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CONTROLLING OF THE BEGINNING OF THE LATENT PERIOD OF ACCIDENTS AT PUMPING STATIONS

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Abstract

It is shown that the control system of pumping stations does not ensure signaling of the beginning of the latent period of accidents. Because of this, their state of emergency is detected at the point when it becomes apparent. At the same time, elimination of a malfunction at the moment of its initiation requires much less resources and time than after-accident repairs of the pump. We propose algorithms and technologies for calculating the estimates of the noise variance and cross-correlation functions between the useful signal and the noise of the vibration signals, which allow forming informative attributes for signaling and control of the beginning of the latent period of malfunctions. These technologies can also be used to improve fault-free operation at reservoir pressure maintenance stations during oil production at compressor stations, at drilling rigs, at artesian wells, etc.

Keywords: water supply, pump stations, control malfunction, vibration signal, oil production accidents

I. Introduction

Nowadays in the pumping stations in any systems of technological water supply and water removal, as well as in urban systems of cold and hot water supply, sewage pumping stations of wastewater pumping and treatment facilities for monitoring and control, automatic control systems are used, which ensures exceptional reliability of stations and allows them to operate for a long time without repair. They process analog and discrete information according to a specified algorithm and form necessary signals to control technological equipment, display information on parameters and state of the technological process, prepare transmission of information on current state of equipment, on parameters and state of the technological process, detect emergency situations or malfunctions of technological equipment, automatically connect additional pumping units in case of insufficient capacity. Thanks to this, the population's vital problem related to water supply, water supply, wastewater pumping, irrigation of agricultural crops, etc., is addressed reliably and successfully. However, for the many advantages of the mentioned control systems, they do not provide signaling of the beginning of the latent period of accidents. The importance of this problem is due to the fact that any accident is always preceded by the initiation of certain defects, after which the latent period of accidents begins. After some time, it develops and only after that it is reflected in the readings of measuring instruments of control and monitoring systems. The duration of the latent period depends on the dynamics of defect development. Because of the above mentioned, control systems of pumping stations detect the beginning of their emergency state at the moment when it takes on explicit form. Therefore, in practice there are cases when it turns out to be late and the accident cannot be prevented. Naturally, to eliminate this drawback it is necessary to create new technologies for the monitoring and signaling of the beginning of the latent period of the emergency state of the equipment of pumping stations.

II. Problem statement

Currently, in pumping stations, the control of technological processes is carried out by means of control systems, which allow obtaining all kinds of information in time and promptly managing the process of operation of pumping stations. However, these systems do not provide the operating personnel with adequate information about the initial latent period of the emergency state. Because of this, the probability of an accident depends to a certain extent on the attentiveness and qualification of the operating personnel.

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

At the same time, determining the moment of emergence of correlation between the useful signal and the noise of vibration signals makes it possible to adequately monitor the beginning of changes in the technical condition of the pumping station. Consequently, there is a possibility to create a tool to determine the moments of emergence of correlation between the useful signal and the noise, which allows to signal the beginning of a latent period of the emergence of an accident situation.

Thus, at the beginning of the latent period of the emergency state in the pumping unit on the vibration signals $\boldsymbol{g(t)}$ along with the noise $\boldsymbol{\varepsilon_1(t)}$ caused by external factor, the noise $\boldsymbol{\varepsilon_2(t)}$ emerges, correlated with the useful signal $\boldsymbol{X(t)}$, which is a carrier of information about the beginning of the latent accident period [1,2]. In this case, due to the presence of correlation between the useful signal $\boldsymbol{X(t)}$ and total noise $\boldsymbol{\varepsilon(t) = \varepsilon_1(t) + \varepsilon_2(t)}$, the following equality takes place:

$$\boldsymbol{D_g = M\big[(X(t) + \varepsilon(t))(X(t) + \varepsilon(t))\big] = M[X(t)X(t)] + M[X(t)\varepsilon(t)] + M[\varepsilon(t)X(t)] + M[\varepsilon(t)\varepsilon(t)]}.$$

