MODELING RESIDUAL LIFE OF MAIN LINE PUMP FROM ITS VIBRATION CONDITION

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Abstract. Pumping oil through pipelines is provided by Main Line Pumps (MLPs), whose stable operation is critical for general efficiency of the pipeline transportation. Vibration is one of the strongest adverse factors influencing the MLP useful life. Its value depends on conditions of all the elements of the MLP, thus, vibration signals are an important source of diagnostic information. However, for its practical application, mathematical models are required that adequately link physical events in the MLP to obtained numerical data. This paper proposes a regression mathematical model allowing performing vibration-based diagnostics of MLP equipment technical condition from bearing wear parameters and vibration. Data gathered from NM 10000-210 pump unit with STDP-8000 electric motor were used for construction of the model. The model allows calculating remaining life of an MLP for the current value of observation interval or from measurements, as well as determining design vibration value for a certain period of pump operation to compare it with an actual measured value. Application of the model allows optimizing periodicity of scheduled activities, timely revealing undesired changes in MLP operation and extending its operational life.

1. Introduction

One of the main condition for stable development of pipeline transportation of oil and petroleum products is ensuring reliability, safety and efficiency of operation of oil pumping equipment, including that of main line pumps (MLP). At that, reliability and economical operation of the pumps themselves is determined by a number of factors, such as quality of manufacturing, operating conditions, adaptability, timeliness of maintenance, etc. Increased vibration makes the most adverse effect on reliability of pumping units. About 38-45% of all centrifugal pump failures happen due to vibration, at that 42-53% of all pump failures are due to failures in face seals and bearings [1].

Currently-operated MLPs have a wide range of total hours: from hundreds to several hundred thousands hours. Attaining maximum hours in service leads to significant changes in MLP parameters, at that, common techniques of technical condition evaluation become significantly inaccurate. Thus, there is a practical interest in modeling and study of dynamics of aging, i.e., determination of trends in changes of operational characteristics of MLP while it is going through its intended lifespan. Accounting for such dynamic characteristics will allow introducing relevant corrections into calculation methods and to a certain degree optimize operational parameters of MLPs having completely exhausted their service hours [2].

As it has been mentioned above, one of the main factors influencing MLP condition is vibration [3, 4], thus, regularity of changes in its parameters depending on technical condition of separate elements may be used as a basis for development and improvement of assessment methods for technical condition evaluation of unit as a whole. Excess of maximum allowable vibration level is an objective
indicator of defects leading to accelerated wear and further failure of critical parts and elements [5, 6]. At that, it is necessary to note, that using vibration signal as a diagnostic information carrier has its advantages and disadvantages alike. On the one hand, minuscule changes in the most wearable parts are reflected in changes of the vibration signals, allowing early diagnostics of defect and taking necessary measures. On the other hand, as the vibrational signal is a sum of signals coming from all parts and elements of the MLP, separation of necessary informative elements is a complex task, requiring not only good diagnostic equipment, but reliable mathematical models that adequately describe underlying physical phenomena as well.

Thus, creation of mathematical models for vibration condition of MLP allowing evaluation of technical conditions of its components is a timely scientific and practical task in the field of creation and improvement of vibration diagnostics methods.

2. Problem statement
The following results [7] are expected from development of vibration condition modeling methods for oil pumping equipment and prognostic methods for remaining lifetime from vibration parameters:

– determination of optimal repair frequency;
– prevention of unplanned downtime and break of normal operation mode;
– provision of increased efficiency of equipment by means of timely detection and rectification of efficiency deteriorating events.

Forecasting of remaining lifetime is possible only when the following conditions hold simultaneously [8]:

– vibration parameters, which determines limit state and normal technical condition of MLP, are known;
– there is a possibility of continuous (or periodic) monitoring of vibration parameters.

During the MLP operation, it is important to give correct assessment of parts' wear and timely determine necessity of repair, as after the components exhaust their resource, continuing operation of equipment is impractical from the economic point of view. Thus, it is practical to perform vibration-diagnostic monitoring of MLP technical condition from bearing wear parameters and vibration [9 – 13].

3. Results and Discussion
In [14], an analytical function is proposed to describe current level of vibration (vibration velocity) of a NM 10000-210 pump unit with an STDP-8000 motor, which is in its general form a one-dimensional linear regression model

\[ y = a_0 + a_1 x. \] (1)

To obtain the model of an object from observation results, it is necessary to identify it, i.e., to discover how it reacts to disturbances coming from the external environment [15]. Identification is obtaining mathematical models from results of input and output values of the observed object. At that, it is often assumed, that physical theory of the object operation is lacking or totally inapplicable, and the object is represented as a black box with several measurable (and sometimes adjustable) inputs \( x \) and one or several measurable (observable) outputs \( y \) [16, 17].

