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HARMONIC ANALYSIS OF LOADING CHARACTERISTICS RESEARCH OF PUMP JACK

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Abstract- The possibility to use the harmonic analysis method of the reversing mechanic's gear box' crankshaft torque is considered in this article. It is concluded that the torque curve expansion into a simple harmonic creates possibility for theoretical investigation in equipment's durability increase. A study of the rubber seals of the fasteners showed that the sealants sometimes broke without fatigue, according to the analysis of the research. This is related to physical resonances created by dynamic forces. Early consideration of resonance efficiency in the design of elastic elements will increase their longevity. As a result of the research, we found that the rubber spacers fail due to the dynamic resonances created in the machine. In order to avoid this problem, the control of resonance was studied and an analytical expression was obtained for its determination.

Keywords: Harmonic Equation, Pump Jack, Periodic Functions, Connecting Rod.

1. INTRODUCTION

The most efficient way to continue the fountain process in oil and gas extraction is the operating method with rod pump units. Increasing the efficiency of this method is an urgent issue in countries engaged in oil and gas business. Rod pump units are mainly divided into two parts. Pumping equipment and pump-transmission equipment. Increasing the efficiency of the pumping equipment directly increases the productivity of the pump. Therefore, in the article, the problem of increasing the working capacity of the plunger of the rod pump unit was raised and its transmission was studied [1, 7, 8, 9].

The most common parts of a pump that fail are its valve parts and rubber sealing parts. In various articles, these problems have been solved by replacing the valve material with materials resistant to hydro abrasive corrosion. By changing both the material and the construction of rubber conditioners, they increased its durability [2, 4, 5, 6].

With the mechanized method of oil production using downhole rod pumping units, the most common drive of a downhole rod pump is a balancing pumping jack. The kinematic scheme of pumping jacks remains practically unchanged throughout the entire period of their introduction into operation, starting from the 50s of the last centuries. The pumping jack is a four-link mechanism that converts the rotational movement of the motor shaft into the reciprocating movement of the rod suspension point, which is a rope suspension in which the ends of the rope thrown through the bushing of the balancer head and the polished rod are connected [5, 6].

The lower end of the polished rod is connected to the sucker rod string, to which the plunger of the downhole rod pump is attached. The operational reliability of pumping units depends on the reliability of each of its nodes, which is the subject of this study. The reliable operation of pumping units is influenced by such factors as the correctly chosen kinematic scheme, balancing the operation of the engine, torque on the drive shaft of the gearbox, the load at the suspension points of the rods, etc. [2, 3, 4, 13, 14, 15].

The reliability of the pump depends on the reliability of its individual nodes. To increase the reliability of a node, it can be done by increasing the reliability of each of its nodes or any node.

2. METHODS FOR SOLVING THE STATED PROBLEM

In technology, we often meet with repeats of periodic researches, i.e., occurring cases during a certain time are the period of the current process T. Describing these different cases in time t represent a function, after the expiration of T, they take previous value [1, 10, 11, 12].

$$F(t+t)=f(T) \quad (1)$$

As an example, could indicate the strength and voltage of the alternating current (AC), the torque of the pump jack, etc. A simplified formula for periodic functions:

$$Y=a\sin(\omega T+\alpha) \quad (2)$$

where, $\omega=2\pi/T$ is the frequency is depending on the time T in relation. We can get more complex function from these functions. Then the structure of the periodic functions must consist of different times (or frequency).

If summarizing several functions (periodic) with the division of the lowest of them by the frequency of time, then in comparison with the function, we obtain a periodic function with period *T*. For example;

$$y_1 = A_1 \sin(\omega t + \alpha_1) \quad (3)$$

$$y_2 = A_2 \sin(\omega t + \alpha_2) \quad (4)$$

But during the solving several technical problems, mutual direction of research takes place are division with time *T*/1, *T*/2, *T*/3 and complex periodic function, finite or infinite $A\sin(\omega t+\alpha)$ sinusoidal coefficients in the sum form.

$$y = \sin t + \frac{1}{2}\sin 2t + \frac{1}{4}\sin 3t \quad (5)$$

The research shows that any periodic function can be represented in a compiled trigonometric series, this indicates that any time function *T* can be divided into an $f(t)$ infinite series of assembled sinusoidal coefficients.

$$f(t) = A_0 + A_1\sin(\omega t + \alpha_1) + A_2(2\omega t + \alpha_2) + ... = = A_0 + \sum_{n=1}^{\infty} A_n \sin(n\omega i + \alpha_n) \quad (6)$$