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

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

We have

$$\boldsymbol{D_g \approx M[X(t)X(t)] + 2M[X(t)\varepsilon(t)] + M[\varepsilon(t)\varepsilon(t)]}.$$

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

$$\boldsymbol{D_g \approx D_X + 2M[X(t)\varepsilon(t)] + D_\varepsilon}. \tag{1}$$

From formula (1) it is obvious that at the beginning of the malfunction as a result of the emergence of the noise $\boldsymbol{\varepsilon_2(t)}$, due to the correlation between the useful signal $\boldsymbol{X(t)}$ and the total noise $\boldsymbol{\varepsilon(t)}$, the variance of the total noise $\boldsymbol{D_{\varepsilon\varepsilon}}$ has the following form:

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

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

III. Difficulties of controlling the onset of malfunctions by estimates of the correlation characteristics of vibration signals

As stated above, pumping units in the process of operation tend to go into the latent period of an emergency state as a result of various defects [1-4]. Usually, this process is reflected on the vibration signals in the form of noise $\varepsilon(i\Delta t)$, which has correlation with the useful signals $X(i\Delta t)$ when a malfunction occurs [1, 5, 6]. Consequently, during this period the total noise $\varepsilon(i\Delta t)$ forms from the noise $\varepsilon_1(i\Delta t)$, which arises from the influence of external factors and from the noise $\varepsilon_2(i\Delta t)$, which arises from the emergence of various malfunctions. In this case, the variance of the vibration signal has the form:

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

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

$$R_{gg}(\mu) \approx \frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)\, g((i+\mu)\Delta t) \approx \frac{1}{N}\sum_{k=1}^{N} (X(i\Delta t) + \varepsilon(i\Delta t))(X((i+\mu)\Delta t) + \varepsilon((i+\mu)\Delta t)) \approx$$
$$\approx \frac{1}{N}\sum [X(i\Delta t)X((i+\mu)\Delta t) + \varepsilon(i\Delta t)X((i+\mu)\Delta t) + X(i\Delta t)\varepsilon((i+\mu)\Delta t) + \varepsilon(i\Delta t)\varepsilon((i+\mu)\Delta t) \approx$$
$$\approx R_{XX}(\mu) + R_{\varepsilon X}(\mu) + R_{X\varepsilon}(\mu) + R_{\varepsilon\varepsilon}(\mu) \approx \begin{cases} R_{XX}(0) + 2R_{X\varepsilon}(0) + R_{\varepsilon\varepsilon}(0) \; when\; \mu = 0 \\ R_{XX}(\mu) + 2R_{X\varepsilon}(\mu) \; when\; \mu \neq 0 \end{cases}. \qquad (3)$$

Experimental studies have shown [1-4] that during the operation of pumping station equipment, during the latent period of accidents $R_{X\varepsilon}(\mu)$, $R_{\varepsilon\varepsilon}(\mu)$ are tangible quantities, i.e., the following inequality takes place:

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

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

Because of this, it becomes difficult to ensure the adequacy of the results of monitoring the operation of equipment by traditional technologies. This is one of the factors preventing 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 errors from the influence of the noise $\varepsilon(i\Delta t)$ improve the adequacy of the obtained results.

From expressions (2) and (3) 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:

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

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

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

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

$$D_X = D_g - D_{\varepsilon\varepsilon}.$$

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

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

Studies have shown [1, 2] that the nature of the relationship between the noise and the useful signal is clearly reflected on the estimate of the cross-correlation function $R_{gg'}(\mu)$ between the centered $g(i\Delta t)$ and non-centered $g'(i\Delta t)$ noisy signals, which can be determined from the expression:

$$R_{gg'}(\mu) = \frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)g'((i+\mu)\Delta t), \tag{4}$$

$$\begin{cases} g(i\Delta t) = X(i\Delta t) + \varepsilon(i\Delta t) \\ g'(i\Delta t) = X'(i\Delta t) + \varepsilon'(i\Delta t)' \end{cases} \tag{5}$$

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.