The task of model identification is to determine coefficients \( a_0 \) and \( a_1 \).

According to [18], formulas for regression equation coefficients are as follows

\[ a_0 = \bar{y} - b\bar{x}; \quad a_1 = \frac{\text{cov}(x, y)}{\sigma_x^2} = \frac{\bar{y}\bar{x} - \bar{y}\bar{x}}{\bar{x}^2 - (\bar{x})^2}. \] (2)

In the linear regression model (1) the input parameter (factor) is the duration of motor operation \( t \) (hours), and output \( y \) is vibration velocity \( V \) (m/s), that is, in this case the model (1) takes the form of

\[ V_t = a_0 + a_1 t. \] (3)

Table 1 gives input data for calculation of regression equation coefficient and control of its
adequacy.

**Table 1.** Input data for calculation of regression equation coefficient and control of its adequacy.

| no. of experiment | $t$, hour | $V$, mm/s | $V \cdot t$ | $\bar{V}^2$ | $V_t$ | $V \cdot V_t$ | $(V \cdot V_t)^2$ | $V \cdot \bar{V}$ | $(V \cdot \bar{V})^2$ |
|------------------|-----------|-----------|-------------|-------------|-------|---------------|----------------|----------------|----------------|
| 1                | 0         | 1.5       | 0           | 0           | 0.545 | 0.955         | 0.912          | -1.45455       | 2.115701       |
| 2                | 1000      | 1         | 1000        | 1.0 × 10^6  | 0.775 | 0.225         | 0.051          | -1.95455       | 3.820246       |
| 3                | 2000      | 0.9       | 1800        | 4.0 × 10^6  | 1.004 | -0.104        | 0.011          | -2.05455       | 4.221155       |
| 4                | 3000      | 1.3       | 3900        | 9.0 × 10^6  | 1.234 | 0.066         | 0.004          | -1.65455       | 2.737519       |
| 5                | 4000      | 1.5       | 6000        | 16.0 × 10^6 | 1.463 | 0.037         | 0.001          | -1.45455       | 2.115701       |
| 6                | 5000      | 1.9       | 9500        | 25.0 × 10^6 | 1.693 | 0.207         | 0.043          | -1.05455       | 1.112065       |
| 7                | 6000      | 1.8       | 10800       | 36.0 × 10^6 | 1.922 | -0.122        | 0.019          | -1.15455       | 1.332974       |
| 8                | 7000      | 2.3       | 16100       | 49.0 × 10^6 | 2.152 | 0.148         | 0.022          | -0.65455       | 0.428429       |
| 9                | 8000      | 2.2       | 17600       | 64.0 × 10^6 | 2.381 | -0.181        | 0.033          | -0.75455       | 0.569338       |
| 10               | 9000      | 2.5       | 22500       | 81.0 × 10^6 | 2.611 | -0.111        | 0.012          | -0.45455       | 0.206611       |
| 11               | 10000     | 2.6       | 26000       | 1.0 × 10^8  | 2.840 | -0.24         | 0.058          | -0.35455       | 0.125702       |
| 12               | 11000     | 2.8       | 30800       | 1.21 × 10^8 | 3.070 | -0.27         | 0.073          | -0.15455       | 0.023884       |
| 13               | 12000     | 2.9       | 34800       | 1.44 × 10^8 | 3.299 | -0.399        | 0.159          | -0.05455       | 0.002975       |
| 14               | 13000     | 3         | 39000       | 1.69 × 10^8 | 3.529 | -0.529        | 0.279          | 0.045455       | 0.020660       |
| 15               | 14000     | 3.1       | 43400       | 1.96 × 10^8 | 3.758 | -0.658        | 0.433          | 0.145455       | 0.021157       |
| 16               | 15000     | 3.4       | 51000       | 2.25 × 10^8 | 3.988 | -0.588        | 0.345          | 0.445455       | 0.198430       |
| 17               | 16000     | 3.6       | 57600       | 2.56 × 10^8 | 4.217 | -0.617        | 0.381          | 0.645455       | 0.416612       |
| 18               | 17000     | 4.1       | 69700       | 2.89 × 10^8 | 4.447 | -0.347        | 0.12           | 1.145455       | 1.312067       |
| 19               | 18000     | 4.7       | 84600       | 3.24 × 10^8 | 4.676 | 0.024         | 0.001          | 1.745455       | 3.046613       |
| 20               | 19000     | 5.2       | 98800       | 3.61 × 10^8 | 4.906 | 0.294         | 0.087          | 2.245455       | 5.042068       |
| 21               | 20000     | 5.9       | 118000      | 4.0 × 10^8  | 5.135 | 0.765         | 0.585          | 2.945455       | 8.675705       |
| 22               | 21000     | 6.8       | 142800      | 4.41 × 10^8 | 5.365 | 1.435         | 2.060          | 3.845455       | 14.78752       |
| Σ                | 231000    | 65        | 885700      | 33.1 × 10^8 | 65.01 | –             | 5.685          | –              | 52.31455       |
| Average          | 10500     | 2.95      | 40259.0     | 1.51 × 10^8 | 2.955 | –             | –              | –              | 2.37793        |

