Informatics and Control Problems 43 Issue 1 (2023)
journal homepage: www.icp.az

A technology for monitoring the onset of malfunctions in oil field reservoir pressure maintenance equipment

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ARTICLE INFO

Article history:
Received 21.09.2022
Received in revised form 10.10.2022
Accepted 25.10.2022
Available online 05.04.2023

Keywords:
Malfunction
Control
Diagnosis
Oil fields
Equipment
Vibration signal
Noise
Oil production
Compressor station.

ABSTRACT

Existing control and management systems of oil field reservoir pressure maintenance equipment do not warn of the beginning of the latent period of accidents. At the same time, accidents are preceded by the emergence of certain defects, followed by their latent period, after which they develop. Only after that they begin to affect the readings of measuring instruments of control and management systems. The duration of the latent period depends on the dynamics of defect development. Because of the above, control systems detect the beginning of an emergency when it becomes explicit. This leads to unreasonable costs, since elimination of the defect at the moment of its origin requires much less funds and time than after-accident pump repairs. It is shown in the paper that as a result of continuous rotational motion under high pressure, a vibration process is inevitably formed in this equipment, and the beginning of the latent period of malfunctions makes a clear impact on their noisy vibration signals $g(i\Delta t) = \mathrm{X}(i\Delta t) + \varepsilon(i\Delta t)$*, with a correlation emerging between the noise* $\varepsilon(i\Delta t)$ *and the useful component* $\mathrm{X}(i\Delta t)$*. To control the beginning of malfunctions in reservoir pressure maintenance equipment it is proposed to use the estimates of noise variance and cross-correlation functions between the useful signal and the noise, which allow forming informative attributes for warning and control of the beginning of the latent period of malfunctions. The proposed technologies can also be used to improve accident-free operation at compressor stations of main oil and gas pipelines, at drilling rigs, at artesian wells, in transport, etc.*

1. Introduction

It is known that in the process of oil and gas production, the late stage of oil field development begins over time [1-6]. The need for their further development is due to the fact that, according to many leading oil specialists, in some fields the amount of remaining oil reserves turns out to be greater

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www.icp.az/2023/1-01.pdf https://doi.org/10.54381/icp.2023.1.01

than the oil extracted by all methods. However, over time, ensuring the profitability of their operation becomes more difficult and requires minimization of all costs necessary for their operation. At the same time, the profitability of their operation is accompanied by numerous problems [1–6]. The most important of these problems is the necessity to minimize expenses for energy-intensive processes for reservoir pressure maintenance by pumping water into the formation through injection wells by means of modular cluster pump stations (MCPS). To reduce the costs of these processes, first of all, it is necessary to ensure fault-free operation of these energy-intensive processes [4, 6-8].

2. Problem statement

Let us consider the well-known [1-4] typical flow chart of the oil production process in the late stage of oil field development (Fig. 1).

