Technologies of Robust Noise Monitoring of the Latent Period of Change in Seismic Stability of Offshore Stationary Platforms and Piers

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***Abstract*— In control systems using conventional technologies of signal analysis, results of monitoring of change in seismic stability of offshore structures are determined when they have taken express form. The offered technologies will allow detecting those changes in their initial latent period. It will thereby be possible to organize timely preventive measures to stop further serious deformations in most vulnerable units of a structure, which will allow reducing the general volume of repair works, expenses and unexpected destructions considerably**

***Keywords*— technology, monitoring; seismic stability; offshore stationary platform; pier; noisy signal; correlation function; noise variance; matrix; identification**

I. Introduction

It is known that there is a lack of inexpensive and sufficiently reliable systems for control of seismic stability of offshore stationary platforms, piers and other offshore structures [1-5]. It is also known that weak earthquakes often occur in the countries located in seismically active areas as a result of originating anomalous seismic processes. Obviously, to provide safety of the above-mentioned types of objects after each of such earthquakes, it is efficient to monitor the beginning of the latent period of change in their seismic stability [6-10].

II. Problem Statement

In real life, after a certain period of time T_0 of normal operation of offshore objects of oil extraction and transportation in seismic regions, period of time T_1 of their latent transition into the emergency state begins due to different reasons. It is often a result of weak earthquakes, which leads to changes in their seismic stability. Subsequent weak earthquakes, hurricane winds with rain showers and some other factors cause them to go into time interval T_2 expressed emergency state. Despite the difference in duration of T_0, T_1, T_2, monitoring problem in the cases in question comes to providing reliable indication of the beginning of time T_1 of the period of latent change in the seismic stability of objects.

Thereby, let us consider the matter in more detail.

Assume that in the normal seismic state in the period of time T_0, the known classical conditions hold true for noisy centered signals $g(i\Delta t) = X(i\Delta t) + \varepsilon(i\Delta t)$ received as the output of corresponding sensors, i.e. equalities [4,5] are true:

$$\omega_{T_0}\left[g(i\Delta t)\right] = \frac{1}{\sqrt{2\pi D_g}} e^{-\frac{(g(i\Delta t))^2}{2D_g}}, \; D_\varepsilon \approx 0, \; D_g \approx D_X;$$

$$R_{gg}(\mu) \approx R_{XX}(\mu); \; m_g \approx m_X \approx m_\varepsilon \approx 0;$$

$$R_{X\varepsilon}(\mu = 0) \approx 0, \; r_{X\varepsilon} \approx 0, \tag{1}$$

where $\omega_{T_0}\left[g(i\Delta t)\right]$is distribution law of signal $g(i\Delta t)$; D_ε, D_X, D_g are the estimates of variance of the noise $\varepsilon(i\Delta t)$, the useful signal $X(i\Delta t)$ and the sum signal $g(i\Delta t)$ respectively; $R_{XX}(\mu)$, $R_{gg}(\mu)$ are the estimates of correlation functions of the useful signal $X(i\Delta t)$ and the sum signal $g(i\Delta t)$; m_ε, m_X, m_g are mathematical expectations of the noise $\varepsilon(i\Delta t)$, the useful signal and the sum signal; $R_{X\varepsilon}(\mu = 0)$, $r_{X\varepsilon}$ are the cross-correlation function and the coefficient of correlation between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$.

However, when the latent period of imperceptible change in seismic stability of offshore platforms, piers and communications begins, condition (1) is violated [3-5], i.e.:

$$\omega_{T_0}\left[g(i\Delta t)\right] \neq \omega_{T_1}\left[g(i\Delta t)\right], \; D_\varepsilon \neq 0, \; D_g \neq D_X,$$

$$R_{gg}(\mu) \neq R_{xx}(\mu), m_g \neq m_x,$$

$$R_{X\varepsilon}(\mu = 0) \neq 0, \; r_{X\varepsilon} \neq 0. \tag{2}$$

The period of the normal state T_0 ends and the period T_1 begins. As a result, due to the violation of equality (1), statistical estimates of the signal $g(i\Delta t)$ are determined with certain inaccuracy. Therefore, timely detection of the initial stage of the above-mentioned processes in control systems of technical condition of platforms, piers and other offshore oil and gas extraction objects is complicate in the period of time T_1 [2-5]. Then the period T_1 ends and the period T_2 begins, when processes assume a more express form. Known control systems mainly register violation of seismic stability of objects in the period of time T_2.

The above-mentioned explains the delay in results of monitoring of seismic stability of offshore stationary platforms. Registration of those processes in the period of time T_1 therefore requires development of a technology and system, which would allow one to detect the moment of violation of equality (1). That will allow detecting the latent initial period of change in seismic stability of offshore stationary platforms.

III. Technologies for Noise Monitoring of the Beginning of Time T_1

Our research demonstrated that at the start of time T_1 of violation of seismic stability of offshore oil extraction objects, estimates of noise variance D_ε, noise correlation $R_{X\varepsilon\varepsilon}(\mu=0)$, cross-correlation function $R_{X\varepsilon}(\mu=0)$, coefficient of correlation $r_{X\varepsilon}$ between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$ change in the first place [3-5].