The analysis of equalities (4), (5) has shown that by means of the formula for calculating the estimate of the cross-correlation function between centered and non-centered noisy signals it is possible to estimate the cross-correlation function $R_{X\varepsilon}(\mu)$ between the useful signal $X(i\Delta t)$ and the noisy signal $\varepsilon(i\Delta t)$. In this regard, consider one possible way to analyze the relationship between the useful signal $X(i\Delta t)$ and noise $\varepsilon(i\Delta t)$. From the literature it is known that [1-4], [6-10] under the condition of stationarity, the normal distribution law and the absence of correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$, the following equality takes place:

$$\frac{1}{N}\sum_{i=1}^{N} X(i\Delta t)\varepsilon(i\Delta t) = 0, \tag{6}$$

$$\frac{1}{N}\sum_{i=1}^{N} X'(i\Delta t)\varepsilon'(i\Delta t) = 0 \tag{7}$$

and when calculating the estimates of $R_{gg'}(\mu)$ from formula (6), the following equalities hold between the number N^{++} of positive products of samples $g^{+}(i\Delta t)$, $g'(i\Delta t)$ and the number N^{-+} of negative products of samples $g^{-}(i\Delta t)$, $g'(i\Delta t)$

$$\begin{cases} N^{++} = N^{-+} \\ N^{++} + N^{-+} = N^{\cdot} \end{cases} \tag{8}$$

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

$$R_{\mathrm{g^+g'}}(\mu) = \frac{1}{N}\sum_{i=1}^{N^{++}} g^{+}(i\Delta t)g'((i+\mu)\Delta t) > \frac{1}{N}\sum_{i=1}^{N^{-+}} g^{-}(i\Delta t)g'((i+\mu)\Delta t) = R_{\mathrm{g^-g'}}(\mu). \tag{9}$$

Computational experiments and analysis of expressions (4), (8) showed that when multiplying the samples of the non-centered signal $g'(i\Delta t)$ by their centered samples $g(i\Delta t)$, despite the fulfillment of equality (7), (8), the following inequality takes place

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

In formula (4), (9) the difference of the sum of positive and negative products for $\mu = 0$ is much greater than zero, i.e.,

$$\sum_{i=1}^{N^{++}} g^{+}(i\Delta t)g'((i+\mu)\Delta t) - \sum_{i=1}^{N^{-+}} g^{-}(i\Delta t)g'((i+\mu)\Delta t) \gg 0, \tag{10}$$

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

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

In most real cases, however, the quantity

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

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

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

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

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

Naturally, the error in the estimate of the cross-correlation function depends on the difference $R_{g^+g'}(0) - R_{g^-g'}(0)$. But practically always condition (11) is fulfilled and the difference of the obtained difference from zero can be taken as the information about the presence of correlation between the useful signal and the noise, i.e,

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

In practice, taking into account expression (10), an approximate estimate of $R_{X\varepsilon}(0)$ can be determined from the formula

$$R_{X\varepsilon}(0) = \left[R_{g^+g'}(0) - R_{g^-g'}(0)\right] - R_{gg}(0) = \left[\frac{1}{N}\sum_{i=1}^{N^{++}} g^+(i\Delta t)g'(i\Delta t) - \frac{1}{N}\sum_{i=1}^{N^{-+}} g^-(i\Delta t)g'(i\Delta t)\right] - \frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)g(i\Delta t). \quad (12)$$

Thus, when the noise $\varepsilon_2(i\Delta t)$, which is correlated with the useful signal $X(i\Delta t)$ emerges, the estimate $R_{X\varepsilon}(0)$, which can be determined from formula (12), will be different from zero. However, if there is no correlation between them, then the estimate of $R_{X\varepsilon}(0)$ will be zero. Due to this feature of formula (12) it is evident that it is reasonable to use the estimate of $R_{X\varepsilon}(0)$ to control the onset of malfunctions of pumping stations.