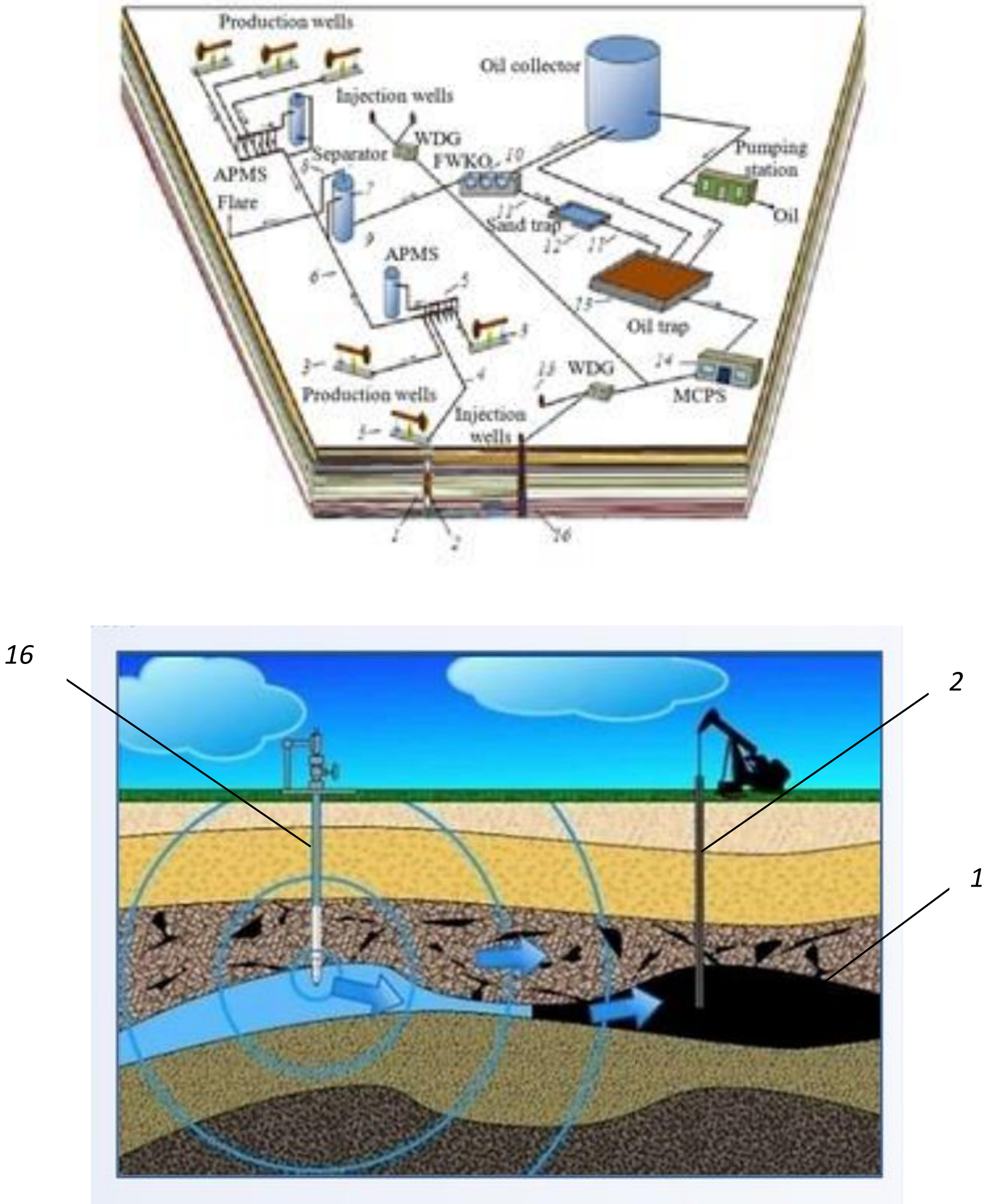

Fig. 1. Typical flow chart for oil production process in the late stage of field development.

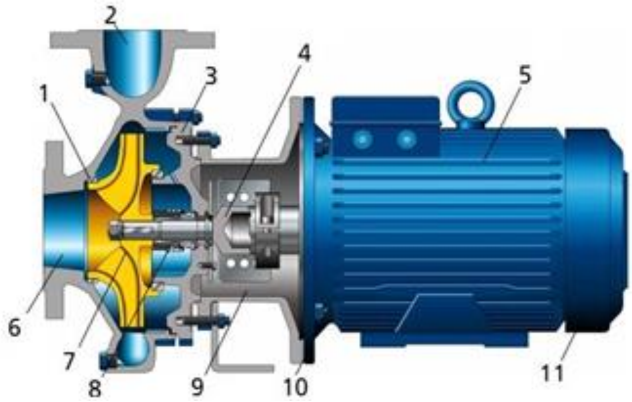

Fig. 2. Design of a single-stage pump of CNS 180 type. 1-Throttling slot; 2-Discharge nozzle; 3- Casing cover; 4- Shaft; 5- Motor casing; 6- Suction nozzle; 7- Impeller; 8- Shaft seal; 9- Drive sump; 10- Rolling bearing; 11- Rolling bearing.

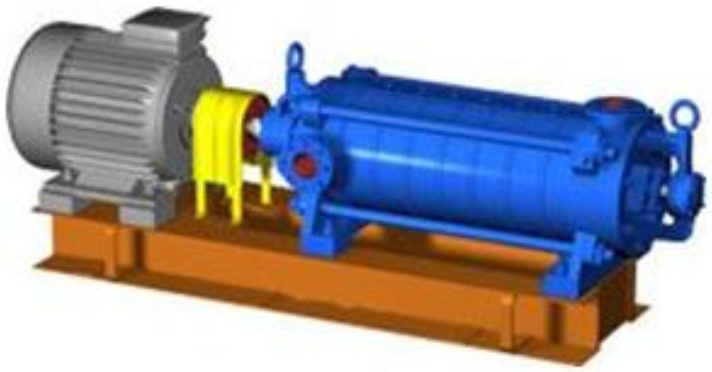

Fig. 3. Design of a multistage horizontal pump of CNS 180-255 type.

