Integral Model of Monitoring the Oil-Trunk Pipelines in Earthquake-Prone Regions

Vasiliy Makarov[1], Tahir Alizada[2], Lyubov Ebert[3]
[1]Technical Institute Branch of Yakut State University, Neryungri, Russia
[2]Cybernetics Institute of ANAS, Baku, Azerbaijan
[3]South Yakut Research Center, Neryungri, Russia
[1]*makarov9jku@rambler.ru*, [2]*TahirAlizada@gmail.com*, [3]*uzent@rambler.ru*

Abstract— **Long-term experience in operating the distributed technical systems (DTS) of main oil-pipeline class proves the low efficiency of transferring the means of monitoring designed for compact DTS. The authors suggest the integral model of prognostication and monitoring of DTS in real time without the need of major apparatus modernization. The model explains the fluctuations in the readings of "Eastern Siberia – Pacific Ocean" oil-trunk pipeline (ESPO-OTP) testing and recording apparatus, gives recommendations on their interpretation and management decision-making. According to its characteristics mentioned the model can be efficient for both management and service staff of ESPO-OTP.**

Keywords— ***intricate anthropotechnical systems; control lag; control stability; cumulative sums***

I. INTRODUCTION

This research has two components: theoretical and empirical. Theoretical one has the basis of hypothesis that general regularities of feedback systems functioning apply to pipelines as well. Uncoordinated observations of peculiarities of managing the "Eastern Siberia – Pacific Ocean" oil-trunk pipeline (hereinafter referred to as ESPO-OTP).

This oil-trunk pipeline characteristics are only ordinary at the extent of 2,694 km, technical corridor of ESPO-OTP in Yakutia constitutes 1,458 km. The peculiarities of the oil-trunk pipeline under consideration are the following parameters:

1) altitudes above sea level between 150 m and 1,300 m;

2) annual fluctuations of temperature lying within the range of [-50°C; +40°C].

The oil-trunk pipeline runs through the areas of different types permafrost and earthquake-prone areas with the possible magnitude above 9 points MSK-6 scale. These and some other peculiarities of ESPO-OTP are recorded in "Special Standards of Design and Construction of ESPO-OTP" [1-4] which expand the field of application of Construction Regulations (SNiP) for designing the oil pipelines with the pressure over 10 MPa being constructed in the areas with permanently frozen soil and in the regions with major seismicity.

The average productivity (flow) is 2,900 – 3,500 m^3/h; maximum – 4,900 m^3/h; annual - $30*10^6$ tons. If the operation is normal, ESPO-OTP is environmentally safe and economically efficient. At the same time, ESPO-OTP can make irreparable harm to the nature of Yakutia in an emergency. Hence the attention paid to the questions of reliability and efficiency of ESPO-OTP work while designing and operating is understandable. Work efficiency does not only depend on the technical condition of the oil-trunk pipeline but on the rationality of using the instruments and equipment by the operating personnel as well. The latter is not always possible as the ESPO-OTP actual operating conditions are always different from the designed ones for several reasons. The authors have carried out the research of the reasons why running complex technical systems always differ from the designed ones. In this report we only mention one of them: at the design stage the human factor is not taken into consideration – the system becomes anthropotechnic complex technical system (ATCTS) in process of transferring it into commercial mode. So long as anthropotechnicity of ATCTS presupposes the existence of a purpose and if this purpose has quantitative characteristics, the quantitative model of ESPO-OTP becomes a necessity. In such general form the justification of mathematical model necessity does not cause rejection with oil industry workers, but will not become the stimulus to the development either. The fact of the matter is not that the known ATCTS mathematical models are either trivial or very complicated. The reasons for the guarded attitude to mathematical models are much deeper – they are based on the methodological thesis: industrial object is not identical with the subject under consideration constructed scientifically, in particular – mathematical model.

II. STATEMENT OF THE TASK

The condition of the linear part and equipment of the oil-trunk pipeline stations is changing while operation; that predetermines changes in oil pipelines capacity and changes in work parameters at constant productivity. Under these circumstances the following operational tasks occur: the selection of an optimum work and management scheme at designated productivity, defining the management parameters at load fluctuations from minimum acceptable to maximum. In the local case (for the certain section) the specified tasks are solved practically by means of telemechanics, leak detection system and the set of instrumentation developed by "Diascan" public corporation. Sensors signal transformation into the form readable by the operating personnel is done by LeakSPY (Expert) – the complex of program-technical facilities carrying out the functions of real-time pipelines hermeticity control following the specified algorithm in all the modes of operation.