In this respect, let us consider one of possible methods of approximate calculation of the indicated estimates. For that end, let us represent the known expression

$$D_g = R_{gg}(\mu=0) = \frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)g(i\Delta t) = \frac{1}{N}\sum_{i=1}^{N} g^2(i\Delta t) \tag{3}$$

as follows:

$$R_{gg}(\mu=0) = \frac{1}{N}\sum_{i=1}^{N}\left[X(i\Delta t)+\varepsilon(i\Delta t)\right]^2 . \tag{4}$$

It is obvious that by opening the brackets we will get the following

$$R_{gg}(\mu=0) = \frac{1}{N}\sum_{i=1}^{N} X^2(i\Delta t) + \frac{1}{N}\sum_{i=1}^{N} 2\left[X(i\Delta t)\cdot\varepsilon(i\Delta t)\right] + \frac{1}{N}\sum_{i=1}^{N}\varepsilon^2(i\Delta t)\cdot \tag{5}$$

Assuming the following notations

$$\frac{1}{N}\sum_{i=1}^{N} X^2(i\Delta t) = R_{XX}(\mu=0), \tag{6}$$

$$\left.\begin{aligned} &\frac{1}{N}\sum_{i=1}^{N} 2\left[X(i\Delta t)\varepsilon(i\Delta t)\right] = 2R_{X\varepsilon}(\mu=0) \\ &\frac{1}{N}\sum_{i=1}^{N}\varepsilon^2(i\Delta t) = R_{\varepsilon\varepsilon}(\mu=0) = D_\varepsilon \end{aligned}\right\}, \tag{7}$$

we get

$$R_{gg}(\mu=0) \approx R_{XX}(\mu=0) + 2R_{X\varepsilon}(\mu=0) + R_{\varepsilon\varepsilon}(\mu=0), \tag{8}$$

$$2R_{X\varepsilon}(\mu=0) + R_{\varepsilon\varepsilon}(\mu=0) = R_{X\varepsilon\varepsilon}(\mu=0), \tag{9}$$

where $R_{X\varepsilon\varepsilon}(\mu=0)$ can be called the estimate of noise correlation value.

Thereby, the approximate estimate $R_{X\varepsilon\varepsilon}(\mu=0)$ of cross-correlation function between the useful signal and the noise can be determined by means of the following expressions

$$2R_{X\varepsilon}(\mu=0) \approx R_{gg}(\mu=0) - R_{XX}(\mu=0) - R_{\varepsilon\varepsilon}(\mu=0). \tag{10}$$

It is known from [4,5] that with equality (1) being true and with the corresponding sampling interval Δt, the following approximate equalities can be regarded as true:

$$R_{gg}(\mu=1) \approx R_{XX}(\mu=1), \tag{11}$$

$$R_{gg}(\mu=2) \approx R_{XX}(\mu=2), \tag{12}$$

$$R_{gg}(\mu=3) \approx R_{XX}(\mu=3), \tag{13}$$

$$\left.\begin{aligned} R_{XX}(\mu=0) &= R_{XX}(\mu=1) + \Delta R_{XX}(\mu=1) \\ R_{XX}(\mu=0) &\approx R_{XX}(\mu=1) + \Delta R_{XX}(\mu=2) \end{aligned}\right\} \tag{14}$$

Taking into account expressions (10)-(14), the following may be written

$$R_{XX}(\mu=0) \approx R_{XX}(\mu=1) + \Delta R_{XX}(\mu=1)$$

$$\approx R_{gg}(\mu=1) + [R_{gg}(\mu=2) - R_{gg}(\mu=3)]. \tag{15}$$

Expression (8) can therefore be represented as follows

$$R_{gg}(\mu=0) = R_{gg}(\mu=1) + [R_{gg}(\mu=2) - R_{gg}(\mu=3)]$$

$$+ 2R_{X\varepsilon}(\mu=0) + R_{\varepsilon\varepsilon}(\mu=0), \tag{16}$$

whence the expression (10) can be reduced to the following form

$$2R_{X\varepsilon}(\mu=0) = \left[R_{gg}(\mu=0) - \left[R_{gg}(\mu=1) + \left(R_{gg}(\mu=2) - R_{gg}(\mu=3)\right)\right] - R_{\varepsilon\varepsilon}(\mu=0)\right]$$

$$R_{X\varepsilon}(\mu=0) \approx \frac{1}{2}\left[R_{gg}(\mu=0) - \left[R_{gg}(\mu=1) + \left(R_{gg}(\mu=2) - R_{gg}(\mu=3)\right)\right] - R_{\varepsilon\varepsilon}(\mu=0)\right] \approx$$

$$\approx \frac{1}{2}\sum\left[g(i\Delta t)g(i\Delta t) - \left[g(i\Delta t)g(i+1)\Delta t + g(i\Delta t)g(i+2)\Delta t - g(i\Delta t)g(i+3)\Delta t - D_{\varepsilon\varepsilon}\right]\right] \tag{17}$$

and the expression (9) can be represented as follows:

$$R_{X\varepsilon\varepsilon}(\mu=0) \approx R_{gg}(\mu=0) - [R_{gg}(\mu=1) + R_{gg}(\mu=2) - R_{gg}(\mu=3)] + \\ + R_{\varepsilon\varepsilon}(\mu=0) - D_\varepsilon = R_{gg}(\mu=0) - [R_{gg}(\mu=1) + R_{gg}(\mu=2) - R_{gg}(\mu=3)], \tag{18}$$

This expression can be used to calculate the value of noise correlation $R_{X\varepsilon\varepsilon}(0)$. The experiments showed that the values of estimates $R_{X\varepsilon}(0)$, $R_{X\varepsilon\varepsilon}(0)$ change sharply at the start of time T_1, and they become carriers of diagnostic information both on change in seismic stability.

The experiments also showed that estimate of noise variance D_ε can also be used as a reliable indicator in the monitoring of seismic stability, which is due to the fact that estimates of characteristics of the noise $\varepsilon(i\Delta t)$ at the start of time interval T_1 change sharply both in the presence and in the absence of correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$. When $R_{X\varepsilon}(0) \approx 0$, the estimate of noise variance D_ε can be determined from the formula [4,5]:

$$D_\varepsilon = \frac{1}{N}\sum_{i=1}^{N}\left[g^2(i\Delta t) + g(i\Delta t)g(i+2)\Delta t - 2g(i\Delta t)g(i+1)\Delta t\right]. \tag{19}$$