The gas-liquid mixture 1 from the well 2 with the help of production pumps 3 of sucker rod wells (SRPU) and electric submersible pumps (ESP) rises to the surface and is directed through flow lines 4 in a closed system under the pressure of the production pumps into automatic pad metering station 5 to determine the amount of yield for each well. After the metering, the well yield is transported through gathering mains 6 to the separator 7. Primary gas separation 8 takes place in the separator. Partially degassed fluid 9 from the separator enters the free water knock out unit 10 for the discharge of produced water from the formation fluid.

Formation water separated in the apparatus of the free water knock out unit FWKO (10) through water conducts 11 through sand traps 12 and oil traps 13 enters modular cluster pump stations (MCPS) 14, where with the help of multistage injection pumps through injection wells 15 are injected into the formation 16. Under the pressure of water in the production horizons, the gas-liquid mixture is displaced from the reservoir into the production well, and so the closed cyclic process of oil production continues in the late stage of field development by mechanized methods. Thus, the late stage of oil field development mainly includes two energy-intensive processes that require large expenses for the operation of the main equipment: these are modular cluster pump stations (MCPS) for pumping water into the reservoir to maintain reservoir pressure and equipment for artificial lift of oil (SRPU and ESP) from wells [1-4].

A study of the mechanism of operation of MCPS shows that information about the technical condition of these objects is reflected in the vibration signals received from the vibration sensors installed on the most informative structures. Therefore, it is possible to control the technical condition of MCNS [1-7] indirectly, as their malfunctions are reflected in the parameters of vibration signals. Such a solution of the problem under consideration is important, since the technology of vibration signals analysis of the above equipment can also be used in systems for controlling the onset of the latent form of emergencies at compressor stations, pumping stations, drilling rigs, etc.

Therefore, in the proposed study, the objective is to create new technologies and tools for early diagnosis of the technical condition of this equipment.

Studies have shown that a vibration process inevitably forms as a result of continuous rotational motion under high pressure in pump units, and during the operation of this equipment the beginning of a malfunction is largely reflected in the vibration signals. Therefore, it is advisable to use vibration sensors to control the beginning of the latent period of malfunctions.

In this case, determining the moment of correlation emerges between the useful signal and the noise of vibration signals makes it possible to adequately control the beginning of changes in the technical condition of the pumping station.

Thus, at the beginning of the latent period of an emergency state, in the reservoir pressure maintenance equipment (RPME), the noise $\varepsilon_2(t)$ correlated with the useful signal $X(t)$ containing information about the beginning of the latent period of the accident emerges in the vibration signals $g(t)$ along with the noise $\varepsilon_1(t)$, which is caused by external factors [1, 2]. In this case, due to the presence of correlation between the useful signal $X(t)$ and the total noise $\varepsilon(t) = \varepsilon_1(t) + \varepsilon_2(t)$, the following equality takes place:

$$D_g = M\big[\big(X(t) + \varepsilon(t)\big)\big(X(t) + \varepsilon(t)\big)\big] =$$
$$= M[X(t)X(t)] + M[X(t)\varepsilon(t)] + M[\varepsilon(t)X(t)] + M[\varepsilon(t)\varepsilon(t)]. \quad (1)$$

Taking into account that for stationary vibration signals $g(i\Delta t)$ with normal law of distribution in the presence of correlation between $X(t)$ and $\varepsilon(t)$, the following conditions and equalities are fulfilled:

$$M[X(t)X(t)] = D_X,\ M[X(t)\varepsilon(t)] = R_{X\varepsilon}(0) \neq 0,\ M[\varepsilon(t)\varepsilon(t)] = D_\varepsilon \neq 0. \quad (2)$$

We have

$$D_g \approx M[X(t)X(t)] + 2M[X(t)\varepsilon(t)] + M[\varepsilon(t)\varepsilon(t)]. \quad (3)$$

