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Real-time condition monitoring of machinery malfunctions

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Abstract

The features of Real-time condition monitoring of machinery and its differences from On-line and Off-line condition monitoring are considered. Taking into account human factor, the model of monitoring system was reviewed. This model shows that observability of units' state and equipment production complex (PC) in whole can be provided by measurement of diagnostic signals (vibroparameters) and rate of their change, which show accurate within scale, generalized units errors and rates of their growth, residual life and rate of its loss, and also safety of the whole complex. Determinate partial ageing functions and their rates defined by generalized errors, structural parameters and rates of their growth are offered to use as variables of unit's state. Regularities of petrochemical complex units operation lied in sporadic character of control acts which are the base of monitoring system generalized model, taking into account «human factor» are identified. Technical state of production complex and correspondingly the risk of its operability loss are offered to evaluate in accordance with minimum residual operability and maximum rate of its loss, observed by diagnostic and monitoring systems among the group of units composing the complex. Required operation speed of diagnostic and monitoring systems (DMS) is offered to estimate in accordance with observability criteria of maximum rate of petrochemical complex residual operability loss. Conclusions of monitoring theory: Monitoring allows to transfer failures of equipment and production complexes from the category «sudden» into the category «gradual»; Necessity of failures reduction by ten times and corresponding increase of equipment run-to-failure requires decrease of monitoring mistakes to minimum (zero); Decrease of statical error and reduction of implementation period up to some months requires development of etalonless diagnostic methods and standard techniques of invariant to equipment type diagnostic features formation; Decrease of dynamic error requires significant excess of monitoring pace over pace of failures development at production complexes, this exclude manual labor by means of automation of all monitoring processes: from parameters measurement and automation of diagnostic output of information about equipment state up to its unhampered and timely delivery and presentation in all levels of production complex control.

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Keywords: real-time condition monitoring; etalonless diagnostic methods; statical error, dynamic error; observability of technical state; petrochemical complex; diagnostic and monitoring systems

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1. Introduction

Monitoring of unit technical state – the observation of its operability change with the purpose of personnel warning about the limiting state obtaining – allows to transfer the majority of failures from the category «sudden» to the category «gradual» due to their early detection and timely warning of personnel. Real-time monitoring has a number of significant differences from on line/off line monitoring the meaning of which is a strict regulation of monitoring interval (Table 1) on the level of 10-20% interval of the most quick development of production complexes (PC) equipment failures. It's possible based on automatic systems with functionally undefined structure which doesn't depend on equipment construction for the wide range of PC's units and includes multilevel expert system. These allow to implement diagnostic and monitoring systems (DMS) in conditions of prior uncertainty when types of bearings, number of impeller blades, etc. are unknown, and to minimize static, dynamic mistakes and risk of the equipment failure passing. The principle of information completeness (π-principle) during the choice of state diagnostic features in conditions of prior uncertainty is formulated. According to this principle features should arrange a complete group in statistical sense including both all known and supplemented features in the selected base of signals. This allows to decrease significantly a probability of defects passing, diagnostic features of which in this base are unknown. The most common and broadband signal base is vibration that's why obtained conclusions will be correct for other signal bases (current, temperature, etc.).

2. Methods

Technical state of the unit S_1 depending on its operation mode S_0 and level of gathered errors of production repair and operation S based on N.G. Bruevich's works we present as follows:

$$S_1 = S_0 + S\,(t) = S(n_0, p_0) + \sum_{j=1}^{m} \frac{\partial S}{\partial q_j} \Delta q_j\,(t)\ , \tag{1}$$

where S_0 = S (n_0, p_0) is a component which characterizes mechanism with minimum, near zero, generalized technological and operational errors, and operates in the range of nominal speed (n_0) and loading (p_0) modes; $\Delta q_j = X_j$ is j-error of mechanism that was laid during manufacturing (t=0), developing and defining wear process, or in general case, the level of mechanism degradation and level of its ageing; $\partial S / \partial q_j$ is sensitivity of generalized error S to j-error of the mechanism according to corresponding generalized coordinate q_j. Here and after, for simplification of writing the argument (t) is given for denoting significant in this case dependence of parameter against time on the reviewed interval.

