Techniques of Oil Well Equipment Diagnostics Using Dynamometer Card

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Abstract. Currently, the most widely used equipment to oil extraction is a sucker rod pump. More than 70% of oil wells are equipped with this mechanism. The advantages a sucker rod pump are usage simplicity and high efficiency, but the main drawback is difficulties with diagnostics and repairing. So providing continuous operation of oil well equipment is the key issue in oil well maintain process. Nowadays, the most efficient method of oil well equipment diagnostics is building and an analysis of dynamometer card, namely dependency of load on rod string on polished rod displacement. This diagnostic method is widely used due to simplicity of its implementation, as well as clarity and easy interpretation of the results. If there are any problems in sucker rod pump operation, shape of dynamometer card changes. Moreover each specific fault in operation has unique characteristic shape of dynamometer card. In this article author proposes techniques overview of oil well equipment diagnostic using dynamometer card, the use of which is a big step in “Industry 4.0” model implementation in the oil production field.

1. Introduction

Nowadays the most widely used equipment to oil extraction is a sucker rod pump. More than 70% of oil wells are equipped with this mechanism [1]. The advantages a sucker rod pump are usage simplicity and high efficiency, but the main drawback is difficulties with failures diagnostics and repairing. The operating conditions of deep-well pump require proper organization and monitoring of its exploitation [2].

Currently the use of dynamometer cards is practically only one supervision method of oil well equipment and deep-well pump. Dynamometer card is dependency of load on sucker rod on polished rod displacement [1, 2, 11]. If sucker rod pump operates normally, then the dynamometer card has the shape similar to parallelogram, as it is shown in Figure 1. When there are some problems with oil equipment operation the dynamometer card shape is changes. Shape analysis allows to determine what exactly failure happened without direct access to deep-well equipment, namely deep-well pump.

There are also other ways to diagnostic oil well equipment, e.g. wattmeter cards and tocograms are used for diagnostic purposes but less frequently [3, 4]. Moreover these methods are usually used to monitor state of surface equipment, e.g. an electric engine, a walking beam unit and so on.

So task of oil well equipment defect detection using dynamometer card is relevant now, because only this method is allows to determine state of deep-well equipment effectively.
In this article, author proposes existed techniques overview of oil well equipment diagnostic using dynamometer card. Most of these techniques are based on the use of machine learning algorithms that allows to do data processing without human participation and make conclusion about equipment malfunction automatically.

The use of these solutions is a big step in “Industry 4.0” model implementation in the oil production field.

2. **Methods of dynamometer card processing**

There are two different classes of sucker rod pump diagnostic methods using dynamometer cards [5].

First, it is pattern recognition of practical dynamometer cards based on comparison with the ideal one. For this class of methods, there are several ways to solve this problem:

- matrix representation of a practical dynamometer card;
- features analysis derived after Fourier transformation of a practical dynamometer card;
- features calculation based on other series different from Fourier one;
- deviation analysis of a practical dynamometer card from an ideal one;
- analysis of relevant points on a practical dynamometer card.

Second, it is fault detection based on the physical laws of obtaining dynamometer card for abnormal pump operation. This class of methods has not found wide practical application.

Next let’s consider some of existed methods of sucker rod pump diagnostics based on analysis of dynamometer cards.

3. **Matrix representation of a practical dynamometer card**

An example of a training of neural network with a matrix representation of a practical dynamometer card is given in [6,7]. In this article, author proposes to transform a practical dynamometer card into a matrix form of a digital representation in binary code with resolution 14×8, as shown in Figure 2 [6].

Further, based on the data obtained as a result of this transformation, binary code of dynamometer card that may be representing as a row vector of 112 elements is formed. For the dynamometer card shown in Figure 2, this vector will be as follows:

![Figure 1. An example of the practical dynamometer card of normal sucker rod pump operation](image)
To implement the dynamometer card recognition algorithm, a two-layer feedforward neural network was chosen. The network parameters are obtained based on class number of dynamometer card need to recognize and the way of their digital representation. As an activation function, a sigmoidal function shifted to positive area is used.