According to (2) and data from Table 1, the regression coefficients are calculated:

$$a_1 = \frac{\bar{V} \cdot t - \bar{V} \cdot \bar{V}}{\bar{V}^2 - (\bar{V})^2} = \frac{40259.09 - 10500 \cdot 2.955}{1.51 \cdot 10^8 - 10500^2} = 2.295 \cdot 10^{-4} \, \text{mm} / \text{s} / \text{h};$$

$$a_0 = \bar{V} - a_1 \bar{t} = 2.955 - 2.295 \cdot 10^{-4} \cdot 10500 = 0.545.$$  

The regression equation takes the following form

$$V_t = a_0 + a_1 t = V_0 + a_1 t = 0.545 + 2.295 \cdot 10^{-4} t. \quad (4)$$

Variance of mathematical model outputs from the average value of system outputs is used to determine system adequacy [17, 18].

Variance comparison is performed with Fisher predictive criterion (F-criterion) [19]:

$$F_B = \frac{S_{ad}^2}{S_{common}^2}, \quad (5)$$
\[
S_{ad} = \frac{\sum_{i=1}^{n} (V_i - \bar{V})^2}{f - \phi} = \frac{5.685}{22 - 2} = 0.284
\]
where \(S_{ad}^2\) is a variance describing the nature of error in the model (adequacy variance or residual variance), it characterizes average dispersion of experimental points with respect to the regression line. Its minimum value is an evidence of a well-chosen residual regression;

\(f_r\) is the number of degrees of freedom of the mathematical model for a single-factor experiment \(f = n - 2;\)

\[
S_{common}^2 = \frac{\sum_{i=1}^{N} (V_i - \bar{V})^2}{n - 1} = \frac{52.315}{21} = 2.491
\]
is a variance of the output parameter or general variance.

From formula (5), the calculated value of \(F_{calc}\) is obtained:

\[
F_p = \frac{0.284}{2.491} = 0.114.
\]
The critical value of Fisher quantile for significance level of \(q = 0.05\) is taken from the table [19]:

\(F_{crit}(20; 21; 0.05) = 2.2.\)

As \(0.114 < 2.2\), then, with a probability of 95% we may state that the regression equation is adequate and may predict experimental results with the stated accuracy.

To evaluate relations between the values \(V\) and \(t\), a linear correlation coefficient is employed that characterizes a degree of linear relation between the two samples. Using the data from Table 2, the correlation coefficient is calculated with the formula

\[
r = \frac{\sum_{i=1}^{n} (t_i - \bar{t}) \cdot (V_i - \bar{V})}{\sqrt{\sum_{i=1}^{n} (t_i - \bar{t})^2 \cdot \sum_{i=1}^{n} (V_i - \bar{V})^2}} = \frac{203200}{\sqrt{52.31455 \cdot 10^5 \cdot 8855}} = 0.944,
\]

where \(\bar{t}\) and \(\bar{V}\) are input and output experimental values; \(t\) and \(V\) are their averages.