This complex was created for detecting the leaks caused by both nature factors or mechanical damage and unauthorized cuttings-in into oil/oil product pipelines. The complex allows detecting the leaks with the flow of less than 0.5% of total flow in the pipeline. Apart from the leakage fact, LeakSPY (Expert) defines the coordinate, the flow and the time of the leakage start. The inaccuracy of defining the leakage coordinate is about 400 meters. But the initiation of signal "Oil-trunk pipeline transition into emergency mode" is also possible without depressurization. For instance, the effective oil pipe diameter can change under the influence of thermodynamic parameters only. Or during operation the inner chamber of the oil-trunk pipeline can be contaminated with water, paraffin deposits and mechanical impurities. In some cases in the elevated sections the oil vapor can be accumulated. The presence of aggregates causes the rise of hydraulic resistance and, consequently, fall-off in accuracy of predictive estimate of oil pipeline operating mode. LeakSPY (Expert) system is local in algorithm whereas for detecting the change in the hydraulic efficiency it is necessary:

1) to monitor the change in oil flow characteristics in lengthy sections;

2) to consider delay/advance of both sensors signals and the time of control actions execution.

The task marked as "2)" has its analogue: John von Neumann attended to the task of creating "reliable systems from unreliable elements" and nowadays his solution became self-evident truth. In the case of ESPO-OTP operating arises the task equivalent in its complexity but inverse in its structure: to ensure the stability of control of distributed ATCTS whose subsystems are reliable by hypothesis. We can illustrate the nontriviality of this task with the example of intercommunication of three adjacent sections of some abstract line circuit which we denote as $\{x, y, z\}$. Let each of the three sections before unification be stable and be described with the linear equation:

$$\left.\begin{aligned} dx/dt &= -x - 2q - 2r \\ dy/dt &= -2p - y + r \\ dz/dt &= p + q - z \end{aligned}\right\} \qquad (1)$$

Let us join them admitting $p = x$, $q = y$ and $r = z$. The system derived has its own numbers +1, −2, −2 and consequently, is unstable. In case of oil-trunk pipeline the instability can initiate the false probes triggering and after the pressure release in ESPO-OTP the leak signal will disappear "for no reason". It is rather difficult to understand without a mathematical model why the false signal appeared.

Thus, the idealization of the actual oil pipeline work to the level of mathematical models is completely justified. Naturally, the tasks of ensuring the efficiency, reliability and controllability of ESPO-OTP presuppose the construction of several criteria and mathematical models. The authors confine themselves to two of them: building the stability zone edges overrunning which results in loss of controllability and defining the class of informative indicative signals.

III. Task solution

One of the main characteristics of ATCTS is their ability to evolve which can be described in simple cases with the equation

$$\dot{X} = k_1 X + k_2 X^2$$

or the reverse curve. Another important property of ATCTS is their programmed control. Explanation: to define the programmed control means to find the dependence of control function u_1; u_2; $\ldots u_n$ not on time, but on the control objective and the condition of the object irrespective of its history. In general case the processes of development include the areas of parameters increase, decrease and the modes of fluctuation in the steady-state mode or in combination with rise and fall. The simplest model answering the description of processes of such type can be represented with the differential equation with the divergent argument of the following type:

$$\dot{X} = k_R X(t - \tau_R), \qquad (2)$$

where R is «reproduction of condition», $X(t-\tau_R)$ is the system condition at the moment of time retarding in regard to t in point with the interval τ_R; k_R is reproduction constant. In general case $\varphi(\tau_R, k_R) = 0$; equation (2) corresponds to the model of extended reproduction in regard to the moment under consideration and in special case it is exponential. For describing the local technical devices (even rather complicated) the Markovian process apparatus can be used. At the same time, the influence of the previous development on the consecutive one is characteristic for most of ATCTS. Then the retardation time itself depends on the condition of the system, the moment of its development, the mode of its organization, etc. The mechanism of the condition reproduction is interconnected with the programmed control expressed in the advance type equation:

