A new state evaluation method of oil pump unit based on AHP and FCE

Yang Lin, Wei Liang*, Zeyang Qiu, Meng Zhang and Wenqing Lu
College of Mechanical and Transportation Engineering, China University of Petroleum-Beijing
lw@cup.edu.cn

Abstract. In order to make an accurate state evaluation of oil pump unit, a comprehensive evaluation index should be established. A multi-parameters state evaluation method of oil pump unit is proposed in this paper. The oil pump unit is analyzed by Failure Mode and Effect Analysis (FMEA), so evaluation index can be obtained based on FMEA conclusions. The weights of different parameters in evaluation index are discussed using Analytic Hierarchy Process (AHP) with expert experience. According to the evaluation index and the weight of each parameter, the state evaluation is carried out by Fuzzy Comprehensive Evaluation (FCE) and the state is divided into five levels depending on status value, which is inspired by human body health. In order to verify the effectiveness and feasibility of the proposed method, a state evaluation of oil pump used in a pump station is taken as an example.

Keywords. State evaluation; Oil pump; FMEA; AHP; FCE

1. Introduction
The pipeline system has been serving as a main transportation channel of oil and natural gas, in which the oil pump is a so pivotal component that it guarantees oil and gas transmission safety with the ever-increasing demand of oil [1]. In general, the oil pump driven by motor is the typical form in oil pipeline supporting for long distance transmission of oil. However, unexpected shutdown of such component significantly threatens the production safety and enterprise profits, even causes casualties because of its high running speed and continuous operation for a long period [2]. Therefore, increasing attention has been attracted to the condition assessment of oil pump unit in the last decades.
The first service system for mechanical equipment was designed to consider the age not current condition in the early 90s [3]. With the advancement of condition monitoring instruments and computer technology, running state evaluation of equipment has been paid more attention based on their one or more state feature values such as temperature, vibration and so on [4-6]. However, because the structure of equipment is complex and the relevancy among components of equipment is always close, it’s difficult to use some of the feature parameters to evaluate the entire equipment condition [7-9]. Therefore, a state evaluation method for equipment based on multi feature parameters is essential to ensure safety operation.
As an application of fuzzy mathematics, FCE has been widely used to state evaluation in recent years [10]. However, evaluation index and its weighted value in the method usually given by experience are inevitably subjective. Although there isn’t an applicable method to establish the evaluation index, the weight vector of evaluation index has been solved by fuzzy AHP, an extension of AHP proposed by
Saaty [11]. Gu et al, calculated the weighted value of all level’s evaluation factors in the mechanical movement program evaluation system based on a fuzzy AHP method [12]. Chang et al, proposed a new extent analysis approach for the synthetic extent values of the pair-wise comparison by fuzzy AHP [13]. In order to obtain an objective and comprehensive evaluation index, FMEA is used to establish the evaluation index of oil pump unit in this paper. The remainder of this paper is organized as follows: the evaluation index of oil pump unit is established based on FMEA in section 2. Section 3 deals with determining weights of parameters in evaluation index. Section 4 presents an application of the proposed multi-parameters state evaluation method based on AHP and FCE. Finally in section 5, conclusions are presented and discussed.

2. Establishment of evaluation index

2.1. FMEA
FMEA was first implemented in 1949 by the United States Army and then it has been widely used in various fields with its strength and robustness. This method is an engineering analysis tool of equipment failure, helping engineers to define, identify, and eliminate known or potential failures, problems, errors in different times, including design, process or service. The process of FMEA is showed in figure 1.

![Figure 1. Process of FMEA.](image)

2.2. Evaluation index
Oil pump unit driven by motor, the subject in this paper, is composed of two important parts: oil pump and driven motor. And there are so many monitoring parameters that it couldn’t be totally contained in evaluation index of oil pump unit. At present, evaluation index of oil pump unit is established based on experience, so it is possible to ignore some important parameters in evaluation index. To establish a comprehensive evaluation index, FMEA is applied and Table 1 shows FMEA results for oil pump. Compared to conventional FMEA, Table 1 adds detection method and it can help select important parameters to establish evaluation index.