**Table 2.** Data for correlation coefficient calculation

| no. of experiment | \(t\), hour | \(V\), mm/s | \(t - \bar{t}\) | \((t - \bar{t})^2\) | \(V - \bar{V}\) | \((V - \bar{V})^2\) | \((t - \bar{t}) \cdot (V - \bar{V})\) |
|------------------|-------------|-------------|----------------|------------------|----------------|-----------------|------------------|
| 1                | 0           | 1.5         | -10500         | 11025 \cdot 10^4 | -1.45455 | 2.115701        | 15272.72         |
| 2                | 1000        | 1           | -9500          | 9025 \cdot 10^4  | -1.95455 | 3.820246        | 18568.18         |
| 3                | 2000        | 0.9         | -8500          | 7225 \cdot 10^4  | -2.05455 | 4.221155        | 17463.63         |
| 4                | 3000        | 1.3         | -7500          | 5625 \cdot 10^4  | -1.65455 | 2.737519        | 12490.09         |
| 5                | 4000        | 1.5         | -6500          | 4225 \cdot 10^4  | -1.45455 | 2.115701        | 9454.543         |
| 6                | 5000        | 1.9         | -5500          | 3025 \cdot 10^4  | -1.05455 | 1.12065         | 5799.998         |
| 7                | 6000        | 1.8         | -4500          | 2025 \cdot 10^4  | -1.15455 | 1.332974        | 5195.453         |
| 8                | 7000        | 2.3         | -3500          | 1225 \cdot 10^4  | -0.65455 | 0.428429        | 2290.908         |
| 9                | 8000        | 2.2         | -2500          | 625 \cdot 10^4   | -0.75455 | 0.569338        | 1886.363         |
| 10               | 9000        | 2.5         | -1500          | 225 \cdot 10^4   | -0.45455 | 0.206611        | 681.8175         |
| 11               | 10000       | 2.6         | -500           | 25 \cdot 10^4    | -0.35455 | 0.125702        | 177.2725         |
| 12               | 11000       | 2.8         | 500            | 25 \cdot 10^4    | -0.15455 | 0.023884        | -77.2725         |
| 13               | 12000       | 2.9         | 1500           | 225 \cdot 10^4   | -0.05455 | 0.002975        | -81.8175         |
| 14               | 13000       | 3           | 2500           | 625 \cdot 10^4   | 0.045455 | 0.002066        | 113.6375         |
The obtained value of the correlation coefficient \( r \) is larger than 0.9, meaning that the strength of relationship is very strong, that is, there is a linear dependence.

Student's test is employed to check the significance of the correlation coefficient

\[
t_{\text{calc}} > t_{\text{crit}},
\]

where

\[
t_{\text{calc}} = \frac{r \sqrt{n-2}}{\sqrt{1-r^2}} = \frac{0.944\sqrt{22-2}}{\sqrt{1-0.944^2}} = 12.808;
\]

\[
t_{\text{crit}} = f(k;q) = f(20; 0.05) = 2.09
\]

is found in a Student's distribution table.

Student's test (7) holds, that is, there is a relation between the variables \( t \) and \( V \), and the correlation coefficient obtained is significant.

Control of significance of the linear regression coefficient is also performed with the Student's \( t \)-test (7). For that end, actual (calculated) values \( t_{\text{расч}} \) of the test for coefficients \( a_0 \) and \( a_1 \):

\[
t_{a_0} = \frac{|a_0|}{S_{a_0}}; t_{a_1} = \frac{|a_1|}{S_{a_1}}.
\]

Standard error values in linear regression equation coefficients are calculated with the formulas

\[
S_{a_0} = S_V \sqrt{\frac{\sum t_i^2}{n \cdot S(t)}}; \quad S_{a_1} = \frac{S_V}{S(t)\sqrt{n}}.
\]

where \( S(t) \) is a root mean square deviation of the input value (factor) from average :

\[
S(t) = \sqrt{\frac{\sum t_i^2}{n} - (\bar{x})^2} = \sqrt{\frac{33.1 \cdot 10^8}{22} - (10500)^2} = 0.636 \cdot 10^4;
\]

\( S_V \) is a root mean square (RMS) of the experimental output from the average velocity value:

\[
S_V = \sqrt{\frac{\sum (V_i - \bar{V})^2}{n-2}} = \sqrt{\frac{5.685}{22-2}} = 0.533.
\]

Substituting RMS into formulas (10) and (9) respectively we get
Test (7) holds for both coefficients, thus both coefficients are significant. Lower and upper 95% confidence interval limits for the regression equation coefficients $a_i$ are equal to:

- lower 95% = $a_i - S_{a_i} \cdot t_{cr}$;
- upper 95% = $a_i + S_{a_i} \cdot t_{cr}$.

Or, respectively: for $a_0 = 0.545 \pm 0.45771$; for $a_1 = (2.295 \pm 0.611) \cdot 10^{-4}$, i.e., regression coefficients are larger than their confidence intervals, which supports significance of these coefficients.

