Performance Reliability Assessment Method of a Pump Based on Multi-Performance Parameters

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***Abstract*—A certain type of pump is a product with long life, few failure data and high reliability, as a result, the best way to evaluate the reliability is to use the method based on performance degradation data. The structure of the pump is complex and there are multi-performance parameters. Furthermore, there are correlations among the parameters. If the traditional performance reliability evaluation methods are used to evaluate the reliability, the errors may be so large that it cannot be acceptable. Therefore, the multivariate linear regression method is used to analyze multi-performance parameters and establish regression equation to standardize the performance degradation data. Then, the Wiener process is used to fit and replace the standardized data to realize the performance reliability evaluation of the equipment.**

Keywords- life prediction; reliability evaluation; multiple linear regression; Wiener process

I. INTRODUCTION

The failure data of long life and high reliability equipment are very few, even no failure data. For the equipment with simple structure, the reliability evaluation method based on performance degradation can be used to realize the early warning and diagnosis of equipment faults, such as valves, gears, bearings and so on. In addition, for the equipment with lower procurement cost, reliability data can be obtained through a large number of reliability tests to support the data of reliability evaluation. For complex mechanical and electrical equipment such as pumps, motors and engines, there are many state performance parameters, and the trend of performance degradation is not obvious, so it is difficult to use traditional methods to achieve reliability evaluation. At the same time, because of its high purchase cost, it is difficult to bear the economic cost of carrying out a large number of reliability tests. Therefore, the lack of failure data or complete absence of complex equipment has always been a problem for relevant researchers.

A certain type of pump has the characteristics of long life and high reliability, it is a good choice to use performance degradation modeling method to evaluate the reliability based on the performance degradation data. In actual fact, the pump has many performance parameters and most parameters are unstable in the working process. Furthermore, the changes of these parameters will directly affect its key performance parameters. If the influence of other parameters is ignored, the predicted results may be far from the real situation.

Relevant research has been carried out on the reliability evaluation of such products with multiple performance parameters[1-5]. Most of the related research focuses on how to build reliability evaluation model for multi-performance degradation. Therefore, it is very necessary to study how to process the performance data of the equipment so that the data can reflect the real state of the equipment. Only in this way can we ensure the accuracy of reliability evaluation results.

In this paper, it is studied that how to build a model to process multi-performance data of equipment in order to improve the accuracy of reliability assessment results. Firstly, the data of the pump are analyzed by the method of multiple linear regression, and various factors affecting the key performance parameters are found out. The multiple linear regression equation is established to standardize the data of key performance parameters. Then, the processed data are substituted into the reliability evaluation model based on Wiener process to realize the reliability evaluation of pumps. Finally, the full paper is summarized.

II. MULTI-PERFORMANCE DATA PROCESSING

A. Data of the Pump

Through the analysis of the working principle and failure mechanism of the pump, it can be seen that the outlet pressure can be used as a key performance parameter to determine the failure state of the pump. That is to say, with the increase of working time, the pump is aging gradually and the outlet pressure decreases gradually. When the outlet pressure drops below the failure threshold, the pump is considered to be failed. There are eight parameters are recorded, including time, flow rate, inlet pressure, outlet pressure, tank pressure, electric current, DT opening and temperature. A part of data is shown in Fig. 1 to Fig. 4.

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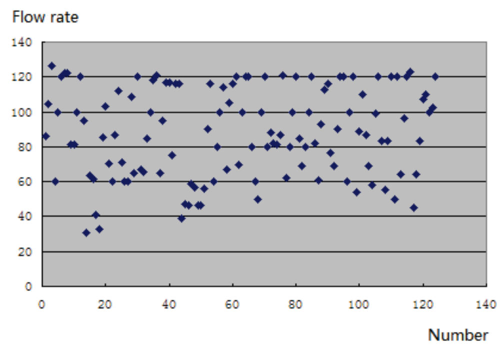

