculate the exponential form. According to the common means, both sides take the logarithm. The above likelihood function can be transformed into equation (2):

$$\ln(L) = n \cdot \ln m - n \cdot m \ln \eta + (m-1)\sum_{i=1}^{n} \ln(t_i) - \frac{1}{\eta^m}\sum_{i=1}^{n} (t_i)^m \tag{2}$$

In the above equation, n is the random sample size,$t_i$is the sample value, which is the time value of the gearbox seal failure during the subsequent paper writing process. In order to find the two undetermined parameters, we need to find their partial derivatives [15]. The likelihood function equations about the two parameter Weibull distribution are as follows (3):

$$\begin{cases} \frac{\partial \ln L}{\partial m} = \frac{n}{m} - n \ln \eta + \sum_{i=1}^{n} \ln(t_i) - \frac{\ln \eta}{\eta^m}\sum_{i=1}^{n} (t_i)^m - \frac{\sum_{i=1}^{n} (t_i)^m \ln(t_i)}{\eta^m} = 0 \\ \frac{\partial \ln L}{\partial \eta} = -\frac{n \cdot m}{\eta} + \frac{m}{\eta^{m+1}}\sum_{i=1}^{n} (t_i)^m = 0 \end{cases} \tag{3}$$

For solving this kind of nonlinear equations, software tools can be used to fit graphs as shown in figure 4 and figure 5:

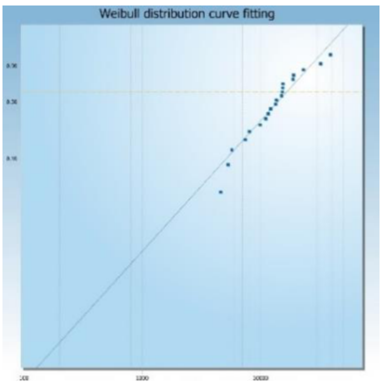

Figure 4. Weibull distribution curve fitting.

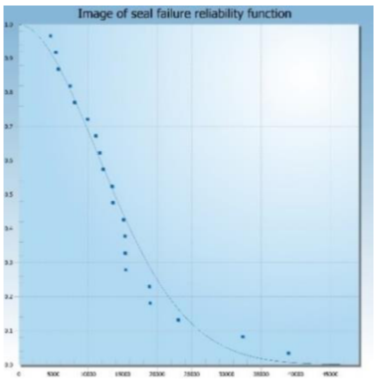

Figure 5. Image of seal failure reliability function.

The parameter values obtained from software analysis combined with the two-parameter Weibull distribution formula can be used to determine the fault distribution function of sealing failure, as shown in equation (4):

$$F(t) = 1 - \exp\left[-\left(\frac{t}{16804}\right)^{1.887}\right](t \geq 0) \tag{4}$$

3.1.2.2. Solving other Event Distribution Functions

When the event failure rate is a constant value, the distribution it obeys is Exponential distribution according to the previous description. The expression of the reliability of the Exponential distribution is as follows (5):

$$F(t) = 1 - e^{-\lambda_i t}(t \geq 0) \tag{5}$$

3.2. Results of Quantitative Fault Tree Analysis

3.2.1. Probability of Occurrence of Event Faults

After obtaining the cumulative failure probability distribution of each event that needs to be calculated, taking the gearbox gear running for 10800 hours as an example, the failure probability of each event at that time can be calculated as shown in table 3:

Table 3. Probability of failure occurrence for each event.

Fault Code	**Probability of failure occurrence**	**Fault Code**	**Probability of failure occurrence**
X1	0.02137	X15	0.02137
M11	0.01288	X16	0.02137
X5	0.01500	X17	0.33159
X6	0.00538	X18	0.00024
X7	0.00431	X19	0.35223
X8	0.02137	X20	0.05257
X9	0.01288	X21	0.01607
X10	0.01288	X22	0.00538
X11	0.00021	X23	0.00860
X12	0.00538	X24	0.00129
X13	0.01181	M32	0.00431
X14	0.000011		

3.2.2. Solution of Critical Importance

The key importance formula of the fault tree can be used to obtain the key importance of each event. After sorting them, it is shown in table 4 that sealing, electric oil pump failure, and heavy load are the main factors that cause gear operation failure. It is necessary to pay special attention to these factors.

Table 4. Critical importance of each event.

Fault Code	Event Name	Critical importance of events	Fault Code	Event Name	Critical importance of events
X19	Sealing failure	0.23840	X13	Improper bearing installation	0.00524
X17	Fault of electric oil pump	0.21749	X23	Improper gear assembly	0.00380
X20	Heavy-duty operation	0.02433	X6	Serious shaft overload	0.00237
X1	Fatigue fracture	0.00957	X12	Variation of bearing clearance	0.00237
X8	Improper shaft assembly	0.00957	X22	Foreign object intrusion between meshing teeth	0.00237
X15	Deterioration of lubricating oil	0.00957	X7	Insufficient shaft processing accuracy	0.00190
X16	Impurities in lubricating oil	0.00957	M32	Gear manufacturing problem	0.00190
X21	Rupture of lubricating oil film	0.00716	X24	Inadequate pre-tightening force of important bolts	0.00056
X5	Poor shaft material	0.00668	X18	Magnetic failure of drain plug	0.00010
M11	Overload fracture	0.00572	X11	Poor bearing quality	0.00009
X9	Shaft fatigue damage	0.00572	X14	Insufficient oil injection in the box	0.0000047
X10	Serious bearing overload	0.00572			

4. Conclusion

(1) In this paper, based on the relevant fault data of reducer gears collected by a well-known reducer manufacturing enterprise, the reliability modeling of gears is carried out using the Fault tree analysis method in reliability engineering after summarizing and sorting them out; In order to reflect the integrity of the fault tree of the gearbox gear, that is, the gear not only has its own faults during operation, but also takes into account the impact of other component faults on the gear operation under its operating environment. A comprehensive analysis of the direct and indirect faults that may cause gear faults. By establishing a fault tree for the gearbox gear, it is possible to have a clearer understanding of the fault modes and mechanisms that cause gear failures.

(2) Before conducting quantitative analysis of the fault tree, it is necessary to understand the failure probability of the bottom event. This article simplifies the complex event, namely the fault subtree of seal failure, and solves the fault probability of seal failure using the time data of seal failure collected by the enterprise. The maximum likelihood estimation method is used and the Weibull distribution parameters are estimated using Relex software to obtain the fault distribution function of the event; For the probability solution of other bottom events, the specific distribution is obtained through the Failure rate data of similar products in the relevant manuals and literature. Finally, the quantitative analysis of the fault tree is carried out. According to the analysis results of the importance, it is judged that seal failure,

electric oil pump failure and heavy load operation are the important factors that cause the gear failure of the reducer. Therefore, regular maintenance and inspection of the sealing condition should be paid attention to in the actual use process, On the one hand, it is whether the welding of the box is firm and reliable, whether the sealant at the junction of the box is evenly applied, whether the pre tightening force of the bolts on the end cover is in place, whether the sealing components such as the oil seal at the penetration cover are aged or deformed, and whether there is oil leakage; On the other hand, it is necessary to observe whether there is any damage to the breathable cap, rainwater infiltration, and many factors leading to sealing failure. When inspecting, it is necessary to consider all aspects of the situation. To ensure the normal operation of the gears during operation, try to avoid the load exceeding the maximum load, and sometimes reduce the load operation to improve the service life of mechanical products.

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