Consequently, the variance D_g of the total vibration signal $g(i\Delta t)$ is determined from the formula

$$D_g \approx D_X + 2M[X(t)\varepsilon(t)] + D_\varepsilon. \quad (4)$$

From formula (4) it is obvious that at the beginning of the malfunction as a result of the emergence of noise $\varepsilon_2(t)$, due to the correlation between the useful signal $X(t)$ and the total noise $\varepsilon(t)$, the variance of the total noise $D_{\varepsilon\varepsilon}$ takes the form

$$D_{\varepsilon\varepsilon} = 2R_{X\varepsilon}(0) + D_\varepsilon \quad (5)$$

Obviously, the estimates D_ε and $R_{X\varepsilon}(0)$ of the vibration signal $g(t)$ practically can be used as an informative attribute of the beginning of the latent period of failures of RPME. Consequently, to control the beginning of the latent period of malfunctions in the control system of pumping stations, it is necessary to determine the estimates of $R_{X\varepsilon}(0)$ and D_ε of the vibration signal $g(i\Delta t)$.

3. Analysis of the state of the art in existing systems for controlling the technical condition of RPME

Ensuring fault-free operation of energy-intensive equipment in oil fields is an important problem. In this regard, we will first consider the shortcomings of the existing technologies for controlling the technical condition of this equipment.

First of all, it should be noted that, unfortunately, at present there is no single diagnostics concept, but separate methods exist and are successfully applied. Essentially, they are carried out on the basis of an analysis of the readings of control and measuring instruments during regular checks and on the basis of test results during scheduled and unscheduled repairs.

An analysis of reservoir pressure maintenance technologies shows [1-4] that both single-stage and multi-stage MCPS are most widely used as pumps for pumping water into reservoirs (Fig.2, Fig.3).

These pump units are usually equipped with a three-phase asynchronous motor with a squirrel-cage rotor is used.

Taking into account the design features and the principle of operation of these pumps, the following diagnostic methods are used:

- vibration diagnostic methods based on the analysis of vibration parameters of these objects;
- acoustic diagnostic methods based on the analysis of the parameters of sound waves generated by these objects and their components;
- electrodiagnostic control of the pump motor.

All these diagnostic methods make it possible to identify individual faults when they have a pronounced form, which often turns out to be belated and their repair leads to high economic costs [6-10].

4. Difficulties of the control of the onset of malfunctions on the basis of estimates of the correlation characteristics of vibration signals

As it was mentioned above, RPME in the process of operation typically goes into the latent period of an emergency state as a result of the initiation of various defects [1-4]. Usually, this process is reflected in the vibration signals in the form of the noise $\varepsilon(i\Delta t)$, which has a correlation with the useful signals $X(i\Delta t)$ when a malfunction emerges [1, 6, 7]. Consequently, during this period the total noise $\varepsilon(i\Delta t)$ is formed from the noise $\varepsilon_1(i\Delta t)$, which arises from the influence of external factors and from the noise $\varepsilon_2(i\Delta t)$, caused by the emergence of various malfunctions. In this case, the variance of the vibration signal has the form:

$$D_g \approx R_{gg}(0) \approx \frac{1}{N}\sum_{i=1}^{N} g^2(i\Delta t) \approx \frac{1}{N}\sum_{i=1}^{N} X^2(i\Delta t) + 2\frac{1}{N}\sum_{i=1}^{N} X(i\Delta t)\varepsilon(i\Delta t) + \\ + \frac{1}{N}\sum_{i=1}^{N} \varepsilon^2(i\Delta t) \approx R_{XX}(0) + 2R_{X\varepsilon}(0) + R_{\varepsilon\varepsilon}(0) \qquad (6)$$

It is also known from literature [1-4] that in this case the formula for determining the estimate of $R_{gg}(\mu)$ can be represented in the form:

$$R_{gg}(\mu) \approx \frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)\, g((i+\mu)\Delta t) \approx \frac{1}{N}\sum_{k=1}^{N} (X(i\Delta t) + \varepsilon(i\Delta t))(X((i+\mu)\Delta t) + \varepsilon((i+\mu)\Delta t)) \approx \\ \approx \frac{1}{N}\sum [X(i\Delta t)X((i+\mu)\Delta t) + \varepsilon(i\Delta t)X((i+\mu)\Delta t) + X(i\Delta t)\varepsilon((i+\mu)\Delta t) + \varepsilon(i\Delta t)\varepsilon((i+\mu)\Delta t) \\ \approx \\ \approx R_{XX}(\mu) + R_{\varepsilon X}(\mu) + R_{X\varepsilon}(\mu) + R_{\varepsilon\varepsilon}(\mu) \approx \begin{cases} R_{XX}(0) + 2R_{X\varepsilon}(0) + R_{\varepsilon\varepsilon}(0)\ when\ \mu = 0 \\ R_{XX}(\mu) + 2R_{X\varepsilon}(\mu)\ when\ \mu \neq 0. \end{cases} \qquad (7)$$

