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Mathematical modeling of hydraulic chains as cyber-physical objects

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Abstract. The article attempts to substantiate a new direction of scientific research of pipeline systems (PLS) of the energy sector as cyber-physical objects. The relevance of this direction is determined by the practical formation of new properties of PLSs in the process of their renovation, intellectualization and digitalization, along with the absence of a general theory of classification of the goals pursued, emerging problems and solution methods. It is proposed to base such studies on the theory of hydraulic circuits, the subject of which is the general methods of mathematical modelling, calculation and optimization, applicable in principle for any PLS (heat, water, oil and gas supply, etc.). The concepts of controlled and cybernetic hydraulic circuit are introduced as a new object of study of this theory. The content of new classes of problems of research and modelling of hydraulic circuits as cybernetic is revealed. The characteristics of the available results in the field of methods of analysis and synthesis of PLSs as cyber-physical objects are given. Mathematical models and methods of analysis of the consequences of regime control in conditions of stochastic of external influences and uncertainty of the internal state are presented. A set of indicators for the integral assessment of the controllability of the PLS is proposed, reflecting the main aspects of management: admissibility, reliability and efficiency. Integral indices of PLS identifiability and methods of their calculation are proposed. The interrelation of these indicators, which can be used to develop methods of analysis, synthesis, norms and standards of controllability and identifiability, as the main cybernetic properties of PLS, is disclosed.

Introduction

The modern scientific and technical situation in Russia is characterized by the processes of transition to a new economic order, combined with the transition to a new technological order in the world. This creates unique challenges that present new requirements for technical policy and scientific and methodological support of the tasks of innovative transformation of pipeline energy systems (PLS) heat, water, gas, oil supply, etc., which are playing an ever-increasing role in energy, industry, social sphere and economy most industrialized countries.

The main direction of overcoming these challenges in the country and abroad is associated with the digitalization and intellectualization of the PLS [1]. In technical terms, these trends are manifested in the combination of the unique capabilities of modern equipment, telecommunications and information technologies in real control loops of the PLS. In this case, PLS implicitly acquire the properties of cyber-physical systems [2], when these technical objects are already carriers of information and computational resources that directly affect their functioning.

At the same time, it should be noted that there is no general understanding of the problems arising on the path of such transformation, the pursued goals and the acquired properties of the PLS. At present, both in the country and abroad, it should be noted that there is no scientific and methodological base for intellectualization and digitalization of PLS, suitable for wide practical use.

In this article, an attempt is made to systematize a new problematic (formulated and developed in the ISEM SB RAS of the original scientific direction) – the theory of hydraulic circuits associated with the mathematical modeling of PLS as cyber-physical systems, in order to obtain results that are of general importance for PLS of various types.

1 Intelligent and integrated PLS

The main goal of creating intelligent PLS is to obtain a fundamentally new platform that harmonizes the requirements and capabilities of all parties involved in the processes of obtaining, transporting and consuming the target product (water, gas, heat energy, etc.). In this case, the consumer is assigned the role of an active, equal participant, influencing the volumes of consumption, quality and prices.

Enlarged, the main features of the PLS intelligence are associated with the presence [1]: 1) a single digital space as the main backbone factor responsible for the

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observability of production, distribution and consumption processes for all participants in these processes; 2) a high level of technological controllability of the PLS, as the main way of harmonizing the requirements of consumers and producers; 3) a dynamic pricing system that encourages consumers to change their usual consumption schedules.

The implementation of these tasks presupposes the solution of a large range of regulatory, technical, technological, economic, informational and other issues. This also requires a revision of the established practice of design, operation and dispatch control of the PLS. An analysis of the main problems of this practice and directions for overcoming them is given in [3].

It seems that the intellectualization of the PLS can be associated with a full-scale transition to the concept of compromise adaptive control in the state space with feedback. The concept of compromise management means the need to dynamically reconcile supply and demand between suppliers and consumers, as well as with adjacent systems, through the efficient use of available technical capacities and a flexible pricing (tariff) policy. The state space is understood as the space of mode parameters, the relationship between which satisfies the physical laws of flow distribution, which implies the involvement of appropriate state models. Adaptive feedback control is understood as the ability to adapt the models involved (through their identification) to changes in the internal state of the PLS and external influences based on the observation and measurement of the parameters of the state and manifestations of the external environment.