It is obvious that, knowing estimate D_ε, it is also possible to determine the estimate of useful signal variance D_x from the expression

$$D_x = D_g - D_\varepsilon. \tag{20}$$

It is only possible to determine the estimate of noise variance D_ε and cross-correlation function $R_{X\varepsilon}(\mu=0)$ from the expressions (17), (19) when there is no correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$. To calculate them in the presence of correlation, a technology for determination of the estimate of relay cross-correlation function $R^*_{X\varepsilon}(\mu=0)$ must be developed. It is also reasonable to use the estimate of relay cross-correlation function $R^*_{X\varepsilon}(\mu=0)$ as a carrier of diagnostic information to increase the reliability and adequacy of monitoring results of the start of time T_1. Taking the above-mentioned into account, let us consider the matter in more detail. For that end, let us first assume the following notations:

$$\operatorname{sgn} g(i\Delta t) = \operatorname{sgn} x(i\Delta t) = \begin{cases} 1, & g(i\Delta t) > 0 \\ 0, & g(i\Delta t) = 0 \\ -1, & g(i\Delta t) < 0 \end{cases} \tag{21}$$

and

$$\left.\begin{aligned} &\frac{1}{N}\sum_{i=1}^{N}\operatorname{sgn} g(i\Delta t)\cdot\varepsilon(i+\mu)\Delta t \neq 0, && \mu = 0 \\ &\frac{1}{N}\sum_{i=1}^{N}\operatorname{sgn} g(i\Delta t)\cdot\varepsilon(i+\mu)\Delta t = 0, && \mu \neq 0 \\ &\frac{1}{N}\sum_{i=1}^{N}\varepsilon(i\Delta t)\cdot\varepsilon(i\Delta t) \neq 0, && \mu = 0 \\ &\frac{1}{N}\sum_{i=1}^{N}\varepsilon(i\Delta t)\cdot\varepsilon(i+\mu) = 0, && \mu \neq 0 \end{aligned}\right\}. \tag{22}$$

The formula for determination of estimates of relay correlation function $R^*_{gg}(\mu=0)$ in the presence of correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$ here can be represented as follows:

$$\begin{aligned} R^*_{gg}(\mu=0) &= \frac{1}{N}\sum_{i=1}^{N}\operatorname{sgn} g(i\Delta t)g(i\Delta t) = \\ &= \frac{1}{N}\sum_{i=1}^{N}\operatorname{sgn} g(i\Delta t)\cdot[X(i\Delta t)+\varepsilon(i\Delta t)] = \\ &= \frac{1}{N}\sum \operatorname{sgn} X(i\Delta t)X(i\Delta t) + \\ &+ \frac{1}{N}\sum_{1}\operatorname{sgn} X(i\Delta t)\varepsilon(i\Delta t) = R^*_{XX}(\mu=0) + R^*_{X\varepsilon}(\mu=0). \end{aligned} \tag{23}$$

It is known from [5-8] that in the presence of correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$, the following expressions can be regarded as true:

$$\left.\begin{aligned} &\Delta R^*_{gg}(\mu=0) - \Delta R^*_{gg}(\mu=1) \neq \Delta R^*_{gg}(\mu=1) - \Delta R^*_{gg}(\mu=2) \\ &\Delta R^*_{gg}(\mu=1) - \Delta R^*_{gg}(\mu=2) \approx \Delta R^*_{gg}(\mu=2) - \Delta R^*_{gg}(\mu=3) \approx \Delta R^*_{gg}(\mu=3) - \Delta R^*_{gg}(\mu=4) \approx 0 \\ &\Delta R^*_{XX}(\mu=1) - \Delta R^*_{XX}(\mu=2) \approx \Delta R^*_{gg}(\mu=2) - \Delta R^*_{gg}(\mu=3) \approx \Delta R^*_{gg}(\mu=3) - \Delta R^*_{gg}(\mu=4) \approx 0 \end{aligned}\right\} \tag{24}$$

It follows from the equality (21)-(24) that the estimate of relay cross-correlation function $R^*_{X\varepsilon}(\mu=0)$ can be determined from the formula:

$$\Delta R^*_{gg}(\mu=0) \approx R^*_{XX}(\mu=0) + R^*_{X\varepsilon}(\mu=0), \tag{25}$$

where

$$R^*_{X\varepsilon}(0) \approx \Delta R^*_{gg}(\mu=0) - R^*_{XX}(\mu=0) \tag{26}$$

Therefore, to calculate $R^*_{X\varepsilon}(\mu=0)$ by means of the expression (26), $R^*_{XX}(\mu=0)$ must be determined. Equalities (24) imply that estimate $R^*_{XX}(\mu=0)$ can be calculated by means of the following expression

$$R^*_{XX}(\mu=0) \approx R^*_{XX}(\mu=1) + \Delta R^*_{XX}(\mu=1) \approx \\ \approx R^*_{gg}(\mu=1) + \Delta R^*_{gg}(\mu=1) \approx R^*_{gg}(\mu=1) +$$

$$+\left[R^*_{gg}(\mu=1)-R^*_{gg}(\mu=2)\right]= \\ =2R^*_{gg}(\mu=1)-R^*_{gg}(\mu=2). \qquad (27)$$

Thus, the expression (26) can represented as follows:

$$R^*_{X\varepsilon}(\mu=0)=R^*_{gg}(\mu=0)- \\ -\left[2R^*_{gg}(\mu=1)-R^*_{gg}(\mu=2)\right]= \\ =R^*_{gg}(\mu=0)-2R^*_{gg}(\mu=1)+R^*_{gg}(\mu=2). \qquad (28)$$

The expression for calculation of the estimate of relay cross-correlation function $R^*_{X\varepsilon}(\mu=0)$ between the useful seismic acoustic signal $X(i\Delta t)$ and its noise $\varepsilon(i\Delta t)$ can therefore be written as follows:

$$R^*_{X\varepsilon}(\mu=0)\approx\frac{1}{N}\sum_{i=1}^{N}\left[\operatorname{sgn}g(i\Delta t)g(i\Delta t)-2\operatorname{sgn}g(i\Delta t)g((i+1)\Delta t)+\operatorname{sgn}g(i\Delta t)g((i+2)\Delta t)\right] \qquad (29)$$

As was indicated above, it is possible to calculate the estimates of D_ε when $R_{X\varepsilon}(\mu=0)\approx 0$, using expression (19). It is, however, impossible to use this expression in the presence of correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$. Accordingly, let us consider the possibility of determining D_ε when $R_{X\varepsilon}(\mu=0)\neq 0$, using the estimates $R_{X\varepsilon\varepsilon}(\mu=0)$, $R^*_{X\varepsilon}(\mu=0)$, $\Delta R_{gg}(\mu=0)$ and $\Delta R^*_{gg}(\mu=0)$ in more detail.