Figure 1. The data of flow rate

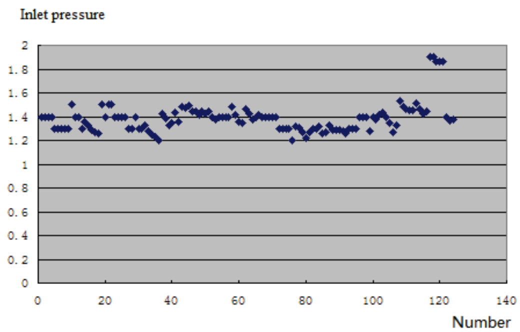

Figure 2. The data of inlet pressure

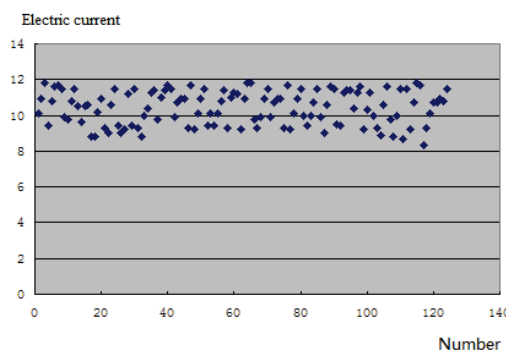

Figure 3. The data of electric current

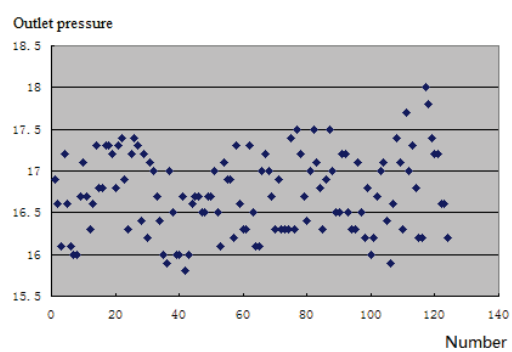

Figure 4. The data of outlet pressure

When preprocessing the above data, the hypothesis are shown as follows:

Hypothesis 1: All important factors that may affect outlet pressure have been fully recorded.

Hypothesis 2: The factors affecting the performance of the pump only change in a certain range.

Hypothesis 3: In the process of performance degradation of the pump, the influence of maintenance factors on outlet pressure can be ignored.

B. *Relevance Hypothesis Test*

The mathematical model of multiple linear regression is as follows:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_p x_p + \varepsilon \qquad (1)$$

In the formula, y is a dependent variable and a random and quantitative observation value, $x_1, x_2, \cdots, x_p$ are independent variables; β_0 is a constant term, $\beta_1, \beta_2, \cdots, \beta_p$ are regression coefficient. ε is the random error, which obeys normal distribution.

Before multivariate linear regression, it is necessary to test the correlation of data in order to ensure that data are independent of each other. The calculation formula is as follows:

$$r = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2}\sqrt{\sum(y-\bar{y})^2}} \qquad (2)$$

The correlation coefficient $r(0 \le r \le 1)$ has no unit. The absolute value of r indicates the degree of correlation, and the closer the absolute value approaches 1, the closer the relationship between the two variables is.

Through the correlation analysis of all data, it is found that time, flow rate, inlet pressure, tank pressure, electric current, DT opening and temperature are correlated to the outlet pressure. Furthermore, there are other correlations among the parameters, including: (1) DT opening and flow, (2) tank pressure and inlet pressure, (3) pump current and temperature. These correlations can be explained from the working principle of the pump. The reasons are as follows:

(1) Changing DT opening is one of the measures to regulate the flow. The larger DT opening is, the larger the flow is.

(2) The inlet of storage tank and a certain type of pump is directly connected by pipeline. The greater the pressure of storage tank, the greater the inlet pressure.

(3) If the pump current increases, it will inevitably lead to an increase in internal heat dissipation of a certain type of pump, resulting in an increase in temperature.

As a result, there are three parameters are should be considered in the in the regression equation, including flow rate, electric current, and inlet pressure. These parameters have stronger correlations to the outlet pressure than the other parameters.

C. Parameter Estimation of Regression Equation

$\beta = (\beta_1, \beta_2, \cdots, \beta_p)$ can be calculated by transforming the normal equations into matrices. When the coefficient matrix is full rank, the least square estimation of the parameters can be obtained as follows:

$$\beta = (X^T X)^{-1} X^T Y \quad (3)$$

The parameters can be estimated by following equation (3). The Final equation is shown as follows:

$$y = 16.58 - 0.022x_1 + 1.119x_2 - 0.014x_3 \quad (4)$$

In equation (4), x_1 denotes the electric current, x_2 denotes inlet pressure, x_3 denotes flow rate and y denotes the outlet pressure.

D. Significance test

Although the regression equation can be established, it also needs to use the actual observation data to test the significance of the whole regression equation and each regression coefficient.

SPSS 13.0 is used to test the significance of regression equation and regression coefficient. It is can be calculated that R=0.892， F=149.496. After viewing the correlation coefficient test threshold table and F distribution quantile table, it can be known that the regression equation has statistical significance.

The significance test results of regression coefficients are shown in Table 1.