The generalized mathematic model of the monitoring system based on equation of state variables we present in the following way:

$$\{\dot{S}(t)\} = [A]\{S(t)\} + [B]\{U\}$$

$$\{Y(t)\} = [C]\{S(t)\} + [D]\{U\}, \tag{2}$$

where {S(t)} is a vector of unit ageing functions of m dimensionality, in which every component characterizes its generalized (common) structural parameter a subject to estimation and describing residual partial resource of unit according to this generalized parameter, has in time multimodal character by virtue of partial errors summing (1); { $\dot{S}(t)$ } is a vector of ageing speed (wear, reduction of trouble-free operation, safety, residual resource) also having multimodal character; {U} is a vector of dimensionality control variables (p+k) includes varying tasks of unit's operation mode {U_p(t)} and factors of personnel influence during the control and maintenance of object {U_k(t)}; {Y(t)} is a vector of dimensionality diagnostics signals n ≥ m measured by monitoring system. Matrixes [A], [B], [C], [D] represent correspondently square matrix of the system [A] = [a_{ij}]; rectangular matrix of control [B] = [b_{ij}] determining the influence of personnel actions to the unit state; observation matrix (matrix of output) [C] = [c_{ij}]

determining observability of internal state; transfer matrix [D] = [d_{ij}] determining influence of operating and maintenance personnel to unit vibration parameters. Elements of matrix [A] are random processes which values are determined according to the mathematical expression during each moment of time (11). Elements of matrix [B], [C], [D] are coefficients of corresponding regression equations. Monitoring system (2) is quite manageable as production complex and observable on conditions that matrix ranks [A] with [C] are concurred, and zero columns in the last one are absent. Dimensionality of vector {S(t)} (matrix [A]), which determines a level of real observability of unit state, is recommended to use based on reasons and statistics of each type units failures. Components {S(t)}, as a rule, are inaccessible for direct observation and estimated according to indirect measurements. Management vector {U} changes sporadically during start-stop and maintenance of unit. Between these moments {U} = const. full indirect observability of petrochemical units state during monitoring is reached by measurement of diagnostic signals and rates of their change in time by virtue of their independence; limiting state of unit {S_{NDP}} and dangerous speed of its degradation {S_{NDP}} accurate within scale coincide with critical values of diagnostic features and rates of their change; increment of diagnostic signals (vibroparameters) is proportional to increment of wear, loss of safety and decrease of residual resource of petrochemical complex's unit in whole:

$$\{\Delta Y\} = [C]\{\Delta S\},\ \{\dot{Y}(t)\} = [C]\{\dot{S}(t)\},\ \{Y_{NDP}\} = [C]\{S\},\ \{\dot{Y}_{NDP}\} = [C]\{\dot{S}_{NDP}\}, \quad (3)$$

Each **i**-generalized error expresses partial function of unit ageing. Its changes in time (trend) represent the sum of trends of including structural parameters $X_j(t)$, and, in common has multimodal character. Rate of diagnostic features changes, vibroparameters, is unambiguously determined by weighted sum of correspondent unit errors change rates. Increment of vibroparameters vector $\{\Delta Y_n\}$ is in direct proportion to increment of object's ageing vector (generalized errors – structural parameters) $\{\Delta \dot{S}_m\}$, and increment of initial diagnosed errors of unit's mechanisms $\{\Delta X_k\}$.

The primary goal of diagnostic and monitoring systems is synthesis of orthogonal diagnostic features {Y_i}, correspondingly representing formulated orthogonal classes of failures {S_i}. It corresponds to reduction of observation matrix [C] to diagonal square matrix defining one-one (regressive) relation between diagnostic feature and corresponding generalized error. So, the problem of condition monitoring consists of correct interpretation formation of this generalized error taking into account rate of failures classes' appearance. For example, growth of petrochemical centrifugal pump case vibrovelocity which pumping gasoline corresponds to growth of generalized error «misalignment - disbalance». At the same time in 85% cases misalignment, and only in 10-15% - disbalance is observed. 5 % of vibrovelocity growth has other reasons. Presence of such interpretation «reason - consequence» (errors – vibration) is equivalent to reduction of observation matrix to diagonal square form and corresponds to condition monitoring. Lack of such interpretation corresponds to parameter monitoring (vibration, temperature, etc.). Often failures of units (destruction of friction surface, weakening of fastening, etc.) are immeasurable strong scales (rations of intervals). In these cases values of measured diagnostic features (vibroparameters) are used to measure such failures according to (3).

