Fuzzy Comprehensive Evaluation of Running Status of Engine Based on Information Fusion of Vibration and Oil Physicochemical Property

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Abstract. Based on the vibration information of engine and the physicochemical property information of oil of engine, the fuzzy comprehensive evaluation model of running status of engine is established. According to the evaluation model, the fuzzy comprehensive evaluation method is put forward. By the evaluation method, the evaluation of running status of engine is analyzed by an example. The results show that the fuzzy comprehensive evaluation method based on the information fusion of vibration of engine and physicochemical property of oil of engine is reliable and reasonable.

Introduction

With the continuous improvement of complexity of engine structure, the factors which affect the running status of engine become more complexly and diversely and the evaluation of running status of engine has become more difficult. In order to ensure the engine to operate safely and reliably, the investigation of method of comprehensive evaluation of running status of engine become more and more important.

Nowadays, there are two main methods to evaluate the running status of engine. One method is based on the vibration information [1-3]. The other main method is based on the oil information [4-6]. However, it’s very difficult to monitor the engine reasonably only by using the vibration information or the oil information, because either the vibration information or the oil information has been limit to comprehensively reflect the real running status of engine. Obviously, the vibration information can be represented by the characteristic parameters of vibration, such as amplitude of vibration accelerate, mean square value of vibration accelerate and so on. And the oil information can be represented by the physicochemical indexes, such as viscosity, mechanical impurity and so on, because there are many advantages to obtain the oil information by physicochemical property analysis, such as low-cost, less time-consuming and low demand for researcher’s experience [7]. According to the working mechanism of engine, both the characteristic parameters of vibration and the physicochemical indexes of oil have the fuzzy uncertainty. So it is necessary to consider the fuzzy uncertainty of characteristic parameters of vibration and the physicochemical indexes of oil when the running status of engine is evaluated based on the information fusion of vibration and oil. However, the studies on the fuzzy comprehensive evaluation of running status of engine based on information fusion of vibration and oil are seldom reported in the literatures.

The purpose of this paper is to investigate the fuzzy comprehensive evaluation method of running status of engine based on the information fusion of vibration and oil.

Evaluating Indicators of Running Status of Engine

Factor Sets

Because the running status of engine is evaluated based on both the characteristic parameters of vibration and the physicochemical indexes of oil, the factor sets of running status of engine should include the vibration factor set and the oil factor set.
Assume that the oil factor set $U_1$ includes $m$ factors and the vibration factor set $U_2$ includes $n$ factors, so the oil factor set $U_1$ can be expressed as:

$$ U_1 = \{u_1^{(1)}, u_2^{(1)}, \ldots, u_m^{(1)}\} $$

where $u_i^{(1)} (i = 1, 2, \ldots, m)$ is the $i$-th factor of $U_1$.

And the vibration factor set $U_2$ can be expressed as:

$$ U_2 = \{u_1^{(2)}, u_2^{(2)}, \ldots, u_n^{(2)}\} $$

where $u_j^{(2)} (j = 1, 2, \ldots, n)$ is the $j$-th factor of $U_2$.

Because the first-level factor set of running status of engine contains the second-level factor sets $U_1$ and $U_2$, so the factor set of running status of engine $U$ can be expressed as:

$$ U = \{u_1^{(1)}, u_2^{(1)}, \ldots, u_m^{(1)}, u_1^{(2)}, u_2^{(2)}, \ldots, u_n^{(2)}\} $$

### Weight Coefficients of Factors

Obviously, the importance of vibration factors is not as same as that of oil factors when the running status of engine is evaluated by the factors of vibration and oil. Meanwhile, the different factors among the vibration factors or among the oil factors have not same importance also. In order to consider the influence of different factors on the evaluation of running status of engine, the corresponding weight coefficients are allocated for each factor.

According to the importance of $U_1$ and $U_2$, the weight coefficients of first-level factor set of running status of engine can be expressed as:

$$ A = \{A_1, A_2\} $$

where $A_1$ is the weight coefficient of $U_1$, $A_2$ is the weight coefficient of $U_2$.