Experimental studies have shown [1,3,4,6] that during the operation of the RPME during the latent period of accidents, the estimates of $R_{X\varepsilon}(\mu)$, $R_{\varepsilon\varepsilon}(\mu)$ are tangible values, i.e., the inequality

$$\begin{cases} R_{X\varepsilon}(\mu) \gg 0 \\ R_{\varepsilon\varepsilon}(\mu) \gg 0 \end{cases}$$

takes place, and therefore there is a significant error in the estimate of $R_{gg}(\mu)$.

Because of this there is a difficulty in ensuring the adequacy of the results of controlling the operation of this equipment by traditional technologies. This is one of the factors hindering the use of traditional technologies of correlation analysis of noisy signals to control the specified equipment. In this regard, it is obviously necessary to create new effective technologies of vibration signal analysis, allowing to reduce the errors from the influence of the noise $\varepsilon(i\Delta t)$ and improve the adequacy of the obtained results.

From expressions (6) and (7) it is obvious that in the presence of correlation between the useful signal and the noise, the estimate of the correlation function $R_{XX}(\mu)$ of the useful signal $X(i\Delta t)$ can be determined from the expression:

$$R_{XX}(\mu) = \begin{cases} R_{gg}(0) - 2R_{X\varepsilon}(0) - R_{\varepsilon\varepsilon}(0) \text{ when } \mu = 0 \\ R_{gg}(\mu) - 2R_{X\varepsilon}(\mu) \quad \text{when } \mu \neq 0 \end{cases} \tag{8}$$

It was shown in [1, 2] that the estimate of the variance $D_{\varepsilon\varepsilon}$ of the total noise $\varepsilon(i\Delta t)$ can be determined from the expression:

$$D_{\varepsilon\varepsilon} \approx R_{\varepsilon\varepsilon}(0) \approx \frac{1}{N}\sum_{i=1}^{N}\left[g^2(i\Delta t) + g(i\Delta t)g\big((i+2)\Delta t\big) - 2g(i\Delta t)g\big((i+1)\Delta t\big)\right] \tag{9}$$

Due to this it is possible to determine the estimate of the variance of the useful signal $\mathrm{X}(i\Delta t)$ according to the formula

$$D_{\mathrm{X}} = D_g - D_{\varepsilon\varepsilon} \tag{10}$$

However, despite the availability of the estimate of $D_{\varepsilon\varepsilon}$ and D_{X}, to solve the problem under consideration, there is an obvious need to create a technology for determining the estimate of the cross-correlation function between the useful signal and the noise $R_{X\varepsilon}(\mu)$.

5. Technology for determining the estimate of the cross-correlation function between the useful signal and the noise of vibration signals

The conducted studies show [1, 6] that the nature of the relationship between the noise and the useful signal is clearly reflected in the estimate of the cross-correlation function $R_{gg'}(\mu)$ between the centered $g(i\Delta t)$ and the non-centered $g'(i\Delta t)$ noisy signals, which can be determined from the expression:

$$R_{gg'}(\mu) = \frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)g'\big((i+\mu)\Delta t\big) \tag{11}$$

$$\begin{cases} \mathrm{g}(\mathrm{i}\Delta \mathrm{t}) = X(i\Delta t) + \varepsilon(i\Delta t) \\ \mathrm{g}'(\mathrm{i}\Delta \mathrm{t}) = X'(i\Delta t) + \varepsilon'(i\Delta t) \end{cases} \tag{12}$$

where $g(i\Delta t)$, $g'(i\Delta t)$, $X(i\Delta t)$, $X'(i\Delta t)$, $\varepsilon(i\Delta t)$, $\varepsilon'(i\Delta t)$ are centered and non-centered samples of the noisy signal $g(i\Delta t)$, the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$, respectively.