Taking into account the conditions (24) and equalities (25) – (29), the following can be written:

$$\left.\begin{aligned} &R^*_{X\varepsilon}(\mu=0)+\Delta R^*_{XX}(\mu=0)\approx\Delta R^*_{gg}(\mu=0)\\ &R_{X\varepsilon}(\mu=0)+R_{\varepsilon\varepsilon}(\mu=0)+\Delta R_{XX}(\mu=0)\approx\Delta R_{gg}(\mu=0)\\ &R_{X\varepsilon}(\mu=0)+R_{\varepsilon\varepsilon}(\mu=0)+\Delta R_{gg}(\mu=1)\approx\Delta R_{gg}(\mu=0)\end{aligned}\right\} \qquad (30)$$

It is known from [5] that the correlation between the estimates $R^*_{X\varepsilon}(\mu=0)$; $R^*_{XX}(\mu=1)$ and $R_{X\varepsilon}(\mu=0)$; $\Delta R_{XX}(\mu=1)$, as well as the correlation between the estimates $R^*_{X\varepsilon}(\mu=0)$; $\Delta R^*_{gg}(\mu=1)$ and $R_{X\varepsilon}(\mu=0)$; $\Delta R_{gg}(\mu=1)$ allow one to assume that the following approximate equalities are true:

$$\left.\begin{aligned} &\frac{R^*_{X\varepsilon}(\mu=0)}{\Delta R^*_{XX}(\mu=1)}\approx\frac{R_{X\varepsilon}(\mu=0)}{\Delta R_{XX}(\mu=1)}\\ &\frac{R^*_{X\varepsilon}(\mu=0)}{\Delta R^*_{gg}(\mu=1)}\approx\frac{R_{X\varepsilon}(\mu=0)}{\Delta R_{gg}(\mu=1)}\end{aligned}\right\} \qquad (31)$$

In this case, we obtain the following equality:

$$R_{X\varepsilon}(\mu=0)\Delta R^*_{gg}(\mu=1)\approx R^*_{X\varepsilon}(\mu=0)\Delta R_{gg}(\mu=1). \qquad (32)$$

Thus, in the presence of correlation between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$, the estimate $R_{X\varepsilon}(0)$ can be determined from the formula:

$$R_{X\varepsilon}(\mu=0)\approx\frac{R^*_{X\varepsilon}(\mu=0)\cdot\Delta R_{gg}(\mu=1)}{\Delta R^*_{gg}(\mu=1)} \qquad (33)$$

It is clear that after estimate $R_{X\varepsilon}(0)$ is determined, estimate of noise variance D_ε can be determined either by means of the expression:

$$D_\varepsilon=R_{\varepsilon\varepsilon}(\mu=0)\approx\Delta R_{gg}(\mu=0)-\Delta R_{gg}(\mu=1)-R_{X\varepsilon}(\mu=0), \qquad (34)$$

or by means of the expression:

$$D_\varepsilon=R_{X\varepsilon\varepsilon}(\mu=0)-R_{X\varepsilon}(\mu=0), \qquad (35)$$

where $R_{X\varepsilon\varepsilon}$ is determined from the formula (18).

IV. Robust Technology for Identification of Technical Condition and Seismic Stability of Offshore Oil and Gas Extraction Objects

To solve the problem of identification of seismic stability of offshore platforms, piers and communications, let us first of all consider the possibility of applying methods of theory of random processes to that purpose. It is known that state of seismic stability of a structure in the period of time T_1 in the general case is described with matrix equalities of the following type [1,4]

$$\vec{R}_{XY}(\mu)=\vec{R}_{XX}(\mu)\vec{W}(\mu), \\ \mu=0,\quad \Delta t,\quad 2\Delta t,\quad \ldots,\quad (N-1)\Delta t, \qquad (36)$$

where

$$\vec{R}_{XX}(\mu)\left\|\begin{matrix} R_{XX}(0) & R_{XX}(\Delta t) & \ldots & R_{XX}[(N-1)\Delta t]\\ R_{XX}(\Delta t) & R_{XX}(0) & \ldots & R_{XX}[(N-2)\Delta t]\\ \ldots & \ldots & \ldots & \ldots\\ R_{XX}[(N-1)\Delta t] & R_{XX}[(N-2)\Delta t] & \ldots & R_{XX}(0)\end{matrix}\right\|, \qquad (37)$$

$$\vec{R}_{XY}(\mu)=\left[R_{XY}(0)\quad R_{XY}(\Delta t)\quad\ldots\quad R_{XY}[(N-1)\Delta t]\right]^T, \qquad (38)$$

$$\vec{W}(\mu)=\left[W(0)\quad W(\Delta t)\quad\ldots\quad W((N-1)\Delta t)\right]^T, \qquad (39)$$

where $\vec{R}_{XX}(\mu)$ is the square symmetric matrix of auto-correlation functions with dimension $N\times N$ of centered input signal $X(t)$; $\vec{R}_{XY}(\mu)$ is the column vector of cross-correlation functions between the input $X(t)$ and output $Y(t)$; m_X, m_Y are mathematical expectations of $X(t)$, $Y(t)$ respectively; $\vec{W}(\mu)$ is the column vector of impulsive admittance functions.