Network training is carried out using the iterative combined back-propagation error algorithm with perturbation and adaptation of the tuning rate parameter.

The matrix representation of a practical dynamometer card is also used by the Oganezov technique [5, 8]. The dynamometer card is represented as a binary matrix. Practical dynamometer card is divided into M×N cells. A cell that contains a part of a dynamometer card is denoted as 1, and an empty one is 0. To failure diagnostics a neural network trained on several reference dynamometer cards for each fault is used. Reference dynamometer cards are also represented in the matrix form. The neural network learns each concept using dynamometer card belonging to particular class. After that, for each fault, a total matrix is built, which is obtained by summing values in the corresponding cells. As a result, after dividing each value in the total matrix by the number of ideal patterns, a probability matrix is obtained.

\[ V = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \] (1)

Figure 2. An example of a dynamometer card transformation.

To recognize a particular dynamometer card, congruent matrices for each fault are built. They are obtained by multiply value of each cell of particular matrix on corresponding values of probability matrices.

In the next step diversive matrices are built. They are obtained as follows: if the difference between the value of a cell from the matrix of the particular dynamometer card and the corresponding value of a cell from the probability matrix is 1, then the corresponding cell in the diversive matrix takes a value equal to 1, otherwise a value equal to 0.

Next, as a result of subtracting the values of cells of probability matrices with the corresponding values of the cell from the congruent matrices, passive matrices are created.
Finally, at the last stage, symbiotic matrices are built. They are obtained by transferring the values of cells that are not equal to 0 from congruent, diverse and passive matrices into one common matrix. The block diagram of the algorithm is presented in Figure 3.

![Figure 3. Block diagram of the Oganezov’s technique](image)

Since the scale of dynamometer card depends on technical parameters of oil well equipment, to obtain correct results normalization is required. To avoid gaps in dynamometer card contour and improve method accuracy, approximation is also used before transformation to matrix form.

4. Features analysis after fourier transformation

Let’s consider the technique of Aliyev and Ter-Khachaturov [9]. This technique is based on approximation of dynamometer card by truncated Fourier series as well as computation and classification of Fourier features. Algorithms for comparison with the samples of different defects are based on the logical characteristics of dynamometer card shape description. During making a decision on a dynamometer card attachment to a certain class, the resulting feature set of the dynamometer card is compared with the features of existed class sets.

This technique fully describes algorithms for diagnostics of dynamometer cards using Fourier features. It contains recommendations for the transformation of feature space to minimize difference of instances belonging to one class and maximize distances between instances of other classes. This method proposes training on several dynamometer cards belonging for each fault. For each fault class a reference vector is constructed, the coordinates of which is the mathematical expectation of the given attribute for all images of the class.

The block diagram of this algorithm is shown in Figure 4 [9].

![Figure 4. Block diagram of the technique of Aliyev and Ter-Khachaturov](image)

The main drawback of the method is the lack of accurate number of Fourier features sufficient to achieve good results. Author proposes to choose number of Fourier features using expert opinion. During testing of the method at one big enterprise from 80 to 800 features were considered [5,7].

5. Deviation analysis from an ideal dynamometer card

The GRID PATTERN technique is related to this class of dynamometer card analysis methods [5,12-14]. It is based on simple algorithm of imposing the actual dynamometer card on the ideal one and then calculating the deviation values. Small deviation of the actual dynamometer from the reference
one of the particular defect means big likelihood of this defect in sucker rod pump. The method uses both an ordinary calculation of the total deviation and a more complicated approach. Practical dynamometer card evenly divided into cells. Those cells that contain part of a dynamometer card or are located inside the border of the dynamometer card are given the value 1, otherwise - 0. The ideal dynamometer card is built according to the following principle: the cells containing a piece of the dynamometer card are assigned the value 1; the cells inside are given the values 2, 3, ..., N depending on the distance of the cell from the border; cells outside the border are given values 0, −1, ..., −M, depending on the distance of the cell from the border. The values of N and M are determined depending on the dimension of the matrix. The diagnostic method is based on the calculated value of function \( C(A, B) \) using following formula [5]:

\[
C(A, B) = \sum_{i=1}^{X} \sum_{j=1}^{Y} |a_{ij} - b_{ij}|
\]  

(2)

where \( X \) – number of rows in the matrix,
\( Y \) – number of columns in the matrix,

\( a_{ij} \) – cell value of actual dynamometer card matrix,

\( b_{ij} \) – cell value of ideal dynamometer card matrix.