It's rational to determine technical state of unit according to partial component of its vector of state {S(t)} which has the maximum value $S_{max}(t)$ among all diagnosed parameters of this unit.

Danger of unit technical state is due to partial component $S_{max}(t)$ which is the maximal one among all wear rates of diagnosed unit.

Technical state of units set in production complex corresponds to partial component of its vector of state which has the maximum value among all diagnosed parameters of all units in production complex.

Danger of production complex state is the partial component $S_{max}(t)$ which is the maximal one among all wear rates of all units in production complex.

Similar formulations are correct also for space of diagnostic features in accordance with generalized mathematical model (2), (3). Technical state of unit and production complex in whole is determined by partial component of diagnostic features vector $Y_{max}(t)$ which is observed by DMS among unit components and whole petrochemical complex accordingly.

Danger of unit and whole production complex state is defined by maximal partial component of vibroparameters trend growth rate $\dot{Y}_{max}(t)$ which is observed by DMS among all rates of unit components and whole petrochemical complex accordingly. Necessary operating speed of DMS is determined by maximum speed of operability loss and minimum reserve of diagnosed unit limiting state:

$$F = \frac{1}{T} = Max\left(B\frac{\dot{S}_{NDP}}{S_{NDP}} \right) = Max\left(B\frac{\dot{Y}_{NDP}}{Y_{NDP}} \right). \tag{4}$$

Parameter B in (4) characterizes the quality of estimation algorithm of measured diagnostic features growth rate. The offered models and definitions are the base of diagnostic means and DMS with functionally undefined structure, the novelty of which is confirmed by patents for invention.

Taking into account human factor which determines exponential form of connection between diagnostic features, structural parameters and residual life, the dynamic model of unit state and vibration on the lifetime interval is developed:

$$\{\dot{Y}\} = [a]e^{[a]T}\{Y_0\};$$

$$\{\dot{S}\} = [C]^{-1}[a]e^{[a]T}\{Y_0\}. \tag{5}$$

The equation (5) completely defines dynamics of petrochemical complex units' state by dynamics of diagnostic features of vibration, temperature, etc. and speeds of their change (Figure 1). The offered models allow to consider different factors, influencing on unit vibroloading, its operability and residual life. Human factor becomes evident in unit's operating mode irregularity (hydroblow, cavitation, warps, etc.) and rules of its operation (lining of impure oil, lack of cooling water, etc.), that causes fast rends and sudden surges of vibration, temperature, current and accomplished by raid loss of unit's operability. Generalized dynamic model of technical state in practically important case of square matrix of diagonal errors transformation is determined by equation:

$$\Delta S_i = \frac{\partial S_i}{\partial q_i} \cdot \Delta X_i(t), \quad \dot{S}_i = \frac{\partial S_i}{\partial q_i} \cdot \dot{X}_i(t). \tag{6}$$

In practically important cases of orthogonal features the generalized dynamic model of vibrosignal looks like:

$$\Delta Y_i = C_{ii} \cdot \Delta S_i(t), \quad \dot{Y}_i = C_{ii} \cdot \dot{S}_i(t), \tag{7}$$

and in case of square diagonal matrix of errors transformation:

$$\Delta Y_i = C_{ii} \cdot \frac{\partial S_i}{\partial q_i} \cdot \Delta X_i, \quad \dot{Y}_i = C_{ii} \cdot \frac{\partial S_i}{\partial q_i} \cdot \dot{X}_i, \tag{8}$$

The technique of dynamic diagnostics and prediction of dangerous degradation of units' state in petrochemical complex according to phase trajectory of life cycle which allows to use equipment resource in full with keeping of its safety and maintainability is developed.