Matrices (37), (38) and equation (36) are formed from the estimates of useful signals $X(t)$ and $Y(t)$. However, in the process of solving of real tasks, these matrices are formed from estimates of technological parameters installed at corresponding units of offshore platforms, piers and communications, representing noisy signals $g_1(i\Delta t), g_2(i\Delta t), \ldots, g_m(i\Delta t)$. Thus, they contain errors from noises $\varepsilon_1(i\Delta t), \varepsilon_2(i\Delta t), \ldots, \varepsilon_m(i\Delta t)$. With estimates of noise variances and cross-correlation function between the useful signal and the noise changing, their errors change as well. To ensure adequate results of identification of technical condition and seismic stability of offshore objects by means of matrix equation (36), it is therefore first of all necessary to ensure robustness of estimates of elements of those matrices [1,5]. There is a good reason to use the technology of calculation of robust estimates of auto- and cross-correlation functions from the following expressions:

$$R_{gg}^R(\mu) = \frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)g((i+\mu)\Delta t) - [N^+(\mu) - N^-(\mu)]\langle\Delta\lambda(\mu=0)\rangle \tag{40}$$

$$R_{g\eta}^R(\mu) = \frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)\eta((i+\mu)\Delta t) - [N^+(\mu) - N^-(\mu)]\langle\Delta\lambda(\mu=0)\rangle, \tag{41}$$

where

$$\left.\begin{aligned} \left|R_{gg}(\mu=1) - R_{gg}^*(\mu=1)\right| &= \lambda(\mu=1) \\ \left|R_{g\eta}(\mu=1) - R_{g\eta}^*(\mu=1)\right| &= \lambda(\mu=1) \end{aligned}\right\} \tag{42}$$

$$\langle\Delta\lambda(\mu=1)\rangle = [1/N^-(\mu=1)]\lambda(\mu=1). \tag{43}$$

Here, $R_{gg}(\mu=1)$, $R_{gg}^*(\mu=1)$, $R_{g\eta}(\mu=1)$, $R_{g\eta}^*(\mu=1)$ are the estimates of auto- and cross-correlation functions of centered and uncentered signals $g(i\Delta t)$, $\eta(i\Delta t)$ respectively. $N^+(\mu)$, $N^-(\mu)$ are the quantities of products $g(i\Delta t)g(i+\mu)\Delta t$ or $g(i\Delta t)\ \eta(i\Delta t)$ with positive and negative signs respectively.

It is obvious that when elements of matrices (37), (38) will be formed from robust estimates from expressions (40), (41), matrix equation (37) can be represented as follows.

$$\overrightarrow{R_{g\eta}^R}(\mu) \approx \overrightarrow{R_{gg}^R}(\mu)\vec{W}(\mu),\ \mu = 0, \Delta t, 2\Delta t, \ldots, (N-1)\Delta t. \tag{44}$$

Elements of matrices $\overrightarrow{R_{gg}^R}(\mu)$, $\overrightarrow{R_{g\eta}^R}(\mu)$ here are robust estimates of noisy signals, i.e.

$$\vec{R}_{gg}^R(\mu) = \begin{Vmatrix} R_{gg}^R(0) & R_{gg}^R(\Delta t) & \ldots & R_{gg}^R[(N-1)\Delta t] \\ R_{gg}^R(\Delta t) & R_{gg}^R(0) & \ldots & R_{gg}^R[(N-2)\Delta t] \\ \ldots & \ldots & \ldots & \ldots \\ R_{gg}^R[(N-1)\Delta t] & R_{gg}^R[(N-2)\Delta t] & \ldots & R_{gg}^R(0) \end{Vmatrix}, \tag{45}$$

$$\overrightarrow{R_{g\eta}^R}(\mu) = \left[R_{g\eta}^R(0)R_{g\eta}^R(\Delta t)\ldots R_{g\eta}^R[(N-1)\Delta t]\right]^T. \tag{46}$$

According to [4,5], in calculation of correlation function from expressions (40), (41), errors from noises are virtually excluded from robust estimates of elements of matrices (45), (46). The following equality can thereby be regarded as true

$$\left.\begin{aligned} &\vec{W}(\mu) = [W'(0)\quad W'(\Delta t)\quad \ldots\quad W[(N-1)\Delta t]]^T \\ &W'(0) \approx W(0), W'(\Delta t) \approx W(\Delta t), \ldots, W'[(N-1)\Delta t] \approx W[(N-1)\Delta t] \end{aligned}\right\} \tag{47}$$

Thus, it can be assumed that adequacy of the results obtained in the process of identification of seismic stability of offshore platforms and piers by means of matrix equation (44) will be satisfactory.

However, different sensors are usually used in control systems of real offshore objects to diagnose their technical condition, signals at the output of those sensors often reflecting various physical quantities (vibration, pressure, motion, etc.). Estimates of correlation functions of signals $g_1(i\Delta t), g_2(i\Delta t), \ldots, g_n(i\Delta t)$ must be therefore reduced to dimensionless quantities.

This is realized by using the procedure of normalization of matrix elements (37), (38), (45), (46) [1,4,5]. Only values of auto-correlation function in this case prove to be accurate when time shift is equal to zero μ =0. In all other cases, i.e. normalization for estimates of auto-correlation functions at time shifts $\mu \neq 0$ and for estimates of cross-correlation functions at all time shifts μ, unfortunately, leads to emergence of additional errors from the noise. In the presence of correlation between the useful signal and the noise, normalization of the value of estimate error results in even greater inadequacy of solution of the above-mentioned problems. In this respect, a technology is required that ensures elimination of estimation error caused by normalization.

V. Robust Technology for Normalization of Estimates of Auto- and Cross-Correlation Functions

It follows from the above-mentioned that to ensure adequate results of monitoring and identification of change in seismic stability of offshore stationary platforms, a technology must be developed, which is oriented to eliminate the noise errors that arises at normalization of the estimate of correlation function both in the absence of correlation between the useful signal and the noise and in the presence of such.