This function is calculated for each class of defect. After that the minimal value of this function among all cases is determined, that means high likelihood oft of this defect presence in researched dynamometer card.

The block diagram of this technique is shown in Figure 5 [5, 12].

The results of the method can be better due to using of normalization, increasing the matrix dimensionality, improving accuracy in distance calculation from matrix cell to dynamometer card bounds.

6. Analysis of relevant points on a practical dynamometer card

Let’s consider the technique of Belov-Gilaev [10] that is belonged to this class of methods. This technique is based on analysis of relevant points obtained using theory and practice experience.

The method involves the determination of the failure, based on the physical laws of obtaining dynamometer cards of abnormal pump operation. It is based on a visual comparison of the actual and theoretical dynamometer cards. Any significant deviation of the actual dynamometer card from the theoretical one indicates an abnormal pump operation.

The algorithm is based on the description of I.G. Belova about recognition deep-well pump state using dynamometer cards.
According to this technique, the seven most relevant points of dynamometer cards are determined. The use of parameter values in these points and criteria proposed by the author allows to set a sequence of arithmetic operations and comparisons to make a specific conclusion about the sucker rod pump operation.

The coordinates of the relevant points are determined by combining the theoretical dynamometer card with the practical one. However this description doesn’t include formalized features that could be related to a particular fault.

As an example shown in Figure 6 [10], consider the fluid leakage diagnostics in traveling valve of deepwell pump. Among the features of the dynamometer card, which can help to detect leakage the following one should be considered:

- The curve of load perception AB* having a smaller angle of inclination to the horizontal in comparison with the same curve AB during normal operation of the equipment;
- the sharp outline of the lower left corner of the dynamometer card;
- the rounding of the right upper corner;
- the big difference in fluctuation intensity when plunger moves up and when plunger moves down;

The main drawback of the technique is problem with features extraction from practical dynamometer card for further analysis. Since this technique doesn’t include particular recommendations for this task, it hinders its usage on practice.

![Figure 6: The example of Belov-Gilaev technique usage](image)

7. Conclusions

Methods of dynamometer card analysis currently remain one of the most effective ways to identify faults in oil well equipment. There is a huge number of techniques that can be divided into two classes.

The first class is based on pattern recognition of practical dynamometer card based on comparison with the ideal one. Methods belonging to this approach is widespread and continues to expand with new methods and techniques. This class includes techniques that widely use the neural network approach [12-15] for recognition tasks and other methods of data mining and machine learning [16]. For feature extraction the following approaches are used:

- The matrix form of dynamometer card presentation, e.g. Oganezov technique[8];
- The Fourier series approximation, e.g. Aliyev and Ter-Khachaturov technique[9];
- The deviation analysis from an ideal dynamometer card, e.g. GRID PATTERN[5,12];
- The analysis of relevant points, e.g. Belov-Gilaev technique[11];
- Other methods, e.g. the use of wavelet analysis [16].

The second class of methods describes the theoretical basis for obtaining a practical dynamometer card of a fault, but it doesn’t give formalized features of this or that malfunction. In other words, it describes how the fault dynamometer card is obtained, but doesn’t contain mathematical approaches for describing its features. In this regard, this class of methods is practically not used.
Proposed solutions allow to improve efficiency of deep-well equipment malfunction detection and eliminate human factor from this process.

Further researches in this area will lead to implement new production model “Industry 4.0” in the oil production that is now gaining popularity in other fields of industry rapidly.

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