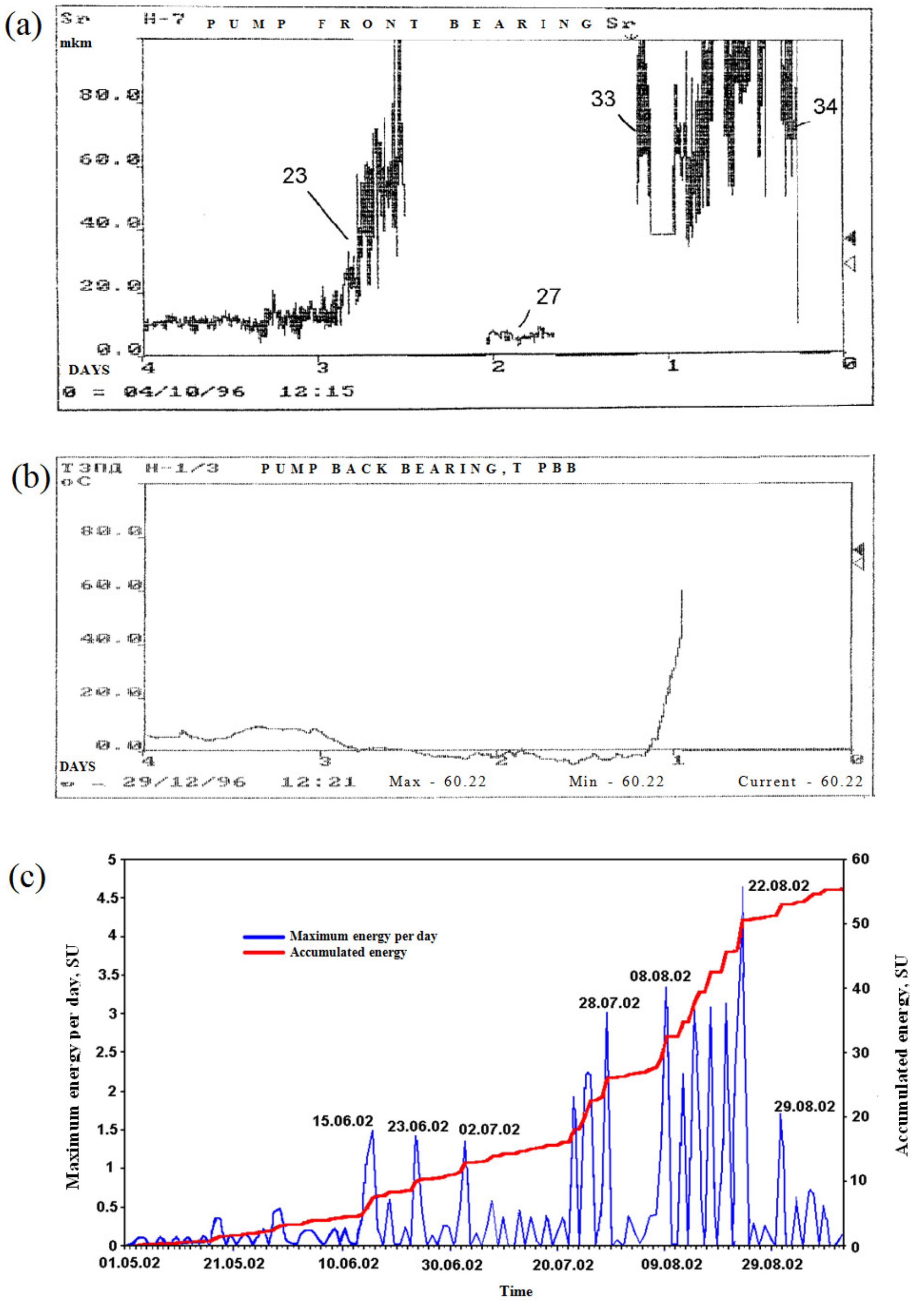

Fig.1. Exponential trends of diagnostic features: (a) vibrodisplacement in case of pump NK210 fastening weakening; (b) temperature of electric motor BAO500L-2 plain bearing; (c) energy of acoustic-emissive impulses during reactor's destruction

For a scalar case we'll get the estimation of growth rate parameter a(t) and interval of prognosis T(t):

$$a(t) = \frac{1}{(1-n)\tau}\left[-\frac{\Delta_n^1 Y(t)}{Y(t)} \times \frac{(n-1)\tau}{(n-1)\tau}\right] = \frac{V_Y(t)}{Y(t)}\ , T(t) = \frac{Y(t)}{V_Y(t)} \ln \frac{Y_{NDP}}{Y(t)} \qquad (10)$$

where τ is interval of delay (interval of trend's readout); Y_{NDP} is critical value of parameter corresponding to unit's limiting state «INTOLERABLE»; $\Delta_n^1 Y(t) = Y(t) - Y(t - n\,\tau)$ is finite difference of the 1-st order of n-delay – increment of Y parameter during nτ-delay; V_Y is growth rate of vibroparameters.