According to the importance of factors of $U_1$, the weight coefficients of second-level factor set $U_1$ can be expressed as:

$$ A^{(1)} = \{A_{11}, A_{12}, \ldots, A_{1m}\} $$

where $A_{ij} (i = 1, 2, \ldots, m)$ is the weight coefficient of $i$-th factor $u_i^{(1)}$ of $U_1$.

According to the importance of factors of $U_2$, the weight coefficients of second-level factor set $U_2$ can be expressed as:

$$ A^{(2)} = \{A_{21}, A_{22}, \ldots, A_{2n}\} $$

where $A_{ij} (i = 1, 2, \ldots, n)$ is the weight coefficient of $i$-th factor $u_j^{(2)}$ of $U_2$.

### Evaluation Set

The evaluation set is constructed by all kinds of evaluation result of running status of engine. According to the actual monitoring results of the vibration characteristic parameters and the physicochemical indexes of lubricating oil of engine, the running status of engine is divided into $k$-grades. Therefore the evaluation set $V$ of running status of engine can be expressed as:

$$ V = \{v_1, v_2, \ldots, v_k\} $$

where $v_i (i = 1, 2, \ldots, k)$ represents the $i$-th grade running status of engine.
Determination of Evaluation Indicators

Because both the vibration characteristic parameters and the physicochemical indexes of lubricating oil have the fuzzy uncertainty, it is necessary to consider the fuzzy uncertainty of vibration characteristic parameters and physicochemical indexes of oil when the running status of engine is evaluated based on information fusion of vibration and oil. According to the theory of fuzzy mathematics [8], the membership functions of factors of $U$ in contrast with the grades $v_i$ of $V$ are regarded as the evaluation indicators to evaluate the running status of engine.

Here the semi trapezoid membership function model is used which can be expressed as:

$$
\mu(u_i^{(j)}) = \begin{cases} 
1, & u_i^{(j)} \leq a_i^{(j)} \\
\frac{d_i^{(j)} - u_i^{(j)}}{d_i^{(j)} - a_i^{(j)}}, & a_i^{(j)} \leq u_i^{(j)} \leq d_i^{(j)} \\
0, & u_i^{(j)} > d_i^{(j)}
\end{cases}
$$

where $u_i^{(j)}$ is one of the factors of $U$, when $j = 1, i = 1, 2, \ldots, m$, and when $j = 2, i = 1, 2, \ldots, n$; $a_i^{(j)}$, $d_i^{(j)}$ are respectively the upper limit and lower limit of factors, which can be set by the practical running status of engine [8].

Comprehensive Evaluation Model of Running Status of Engine

Evaluation Matrix of Second-Level Factors

The memberships of factor $u_i^{(1)}$ ($i = 1, 2, \ldots, m$) of $U_1 = \{u_1^{(1)}, u_2^{(1)}, \ldots, u_m^{(1)}\}$ by contrast to $V = \{v_1, v_2, \ldots, v_k\}$ can be expressed as:

$$
\mu(u_i^{(1)}) = \{r_{i1}^{(1)}, r_{i2}^{(1)}, \ldots, r_{ik}^{(1)}\} (i = 1, 2, 3\ldots m)
$$

(9)

The evaluation matrix of oil factors can be written as:

$$
R_1 = \begin{bmatrix} 
 r_{11}^{(1)} & r_{12}^{(1)} & \cdots & r_{1k}^{(1)} \\
 r_{21}^{(1)} & r_{22}^{(1)} & \cdots & r_{2k}^{(1)} \\
 \vdots & \vdots & \ddots & \vdots \\
 r_{m1}^{(1)} & r_{m2}^{(1)} & \cdots & r_{mk}^{(1)}
\end{bmatrix}
$$

(10)

where the evaluation matrix of oil factors $R_1$ is the $m \times k$ order matrix.

According to the compositional rule of fuzzy inference, the evaluation matrix of oil factors can be expressed as:

$$
B_1 = A^{(1)} \circ R_1
$$

(11)

where “$\circ$” is the fuzzy arithmetic operators.