This concept assumes the presence of the following levels of regime management: 1) technical and economic (regime management, demand management using tariffs); 2) calendar-time (planning modes, operational management); 3) territorial-organizational (levels of the technological hierarchy, interdepartmental and inter-system).

The transition to the concept of such management will create the necessary prerequisites for overcoming the departmental disunity of the technologically related parts of the PLS and related systems. The feasibility of integrating heat, water, gas, and power supply systems for settlements and territories is due to the interconnection of their operating modes, the increase in the degree of freedom of consumers in choosing the type of resource, the volume and time of its consumption, the needs of producers to expand sales markets, and many other factors.

The primary task on the path of such integration is associated with the creation of a single digital space as the basis for coordinating pricing policy and technological management solutions. This space, in turn, presupposes: 1) the creation of unified corporate, interdepartmental, territorial (for example, city) information and measurement systems (IMS); 2) integration of technological and commercial accounting systems; 3) information security of consumers; 4) the use of new high-speed telecommunication technologies for collecting and processing large amounts of information. The creation of a unified IMS will not only allow synchronizing control solutions, but also significantly reduce the cost of these systems themselves.

2 Controlled PLSs as a new object of application of the theory of hydraulic circuits

Theory of hydraulic circuits (THC) [4] is a scientific and technical discipline, the subject of which is general methods for solving problems of calculating and optimizing PLS that arise during their study, design and operation. The term "general methods" means their applicability to pipeline and hydraulic systems of arbitrary configuration and regardless of the specific purpose. Thus, the object of the THC is a hydraulic circuit (HC) as a set of devices and pipelines connecting them (closed or open channels) that transport compressible or incompressible fluids. The feasibility of developing and developing a unified theory for PLS of various types is determined by the generality: 1) their structural and topological properties; 2) physical laws of liquid (gas) flow for individual elements; 3) network conservation laws; 4) meaningful and, mainly, mathematical formulations of calculation problems.

Let us introduce a classification of traditional THC problems based on the following position - the study of any complex system is associated with the study of a chain of cause-and-effect relationships (Fig. 1), and the tasks solved in this case consist in the restoration of individual links of this chain.

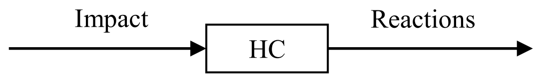

Fig. 1. Links of cause-and-effect relationships.

From these positions, four main classes of THC tasks can be distinguished, which are of general importance for PLS of various types and purposes: analysis, synthesis, control and identification. The differences between these tasks are shown in Table 1, in which the "√" symbol indicates what is specified, and the "?" Symbol indicates what needs to be determined.

Table 1. Relationships between the assigned and sought links of cause-and-effect relationships for various classes of problems

Task classes	Cause-and-effect relationships		
	Impact	System	Reactions
1. Analysis	√	√	**?**
2. Synthesis	√	**?**	√
3. Control	**?**	√	√
4. Identification	√ (?)	**?** (√)	√ (?)

The meaningful formulations of these classes of problems are as follows. The tasks of the analysis are to determine the reaction of a system with known characteristics under given influences. The tasks of synthesis are to calculate the characteristics of a system that would have the desired reactions to the intended influences. The task of control is to find influences that give the desired response of a system with known characteristics. Identification tasks are to determine completely and partially unknown characteristics of the system based on the results of partial measurements, both of influences and reactions.

The current stage of the THC development at the ESI SB RAS, reflected in the works [5 - 9, etc.], has the following main features.

1. Instead of a chain of causal physical and technical links, the contours of these links, closed through information flows, are considered (Fig. 2).

2. The object of research is controlled HC (CHC), which are HC equipped with technical means of control and measurement, as well as cyber-physical HC as a set of CHC and information and control computer systems (Fig. 2).

3. In the context of Fig. 1, in the role of influences on the CHC, the effects of the external environment are considered, and in the role of reactions - a set of indicators of efficiency, reliability, quality of functioning, etc.