3. Results and discussion

Real-time continuous measurement of the new independent diagnostic feature – growth rate of the trend – almost in two times increased interval of time during which personnel of petrochemical complex can prevent failure, manufacturing defect and restore a safe state of object without violation of technological process normal functioning. Maximum interval of prediction exceeds almost in 10 times interval of observation with prediction mistakes less than 15%. Such comprehensiveness of prediction became possible due to the effective mathematical model. Practical realization of mentioned theoretical approaches in complex monitoring systems COMPACS® which use different methods of diagnostics – viabroacoustic, acoustic-emissive, thermal, electric, etc., provided their wide implementation. More than 500 systems were implemented for the last 20 years almost in open air at the enterprises of such large companies as PLC «Gazprom», PLC «Lukoil», PLC «Rosneft», PLC «TNK-British Petroleum», Russian Railways etc. and also abroad; on domestic and import equipment of more than 1000 types; in different geographical and climatic zones.

Table 1. Characteristics of Real-time monitoring

MONITORING			
Function	ON LINE	REAL TIME	OFF LINE
1. Preparation of object and equipment	Measurement with minimum interval	Execution of all procedures 1-7 with regulated general interval which is not exceeds 10-20% of the shortest interval of failures development.	Execution of procedures 1-4 as required. Interval of time is not regulated. Procedures 1-4 is poorly observable!
2. Measurement of informative parameters and alarming			
3. Formulation and documentation of diagnosis	Interval of time for procedures 3-7 is not regulated. Procedures 3-7 are not observable!	Necessity of automation of all procedures 1-7 for providing of minimum static –s, dynamic –d errors and risk of equipment failure passing – r=s+d	
4. Preparation of diagnostic directions			
5. Delivery of directions to personnel for corrective actions			Interval of time for procedures 5-7 is not regulated. Procedures 5-7 poorly observable!
6. Performing of corrective actions for restoration of object's operability		Total period of real-time condition monitoring Exactly fixed:	
7. Management control of personnel actions and their correction in case of need			
	Tn=T1+T2+T3+T4	Trt=To<<Tcr	T3+T4=? Tf=?

Tn=?

Real time monitoring in common case is possible in the presence of (Table 1):

1. Automatic measurement system with short time of measurement;
2. Automatic expert system executing analysis and interpretation of measured data in terms of equipment, its units and components technical state, documentation and presentation of diagnostic direction to personnel which control equipment during limited period of time;
3. Automatic diagnostic system executing unhampered delivery of directions and results of monitoring of personnel operation actions with equipment to management of all levels in real-time.
4. Necessity of all these steps is defined by requirements of subjective human factor exception and short total time interval of all these steps executions – for petrochemical complexes – no more than 10-15 minutes.

4. Conclusions

1. The determined partial functions of unit's ageing and their rates defined by generalized errors, structural parameters and rates of their growth, are offered for use as variables of unit's condition.
2. Technical condition of production complex and correspondingly the risk of its operability loss are offered to evaluate in accordance with minimum residual operability and maximum rate of its loss, observed by diagnostic and monitoring systems among the group of units composing the complex.
3. The necessary operating speed of diagnostic and monitoring system is offered to estimate according to the observability criteria of maximum speed of residual operability loss in petrochemical complex.
4. Real-time monitoring allows transferring failures of equipment and production complexes from the category «sudden» to the category «gradual».
5. The necessity of failures reduction by dozens of times and corresponding increase of equipment run-to-failure requires decrease of monitoring mistakes up to the minimum percent and less (zero-monitoring).
6. Decrease of static error and reduction of terms for Real-time monitoring systems implementation up to several months requires development of etalonless diagnostic methods and standard techniques of invariant to equipment type diagnostic features formation.
7. Decrease of dynamic error requires significant excess of monitoring rate, i.e. not only measurements but also diagnosis and its realization, over rates of failure development in production complexes.
8. Safe-Money-Saving maintenance™ (SMS-maintenance™) of equipment requires Decrease of summary error, involving human factor, and deletion of the human factor by automation of all monitoring techniques from measurement of parameters and automation of diagnostic output of information about equipment condition up to its unhampered, timely delivery and presentation in all levels of management of dangerous plant.
9. It achieves only Real-time Condition Monitoring, which has fixing time interval of whole diagnostic process from measurement of equipment's parameters till realization of diagnostic directions in difference from On-line and Off-line Monitoring.

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