

Evaluation of Probability Errors in Condition Monitoring of Heat-Exchange Equipment

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Abstract. This paper focuses on problems of selecting and defining boundary values for criteria in condition assessment of diesel hydrotreating process units' heat-exchange equipment. The objective of this paper is to define critical parameters of heat exchangers operation. Substantiation of the selected condition assessment criterion is presented. The value of the proposed criterion was calculated using statistical data relevant to the condition assessment of heat-exchange equipment and probabilistic-statistical methods of decision making.

1. Introduction

Control and monitoring of the technical condition of refinery process equipment is the fundamental basis of manufacturing execution systems (MES) implementation process, and based thereon, the strategy of integrating production with manpower management, financial management, and asset management activities (ERP).

Technical condition monitoring of machinery and equipment is mostly carried out using vibration parameters, temperature of assemblies, and consumed power. When vibration is measured, root mean square values [1, 2, 3] of vibration acceleration, speed, and displacement, as well as the rate of change thereof are generally used; occasionally, excess of probability density of momentary values of vibration acceleration is used to assess the condition of rolling bearings [1, 2]. It can be also noted that parameters of probability density of momentary values of vibration signals [4] are used to monitor bearing condition, and envelope curve of vibration acceleration is used to determine the type of bearing defects and malfunctions [1, 2].

Reciprocating machines and in particular refinery compressors are monitored using root mean square values of vibration parameters [5, 6], peak values of the vibration signal [5, 6, 7, 8], by analyzing vibration parameters in accordance with the compressor operation cyclogram [6, 7]. More sophisticated methods of vibration parameter analysis are also used to assess the technical condition of reciprocating machines, for example, based on the method of signal principal component analysis [9, 10, 11], as well as cross-regression functions, multidimensional spectral and statistical characteristics [12, 13]. The accumulated experience of development, implementation, and use of systems for the monitoring of dynamic mechanical process equipment ensures sufficiently reliable, timely, and adequate real-time condition monitoring of such equipment [14, 15, 16].

The most difficult to solve is the problem of real-time monitoring of static mechanical process equipment, which includes process pipelines, pressure columns and vessels, heat exchangers and heaters of refineries. Known systems for the monitoring of columns, vessels, and pipelines are based



on such technical condition parameters as acoustic emission and temperature with the use of process variables to monitor operating mode of an item of a process unit [17, 18, 19].

The problem of the operation of heat-exchange equipment mostly consists in necessity and possibility of preventing losses related to its operation resulting from degradation of heat exchange process conditions caused by deterioration of the technical condition of such equipment. For example, a light naphtha isomerization unit with a feed preparation (hydrotreating) section had three unscheduled shutdowns in a year. Such shutdowns were caused by pressure drops at the inlet and the outlet of the heat exchange train. The pressure drops resulted from increased shell side fouling in one of the shells of a heat exchanger of the hydrotreating section. Resulting refinery losses exceeded 600 million rubles year, because each shutdown lasted at least a week, and each downtime day was evaluated at 30 million rubles. A similar situation has also been developing at naphtha hydrotreaters and diesel hydrotreaters.

In any case, financial losses are a combination of increased utility consumption caused by a decrease in heat exchanger performance and losses incurred in the event of a complete shutdown of heat-exchange equipment when critical operating conditions are reached.

The use of special procedures for integrity evaluation or heat exchanger diagnostic software would make it possible to prevent similar situations. Recommendations available in technical publications and regulatory documents, which make it possible to evaluate values of thermal resistance of several foulant types, are often contradictory, insufficiently substantiated, and incorrect. In particular, deposit diagnostic procedures for refrigeration equipment using water as a coolant focus on hardness salts with known thermodynamic characteristics [20]. The applicability of equations used to calculate thickness of deposits in recuperative heat exchangers of CDU/VDU processes given in procedure is also limited. The analysis of existing software and procedures showed that existing tools are not applicable to heat exchangers of the oil product hydrotreating process, and it is therefore necessary to develop a diagnostic technique for heat-exchange equipment of the hydrotreating process based on process conditions.

2. Problem Statement

In order to determine the operating efficiency of DHT heat-exchange equipment, a diagnostic technique was developed, which functions by comparing the difference between the hot side temperatures of a vessel at the current time point and at the time point when the heat transfer surface was clean. Temperature data are acquired using the refinery real-time monitoring system allowing access both to current values and to process values for an arbitrary past period.

The diagnostic technique, implemented as software for the real-time condition monitoring of DHT heat-exchange equipment, is a PI ProcessBook display (Figure 1) [21].

Condition monitoring software is based on the principle of calculation of the temperature difference between the inlet hot stream and the outlet cold stream at the sides of heat exchangers. The criterion for the assessment of the heat-exchange process state is the ratio of temperature differences at the current time point and at a specified time point, e.g. a time point selected for comparison. A preselected criterion value makes it possible to assess the condition of heat exchangers and to monitor the results of their maintenance, inspection, and repair in a targeted manner. The accumulated information enabled statistical data processing.

The objective of this paper is to determine boundary or critical values for the real-time condition monitoring of DHT heat-exchange equipment.

3. Theory

The classical approach to the determination of boundary values of diagnostic indicators delimiting the conditions of an item consists in separating the item condition into good one (D_1) and faulty one (D_2) on the basis of the following rule: if the value of the condition criterion $x < x_0$, it is assumed that the item is in good and operable condition, and if $x > x_0$, it is assumed that the faulty condition is in place [29–33]:

$$\begin{aligned} x &\in D_1, \text{ if } x < x_0, \\ x &\in D_2, \text{ if } x > x_0. \end{aligned} \quad (1)$$

The value of x — current (measured) value of the condition criterion — is a random value.