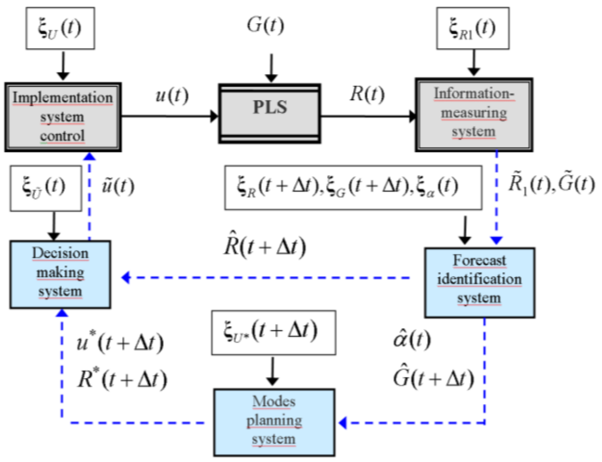

Fig. 2. Cause-and-effect contours for controlled HC.
$R, R^*, \hat R$ – - vector of parameters of the regime, its planned value and assessment; $\tilde R_1$ – - vector of measurements of a certain subset R; $G, \tilde G, \hat G$ – - vector of random influences of the external environment, its measured value and assessment; $u, u^*, \tilde u$ – control vector, its planned and corrected values; $\hat\alpha$ – vector of estimates of the parameters of elements (model coefficients); $\xi_U, \xi_{\tilde U}, \xi_{U^*}$ – errors of implementation, correction and planning of management; $\xi_{R1}, \xi_R, \xi_G, \xi_\alpha$ – errors of measurement, forecasting of the mode, environmental influences and identification of system parameters.

At the level of considering HC as CHC, the following relatively new main tasks arise.

In the field of analysis - a quantitative assessment of the controllability, identifiability, efficiency and other properties of the PLS, taking into account the dynamics and stochastics of external influences, uncertainty factors of the internal state of the PLS, the characteristics of control and monitoring systems.

In the field of synthesis - joint optimization of the structure and parameters of both the PLS themselves and the control and measurement systems.

In the field of management - the development of concepts and methods of management, decision-making systems, tuning and adaptation of control loops.

In the field of identification - tracking modes, parameters, diagnostics of the state of both PLS and measurement and control systems.

3 Modeling HCs as cyber-physical objects

In real conditions, the change in the PLS operating modes in time is a random process, the individual implementations of which are almost never repeated. Actually, the change of modes is carried out under the influence of three main factors: 1) regular influences of the external environment (vector G); 2) targeted management (vector u); 3) sudden changes in the internal state of the PLS of a random nature. Analysis of the influence of (relatively rare) disturbances (equipment failures, accidents, etc.) on the functioning of the PLS of the last type is the subject of the theory of reliability and is not considered here.

The parameters that simultaneously belong to both the model and the external environment will be called boundary conditions. With this in mind, it is possible to decompose the mode parameters $R = \{Y, G\}$. Uncertainty factors are associated not only with the stochastics of the vector G, but also with the approximation of information on the parameters of the PLS elements (vector α), which specify the internal technical state of the PLS.

Accordingly, the equations of controlled flow distribution can be written as $U(Y,G,u,\alpha)=0$ or $Y=\varphi(G,u,\alpha)$, where φ is an implicit vector function that uniquely determines the values of the dependent parameters of the mode Y at the given values of the vectors G, u and α. The introduced functional dependence reflects the deterministic causal relationship of the parameters of the controlled flow distribution.

We will consider vectors G,α as random and obeying the normal distribution law with parameters obtained as a result of solving problems of measurement, forecast or identification. That is $G: N_{mg}(\hat G, C_G)$ and $\alpha: N_{na}(\hat\alpha, C_\alpha)$, where $\hat G = E(G)$ is the mathematical expectation G; $\hat\alpha \approx E(\alpha)$ – vector of parameter estimates α; $C_G = E(\xi_G \xi_G^T)$, $C_\alpha = E(\xi_\alpha \xi_\alpha^T)$ – covariance matrices; $\xi_G = (G - \hat G)$ – vector of random deviations G from its mathematical expectation; $\xi_\alpha = (\alpha - \hat\alpha)$ – vector of estimation errors α; $mg = \dim(G)$; $na = \dim(\alpha)$. Without loss of generality, the identification results α will be considered uncorrelated with the stochasticity of the boundary conditions, and the control vector will be deterministic.