An analysis of equalities (11), (12) showed that using the formula for determining the estimate of the cross-correlation function between centered and non-centered noisy signals, it is possible to determine the estimate of the cross-correlation function $R_{X\varepsilon}(\mu)$ between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$. In this regard, we will consider one of the possible options for solving the problem for the analysis of the relationship between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$. It is known from the literature [1-4], [6-10] that when the conditions of stationarity, normality of the distribution law and the absence of correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$ are fulfilled, the following equalities take place

$$\frac{1}{N}\sum_{i=1}^{N} X(i\Delta t)\varepsilon(i\Delta t) = 0 \tag{13}$$

$$\frac{1}{N}\sum_{i=1}^{N} X'(i\Delta t)\varepsilon'(i\Delta t) = 0 \tag{14}$$

and when calculating the estimate of $R_{gg'}(\mu)$ from formula (13), the following equalities take place between the number of N^{++} positive products of samples $g^{+}(i\Delta t)$, $g'(i\Delta t)$ and the number of N^{-+} negative products of samples $g^{-}(i\Delta t), g'\ (i\Delta t)$

$$N^{++} = N^{-+}$$
$$N^{++} + N^{-+} = N \tag{15}$$

At the same time, at the beginning, with a time shift $\mu = 0\Delta t, 1\Delta t, 2\Delta t$ the following inequality takes place between the absolute values of the samples $g(i\Delta t)$, $g'(i\Delta t)$ and between the sums of positive and negative products

$$R_{g^{+}g'}(\mu) = \frac{1}{N}\sum_{i=1}^{N^{++}} g^{+}(i\Delta t)g'((i+\mu)\Delta t) > \frac{1}{N}\sum_{i=1}^{N^{-+}} g^{-}(i\Delta t)g'((i+\mu)\Delta t) = R_{g^{-}g'}(\mu). \tag{16}$$

The computational experiments performed and the analysis of expressions (11), (15) showed that when multiplying the samples of the non-centered signal $g'(i\Delta t)$ by its centered samples $g(i\Delta t)$, despite the fulfillment of equality (14), (15), the following inequality takes place:

$$\frac{1}{N}\sum_{i=1}^{N^{++}} \left|g^{+}(i\Delta t)g'((i+\mu)\Delta t)\right| \neq \frac{1}{N}\sum_{i=1}^{N^{-+}} \left|g^{-}(i\Delta t)g'((i+\mu)\Delta t)\right| \tag{17}$$

In formula (11), (16), the difference between the sum of positive and negative products at $\mu = 0$ turned out to be significantly greater than zero, i.e.

$$\sum_{i=1}^{N^{++}} g^{+}(i\Delta t)g'((i+\mu)\Delta t) - \sum_{i=1}^{N^{-+}} g^{-}(i\Delta t)g'((i+\mu)\Delta t) \gg 0 \qquad (18),$$

which shows that the correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$ is clearly reflected in the estimate of $R_{g^{+}g'}(0)$, since the following inequality always holds for $\mu = 0$:

$$\frac{1}{N}\sum_{i=1}^{N^{++}} g^{+}(i\Delta t)g'((i+\mu)\Delta t) \gg \frac{1}{N}\sum_{i=1}^{N^{-+}} g^{-}(i\Delta t)g'((i+\mu)\Delta t) \tag{19}$$

However, in most real-life cases, the value of

$$R_{g^{+}g'}(0) \approx \frac{1}{N}\sum_{i=1}^{N^{++}} g^{+}(i\Delta t)g'(i\Delta t) \tag{20}$$

is practically a rough estimate of $R_{gg'}(\mu)$ at $\mu = 0$, i.e.,

$$R_{gg'}(0) \approx R_{g^{+}g'}(0) \tag{21}$$

Due to this, in these cases, the estimate of the coefficient correlations $R_{X\varepsilon}$ between the useful signal and the noise can be determined by the magnitude of the difference between $R_{g^{+}g'}(0)$ and $R_{gg}(0)$ according to the formula

$$R_{X\varepsilon}(0) \approx R_{g^+g'}(0) - R_{gg}(0) = \frac{1}{N}\sum_{i=1}^{N^{++}} g^+(i\Delta t)g'(i\Delta t) - \frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)g(i\Delta t) \quad (22)$$