Substituting Eqs. (5), (10) into Eq. (11), and rearranging, $B_1$ is given as:

$$
B_1 = \{b_{11}, b_{12}, \ldots, b_{1k}\}
$$

(12)

The memberships of factor $u_j^{(2)}$ ($j = 1, 2, \ldots, n$) of $U_2 = \{u_1^{(2)}, u_2^{(2)}, \ldots, u_n^{(2)}\}$ by contrast to $V = \{v_1, v_2, \ldots, v_k\}$ can be expressed as:

$$
\mu(u_j^{(2)}) = \{r_{j1}^{(2)}, r_{j2}^{(2)}, \ldots, r_{jk}^{(2)}\} (j = 1, 2, 3\ldots n)
$$

(13)

The evaluation matrix of vibration factors can be written as:
\[
R = \begin{bmatrix}
I^{(2)}_{11} & I^{(2)}_{12} & \cdots & I^{(2)}_{1k} \\
I^{(2)}_{21} & I^{(2)}_{22} & \cdots & I^{(2)}_{2k} \\
\vdots & \vdots & \ddots & \vdots \\
I^{(2)}_{n2} & I^{(2)}_{n2} & \cdots & I^{(2)}_{nk}
\end{bmatrix}
\]  
(14)

where the evaluation matrix of oil factors \( R \) is the \( n \times k \) order matrix.

According to the compositional rule of fuzzy inference, the evaluation matrix of vibration factors can be expressed as:

\[
B = A^{(2)} \circ R
\]  
(15)

Substituting Eqs. (6), (14) into Eq. (15), and rearranging, \( B \) is given as:

\[
B = \{b_{21}, b_{22}, \ldots, b_{2k}\}
\]  
(16)

**Comprehensive Evaluation Model**

The comprehensive evaluation matrix of running status of engine \( R \) can be obtained by \( B \) and \( R \), that is

\[
R = \left[ B_2, B_1 \right]^T
\]  
(17)

Substituting Eqs. (12), (16) into Eq. (17), \( R \) is given as:

\[
R = \begin{bmatrix}
b_{11} & b_{12} & \cdots & b_{1k} \\
b_{21} & b_{22} & \cdots & b_{2k}
\end{bmatrix}
\]  
(18)

According to the compositional rule of fuzzy inference, the comprehensive evaluation model of running status of engine can be expressed as:

\[
B = A \circ R
\]  
(19)

Substituting Eqs. (4), (18) into Eq. (19), and rearranging, \( B \) is given as:

\[
B = \{b_1, b_2, \ldots, b_k\}
\]  
(20)

Eq. (20) is the fuzzy comprehensive evaluation model of running status of engine based on the information fusion of vibration and oil. According to the principle of maximum degree of membership (MDM) in fuzzy evaluation principle, the evaluation result of running status of engine can be obtained by Eq. (20).

**Example**

**Experimental Data**

The type of engine is Yuchai’s 4D20 diesel engine which is vertical, water cooled, four cylinder high speed direct injection diesel engine. The main parameters of engine are as follows: the piston displacement is 2 L; the maximum torque is 286 N·m; the maximum rotating speed is 4000 r/min; the firing order is 1-3-4-2. According to the characteristics of 4D20 diesel engine, the vibration signals are extracted from the measuring point 1 and the measuring point 2 by the measurement system, as shown in Fig. 1. Meanwhile, the oil sample can be collected and the physicochemical indexes of oil can be obtained by using physicochemical property analysis, as shown in Fig. 2.
The experimental data of engine are shown in Table 1.

<table>
<thead>
<tr>
<th>Samples</th>
<th>$t$ (h)</th>
<th>$D_1$ (mm$^2$/s)</th>
<th>$D_2$</th>
<th>$D_3$ (g)</th>
<th>$D_4$ (g)</th>
<th>$D_5$ (g)</th>
<th>$D_6$ (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>13.11</td>
<td>2.4</td>
<td>15.61</td>
<td>2.03</td>
<td>36.23</td>
<td>4.91</td>
</tr>
<tr>
<td>2</td>
<td>400</td>
<td>14.68</td>
<td>3.8</td>
<td>32.10</td>
<td>4.78</td>
<td>57.45</td>
<td>8.65</td>
</tr>
</tbody>
</table>

where $t$ is the run-time of engine; $D_1$ is the kinematic viscosity of lubricating oil of engine at 100°C; $D_2$ is the quantized values of speckle patterns rating of mechanical impurities of lubricating oil of engine [7]; $D_3$ is the vibration accelerate amplitude at the measuring point 1 of engine; $D_4$ is the mean square value of vibration accelerate amplitude at the measuring point 1 of engine; $D_5$ is the vibration accelerate amplitude at the measuring point 2 of engine; $D_6$ is the mean square value of vibration accelerate at the measuring point 2 of engine.