Let us consider one of possible methods of solving this problem. It is known that normalized auto- and cross-correlation functions of useful signals $X(t)$, $Y(t)$ are calculated from formulas [1]:

$$r_{XX}(\mu)=R_{XX}(\mu)/D(x), \tag{48}$$

$$r_{XY}(\mu)=R_{XY}(\mu)/\sqrt{D(X)D(Y)}, \tag{49}$$

$$D(x)=R_{XX}(0),\ D(Y)=R_{YY}(0),$$

where $R_{XX}(\mu)$, $R_{XY}(\mu)$ are estimates of auto- and cross-correlation functions, estimates of variances of signals $X(t)$, $Y(t)$; μ=0, $\mu=\Delta t$, μ=2 Δt, μ=3 Δt, … .

Accordingly, normalized auto- and cross-correlation functions $r_{gg}(\mu)$, $r_{g\eta}(\mu)$ of noisy signals consisting of the sum of random useful signals $X(t)$, $Y(t)$ and corresponding noises $\varepsilon(t), \varphi(t)$

$$g(t)=X(t)+\varepsilon(t),\ \eta(t)=Y(t)+\varphi(t), \tag{50}$$

are calculated from the following formulas

$$r_{gg}=R_{gg}(\mu)/D(g), \tag{51}$$

$$r_{g\eta}(\mu)=R_{g\eta}(\mu)/\sqrt{D(g)D(\eta)}, \tag{52}$$

where

$$R_{gg}(\mu)=\frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)g((i+\mu)\Delta t)=$$
$$\frac{1}{N}\sum_{i=1}^{N}(X(i\Delta t)+\varepsilon(i\Delta t))(X((i+\mu)\Delta t)+\varepsilon((i+\mu)\Delta t)), \tag{53}$$

$$R_{g\eta}(\mu)=\frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)\eta((i+\mu)\Delta t)=$$
$$\frac{1}{N}\sum_{i=1}^{N}(X(i\Delta t)+\varepsilon(i\Delta t))(Y((i+\mu)\Delta t)+\varphi((i+\mu)\Delta t)). \tag{54}$$

Here, $D(g)=R_{gg}(0)$, $D(\eta)=R_{g\eta}(0)$ are estimates of variances of signals $g(t)$, $\eta(t)$; m_g, m_η are mathematical expectations $g(t)$, $\eta(t)$.

Comparing expressions (48)-(49) with expressions (51)-(52), we can see that estimates of normalized auto- and cross-correlation functions of useful signals differ considerably from estimates of normalized auto- and cross-correlation functions of noisy signals, i.e.

$$r_{gg}(\mu)\neq r_{XX}(\mu), \tag{55}$$

$$r_{g\eta}(\mu)\neq r_{XY}(\mu). \tag{56}$$

It is therefore required to develop robust technologies for calculation of estimates of normalized auto- and cross-correlation functions $r_{gg}^R(\mu)$, $r_{g\eta}^R(\mu)$, which would ensure that the following equalities hold true

$$r_{gg}^R(\mu)\approx r_{XX}(\mu), \tag{57}$$

$$r_{g\eta}^R(\mu)\approx r_{g\eta}(\mu) \tag{58}$$

both in the presence of correlation between the useful signal and the noise and when the correlation is equal to zero.

For that end, let us first consider the sources of errors that emerge in the process of calculation of estimates of normalized correlation functions.

Seeing that the values $\varepsilon(i\Delta t)$ and $\varepsilon((i+\mu)\Delta t)$ do not correlate when $\mu\neq 0$, i.e.

$$\frac{1}{N}\sum_{i=1}^{N}\varepsilon(i\Delta t)\varepsilon((i+\mu)\Delta t)\approx 0 \text{ at } \mu\neq 0 \tag{59}$$

and the mean-square value of the noise is equal to the estimate of variance $D(\varepsilon)$ of the noise $\varepsilon(i\Delta t)$, i.e.

$$D(\varepsilon)=\frac{1}{N}\sum_{i=1}^{N}\varepsilon(i\Delta t)\varepsilon(i\Delta t). \tag{60}$$

Then in the presence of correlation between the useful signal $X(t)$ and the noise $\varepsilon(t)$ at time shift μ=0 and in the absence of correlation at $\mu\neq 0$, the following correlation will be true

$$R_{X\varepsilon}(\mu=0)\neq 0,\ R_{\varepsilon X}(\mu=0)\neq 0,\ R_{X\varepsilon}(\mu\neq 0)=0,$$
$$R_{\varepsilon X}(\mu\neq 0)=0 \tag{61}$$

The expression of calculation of $R_{gg}(\mu)$ can be accordingly written in the following form:

$$R_{gg}(\mu=0)=\frac{1}{N}\sum_{i=1}^{N}g(i\Delta t)g(i\Delta t)=R_{XX}(\mu=0)+2$$
$$R_{X\varepsilon}(\mu=0)+D(\varepsilon), \tag{62}$$

$$R_{gg}(\mu\neq 0)=\frac{1}{N}\sum_{i=1}^{N}g(i\Delta t)g((i+\mu)\Delta t)=$$
$$R_{XX}(\mu\neq 0), \tag{63}$$

where

$$R_{X\varepsilon}(\mu=0)=\frac{1}{N}\sum_{i=1}^{N}X(i\Delta t)\varepsilon(i\Delta t). \tag{64}$$

