Life Prediction of Lubricating Oil Based on GM Model

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Abstract. According to the method of testing the life of lubricating oil in the bench test of lubricating oil plunger pump, this paper puts forward the prediction method of lubricating oil life based on the combination prediction model of grey theory and GM model. The method carries out data processing on the original data through gray accumulation generating operation to enhance the regularity of the data; GM is used for prediction, and grey cumulative reduction is used to generate operation reduction data to obtain prediction results. The acid value change data of lubricating oil is selected as the life characteristic information of lubricating oil. The model is used to predict the life of lubricating oil, which solves the problems of less data information and uncertain prediction in one oil change cycle. The model is proved to have high prediction accuracy by posterior difference test.

1. Introduction
Oil pollution has a very significant impact on the wear life of the pump. In some cases, even a small amount of pollution in time will cause serious wear to the hydraulic pump, thus causing the volumetric efficiency of the pump to drop sharply and losing its working performance. Therefore, in modern hydraulic transmission, the life of the pump depends on the wear life to a great extent. At present, researchers use different methods to predict the life of hydraulic pumps.

2. Methods and parameters for routine inspection of oil indicators
There are many methods to evaluate the service life of reused oil products, among which the conventional five inspection methods are the common methods to detect the deterioration degree of oil products and have been widely used in practice. In this paper, the service life of oil products is predicted according to the acid value test results. Meanwhile, the kinematic viscosity, moisture, pollutants and other data can be tested to ensure the accuracy of life prediction.

Viscosity is one of the most important indexes of lubricating oil and the most important factor for forming lubricating oil film. Choosing reasonable viscosity plays an important role in the working efficiency of equipment.

Acid value refers to the mg number of potassium hydroxide needed to neutralize acid substances in 1g of oil, expressed in mg KOH/g. Acid value is one of the indexes to measure the oxidation stability of lubricating oil, especially in the presence of water, to accelerate the oxidation of lubricating oil. When the acid value increases to a certain value, it must be replaced.
Moisture refers to the quality of water contained in lubricating oil. The existence of moisture in lubricating oil will promote the oxidation of oil products and destroy lubricating oil film.

Dirt samples are usually produced when the pollutant lubricating oil system fails. On the one hand, it may be caused by oxidation deterioration of lubricating oil itself, on the other hand, it may also be caused by external substances entering the system. For the sediment produced in the equipment body, such as oil sludge, carbon deposit, oil sludge formed by paint film, etc. Under the condition that the physical and chemical inspection methods of lubricating oil are not complete, a reasonable analysis of the composition of oil sludge samples can play an important auxiliary role in fault diagnosis and troubleshooting.

3. Grey modeling GM (1, 1)
Grey theory [1] has the advantages of less data usage and high short-term prediction accuracy, and has been studied and applied by many experts and scholars at present. The grey GM (1, 1) model [2] created by Professor Deng Julong is an equidistant sequence model based on the equidistant sequence [3]. It is a technical system with system analysis, evaluation, modeling, prediction, decision-making and optimization as the main body.

3.1. Basic formula of GM (1, 1)
(1) Generating an accumulation sequence \( X^0 = (x^0(1), x^0(2), x^0(3), ...) \)
Do \( X^0 \) as the accumulation of 1-AGO to generate sequence \( x^1(k) \), where
\[
x^1(k) = \sum_{i=1}^{k} x^0(i), \quad k=1, 2, ...
\]
(2) Carry out quasi-smoothness test on \( X^0 \)
\[
\rho(k) = \frac{x^0(k)}{x^1(k-1)} < 0.5; \quad 2
\]
(3) Check whether \( X^1 \) has quasi-exponential law
\[
(k) = (x1(k))/ (x1(k-1)) \in [1, 1.5]
\]
GM (1, 1) model can be established.
(4) Establishing a sequence
\[
z^1(k) = \frac{1}{2} [x^1(k) + x^1(k - 1)]
\]
(5) Establish a model for a sequence generated by one accumulation:
\[
B = \begin{bmatrix}
-z(2) & 1 \\
-z(3) & 1 \\
\vdots & \vdots \\
-z(n + 1) & 1 \\
\end{bmatrix}, \quad Y = \begin{bmatrix} x^0(2) \\
x^0(3) \\
\vdots \\
x^0(n) \end{bmatrix}
\]
(6) Carry out least square estimation on parameter column \( a = [ a, u ]^T \).
\[
\hat{a} = [a, u]^T = (B^T B)^{-1} B^T Y_N
\]
(7) Determining a differential equation model.
GM (1, 1) model is a first-order differential whitening equation:
\[
\frac{dx^1}{dt} + ax^1 = u
\]
(8) Solve the differential equation and obtain the time response formula:
\[
\hat{x}^1(k + 1) = x^0(1) - \frac{u}{a} e^{-ak} + \frac{u}{a}
\]
(9) The analog value \( X^1(k) \) of \( x1 \) is obtained, and the analog value \( X^0(k) \) of \( X^0 \) is obtained by reducing and reducing the analog value \( X^1(k) \)
\[
\hat{x}^0(k) = \hat{x}^1(k + 1) - \hat{x}^1(k)
\]
(10) The posterior difference method is used to check the error (relative error, correlation degree and mean square deviation ratio). Table 1 lists the accuracy determination indexes.
(a) According to the time test function, calculate the simulation \( x^0(k) \) and prediction values for the original sequence \( \hat{x}^0(k) \).
\[
e(k) = x^0 - \hat{x}^0
\]
Δ = (Δ_k) = (| e^{(0)}(k)/x^{(0)}(k) |)

(b) Test $x^0(k)$ and $\hat{x}^0(k)$ Grey Absolute Correlation Degree.