Accordingly, the probabilistic model of the flow distribution can be represented as:

$$U(Y,G,u,\alpha)=0 \Leftrightarrow Y=\varphi(G,u,\alpha)\,, \qquad (1)$$

$$G:\ N_{mg}(\hat{G},C_G)\,,\ \alpha:\ N_{na}(\hat{\alpha},C_\alpha)\,, E[(G-\hat{G})(\alpha-\hat{\alpha})^T]=0 \qquad (2).$$

In many practical cases, the nonlinear distortion of the distribution $\varphi(G,u,\alpha)$ can be neglected, which makes it possible to approximate it with a normal (Gaussian) distribution with acceptable accuracy. Then the problem is reduced to determining the parameters of this distribution: $\hat{Y}=E(Y)$ and $C_Y=E(\xi_Y\xi_Y^T)$, where $\xi_Y=(Y-\hat{Y})$.

Considering u as a known deterministic vector, we will carry out the linearization (1) in the vicinity of the initial data $\{\hat{G},\hat{\alpha}\}$: $Y\approx\varphi(\hat{G},\hat{a})+\frac{\partial\varphi}{\partial G}(G-\hat{G})+\frac{\partial\varphi}{\partial\alpha}(\alpha-\hat{\alpha})$. Applying the mathematical expectation operation to this expression, we obtain

$$\hat{Y}\approx\varphi(\hat{G},\hat{a})\,. \qquad (3)$$

Wherein $\xi_Y\approx\frac{\partial\varphi}{\partial G}\xi_G+\frac{\partial\varphi}{\partial\alpha}\xi_\alpha$. From here

$$C_Y=E(\xi_Y\xi_Y^T)\approx\frac{\partial\varphi}{\partial G}C_G\left(\frac{\partial\varphi}{\partial G}\right)^T+\frac{\partial\varphi}{\partial\alpha}C_\alpha\left(\frac{\partial\varphi}{\partial\alpha}\right)^T,$$

as $E(\xi_G\xi_\alpha^T)=0$.

The matrix C_Y reflects the degree of uncertainty Y. As seen from (4), this matrix is a function of two terms, the last of which reflects the contribution of identifiability.

Thus, the analysis of the consequences of control u is reduced to solving the traditional problem of flow distribution (3) according to the initial data $\{\hat{G},\hat{a}\}$ in combination with an additional procedure (4) for calculating the covariance matrix C_Y from given matrices C_G, C_α, and matrices of derivatives $\partial\varphi/\partial G$, $\partial\varphi/\partial\alpha$ calculated at a point $\{\hat{G},\hat{a}\}$.

Examples of the vectors, functions and derivatives introduced in relation to the models of the steady-state hydraulic regime are given in [10]. The issues of obtaining relations for covariance matrices in relation to other types of flow distribution models (with lumped, variable and distributed parameters) are given in [11].

4 Analysis and synthesis of the cybernetic properties of the CHC

The most important properties of PLS as cyber-physical objects are their controllability and identifiability. Analysis shows the need to consider such properties as complex. This follows from the multi-purpose nature of real control (ensuring admissibility, reliability, efficiency of modes, etc.) and identification (structural identification, identification of equipment parameters, identification of modes, technical diagnostics, etc.). Let us give a brief summary of the main results obtained in this area.

4.1 Controllability

A system of primary probabilistic indicators is proposed for an integral quantitative assessment of the controllability of the PLS [12], including indicators:

1) the probability of belonging to the admissible region

$$p[\underline{Y}\le Y(u)\le\overline{Y}]=p[\underline{Y}\le\varphi(u,G,\alpha)\le\underline{Y}]=\int_{\underline{Y}}^{\overline{Y}}f(Y)dY$$

where p is the probability; $\underline{Y}$, $\overline{Y}$ – the boundaries of the admissible area of the random vector Y, $f(Y)$ – its probability distribution density function;

2) the probability of violation of the admissible region

$$p_i^+(u)=p_i(Y_i(u)\le\underline{Y}_i)=\int_{-\infty}^{\underline{Y}_i}f(Y,u)dY_i\,,$$

$$p_i^-(u)=p_i(Y_i(u)\ge\overline{Y}_i)=\int_{\overline{Y}_i}^{\infty}f(Y,u)dY_i\,,$$

where p_i^+, p_i^- are the probabilities of violation of the upper and lower boundaries of a single mode parameter Y_i;

3) energy efficiency

$$\eta_M=(N_C+N_\Pi^*+\Delta N_\Pi)/N_B$$

where N_B is the flow power supplied from outside the PLS; N_C – power losses in pipeline networks; N_Π^* – useful power used by consumers; ΔN_Π – excess capacity in consumption nodes.