Quality assessment of the regression model is obtained by mean approximation error, which is found from Table 1 data:

$$
\bar{A} = 1 \sum_{i=1}^{n} \left( \frac{(V_i - V_{nt})}{V_i} \right) \cdot 100\% = 0.28\%.
$$

Allowable limit of error value does not exceed 8-10%, thus, the model is valid.

Confidence intervals of the measurement results are determined with the formula

$$
S = \frac{1}{\cos(\text{arctg}(a_i))} \sqrt{\sum_{i=1}^{n} (V_i - V_{nt})^2} / n,
$$

where $(V_i - V_{nt})^2$ is deviation of the actual value of vibration parameter from the regression line. Substituting Table 1 data, we get

$$
S = \frac{1}{\cos(\text{arctg}(2.295 \cdot 10^{-4}))} \sqrt{\frac{5.685}{22}} = 0.508 \text{ mm/s}
$$

If 68.26% or more of experimental points $V_i$ gets into the area limited by the lines $(V_n - S)$ and $(V_n + S)$, then, the hypothesis that the theoretic function will not differ from the experimental one holds.

If high accuracy of result is necessary, an additional condition is introduced: 95.44% or more of experimental points shall get into the area limited by the lines $(V_n - 2S)$ and $(V_n + 2S)$.

The results of modeling bearing vibration condition in wear are shown in Figure 1, where remaining lifetime of the MLP is shown as determined with the regression model $t_{op}$ and from the results of measurements $t_{op}'$.

It shall be noted, that the limiting vibration level as per [20] for prolonged operation of MLP is 7.1 mm/s. Analysis of the experimental data in the figure shows, that about 70% of the experimental points are within the confidence limits of the measurement results. Thus, the calculation results show that the generated regression model is adequate and the theoretic function does not differ from the experimental one.

Analytical dependence (3) that describes changes in MLP vibration parameters with time [21] may be represented as

$$
V_k = \bar{V} - a_1 (t_k - \bar{t}) = 2.955 - 2.295 \cdot 10^{-4} (t_k - 10500),
$$

where $V_k$ and $t_k$ are current actual measured values of vibration level (mm/s) and observation time interval (h) respectively.
regression model of bearing vibration;
limiting vibration level ($V_{max} = 7.1$ mm/s);
experimental data;
confidence limits of the measurement results ($V_t \pm S$)

**Figure 1.** Results of modeling the bearing wear

The MLP remaining life from the last measurement to the limiting condition as per the figure is determined by the point where the regression line of the model crosses the limiting vibration condition line

$$t_{op} = (t_k - t_0) \left( \frac{V_i - V_0}{V_k - V_0} - 1 \right),$$

where $V_0$ is the basic level of vibration (in this case $V_0 = 0.545$ mm/s);
$t_0$ is the time interval value, corresponding to $V_0$ (in this case $t_0 = 0$).

As an example, let us consider calculation of MLP remaining life $t_{op}$ with the regression model for the current value of the observation time interval $t_k = 18,000$ hours. In Table 1 we find the initial data for our calculations:

- $V_0 = 0.545$ mm/s;
- $V_k = 4.7$ mm/s;
- $V_i = V_{max} = 7.1$ mm/s;
- $t_0 = 0$ h.

Substituting these values in the formula (12), we get:

$$t_{op} = (18000 - 0) \left( \frac{7.1 - 0.545}{4.7 - 0.545} - 1 \right) = 10404 \text{ h},$$

Consequently, we may use the same formula for calculating the MLP remaining life from the measurement results. Input data for calculations:
$$V_0' = V_0 + S = 0.545 + 0.508 = 1.053 \text{ (mm/s)}.$$

$$t_{op} = \frac{(18000 - 0)(7.1 - 1.053)}{4.7 - 1.053} = 9097 \text{ h}.$$

It shall be noted, that the formula (3) allows determining the calculated value of vibration for a certain period of pump operation for its further comparison with the actual measured value. It allows making relevant conclusions about condition of the pump bearings.

4. Conclusions
Analysis of life cycle and vibration condition modeling of MLP is of great interest for MLP remaining lifetime calculations, determination of scheduled maintenance periodicity, finding relations between the vibration parameters, wear, thermodynamic parameters, etc.
Solution of these problems allows revealing unacceptable defects and preventing failures, improving economic indicators, reliability and determining safe operation period of oil pumping station equipment.

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