It can be seen from Equation (6) that the diagram of the periodic function consists of the assembled simplified sinusoid imposed on each other. The individual sinusoidal coefficients in the Equation (6) are called the part of the harmonic content or harmonic of the function $f(t)$. If the dependent variable is not the time and angle, then this division takes a simplified form, so $T = 2\pi$, $n\omega = 1$. Then

$$x = A_0 + A_1\sin(x + \alpha_1) + A_2\sin(2x + \alpha_2) = = A_0 + \sum_{n=1}^{\infty} A_n \sin(nx + \alpha_n) \quad (7)$$

Introducing a new variable into this simplified form can lead to a general division:

$$x = \omega t = 2\pi t / T \quad (8)$$

If in Equation (7) we divide each limit by the sinus summation formula, we obtain Equation (9)

$$f(x) = A_0 + \sum_{n=1}^{\infty}(A_n \sin\alpha_n \cos nx + A_n \cos\alpha_n \sin nx) \quad (9)$$

Note

$$A_0 = a_0 / 2 \quad (10)$$

$$A_n \sin\alpha_n = a_n \quad (11)$$

$$A_n \cos\alpha_n = p_n \quad (n = 1, 2, 3.....) \quad (12)$$

Then we obtain trigonometric series in terms of the Fourier series of trigonometric division.

$$f(x) = \frac{a_0}{2} + (a_1\cos x + b_1\sin x) + (a_2\cos 2x + b_2\sin 2x) + +... = \frac{a_0}{2} + \sum_{n=1}^{\infty}(a_n\cos nx + b_n\sin nx) = = \frac{a_0}{2} + \sum_{n=1}^{\infty}(a_n\cos nx + b_n\sin nx) \quad (13)$$

We transform the formula $(a_n \cos nx + b_n \sin nx)$ into another form:

$$(a_n \cos nx + b_n \sin nx) = = \sqrt{a_n^2 + b_n^2}\left(\frac{a_n}{\sqrt{a_n^2 + b_n^2}}\cos nx + \frac{b_n}{\sqrt{a_n^2 + b_n^2}}\sin nx\right) \quad (14)$$

We note that $\sqrt{a_n^2 + b_n^2} = A_n$ this harmonic amplitude is of a *n*th row; α is phase change angle, $A_0 \times \sin\alpha_0$ is harmony of the row 0, as noted before its constant coefficient is $\frac{a_0}{2}$.

$$\sin\alpha_n = \frac{a_n}{\sqrt{a_n^2 + b_n^2}} \quad (15)$$

$$\cos\alpha_n = \frac{b_n}{\sqrt{a_n^2 + b_n^2}} \quad (16)$$

For this purpose, the amplitude is determined A_n, and also the phase α_n. The definition from a relation $\alpha_n - i\text{tg}\alpha_n = \frac{a_n}{b_n}$ is easier. But first you need to determine the angle of the quarter location α_n. Designation rules:

a_n	b_n	α_n
+	+	I
+	–	II
–	–	III
–	+	IV

At the end;

$$\alpha_n \cos nx + b_n \sin nx = A_n(\sin\alpha_n \cdot \cos nx + \cos\alpha_n \cdot \sin nx) = = A_n \sin(nx + \alpha_n) \quad (17)$$

We make the division periodic function harmonics a_0, a_1, b_1, …an, b_n, the determination of unknown coefficients - The analysis of harmonics.

For determine these coefficients, we introduce formulas into the old analytic problem. The problem is that the coefficients a_0, a_1, b_1, ... a_n, b_n must be chosen in such a way that the sum of (17) row will equal to the period 2π $f(x)$ of the periodic function. If the function $f(x)$ was given only in the last intervals $(0;\pi)$ or $(0;2\pi)$ then it can be continued along the real axis in the interval 2π. If we integrate both sides of the equation, we will obtain $(0;2\pi)$.

$$\int_0^{2\pi} f(x)dx = \int_0^{2\pi}\frac{a_0}{2}dx + \sum_{n=1}^{\infty}(a_n\int_0^{2\pi}\cos nxdx + b_n\int_0^{2\pi}\sin nxdx) \quad (18)$$

From the fact that, the incomings under the notation the integrals sum equals zero, we obtain.

$$\int_0^{2\pi} f(x)dx = \frac{a_0}{2}\cdot 2\pi \quad (19)$$

from here

$$a_0 = \frac{1}{\pi}\int_0^{2\pi} f(x)dx \quad (20)$$

To determine a_t, it is necessary to multiply both sides of the equation by cos*kx* (13) and make the integration

$$\int_0^{2\pi} f(x)\cos kxdx = \frac{a_0}{2}\int_0^{2\pi}\cos kxdx + \\ +\sum_{n=1}^{\infty}(a_n\int_0^{2\pi}\cos nx\cdot\cos kxdx + b_n\int_0^{2\pi}\sin nx\cdot\cos kxdx) \quad (21)$$