Accordingly, the following complex of integral indicators of PLS controllability was proposed:

1) the maximum probability of belonging to the admissible area

$$p_Д^*=\max_u p(\underline{Y}\le Y(u)\le\overline{Y})\,; \qquad (5)$$

2) minimum probability of violation of the admissible region

$$p_H^*=\min_u\left(\max_i\left(\max\left(p_i^+(u),p_i^-(u)\right)\right),\ i=\overline{1,ny}\right), \qquad (6)$$

3) the maximum mathematical expectation of the useful use of the input flow power

$$\hat{\eta}^*=\max_u\ \eta(Y(u),G)\,. \qquad (7)$$

The obtained indicators (5) - (7) can be used as the basis for the analysis of potential effects from the introduction of various components of intellectualization of the PLS, as well as the development of controllability standards.

4.2 Identifiability

In [11], a method was proposed for a differentiated quantitative analysis of identifiability, based on the use of analytical expressions for the covariance matrices (CM) of an arbitrary subset of the PLS parameters. Let us denote $X=\{X_R,\alpha\}$. That is, we will assume that X it always includes the vector of the parameters of the elements α, and X_R is the vector of independent parameters of the mode. Wherein

$$Y = Y(X) = Y(X_R, \alpha). \qquad (8)$$

Comparison of (1) and (8) shows that a vector G can play the role X_R. However, in the context under consideration, this is not essential. In the case of using the measurement results for the N modes, we will assume that

$$X = \{X_R^{(1)}, X_R^{(2)}, \ldots, X_R^{(N)}, \alpha\}, \quad Y = \{Y^{(1)}, Y^{(2)}, \ldots, Y^{(N)}\}.$$

Then [11] $C_X = (J^T C_{Z1}^{-1} J)^{-1}$ – CM of estimation errors X, C_{Z1} – known CM of measurement errors of the vector of measured parameters of the mode Z_1, $J = \partial Z_1 / \partial X = I_{Z1} \begin{pmatrix} E \\ \partial Y / \partial X \end{pmatrix}$ – matrix of partial derivatives of measured parameters of the model as a function of independent ones, E – unit matrix, I_{Z1} – matrix of correspondence of components of vector Z_1 and model parameters, consisting of zeros and ones. The covariance matrix of the dependent variables of the model is defined as $C_Y = (\partial Y / \partial X) C_X (\partial Y / \partial X)^T$. Thus, C_Y it is fully defined if given C_X, and C_X – if matrices I_{Z1}, C_{Z1} and Y'_X are given. Accordingly, the accuracy of the estimates of the model parameters (and, consequently, the identifiability) is determined by three factors - the composition of measurements, their accuracy and sensitivity X to Z_1.

Let us call the matrix $F_X = J^T C_{Z1}^{-1} J$ the informational matrix of the experiment, since it contains all the information extracted from this experiment and necessary to estimate the residual degree of uncertainty about the desired parameters, regardless of the goals of the experiment. Then $C_X = F_X^{-1}$ is the covariance matrix of the experiment. Taking into account the introduced decomposition $X = \{X_R, \alpha\}$, these matrices have the structure

$$F_X = J^T C_{Z1}^{-1} J = \begin{bmatrix} J_R^T C_{R1}^{-1} J_R & J_R^T C_{R1}^{-1} J_\alpha \\ J_\alpha^T C_{R1}^{-1} J_R & J_\alpha^T C_{R1}^{-1} J_\alpha + I_{\alpha 1}^T C_{\alpha 1}^{-1} I_{\alpha 1} \end{bmatrix}, \qquad (9)$$

$$C_X = F_X^{-1} = \begin{bmatrix} C_{XR} & C_{XR\alpha} \\ C_{XR\alpha}^T & C_\alpha \end{bmatrix}. \qquad (10)$$

where the following designations are used: $J_R = \partial R_1 / \partial X_R$; $J_\alpha = \partial R_1 / \partial \alpha$; $I_{\alpha 1}$ – a matrix, similar in meaning I_{Z1}, but with respect to the given pseudo-measurements α_1; vectors of measurements of the parameters of the regime R_1 and α_1 are assumed to be uncorrelated. Wherein

$$J = \begin{bmatrix} J_R & J_\alpha \\ 0 & I_{\alpha 1} \end{bmatrix}, \; C_{Z1} = \begin{bmatrix} C_{R1} & 0 \\ 0 & C_{\alpha 1} \end{bmatrix}, \; I_{Z1} = \begin{bmatrix} I_{R1} & 0 \\ 0 & I_{\alpha 1} \end{bmatrix}.$$