Naturally, in this case, the error in the estimate of the cross-correlation function depends on the difference $R_{g^+g'}(0) - R_{g^-g'}(0)$. But condition (19) is almost always satisfied, and the difference from the obtained difference can be taken as information about the presence of a correlation between the useful signal and the noise, i.e.

$$R_{X\varepsilon}(0) \approx R_{g^+g'}(0) - R_{gg}(0). \quad (23)$$

In practice, taking into account expression (18), an approximate estimate of $R_{X\varepsilon}(0)$ can be determined from the formula

$$R_{X\varepsilon}(0) = \left[R_{g^+g'}(0) - R_{g^-g'}(0)\right] - R_{gg}(0) == \left[\frac{1}{N}\sum_{i=1}^{N^{++}} g^+(i\Delta t)g'(i\Delta t) - \frac{1}{N}\sum_{i=1}^{N^{\mp}} g^-(i\Delta t)g'(i\Delta t)\right] - \\ - \frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)g(i\Delta t) \quad (24)$$

Thus, when the noise $\varepsilon_2(i\Delta t)$, which is correlated with the useful signal $X(i\Delta t)$, emerges, the estimate of $R_{X\varepsilon}(0)$ which can be determined from formula (24) will be different from zero. However, if there is no correlation between them, then the estimate of $R_{X\varepsilon}(0)$ will be equal to zero. Due to this feature of formula (24), the advisability of using the estimate of $R_{X\varepsilon}(0)$ in the control of the onset of malfunctions in the RPME.

6. And example of practical application of estimates of the cross-correlation function between the useful signal and the noise in the control of the onset of malfunctions in RPME

An analysis of the results of the conducted experiments showed that to control and identify the beginning of malfunctions of RPME, it is possible to build an intelligent system, a block diagram of which is shown in Fig. 4. It was found experimentally that the beginning of all typical malfunctions is reflected in the vibration signals of RPME. Automation of this process for the control of the onset of malfunctions is of very important practical interest, since nowadays, during production, ensuring accident-free operation of RPME is of the utmost importance. Therefore, the problem of eliminating the difficulty of the control of the onset of malfunctions and practical application of the ISCI intelligent control and identification system for identifying the beginning of malfunctions can be considered a priority task.

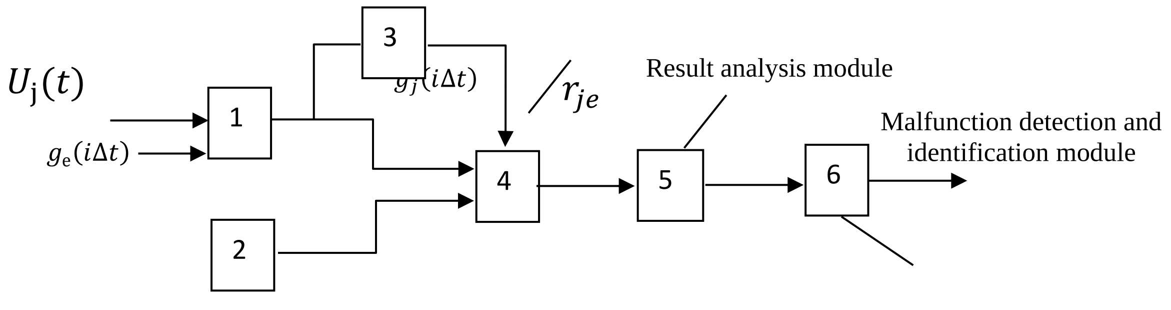

Fig.4. An intelligent system for controlling and identifying the beginning of malfunctions (ISCI)

To tackle this task, taking into account that the technical personnel, having experience with real vibration records experimentally determine and identify malfunctions, Fig. 1 shows a block diagram of one of the possible versions of ISCI, which consists of the following modules [6-8]:

1 – module for analog-to-digital conversion of the noisy vibration signal, $g(i\Delta t) = X(i\Delta t) + \varepsilon(i\Delta t)$ obtained from the vibration sensor output.