Besides the following, all the integrals on the left side of this equation are zero.

$$\int_0^{2\pi}\cos kx\cos kxdx \ , \ n=k \\ \int_0^{2\pi}\cos^2 nxdx = \int_0^{2\pi}\frac{1+\cos 2nx}{2} \ , \ dx=\pi \quad (22)$$

Then, $\int_0^{2\pi} f(x)\cos kxdx = a_k\pi$ from, where

$$a_k = \frac{1}{\pi}\int_0^{2\pi} f(x)\cos kxdx \quad (23)$$

Similarly, we can take the following

$$b_k = \frac{1}{\pi}\int_0^{2\pi} f(x)\sin kxdx \quad (24)$$

The Fourier coefficients of a finite function $f(x)$

$$a_0 = \frac{1}{\pi}\int_0^{2\pi} f(x)dx \qquad a_k = \frac{1}{\pi}\int_0^{2\pi} f(x)\cos kxdx \\ b_k = \frac{1}{\pi}\int_0^{2\pi} f(x)\sin kxdx \quad (25)$$

Usually in practice, the used function of the process is obtained as a result of the experiment, the function is given in a table or on a graph. In this work, was given the function of the dependence of the torque on the shaft of the reduction gear of the pumpjack from the rotation angle change of the connecting rod according to the table φ versus $M_{twi}(f)$. But in this case, according to Equations (24) and (25), it is impossible to find the corresponding analytic formula for the function $M_{twi}(f)$; therefore, it is necessary to make various approximate calculations for the computation of integrals. The template method is widely used.

There are functions $M_{twi}(f)$ in the interval (0; 2π) by the 36-points. The periodic function is the $T=2\pi$ period.

$$a_k = \frac{1}{\pi}\int_0^{2\pi} M_{fir}(\varphi)\cos k\varphi d\varphi \\ b_k = \frac{1}{\pi}\int_0^{2\pi} M_{fir}(\varphi)\sin k\varphi d\varphi \quad (26)$$

It is required to find the first coefficients of the approximate multilateral Fourier function. To calculate the integrals, is used one of the computational formulas for numerical computation-the formula of rectangles.

The interval (0; 2π) is divided into equal parts n by points $\varphi_0 = 0, \varphi_1, \varphi_2 ... \varphi_{n-1}$.

$$\varphi_n = 2\pi \quad (27)$$

$$\varphi_i = i\frac{2\pi}{n} \quad (28)$$

$$\Delta\varphi = \frac{2\pi}{n} \quad (29)$$

Then by the formula of rectangles;

$$a_k = \frac{2}{n}\sum_{i=0}^{n-1} M_{fir}(\varphi)_i \cos k\varphi_i \quad (30)$$

$$b_k = \frac{2}{n}\sum_{i=0}^{n-1} M_{fir}(\varphi)_i \sin k\varphi_i \quad (31)$$

Considering the singularities of the cos$f$ and sin$f$ multipliers the value for $n=12$ is taken or numbers 12, 24, 36 and more (if is not required the high correctness). Consider the case $n=12$. During the period 2π, we divide the functions $M_{twi}(f)$ into 12 parts (Figure 1).

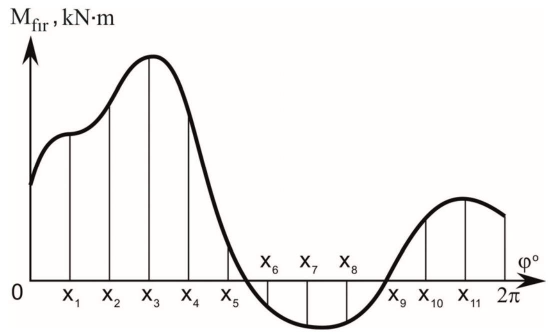

Figure 1. During the period we divide the functions *Mtwi(f)* into 12 parts

We calculate the following form of the coefficient of the Fourier series.

$$M_{f11} = \frac{a_0}{2}\sum_{k=1}^{11} a_k\cos k\varphi + b_k\sin k\varphi \quad (32)$$

$$a_k = \frac{2}{n}\sum_{i=0}^{11} M_{fir}(\varphi)_i \cos k\varphi \quad (33)$$

$$b_k = \frac{2}{n}\sum_{i=0}^{11} M_{fir}(\varphi)_i \sin k\varphi \quad a_0 = \frac{1}{6}\sum_{i=0}^{11} M_{fir}(\varphi) \quad (34)$$

where, $n=12$ and $\Delta\varphi = \frac{2\pi}{n} = 30°$.