Applying to the block matrix inversion rule [14], we obtain the final expressions for the CM of independent parameters of the mode $C_{XR} = F_{XR}^{-1}$ and CM of the parameters of the elements $C_\alpha = F_\alpha^{-1}$, where

$$F_{XR} = J_R^T H_\alpha J_R, \qquad (11)$$

$$F_\alpha = J_\alpha^T H_{R1} J_\alpha + I_{\alpha 1}^T C_{\alpha 1}^{-1} I_{\alpha 1}, \qquad (12)$$

and

$$H_\alpha = C_{R1}^{-1} - C_{R1}^{-1} J_\alpha (J_\alpha^T C_{R1}^{-1} J_\alpha + I_\alpha^T C_{\alpha 1}^{-1} I_\alpha)^{-1} J_\alpha^T C_{R1}^{-1}, \quad (13)$$

$$H_{R1} = C_{R1}^{-1} - C_{R1}^{-1} J_R (J_R^T C_{R1}^{-1} J_R)^{-1} J_R^T C_{R1}^{-1}. \qquad (14)$$

Accordingly, we will call: F_{XR} – the observability matrix, F_α – the identifiability matrix.

Note that if the vector is known and is given deterministically, then $\alpha_1 = \alpha$, $C_{\alpha 1} = 0$, $H_\alpha = C_{R1}^{-1}$ and the observability matrix takes the traditional form

$$F_{XR} = J_R^T C_{R1}^{-1} J_R. \qquad (15)$$

Therefore, (11) gives the relation for the observability matrix, taking into account the uncertainty in the values of the vector α taken into account, through H_α.

Relation (12) reveals the contribution to the resulting identifiability of a priori information about the degree of uncertainty of the parameters α (the second term on the right-hand side), taking into account the uncertainty about the parameters of the modes, taken into account through the matrix H_{R1}.

An important consequence of the introduced concepts and relationships is that:

1) if the system is identifiable, then it is observable, but not vice versa, therefore observability is a particular property of identifiability;

2) the obtained expressions for the CM, allow performing a differentiated analysis of the accuracy of any parameter of the model or their combination, including by constructing confidence intervals or areas that cover the true values with a given probability;

3) such analysis can be performed depending on the goals of the experiment (observation or parametric identification);

4) this technique can be used for both a posteriori and a priori differentiated quantitative analysis of identifiability. The only difference is that the derivatives $\partial Y / \partial X$ are taken either at the solution point of the estimation problem, or at the point of some assumed values of the vector X.

Differentiated analysis does not allow one to unambiguously compare different variants of experimental conditions, since each variant can be better than the other in its group of estimated parameters. For such a comparison, as well as for the purposeful impact on these conditions (synthesis of identifiability), it is proposed to use integral quantitative indicators of the identifiability of PLS as a whole [10, 15, 16]. It is shown that it is advisable to use the *D*-criterion (determinant of the covariance matrix of identifiable parameters) in the role of the basic identifiability indicator, which has the following important properties:

1) a decrease in the degree of uncertainty of the identified parameters of the PLS can be associated with the requirement to reduce the volume of the confidence ellipsoid, which is equivalent to the requirement to minimize the *D*-criterion;

2) as is known from the theory of planning experiments, the optimal value of the *D*-criterion corresponds to the minimum of the maximum variance of the response (dependent variables of the model);

3) it is also possible to interpret this criterion from the standpoint of information theory according to Shannon [10], since the entropy minimum coincides with the D-criterion minimum.

Thus, for the integral assessment of the observability and parametric identifiability of the PLS, it is proposed to use the indicators:

$$D_{XR} = \det(C_{XR}), \quad D_\alpha = \det(C_\alpha). \qquad (16)$$

The lower the values of these indicators, the lower the uncertainty in the corresponding groups of model parameters and, accordingly, the higher the degree of observability and parametric identifiability of the PLS. These indicators already make it possible to comprehensively compare the variants of experimental conditions, but their numerical values depend on the dimension of the variables and do not allow them to be given a physical meaning.