According to FMEA results of oil pump unit, an evaluation index of fourteen parameters including driven motor and oil pump is established. Parameters of oil pump in evaluation index include Outlet Pressure (P1), Inlet Pressure (P2), Vibration of Driving End (P3), Vibration of Free End (P4), Temperature of Driving End (P5), Temperature of Free End (P6), Differential Pressure of Oil seal (P7), Temperature of Pump Case (P8). Parameters of driven motor in evaluation index are Temperature of A Phase (M1), Temperature of B Phase (M2), Temperature of C Phase (M3), Current Value (M4), Temperature of Driving End (M5), Temperature of Free End (M6).
Table 1. FMEA for oil pump.

| Component            | Function             | Failure Causes                                                                 | Failure Effect                                | Detection Method                  |
|----------------------|----------------------|-------------------------------------------------------------------------------|-----------------------------------------------|-----------------------------------|
| Pump Case            | Holding fluid       | 1. Shaft Misalignment  2. Pump vacuum  3. Serious bearing wear  4. Rotor unbalance  5. Anchor bolt loosening | 1. Excessive mechanical damage  2. Pump shutdown | 1. Vibration detection  2. Temperature detection  3. Experience judgment |
|                      |                      | 1. Serious bearing wear  2. Excessive discharge  3. Shaft Misalignment  4. Pump wear  1. Design and manufacturing defects | 1. Excessive mechanical damage  2. Shutdown |                                    |
| Rotor (Impeller)     | Energy conversion   | 2. Poor installation  3. Impeller wear or corrosion  4. Plastic deformation  5. Not concentric between stator and rotor  1. Improper seal installation  2. Severe sleeve wear  3. Rotor eccentricity caused by excessive wear of pump shaft  4. Shaft Misalignment  5. Abnormal seal pressure  6. Poor filler installation  7. Sealing surface damage  8. Pump vacuum in a long time | 1. Performance degradation  2. Shutdown | 1. Vibration detection  2. Comparison test under different load |
| Mechanical Seal      | Preventing leakage  | 1. Improper installation of shaft  2. Shaft Misalignment  3. Material defects | 1. Excessive mechanical damage  2. Shutdown | 1. Temperature detection  2. Differential pressure detection |
|                      |                      | 1. Rotational imbalance  2. Rotor eccentricity caused by excessive wear of pump shaft  3. Impurities or deterioration of lubricating oil  4. Poor installation of bearing  5. Insufficient or excessive lubrication  1. No or insufficient pump priming  2. Inlet pipe blockage or small valve opening  3. Fluid gasification  4. Strong viscosity of fluid  5. Suction pipeline leakage | Vibration detection |
| Pump Shaft           | Torque transmission and fixing rotor | 1. Improper installation of shaft  2. Shaft Misalignment  3. Material defects | 1. Excessive mechanical damage  2. Excessive vibration  3. Shutdown |                                    |
|                      |                      | 1. Excessive bearing wear | Excessive bearing wear | 1. Vibration detection  2. Temperature detection  3. Experience judgment |
| Bearing              | Fixing pump shaft    | 1. Improper installation of shaft  2. Shaft Misalignment  3. Material defects | 1. Excessive mechanical damage  2. Excessive vibration  3. Shutdown |                                    |
|                      |                      | 1. Vibration detection  2. Temperature detection  3. Experience judgment | | |
| Pump Inlet           | Fluid inlet         | 1. Outlet pipeline leakage | Insufficient flow | Pressure detection |
| Pump Outlet          | Fluid outlet         | 1. Outlet pipeline leakage | Abnormal flow | Pressure detection |

3. Determination of weight vector of evaluation index

3.1. AHP
As a well-known multi-criterion decision-making technique, AHP was firstly used for OHS [14-15]. It is a simple method which is a combination of qualitative and quantitative analysis and its main
advantage is checking and reducing the inconsistency of expert judgments. The interaction between
different decision variables is expressed by hierarchy in AHP. The hierarchy is established from more
general criterion to the particular one and determined by pairwise comparison which is made using a
nine-point scale, as shown in Table 2. In this paper, AHP is employed to determine the weight vector
of evaluation index of oil pump unit and it is comprised of four main steps: decomposition of structure
of evaluation index, structure of judgment matrix, determination of weight vector of evaluation index
and coincidence test.