Then each n = 12 values assigned to a function in Equation (8) are multiplied in one of the numbers "+" or "–" of the following M or $M_{twi}(f)$

$$\cos 0 = \sin\frac{\pi}{2} \qquad \cos\frac{\pi}{6} = \sin\frac{\pi}{3} \\ \cos\frac{\pi}{3} = \sin\frac{\pi}{6} \qquad \cos\frac{\pi}{2} = \sin 0 \quad (35)$$

The free value a of the Fourier series is computed by multiplying the sum of all multipliers by $2/n$:

$$a_0 = \frac{1}{6}\Big[M_{fir}(\varphi)_o + M_{fir}(\varphi)_1 + M_{fir}(\varphi)_2 + \\ + M_{fir}(\varphi)_3 + M_{fir}(\varphi)_4 + M_{fir}(\varphi)_5 + \\ + M_{fir}(\varphi)_6 + M_{fir}(\varphi)_7 + M_{fir}(\varphi)_8 + \\ + M_{fir}(\varphi)_9 + M_{fir}(\varphi)_{10} + M_{fir}(\varphi)_{11}\Big] \tag{36}$$

With this method, there are other Fourier coefficients. Thus, by the Equation (32), we determine the approximate exposition of the function $M_{twi}(f)$.

The first coefficients of the Fourier series a_1 and b_1:

$$a_1 = \frac{1}{6}\sum_{i=0}^{11} M_{fir}(\varphi)_i \cos k\varphi = \frac{1}{6}\begin{bmatrix} M_{fir}(\varphi)_0 + M_{fir}(\varphi)_i \cdot \cos 30° + M_{fir}(\varphi)_2 \cdot cos 60° + 0 - \\ -M_{fir}(\varphi)_3 + M_{fir}(\varphi)_4 \cdot \cos 60° + M_{fir}(\varphi)_5 \cdot \cos 30° - \\ -M_{fir}(\varphi)_6 - M_{fir}(\varphi)_7 \cdot \cos 30° - M_{fir}(\varphi)_8 \cos 60° - 0 + \\ +M_{fir}(\varphi)_{10} \cdot \cos 60° - M_{fir}(\varphi)_{11} \cdot \cos 30° \end{bmatrix} \tag{37}$$

$$b_1 = \frac{1}{6}\sum_{i=0}^{11} M_{fir}(\varphi)_i \sin k\varphi = \frac{1}{6}\begin{bmatrix} M_{fir}(\varphi)_1 + M_{fir}(\varphi)_i \cdot \sin 30° + M_{fir}(\varphi)_2 \cdot \sin 60° + \\ +M_{fir}(\varphi)_3 + M_{fir}(\varphi)_4 \cdot \sin 60° + M_{fir}(\varphi)_5 \cdot \sin 30° + 0 - \\ -M_{fir}(\varphi)_7 \cdot \cos 30° - M_{fir}(\varphi)_8 \cdot \cos 60° - M_{fir}(\varphi)_9 - \\ -M_{fir}(\varphi)_{10} \cdot \cos 60° - M_{fir}(\varphi)_{11} \cdot \cos 30° \end{bmatrix} \tag{38}$$

$$M_{fir}(\varphi) \approx \frac{a_o}{2} + a_1 \cos\varphi + a_2 \cos 2\varphi + \ldots + a_6 \cos 6\varphi + \\ + b_1 \sin\varphi + b_2 \sin 2\varphi + \ldots + b_6 \sin 6\varphi \tag{39}$$

As indicated above, for obtaining the high correctness can be taken 12, 24, 36 and more. In this work, during the research of the function $M_{twi}(f)$, the acceptance of n=36 *i*s expedient, because, function was given in ordinate 36 and when $n = 12$ does not provide required high correctness.

3. ANALYSIS OF RESULTS

As an example, Table 1 shows the results of calculating the harmonics that make up the torque curve for domestic pumping jack at their maximum stroke lengths, minimum and maximum diameters of pumps lowered to the maximum possible depth.

In view of the fact that the torque values are calculated using 36 points, a 36th ordinate scheme of harmonic analysis was adopted. This means that the torque curve was decomposed into sinusoids up to 18 times the fundamental frequency. The analysis of the obtained results (Table 1) shows that the shape of the torque curve in all cases is significantly affected by a sinusoid of double frequency from the main one. Frequencies with a multiplicity of 1 to 6 have a lesser effect on the amplitude. The remaining sinusoids have insignificant amplitudes and, due to the large phase spread, form a kind of "white background noise" spectrum and, most likely, depend on factors that do not significantly affect the torque. In principle, when solving theoretical problems, they can be ignored and discarded. At the same time, it is possible that at some moments they can coincide in such a way that their total, cumulative effect can cause a surge, local deformation on the torque curve.