As an auxiliary indicator, it is proposed to use the criterion of relative prediction variance

$$d = \max_{i \in I_2} \left(\frac{\hat{\sigma}_i^2}{\sigma_i^2} \right), \qquad (17)$$

where I_2 is the set of unmeasured parameters of the mode, σ_i^2 is the a priori dispersion of the direct measurement of this parameter, determined from the metrological characteristics of the corresponding measuring device, $\hat{\sigma}_i^2$ is the posterior (predicted) dispersion of this parameter by the model.

A posteriori estimate of the covariance matrix of unmeasured parameters is defined as $C_{Z2} = J_{Z2} C_X J_{Z2}^T$, where $J_{Z2} = \partial Z_2 / \partial X = I_{Z2} \begin{pmatrix} E \\ Y'_X \end{pmatrix}$, I_{Z2} – is the matrix of correspondence of the components of vectors Z_2 and Z, consisting of zeros and ones. From here

$$\sigma_i^2 = (J_{Z2})_i C_X (J_{Z2})_i^T, \ i \in I_2, \qquad (18)$$

where $(J_{Z2})_i$ is the *i*-th row of the matrix J_{Z2}.

Thus, criterion (17) already makes sense of the relative accuracy of estimation of unmeasured parameters in comparison with their direct measurement. If d ? 1, the identifiability is bad, and at $d \approx 1$ – high.

In [10, 13 and others], the relationship between criteria *D* and *d* is disclosed. For the simplest case of analyzing observability (with deterministically given parameters of elements α and a diagonal matrix $C_{R1} = diag\{\sigma_1^2, \sigma_2^2, ..., \sigma_l^2\}$, where $l = |I_1|$, I_1 – is the set of measured parameters of the regime), this relationship has the form

$$D_{XR}(l+1) = D_{XR}(l) / \left(1 + d_{l+1}\right), \qquad (19)$$

where $D_{XR}(l), D_{XR}(l+1)$ – are the determinants of the CM of the mode parameters with the initial composition of l measurements and with the addition of some measurement with the index $l+1$, $d_{l+1} = \hat{\sigma}_{l+1}^2 / \sigma_{l+1}^2$. It can be seen that when adding of measurement some mode parameters, the indicator D_{XR} decreases in inverse proportion to the value $1 + d_{l+1}$.

On these principles, algorithms for arranging measurements [15, 17, etc.] have been developed, which provide the possibility of consistent improvement of the composition of measurements by the *D*-criterion, focusing on the current values of the *d*-criterion. The corresponding algorithms make it possible to find the optimal solution (with minimizing the number of measurements taking into account the limitations on the identification accuracy or maximizing the accuracy with the limitation on the number of measurements) in a finite number of steps, taking into account the permissible locations for new measuring devices and the presence of existing ones.

Conclusion

Against the background of a brief description of the goals and the unfolding processes of intellectualization and digitalization of PLS, the problem of quantitative assessment of synergistic (systemic) effects from the joint application of various components of intellectualization is revealed.

Due to the generality of the problems arising here for PLS of various types and purposes, the expediency of their study on the basis of THC is substantiated, new tasks of this theory are formulated, including the tasks of a comprehensive assessment of indicators of intelligence of PLS from the point of view of their satisfaction with the main cybernetic properties - controllability and identifiability.

The problem of assessing the consequences of regime control in the conditions of stochastics of external influences and uncertainty of the internal state of the PLS is considered. A constructive probabilistic approach for such an assessment is proposed. The direct dependence of the degree of uncertainty of control results on the degree of identifiability of the PLS is shown.

The problem of integral quantitative assessment of controllability associated with the multi-criteria control of modes in conditions of information uncertainty has been investigated. For such an assessment, three indicators are proposed that reflect the main aspects of management: acceptability, reliability and efficiency.

The relationship between the parametric identifiability and observability of the PLS is revealed. It is shown that observability is a particular property of identifiability under conditions of uncertainty of the actual characteristics of the PLS.

Integral quantitative indices of PLS identifiability and methods of their calculation are proposed. Including the *D*-test, which can be attributed to the interpretation of the amount of information according to Shannon and the *d*-test, which reflects the predictive properties of the models obtained as a result of identification. For the classic case of observability analysis, the relationship between these criteria is disclosed.

The proposed criteria can potentially be used to develop norms and standards for controllability and identifiability as the main cybernetic indicators of the intelligence of the PLS.

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