$S^2 = \frac{1}{n-1} \sum_{k=1}^{n} (x^{(0)}(k) - x^{(0)})$

(c) Mean square deviation test

Variance of original sequence $\sigma_1^2 = \frac{1}{n} \sum_{k=1}^{n} [x^0(k) - \bar{x}]^2$

Mean of sequence residuals $\bar{\varepsilon} = \frac{1}{n} \sum_{k=1}^{n} \varepsilon^{(0)}(k)$

Residual variance $\sigma_2^2 = \frac{1}{n} \sum_{k=1}^{n} [\varepsilon^0(k) - \bar{\varepsilon}]^2$

Mean square deviation ratio $C = \frac{\sigma_2^2}{\sigma_1^2}$

| Accuracy class          | Relative error | Correlation | Mean square deviation ratio C |
|-------------------------|----------------|-------------|-----------------------------|
| Good (Grade I)          | <0.01          | >0.90       | <0.35                       |
| Good (Grade II)         | <0.05          | >0.80       | <0.50                       |
| Qualified (Grade III)   | <0.10          | >0.70       | <0.65                       |

3.2. Examples

According to the requirements of JCMAS P045, the A2F plunger pump bench was made in the laboratory, and the acid value of a lubricating oil bench test currently used was analyzed. As shown in Figure 1, the A2F-10 plunger pump bench is mainly composed of plunger pump, overflow valve, air flow controller, cooler, oil tank and filter. The inlet of the pump is provided with air supply device, and the oil tank is internally provided with Cu coil catalyst.

3.3. Theoretical calculation

Considering the harshness of the bench test, the performance of the oil is extremely unstable after reaching 1500h. Taking 1500h sampling as historical data, the 1700h test results are predicted.

(a) The original sequence $X^0 = (x^0(1),x^0(2),x^0(3),...) = (1.75,1.81,2.02,2.30,2.55,2.73)$

Generate cumulative series $x^0(k) = (1.75,3.56,5.58,7.88,10.43,13.16)$

(b) Carrying out quasi-smoothness test on $X^0$, $\rho(k) = \frac{x^0(k)}{x^0(k-1)} < 0.5$, Satisfy quasi-smooth condition, $k > 2$, See table 2.

![Figure 1. Schematic diagram of hydraulic circuit of A2F-10 plunger pump](image-url)
Table 2. Quasi-smoothness Test.

| k  | 2   | 3   | 4   | 5   | 6   |
|----|-----|-----|-----|-----|-----|
| \(\rho\) | 0.43 | 0.49 | 0.41 | 0.32 | 0.26 |

(c) Check whether \(X^1\) has quasi-exponential law \((k)=(X^1(k))/((X^1(k-1))) \in [1,1.5] GM (1,1) model can be established. In this paper, \(k>2\), satisfies the quasi-exponential rule. See table 3.

Table 3. Quasi-exponential Test.

| k  | 2   | 3   | 4   | 5   | 6   |
|----|-----|-----|-----|-----|-----|
| \(\sigma\) | 1.23 | 1.47 | 1.41 | 1.32 | 1.26 |

(d) Determining a data matrix \(B, Y\)

\[
B = \begin{bmatrix}
-2.655 & 1 \\
\vdots & \vdots \\
-14.675 & 1 \\
\end{bmatrix}, \quad Y = \begin{bmatrix}
1.81 \\
\vdots \\
2.73 \\
\end{bmatrix}
\]

(e) Determining a differential equation model

GM (1, 1) model is a first-order differential whitening equation:

\[
\frac{dx^1}{dt} + ax^1 = u
\]

\(a = -0.1002, u = 1.5785\)

(f) The analog value \(X^1(k)\) of \(x1\) is obtained, and the analog value \(X^0(k)\) of \(X^0\) is obtained by reducing and reducing the analog value \(X^1(k)\)

\[
\hat{x}^1(k + 1) = \left[ x^0(1) - \frac{u}{a} \right] e^{-a k} + \frac{u}{a} \\
\hat{x}^0(k) = \hat{x}^1(k + 1) - \hat{x}^1(k)
\]

Table 4. Predicted Acid Value.

| Sampling time/h | 700 | 900 | 1100 | 1300 | 1500 | 1700 |
|-----------------|-----|-----|------|------|------|------|
| Predicted acid value | 1.84 | 2.04 | 2.25 | 2.49 | 2.75 | 3.04 |

Figure 2. Comparison between measured value and theoretical value.

3.4. Test results

Table 5. Test of Results.

| Accuracy class         | Test method | Result deviation |
|------------------------|-------------|------------------|
| The relative error     | 0.01        | Grade I          |
| The correlation degree | 0.91        | Grade I          |
| Mean Square Error Ratio | 0.14        | Grade I          |
The results show that the prediction accuracy is grade I, which indicates the accuracy of the prediction model and the prediction is effective.

4. Conclusion
(1) The grey model has high prediction accuracy for predicting the life of lubricating oil, which can truly reflect the decay trend of hydraulic oil in the use process, save bench test time and cost, improve test efficiency, and has practical value.
(2) When the grey model is used to predict the life of lubricating oil, only 4-5 measuring point data need to be extracted at the normal wear stage of lubricating oil, so the demand for original data is small, and the modeling is simple and easy.
(3) When the predicted wear curve is within the range of normal wear stage, the prediction result is more accurate, but there are also several sequences that are not conventional sequences. The next step is to use grey fluctuation prediction or topological grey prediction [4, 5] and other methods to expand and establish the optimal prediction model. At the same time, similar treatment can be carried out for other important influencing factors to meet the feasibility of prediction.

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