2 – module for saving reference vibration signals of typical malfunctions of the RPME.
3 – module of control of the onset of a malfunction according to estimates of $R_{X\varepsilon}(\mu)$ and D_ε.
4 – module for alternately determining the correlation coefficient between the current values of the vibration signal $g_{\mathrm{j}}(i\Delta t)$ and typical signals $g_X(i\Delta t)$, which are formed in advance experimentally for the corresponding typical malfunctions and are stored in the memory of module 2.
5 – module for determining the number of the typical vibration signal $g_X(i\Delta t)$, at which the estimate of the correlation coefficient r_{jX} takes the maximum value.
6 – module for registering the beginning of a malfunction in the RPME and its identification.

In the process of the operation of ISCI, the current signal $U_j(t) = g_i(t)$ from the vibration sensor is received at the input of module 1, i.e., the input of the analog-to-digital converter, where it is converted into digital code $g_j(i\Delta t)$, which is fed to the inputs of modules 3 and 4. Using module 3, the estimates of the variance D_ε of the noise and the cross-correlation function $R_{X\varepsilon}(0)$ between the useful signal $\mathrm{X}(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$ are determined according to formulas (6) and (4). If they exceed the experimentally established threshold value, i.e., at $D_\varepsilon \geq D_\varepsilon^p$, $R_{X\varepsilon}(0) \geq R_{X\varepsilon}^p(0)$, then the corresponding signal from module 4 is sent to module 5. In this case, between the current and reference signals, alternately according to the formula

$$r_{jX} = \frac{\frac{1}{N}\sum_{j=1}^{n} g_j(i\Delta t) g_X(i\Delta t)}{\frac{1}{N}\sum_{i=1}^{n} g_j^2(i\Delta t)}$$

the estimate of the correlation coefficient is determined, where j is the number of current typical faults, jX is the number of the reference of typical faults, r_{jX} is the estimate of the normalized cross-correlation function between $g_j(i\Delta t)$ and $g_X(i\Delta t)$.

Due to this, by a sequential comparison of the obtained estimates of the correlation coefficients between the current vibration signals and typical signals in module 5, the number of malfunction is determined, at which the obtained estimate r_{jX} has the maximum value. The presence of typical signals in module 2, which are recorded for the typical malfunctions in advance, allows by using ICSI to register the technical condition of the RPME at the current moment. As a result, during the operation of the system, the results obtained through the use of estimates of D_ε and $R_{X\varepsilon}(0)$ allow carrying out real-time detection and identification of the beginning of the malfunction and generating information about it.

Our experiments showed that, on the basis of the number of the typical vibration curve $g_X(i\Delta t)$ at which the estimate of the normalized cross-correlation functions with the current vibration signal curve $g_j(i\Delta t)$ takes the maximum value, it is possible to unambiguously determine the number of the typical malfunction of the RPME. The advantage of using the ICSI to identify the malfunction is that it does not require the involvement of a master technologist. Note that it is mainly intended for controlling the beginning of a malfunction. In this option, modules 2 and 4 are disabled.

7. Conclusion

Noisy signal analysis technologies used in control systems do not provide fault-free operation the main equipment of oil fields. They do not allow the use of noise as a carrier of diagnostic information, because as a result of filtering, important information about the beginning of the latent period of the initiation of defects in the equipment of these facilities is lost. For this reason, there is often a delay in the time of registration of the onset of malfunctions, which leads to unavoidable accidents. Therefore, to ensure fault-free operation and organization of timely maintenance of these facilities, it is necessary to create new, more efficient technologies for analyzing noisy signals. Taking into account the extreme importance of this issue, the paper proposes using noise as a carrier of diagnostic information by determining the estimates of the cross-correlation functions between the useful signal and the noise. To identify malfunctions of the equipment in question, the principle of constructing intelligent systems is proposed.

The above studies have shown that the application of the proposed algorithms and technologies can significantly improve the efficiency and reliability of accident-free operation of similar equipment of the offshore oil and gas complex, petrochemical complexes, power facilities, etc. Many other examples can be given where the use of the proposed technologies is also advisable. For instance, using this technology, it is possible to solve the problem of control and diagnostics on drilling rigs, where at the beginning of the latent period of an accident, information about this is reflected in the wattmeter chart of the electric motor that rotates the drill string. By sending an early warning to the driller, many costly catastrophic accidents can be avoided.

Lastly, in many industries, for instance, in pumping stations, irrigation systems, in compressor stations, main oil and gas pipelines, etc., it is also advisable to use these technologies to ensure control of the onset of malfunctions. Consequently, the algorithms and technologies proposed in this study, in combination with the intelligent system, can be widely used in many other industries.

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