V. Possibility of practical control of the beginning of accidents at pumping stations with the use of noise as a carrier of diagnostic information

Pumping units under the influence of pressure between the inlet and outlet during operation function in a continuous oscillatory mode, and it is vibration signals that contain the most information about the beginning of a latent period of emergency state of this object. However, the control system of the station registers the moment of time, when the object goes into the emergency mode, but the above-mentioned informative attribute is not used. This leads to unreasonable costs, because elimination of malfunction at the moment of its origin requires much less costs and time than after-accident repairs. Therefore, using the estimate of the correlation coefficient $\boldsymbol{R_{X\varepsilon}(0)}$ between the useful vibration signal $\boldsymbol{X(i\Delta t)}$ and the noise $\boldsymbol{\varepsilon(i\Delta t)}$ to control the beginning of the latent period of accidents is the most advisable option.

The importance of this problem is also due to the fact that in real life, most pumping stations are designed for small facilities that cannot purchase and operate expensive equipment with very advanced and expensive control and monitoring systems. In these cases, pumps with inexpensive and simple control systems are used. Here, in order to ensure fault-free operation, first of all, signaling of the beginning of the latent period of accidents is required.

It is generally known that [11, 12] during vibration control, as a rule, vibration displacement, vibration velocity and vibration acceleration sensors are used. Vibration displacement sensors characterize the position of the controlled object, vibration acceleration sensors — the rate of change in its position in time, vibration acceleration sensors — the rate of change of velocity. These three parameters characterizing vibration are interrelated and by controlling, for instance, vibration acceleration by single or double integration it is easy to calculate the other two parameters. In the low-frequency domain, vibration displacement sensors have proved themselves. For medium-frequency objects, vibration velocity sensors are usually used, and for high-frequency objects, vibration acceleration sensors are used. Based on the analysis of possible applications of various vibration sensors to monitor the beginning of changes in the technical condition of pumping units, Bean Device AX-3D type sensors, which can be easily installed on the pump structure, turned out to be one of the possible options. This sensor is preferred because it makes it possible to collect the measurement information from the sensors using Wi-Fi, via a Bean CetanWay Contoller type controller. The range of Wi-Fi signals from the BeanDevice AX-3D sensor is up to 650 meters, which is quite sufficient for the operation of pumping stations. Technical parameters of the BeanDevice AX-3D sensor are described in [1]. Thus, in this version, the signal from the vibration sensor BeanDevice AX-3D, mounted on the pump housing, is picked up at the control panel, where it is analyzed by the Bean CetanWay Contoller according to formula (12). When the estimate of $\boldsymbol{R_{X\varepsilon}(0)}$ is non-zero, an alarm is triggered.

VI. Conclusion

Nowadays, in pumping stations in any systems of technological water supply and wastewater disposal, as well as in urban systems of cold and hot water supply, sewage pumping stations of wastewater pumping and treatment facilities, automatic control system is used for monitoring and control. Thanks to this, the population’s vital problem related to water supply and water supply, wastewater pumping, irrigation of agricultural crops, etc., addressed is reliably and successfully. However, for the many advantages of the mentioned control systems, they do not provide signaling of the beginning of the latent period of accidents. The importance of this issue is due to the fact that any accident is always preceded by the initiation of certain defects, after which the latent period of accidents begins and it develops after some time. Only then it begins to be reflected in the readings of measuring instruments of monitoring and control systems. The duration of the latent period depends on the dynamics of defect development. Because of the above in the control systems of pumping stations the beginning of their emergency state is registered when it takes the explicit form.

The existing technologies for analyzing noisy signals do not allow solving this problem. The algorithms and technologies proposed here for calculating the estimates of the noise variance and the cross-correlation functions between the useful signal and the noise, allow forming informative attributes for the signaling and control of the beginning of the latent period of malfunctions. Application of the proposed technology in any systems of process water supply and water disposal, in urban systems of cold and hot water supply, in sewage pumping stations of wastewater pumping and treatment facilities can increase the degree of fault-free operation of pumping stations. It should be noted that the proposed technologies can also be used to improve fault-free operation of electric centrifugal pump units in oil production, modular cluster pump stations for water injection into the reservoir to maintain reservoir pressure, as well as to improve fault-free operation of compressor stations of main oil and gas pipelines, drilling units, at artesian wells, transport facilities, etc.

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