It is obvious from formula (62) that in the presence of correlation between the useful signal and the noise, estimate error of correlation function at μ=0 is equal to the sum of double estimate of cross-correlation function $R_{X\varepsilon}(\mu=0)$ between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$ and variance $D(i\Delta t)$ of the noise $\varepsilon(i\Delta t)$. At any other time shift $\mu \neq 0$, estimates of auto-correlation function $R_{gg}(\mu \neq 0)$ of noisy signal coincide with the estimates of auto-correlation function $R_{XX}(\mu \neq 0)$ of the useful signal $X(i\Delta t)$

$$R_{gg}(\mu \neq 0) \approx R_{XX}(\mu \neq 0). \tag{65}$$

Normalization at zero time shift $\mu=0$ here results in equality of normalized correlation functions of both the useful signal $X(i\Delta t)$ and the noisy signal $g(i\Delta t)$, which are equal to one:

$$r_{XX}(\mu=0)=r_{gg}(\mu=0)=1. \tag{66}$$

Taking into accounts expressions (48), (51), (62), it is obvious that when $\mu \neq 0$, the formula for determination of the estimate of normalized auto-correlation function of the noisy signal $g(i\Delta t)$ is as follows:

$$r_{gg}(\mu \neq 0)=\frac{R_{gg}(\mu \neq 0)}{D(g)}=\frac{R_{gg}(\mu \neq 0)}{R_{XX}(\mu=0)+2R_{X\varepsilon}(\mu=0)+D(\varepsilon)}. \tag{67}$$

Thus, in the presence of correlation between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$, estimates of normalized auto-correlation function $r_{gg}(\mu \neq 0)$ of the noisy signal $g(i\Delta t)$ at time shifts $\mu \neq 0$ are different from estimates of normalized auto-correlation function $r_{XX}(\mu \neq 0)$ of the useful signal $X(i\Delta t)$ by a double quantity of cross-correlation function $R_{X\varepsilon}(\mu=0)$ and a quantity of noise variance $D(i\Delta t)$ in the radical expression of denominator, due to which inequality (55) takes place.

It is obvious from formula (54) that estimates of cross-correlation functions $R_{g\eta}(\mu)$ of noisy signals $g(i\Delta t)$, $\eta(i\Delta t)$ in the absence of correlation between useful signals $X(i\Delta t)$, $Y(i\Delta t)$ and noises $\varepsilon(i\Delta t)$, $\varphi(i\Delta t)$, as well as between noises $\varepsilon(i\Delta t)$ and $\varphi(i\Delta t)$ themselves, i.e. when the following conditions hold true:

$$R_{X\varepsilon}(\mu) \approx 0,\ R_{Y\varphi}(\mu) \approx 0,\ R_{\varepsilon\varphi}(\mu) \approx 0, \tag{68}$$

equal estimates of cross-correlation function $R_{XY}(\mu)$ of useful signals at an time shift, i.e. the following equality holds true:

$$R_{g\eta}(\mu) \approx R_{XY}(\mu). \tag{69}$$

However, in the presence of correlation between useful signals $X(i\Delta t)$, $Y(t)$ and noises $\varepsilon(i\Delta t)$, $\varphi(t)$ at time shifts $\mu=0$ and $\mu \neq 0$, the following correlation holds true:

$$R_{Y\varphi}(\mu=0) \neq 0,\ R_{\varphi Y}(\mu=0) \neq 0,\ R_{Y\varphi}(\mu \neq 0)=0,$$
$$R_{\varphi Y}(\mu \neq 0)=0. \tag{70}$$

In that case, formula (52) for calculation of estimates of normalized cross-correlation functions takes the following form:

$$r_{g\eta}(\mu)=\frac{R_{g\eta}(\mu)}{\sqrt{D(g)\cdot D(\eta)}}=\frac{R_{g\eta}(\mu)}{\sqrt{\left[D(X)+\underbrace{2R_{X\varepsilon}(0)+D(\varepsilon)}\right]\cdot\left[D(Y)+\underbrace{2R_{Y\varphi}(0)+D(\varphi)}\right]}}. \tag{71}$$

Estimates of normalized cross-correlation function $r_{g\eta}(\mu)$ of noisy signals $g(i\Delta t)$, $\eta(i\Delta t)$ at any time shift μ therefore differ from estimates of normalized cross-correlation function $r_{XY}(\mu)$ of useful signals $X(i\Delta t)$, $Y(i\Delta t)$ by a double quantity of cross-correlation functions $R_{X\varepsilon}(\mu=0)$, $R_{Y\varphi}(\mu=0)$ and a quantity of noise variances $D(\varepsilon)$, $D(\varphi)$ in the radical expression of denominator, due to which inequality (56) takes place.

In the presence of correlation between the useful signal $X(t)$ and the noise $\varepsilon(t)$, the formula for calculation of robust estimates of normalized auto-correlation functions at time shifts $\mu=0,\ \mu=\Delta t,\ \mu=2\Delta t,\ \mu=3\Delta t, \ldots$ can be represented as follows:

$$r_{gg}{}^{R}(\mu)=\begin{cases}1\\ \dfrac{R_{gg}(\mu)}{R_{gg}(0)-R_{X\varepsilon\varepsilon}(0)}\end{cases} \tag{72}$$

In the presence of correlation between useful signals $X(t)$, $Y(t)$ and noises $\varepsilon(t)$, $\varphi(t)$, formula (71) for calculation of robust estimates of normalized cross-correlation function $r^{R}_{g\eta}(\mu)$ at time shifts 0, Δt, 2 Δt, 3 Δt, … can be represented as follows:

$$r^{R}_{g\eta}(\mu)=R_{g\eta}(\mu)/\sqrt{(D(g)-D_{\varepsilon})}\sqrt{(D(\eta)-D_{\varphi})}, \tag{73}$$

or

$$r^{R}_{g\eta}(\mu)=\frac{R_{g\eta}(\mu)}{\sqrt{[R_{gg}(0)-R_{X\varepsilon\varepsilon}(0)][R_{\eta\eta}(0)-R_{g\varphi\varphi}(0)]}}. \tag{74}$$

Thus, application of the developed robust technology for calculation of estimates from expressions (72), (74) practically eliminates errors of normalization caused by noise both in the presence of correlation between the useful signal and the noise and in the absence of such. As a result, a possibility arises to form correlation matrices from estimates of normalized correlation functions, where error from noise effect is eliminated.