$$\dot{X} = k_K X(t + \tau_K), \qquad (3)$$

and at some $\{k_K, \tau_k\}$ having the exponential type solution. Here k_K is control constant, $t + \tau_K$ is the time horizon of forecasting the future situations. Using the method taken from chapter four [5], the authors constructed the sufficient feature of exponential solution of equation (2):

$$U\tau_K \le 1.29$$

where

$$U = \frac{\Delta X}{X}.$$

At the time of transition through this boundary the solution becomes instable and some chaotic fluctuations arise. In our case that means the excitation of pressure-waves stochastic field [6]. Since the equation (3) also has the boundary of exponential solutions

$$U \leq \frac{0.9}{\tau_R},$$

we can define the sufficient condition of stability of ATCTS both in oil transportation and in its control. Namely: when reaching the boundary of exponential development U must change simultaneously at least at three adjacent (separated by gates) sections of the oil-trunk pipeline by 1.29/0.9=1.43 times.

Naturally, this condition only makes sense in case of no-failure operation of technical systems of the oil-trunk pipeline. Reliability supervision is carried out by the monitoring system (MS), in particular, the leak detecting system. The initial information comes to MS from pressure sensors, the average distance between them is $\langle L_1 \rangle=12$ km, at water transitions $\langle L_2 \rangle=100$ m. If it is necessary, the sensors signals actuate the gates distributed lengthwise the pipeline with the period of $\langle L_1 \rangle=20$km. Thus, the Monitor and Control System (M&CS) on-stream in accordance with the project of ATCTS is retarding, local and having the nonzero probability of false triggering. At the same time, there exists the possibility of reorganization of acting M&CS into the integral and minimizing price of false triggering. For solving the above task it is possible to use the algorithm which was successfully tested by the authors in the framework of industrial experiment on the discretely continuous mining system NUR YAKUTUGOL in 2006 – 2007. The algorithm mentioned describing non-Markovian processes is based on the method of cumulative sums (*Q*-sums) calculation. Namely: instead of individual (single-stage) features of the process the past data information is used in the form of *Q*-sums. That is, not the individual magnitudes of features are being researched, but their *Q*-sums. Let $\{x\}_i$ be the set of uniform characteristics of stochastic process ordered according to the variety of time intervals $\{t\}_i$. Then the formation of *Q*-sums will be as follows:

$$S_1 = (x_1 - k),$$

$$S_2 = (x_1 - k) + (x_2 - k) = S_1 + (x_2 - k),$$

$$S_r = \sum_{i=1}^{r} (x_i - k) = S_{r-1} + (x_r - k)$$

Here: $x_1, x_2, \ldots$ is the series of characteristic values; k is the constant representing some reference value. The findings of the successful experiment on forecasting the process of extracting and transportation of overburden rock were not implemented in the process of production control in NUR YAKUTUGOL for the reasons of administrative and economic character. It stands to reason that the result of the work of *Q*-sums algorithm is not equivalent to the solution of the task of minimization both the false trigging probability and the average retarding at the correctly asserted alarm. It is not equivalent for the reason that the method which would minimize both of them at the same time does not exist. The reasonable task statement looks as follows: among all the ways of raising the alarm whose probability of being false would not exceed the preset level, to find the one which would ensure the minimum average retarding time. The task formulated like that allows complete solution. For every moment the a posteriori probability of leakage signal is calculated (as the function of monitoring results) for the whole preceding time interval. The alarm is given as soon as the a posteriori probability reaches level 1—a (the probability that the signal is false or true naturally is equal to 1). The analysis shows that the time of retarding (when the moment of leakage occurrence as a random variable is distributed exponentially) behaves like the logarithm of the average interval between two false alarms. The specified regularity makes it possible to obtain the evaluation of quality of different leak detection systems.

IV. Conclusions

1) It is shown that the quality of distributed systems of ESPO-OTP class is not derived from the quality of its local sections.

2) The boundaries are defined overrunning which can result in the loss of work stability and controllability of ESPO-OTP.

3) The algorithm is suggested which makes it possible to monitor the quality of ESPO-OTP work.

4) The simple criteria of quality evaluation of M&CS systems of ESPO-OTP class.

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