Figure 2 shows the torque curve M for the SKD8-3-4000 pumping unit at H=1950 m, dn= 28 mm, as well as the first 3 harmonics of it (shown approximately in illustrative form as curves 1, 2 and 3). In the "full" form, the torque curve, according to Table 1 can be written as the following explicit function.

$$M(\varphi) = 8.72 + 6.34\cdot\sin(\varphi + 38.7°) + 25.48\cdot\sin(2\varphi - 41°) + \\ +8.502\cdot\sin(3\varphi - 47.6°) + 3.176\cdot\sin(4\varphi - 66.7°) + \\ +2.247\cdot\sin(5\varphi - 69.3°) + 1.925\cdot\sin(6\varphi + 28.5°) + \\ +0.48\cdot\sin(7\varphi + 6°) + +0.59\cdot\sin(8\varphi - 86°) + \\ +0.468\cdot\sin(9\varphi + 87.6°) + 0.314\cdot\sin(10\varphi - 32.3°) + \\ +0.186\cdot\sin(11\varphi + 22.1°) + 0.093\cdot\sin(12\varphi + 39.3°) + \\ +0.092\cdot\sin(13\varphi + 64.2°) + 0.055\cdot\sin(14\varphi - 59.2°) + \\ +0.086\cdot\sin(15\varphi + 43.3°) + 0.124\cdot\sin(16\varphi + 16.8°) + \\ +0.128\cdot\sin(17\varphi - 38.8°) + 0.069\cdot\sin(18\varphi + 90°)\, kH\cdot M \\ 0 \le \varphi \le 360° \tag{40}$$

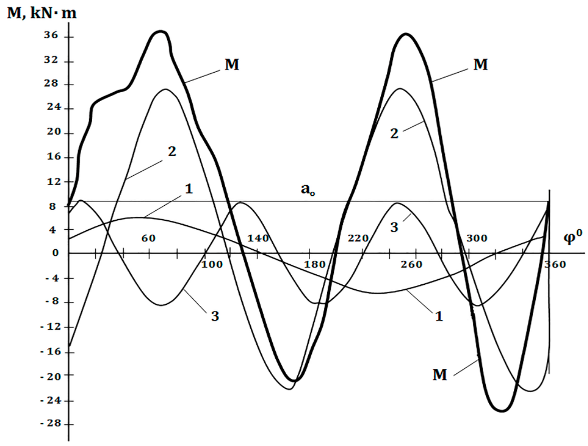

Figure 2. Curves of torque and harmonic components of pumping unit SKD8-3-4000

The convenience of using this type of equations in theoretical studies lies in the fact that, firstly, the number of their terms can be significantly reduced by discarding those of them that have a small amplitude, and secondly, due to the fact that on the right side only the sum of the same type and simple for mathematical operations functions - sines.

In this regard, an interesting direction for research arises - identifying the significance of which frequencies is enhanced or weakened depending on the change in one or another factor from those indicated at the beginning of the article and determining *M*.

The very shape of the torque curve suggested the search for constructive solutions to improve the performance of the pumping unit and its gearbox.

Table 1. The values of the amplitudes and phase angles of the harmonics that make up theoretical torque curve

Index n	a_n	φ_n^o	Index n	a_n	φ_n^o
0	8.72	-	10	0.314	-32.2
1	6.34	38.7	11	0.186	-22.1
2	25.48	-41	12	0.093	39.3
3	8.502	47.6	13	0.092	64.2
4	3.176	66.7	14	0.055	-59.2
5	2.247	-69.3	15	0.086	43.3
6	1.925	28.5	16	0.124	16.8
7	0.48	6	17	0.128	-38.8
8	0.59	-86	18	0.069	-90
9	0.468	87.6			

4. CONCLUSIONS

1. Studies of rubber seals of fasteners have shown that sealants sometimes break down tirelessly. Studies have shown that this is due to physical resonances caused by dynamic forces.
2. With the dynamic behavior of a circular borehole seal under the influence of external pressure, a low frequency physical resonance arises due to a special form of oscillation.
3. An analytical statement was obtained to determine the efficiency of Rezanan.
4. Preliminary consideration of resonant efficiency in the design of elastic elements will increase their longevity.

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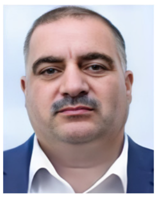
BIOGRAPHIES



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