TABLE I. SIGNIFICANCE TEST OF REGRESSION COEFFICIENT

	Constant Term	*Electronic Current*	*Inlet Pressure*	*Flow Rate*
t	62.923	-9.793	6.647	-18.473
sig	0.000	0.000	0.000	0.000

Looking up the distribution quantile table, it is known that each coefficient has a significant effect on dependent variables.

The significance test of regression equation and the significance test of regression coefficient can pass, which shows that the regression equation has statistical significance. Outlet pressure is affected by current, inlet pressure and flow significantly.

E. Standardization of Data Processing

The purpose of data standardization is to convert the export pressure values of other parameters under different conditions into the outlet pressure values of other parameters under the same conditions. Based on expert experience, it is supposed that $x_1^0 = 10.1$, $x_2^0 = 1.4$ and $x_3^0 = 86$. The conversion equation is:

$$\acute{y} = y - \beta_1(x_1 - x_1^0) - \beta_2(x_2 - x_2^0) - \beta_3(x_3 - x_3^0) \quad (5)$$

In equation (5), $\acute{y}$ denotes the outlet pressure values of other parameters under the same conditions. y, x_1, x_2 and x_3 represent the outlet pressure, electronic current, inlet pressure and flow rate, respectively. The converted outlet pressure data are shown in Fig. 5.

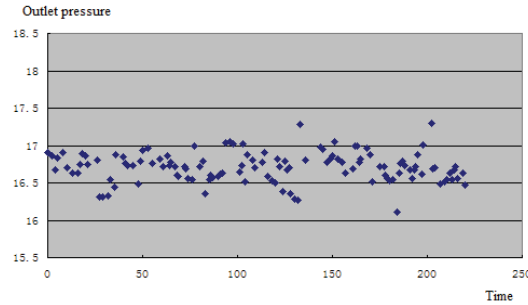

Figure 5. Converted export pressure data

Compared with the original data, the converted data fluctuates less, and the original obscure degradation trend becomes relatively obvious. If the data are fitted directly by simple linear method, the slope is -0.0002. The results show that the actual service life of the pump is much shorter than that of the design due to many factors such as idle time and unstable environment.

III. RELIABILITY ASSESSMENT

The performance degradation data can be used to evaluate the reliability of thermal control pumps based on the Wiener process-based modeling method shown in reference [6]. Wiener process-based modeling method is also used to evaluate the performance reliability of the pump in this paper.

The failure distribution function of the pump is:

$$F(t) = \Phi\left(\frac{\mu t - l}{\sigma\sqrt{t}}\right) + exp\left(\frac{2\mu l}{\sigma^2}\right)\Phi\left(\frac{-l - \mu t}{\sigma\sqrt{t}}\right); \;\; t > 0 \quad (6)$$

As shown in equation (6), μ and σ are unknown parameters of failure distribution function. l denotes the degradation failure threshold.

The process of calculating the value of μ and σ can be founded in reference [7]. It is calculated that $\mu = 0.000057$ and $\sigma = 0.0013$. The final calculation results are shown in Fig. 6. Curve 1 is the reliability curve when $l = 10$ and curve 2 is the reliability curve when $l = 6$.

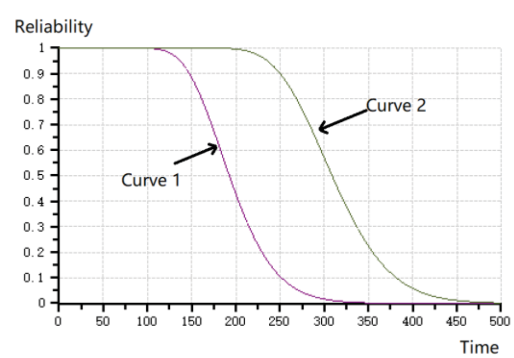

Figure 6. Reliability curve of the pump

Because of the high reliability requirement of the pump in the working process, it is generally required to maintain the reliability of more than 0.9. Therefore, if the failure threshold is 10, the service life of a pump is recommended to be 150 hours;

if the failure threshold is 6, the service life is recommended to be 250 hours.

IV. Conclusion

In this paper, the multivariate linear regression method is used to establish the model, and the data of pump performance parameters are processed. Then, a mathematical model based on Wiener process is established to evaluate the reliability of the pump and to predict its service life. Reasonable and credible results are obtained.

It is very necessary to consider the influence of the other parameters to the key performance, when the performance reliability is evaluated. For further research, it is suggested that the multiple key performance degradation should be noticed.

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