In this respect, in the case when technological parameters of offshore oil and gas extraction objects are represented by various physical quantities, to ensure adequacy of results, it is expedient to solve the problem of identification by means of matrix equation of the following type:

$$\vec{r}^{\,R}_{g\eta}(\mu)=\overrightarrow{r^R_{gg}}(\mu)\vec{W}(\mu),\quad \mu(\Delta t)=0,\ \Delta t,\ 2\Delta t,\ \ldots,\ (N-1)\Delta t \tag{75}$$

where

$$\vec{r}^{\,R}_{gg}(\mu)=\begin{Vmatrix} r^R_{gg}(0) & r^R_{gg}(\Delta t) & \ldots & r^R_{gg}[(N-1)\Delta t] \\ r^R_{gg}(\Delta t) & r^R_{gg}(0) & \ldots & r^R_{gg}[(N-2)\Delta t] \\ \ldots & \ldots & \ldots & \ldots \\ r^R_{gg}[(N-1)\Delta t] & r^R_{gg}[(N-2)\Delta t] & \ldots & r^R_{gg}(0) \end{Vmatrix} \tag{76}$$

$$\vec{r}^{\,R}_{g\eta}(\mu)=\left[r^R_{g\eta}(0)\ \ r^R_{g\eta}(\Delta t)\ \ldots\ r^R_{g\eta}(N-1)\Delta t\right] \tag{77}$$

$$\vec{W}^*(\mu)=\left[W^*(0)\quad W^*(\Delta t)\quad \ldots\quad W^*((N-1)\Delta t)\right]^T \tag{78}$$

Application of the offered technology for normalization of elements of these matrices by means of expressions (72), (74) in this case practically eliminates errors caused by noises.

The following equality can therefore be regarded as true:

$$W^*(0)\approx W(0),\quad W^*(\Delta t)\approx W(\Delta t),\quad \ldots,\quad W^*(N-1)\Delta t\approx W(N-1)\Delta t \tag{79}$$

We can thereby assume that adequacy of results of identification by means of matrix equation (75) will coincide with the result obtained from equation (36).

VI. CONCLUSION

The paper considers the possibility of solving of problems of control of microchanges and diagnostics of the initial phase of the latent period of change in seismic stability of offshore stationary platforms during frequent weak earthquakes and hurricane storms.

Taking into account the peculiarity of formation of noisy signals in the period of earthquakes and storms with hurricanes and rain showers, the offered technologies suggest using noise as a carrier of diagnostic information for control and monitoring of the latent period of violation of seismic stability.

When solving problems with application of statistical methods of identification of technical condition of seismic stability of offshore platforms, piers and other objects, difference in measurement units of different technological parameters received from corresponding sensors leads to the necessity of reducing it to dimensionless quantity by means of normalization. This procedure is carried out through division of the calculated estimates by variance of noisy signal. In that case, at zero time shift, $\mu = 0$ additional errors are introduced in all points but the initial point of correlation function. This is due to the fact that the value of noise variance must be subtracted from the summary variance in the devisor in estimates of these points, which is, unfortunately, not taken into account during normalization in currently used technologies. This results in considerable deviation of obtained normalized estimates from true values. The offered technology allows one to eliminate the mentioned difference by subtracting the value of noise correlation from the divisor. Owing to that, errors of eventual results of monitoring, diagnostics, identification of technical condition of offshore stationary platforms and piers decrease considerably when the offered technology is applied.

During monitoring of microchanges of seismic stability of offshore stationary platforms, estimates of characteristics of noisy signals and their noises obtained at the original state of their seismic stability can be taken as reference ones, and the corresponding matrices can be formed for them. In the process of monitoring of seismic stability during weak earthquakes and storms, current estimates are compared with reference estimates. If the difference exceeds a certain threshold level, it can be assumed that the state of the object has entered time interval T_1.

REFERENCES

[1] Kollakot R.A. Damage diagnostics. M.: Mir, 1989, 512 p. (in Russian)

[2] Aliev T.A., Alizada T.A., Tairova H.S. Hybrid system of control and diagnostics of condition of offshore platforms. // "Neftyanoye hozyaystvo", Moscow, No 1, 2000, pp. 29-31. (in Russian)

[3] Aliev T.A. Robust technology for control of seismic stability of offshore oil and gas deposit objects // "Neftyanoye hozyaystvo", Moscow, No 3, 2001, pp. 66-68. (in Russian)

[4] Telman Aliev. Robust Technology with Analysis of Interference in Signal Processing. Kluwer Academic/Plenum Publishers, New York, 2003, 199 p.

[5] Telman Aliev. Digital noise monitoring of defect origin. London, Springer, 2007, 223 p.

[6] T.A. Aliev, T.A. Alizada, A.A. Abbasov. Method for monitoring the beginning of anomalous seismic process. International Application No PCT/AZ2005/000006, Pub.No WO2006/130933, International Filling Date – December 19, 2005.

[7] T.A. Aliev, A.M. Abbasov, E.R. Aliev, G.A. Guluev. Method for monitoring and forecasting earthquakes. Eurapian Asian patent No 011003. International Application No PCT/AZ2006/00000, Pub.No WO2007/143799, International Filling Date – June 16, 2006.

[8] Aliev T.A., Abbasov A.M., Aliyev E.R., Guluyev G.A. Digital technology and system of collection and analysis of information from deep strata of the earth for the purpose of noise monitoring of technical condition of socially significant objects // "Avtomatika i vychislitelnaya tehnika", Riga, No 2, 2007, pp. 3-15. (in Russian)

[9] T.A. Aliev, A.M. Abbasov. Digital Technology and the system of interference monitoring of the technical state of consractive objects, and the system of the signaling of abnormal seismic processes // Automatic Control and Computer Sciences, Allerton Press, Inc., New York, No.6, 2005, pp.3-10.

[10] T.A. Aliev, N.S. Aliyev. Device for diagnostics of stationary stochastic objects. Author's certificate No 1084746. Applicant: Cybernetics Institute of the AS of AzSSR, application No 3391677, invention priority 27 May, 1982. Registered at the State Register of Inventions of the USSR, 8 December, 1983.