**Comprehensive Evaluation of Running Status of Engine**

**Determination of factor set.** The oil factor set $U_1$ is composed of two factors, that is $U_1 = \{u_1^{(1)}, u_2^{(2)}\}$, where $u_1^{(1)}$ is the degradation rate of kinematic viscosity of lubricating oil of engine; $u_2^{(2)}$ is the degradation rate of mechanical impurities of lubricating oil of engine. The vibration factor set $U_2$ is composed of four factors, that is $U_2 = \{u_1^{(2)}, u_2^{(2)}, u_3^{(2)}, u_4^{(2)}\}$, where $u_1^{(2)}$ is the vibration accelerate amplitude at the measuring point 1 of engine; $u_2^{(2)}$ is the mean square value of vibration accelerate at the measuring point 1 of engine; $u_3^{(2)}$ is the vibration accelerate amplitude at the measuring point 2 of engine; $u_4^{(2)}$ is the mean square value of vibration accelerate at the measuring point 2 of engine. So the factor set of running status of engine can be expressed as:

$$U = \{u_1^{(1)}, u_2^{(1)}, u_1^{(2)}, u_2^{(2)}, u_3^{(2)}, u_4^{(2)}\}$$

**Determination of weight coefficient of factors.** During the comprehensive evaluation process of running status of engine, the vibration factors and oil factors play different roles respectively. So a corresponding weight coefficient is allocated for each factor. According to the importance of $U_1$ and
The weight coefficient of first-level factor set of running status of engine is determined as $A = \{0.4, 0.6\}$. According to the importance of factors of $U_1$, the weight coefficient set of $U_1$ is determined as $A^{(1)} = \{0.4, 0.6\}$. According to the importance of factors of $U_2$, the weight coefficient set of $U_2$ is determined as $A^{(2)} = \{0.2, 0.3, 0.2, 0.3\}$.

**Determination of evaluation set.** According to the actual monitoring situation of the oil and vibration of engine, the running status of engine is divided into four grades which are “good”, “general”, “poor” and “fault”. So the evaluation set $V$ of running status of engine can be determined as $V = \{v_1, v_2, v_3, v_4\}$, where $v_1$ represents that the running status of engine is “good” when the engine works well; $v_2$ represents that the running status of engine is “general” when the engine works normally but not very good; $v_3$ represents that the running status of engine is “poor” when the engine can work safely but its running status is not good; $v_4$ represents that the running status of engine is “fault” when the engine can not work safely and needs to be diagnosed and repaired.

**Evaluation of running status of engine.** According to Eq. (20), $B$ can be obtained as:

$$B = \{0.1414, 0.3372, 0.5102, 0.2098\}$$

By the principle of maximum degree of membership (MDM), the running status of engine can be determined according to $B$. It is known according to $B$ that the running status of engine is “poor”, when the engine can work safely but its running status is not good. The result is consistent with the actual situation of engine. That is to say, the comprehensive evaluation method based on the information fusion of vibration and oil is effective and reliable.

**Summary**

In this paper, the comprehensive evaluation of running status of engine based on the information fusion was investigated. The studies show that:

(1) The vibration and oil information of engine are the two main data on which the running status of engine can be evaluated. The evaluation of running status of engine based on the information fusion of vibration and oil is more reliable than that based on single.

(2) Both the characteristic parameters of vibration and the physicochemical indexes of oil have the fuzzy uncertainty, it is necessary to consider the fuzzy uncertainty of these parameters and indexes when the running status of engine is evaluated based on the information fusion of vibration and oil.

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**References**