Table 2. Important degree judgment.

| f(a, b) | f(b, a) | Definition                  | Verbal explanation                                      |
|--------|--------|-----------------------------|---------------------------------------------------------|
| 1      | 1      | a and b “equally important” | a and b contribute equally to the property               |
| 3      | 1/3    | a and b “slightly important”| The contribution a slightly bigger than b, not obviously |
| 5      | 1/5    | a and b “obvious important” | The contribution a obviously bigger than b, but not extremely obvious |
| 7      | 1/7    | a and b “intense important” | The contribution a extremely obviously bigger than b, but not dominant |
| 9      | 1/9    | a and b “absolutely important” | The contribution a overwhelming superiority bigger than b |
| 2, 4, 6, 8 | 1/2, 1/4, 1/6, 1/8 | a and b situated among various ranks | The assessment falls between two levels |

3.2. Weight vector of evaluation index

The hierarchy structure of evaluation index of oil pump unit is established based on evaluation index
in section 2 and AHP, as shown in figure 2. And then according to judgment matrix of evaluation
index, the weight vector of evaluation index is determined: \( v = [0.1369 \ 0.0963 \ 0.0474 \ 0.0474 \ 0.0282 \ 0.0282 \ 0.0970 \ 0.0187 \ 0.1553 \ 0.0851 \ 0.0851 \ 0.0851 \ 0.0447 \ 0.0447] \). Finally it is proved that weight
distribution is reasonable by coincidence test.

![Figure 2. The hierarchy structure of evaluation index of oil pump unit.](image)

Table 3. State grade of oil pump unit.

| State grade | Status value | Strategy                |
|-------------|--------------|-------------------------|
| Best        | [90, 100]    | Routine maintenance     |
| Good        | [60, 90)     | Critical part monitoring|
| Ill         | [40, 60)     | Further detection       |
| Stiff       | [20, 40)     | Urgent maintenance      |
| Worst       | [0, 20)      | Immediate shutdown and maintenance |
4. State evaluation of oil pump unit

4.1. State grade

In order to accurately describe the state of oil pump unit, the running condition is divided into five levels based on status value, which is inspired by human body health. Five states are defined as best, good, ill, stiff, and worst, and status value ranges from 0 to 100. 100 means the best state and 0 means the worst state, as shown in Table 3.

4.2. State evaluation of oil pump unit

Before evaluating the state of oil pump unit, the state of each parameter in evaluation index should be determined. And there is an operating range of each parameter in evaluation index. Therefore, the state of each parameter in evaluation index can be determined based on its operating range and triangular membership. The oil pump unit in a pump station is taken as an example and the membership vector of each parameter to five state grades is calculated:

\[
\begin{align*}
\mathbf{r}_1 &= [0.2, 0.8, 0, 0, 0], \\
\mathbf{r}_2 &= [0.3, 0.7, 0, 0, 0], \\
\mathbf{r}_3 &= [0, 0.5, 0.5, 0, 0], \\
\mathbf{r}_4 &= [0.4, 0.6, 0, 0, 0], \\
\mathbf{r}_5 &= [0.4, 0.6, 0, 0, 0], \\
\mathbf{r}_6 &= [0.4, 0.6, 0, 0, 0], \\
\mathbf{r}_7 &= [0.4, 0.6, 0, 0, 0], \\
\mathbf{r}_8 &= [0.3, 0.7, 0, 0, 0], \\
\mathbf{r}_9 &= [0.4, 0.6, 0, 0, 0], \\
\mathbf{r}_{10} &= [0.4, 0.6, 0, 0, 0], \\
\mathbf{r}_{11} &= [0.4, 0.6, 0, 0, 0], \\
\mathbf{r}_{12} &= [0.4, 0.6, 0, 0, 0], \\
\mathbf{r}_{13} &= [0.2, 0.8, 0, 0, 0], \\
\mathbf{r}_{14} &= [0.5, 0.5, 0, 0, 0].
\end{align*}
\]

Hence the membership vector of evaluation index to five state grades is obtained:

\[
\mathbf{R} = [\mathbf{r}_1 \mathbf{r}_2 \mathbf{r}_3 \mathbf{r}_4 \mathbf{r}_5 \mathbf{r}_6 \mathbf{r}_7 \mathbf{r}_8 \mathbf{r}_9 \mathbf{r}_{10} \mathbf{r}_{11} \mathbf{r}_{12} \mathbf{r}_{13} \mathbf{r}_{14}].
\]

According to weight vector of evaluation index and membership vector of evaluation index to five state grades, membership vector of oil pump unit to five state grades can be calculated:

\[
\mathbf{A} = \mathbf{vR} = [0.3216, 0.6264, 0.0521, 0, 0].
\]

Therefore, subordinate values that state grade of oil pump unit corresponds to best, good, ill, stiff, and worst are 0.3216, 0.6264, 0.0521, 0, and 0, respectively. The global state of oil pump unit is “good” based on the principle biggest membership. However, it can be concluded that P3 and P4 are not as good as other parameters by membership vector of evaluation index to five state grades.

Monitor values of P3 and P4 in field are 86 and 72, while their alarm values are 100. Similarly, it can also be concluded that the values of P3 and P4 in field are a little large. Therefore, there is in agreement between actual condition of oil pump unit and results of state evaluation. And these two parameters should be given a careful attention in operation of oil pump unit.

5. Conclusions

1. The evaluation index of oil pump unit should be comprised of important parameters that can reflect the state of oil pump unit. To obtain these important parameters, FMEA for oil pump unit is applied and a comprehensive evaluation index is established based on these parameters.

2. Each parameter in evaluation index has a different influence on the running state of oil pump unit. Based on AHP, the weight vector of evaluation index is calculated and the result is proved to be reasonable by coincidence test.

3. A state grade of oil pump unit is made based on status value, which is inspired by human body health. And an evaluation example of oil pump unit proves that the evaluation method is in agreement with actual state.

However, the good global state can’t guarantee that all parts of oil pump unit are good. To evaluate the state of critical part, the relationships between monitoring parameters in evaluation index and the state of critical part should be researched further.

6. Acknowledgements

This paper is supported by National Science and Technology Major Project of China (No. 2011ZX05055), Science Foundation of China University of Petroleum, Beijing (No. 2462015YQ0406).

References

[1] Qiu J, Liang W, Zhang L, et al. The early-warning model of equipment chain in gas pipeline
based on DNN-HMM[J]. Journal of Natural Gas Science & Engineering, 2015, 27: 1710-1722.

[2] de León Hijes F C G, Cartagena J J R. Maintenance strategy based on a multicriterion classification of equipments[J]. Reliability Engineering & System Safety, 2006, 91(4): 444-451.

[3] Tan Z F, Guo L Z, Yong-Xiu H E. Maintenance theory and optimal design for a compound system under a statistical equilibrium state[J]. Systems Engineering & Electronics, 2004, 26(1):125-129.

[4] Yan R, Gao R X. Rotary Machine Health Diagnosis Based on Empirical Mode Decomposition[J]. Journal of Vibration & Acoustics, 2008, 130(2):111-120.

[5] Chen Z S, Yang Y M, Hu Z, et al. Detecting and Predicting Early Faults of Complex Rotating Machinery Based on Cyclostationary Time Series Model[J]. Journal of Vibration & Acoustics, 2006, 128(5):666-671.

[6] Sun Q, Zhang D, Chen P. Pattern Recognition for Automatic Machinery Fault Diagnosis[J]. Journal of Vibration & Acoustics, 2004, 126(2):307-316.

[7] Li X J, Bin G F, Dhillon B S. Model to evaluate the state of mechanical equipment based on health value[J]. Mechanism & Machine Theory, 2011, 46(46):305-311.

[8] Gu Y J, Dong Y L, Yang K. Synthetic evaluation on conditions of equipment in power plant based on fuzzy judgment and RCM analysis[J]. Proceedings of the Csee, 2004.

[9] Ravi B. Rapid tooling manufacturability evaluation using fuzzy-AHP methodology[J]. International Journal of Production Research, 2007, 45(5):1161-1181.

[10] Chen J F, Hsieh H N, Do Q H. Evaluating teaching performance based on fuzzy AHP and comprehensive evaluation approach[J]. Applied Soft Computing, 2015, 28(C):100-108.

[11] Saaty T L. The analytic hierarchy process: Planning, priority setting, resource Allocation. McGraw-Hill, NY, USA[M]/ The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. 1980.

[12] Gu Y. A Fuzzy AHP Approach to the Determination of Weights of Evaluation Factors in Mechanism Scheme Evaluation Process[J]. China Mechanical Engineering, 2007.

[13] Chang D Y. Applications of the extent analysis method on fuzzy AHP[J]. European Journal of Operational Research, 1996, 95(3):649-655.

[14] Henderson R D, Dutta S P. Use of the analytic hierarchy process in ergonomic analysis[J]. International Journal of Industrial Ergonomics, 1992, 9(4):275-282.

[15] ANDRIS FREIVALDS. Comparison of United States (NIOSH Lifting Guidelines) and European (ECSC Force Limits) Recommendations for Manual Work Limits[J]. AIHAJ - American Industrial Hygiene Association, 1987, 48(8):698-702.