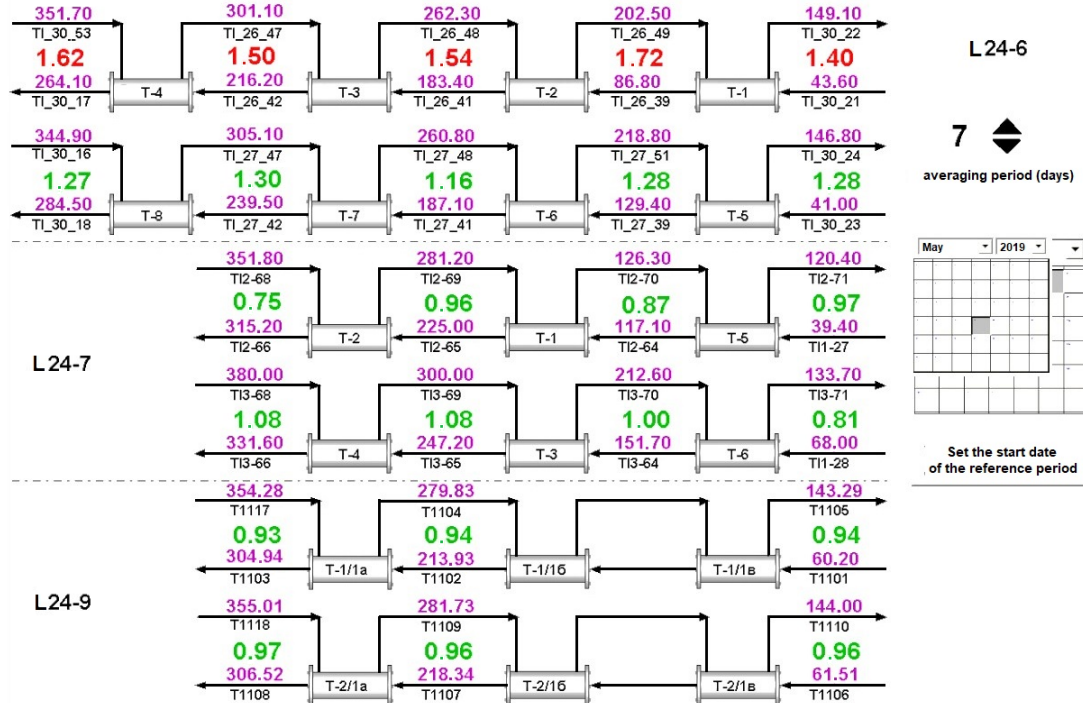


Figure 1. Fragment of screen shot of software for condition monitoring of DHT feed heat exchangers.

The classical approach is therefore based on the fact that the good condition is characterized by a certain diagnostic indicator, whose value is lower in good condition than in faulty condition.

The domains of the good condition (D_1) and the faulty condition (D_2) usually overlap, and in practice it is therefore difficult to select a value of x_0 at which there is no error in determination of a condition type. As a result, a probabilistic-statistic problem arises as to how to select the value of x_0 , which would be in a sense optimal, for example, which would result in the minimum number of wrong solutions or the minimum probability of an undetected faulty condition at a specified probability of a false alarm.

The following errors can be committed while making a decision: a false alarm (an error of the first kind) — an item in good condition is assumed to be defective (D_2 is assumed instead of D_1) and an undetected defect (an error of the second kind) — a defective item is assumed to be in good condition (D_1 is assumed instead of D_2).

If $x > x_0$, and the assembly is in good condition, the probability of a false alarm (P_{FA}) is equal to the product of probabilities of the following two events: availability of the good condition and a value of the condition criterion $x > x_0$ [22-25]:

$$P_{FA} = P(D_1) \cdot P([x > x_0]/D_1) = P(D_1) \int_{x_0}^{\infty} f(x/D_1) dx = P_1 [1 - F(x_0/D_1)] \quad (2)$$

and the probability of an undetected defect (P_{UD}) may be defined as follows:

$$P_{UD} = P(D_2) \cdot P([x < x_0]/D_2) = P(D_2) \int_{-\infty}^{x_0} f(x/D_2) dx = P_2 F(x_0/D_2). \quad (3)$$

The above expressions assume that $f(x/D_1)$ and $f(x/D_2)$ are probability densities of the good and faulty conditions, respectively; diagnoses D_1 and D_2 correspond to the good and faulty conditions of

the item; $P_1 = P(D_1)$ and $P_2 = P(D_2)$ are a priori probabilities of diagnoses D_1 and D_2 , respectively, which are considered to be known on the basis of preliminary statistical data; $F(x_0/D_1)$ is the probability of the good condition in the interval from x_0 to ∞ ; $F(x_0/D_2)$ is the probability of the faulty condition in the interval from $-\infty$ to x_0 .

The probability of making a wrong decision is comprised of probabilities of a false alarm and an undetected defect. If “costs” are assigned to the above probabilities and it is assumed that the costs of right decisions are C_{11} and C_{22} , then an expression is obtained for the average risk of decision making (expected loss value) [22–25]:

$$R = C_{11}P_1 \int_{-\infty}^{x_0} f(x/D_1)dx + C_{21}P_1 \int_{x_0}^{\infty} f(x/D_1)dx + C_{12}P_2 \int_{-\infty}^{x_0} f(x/D_2)dx + C_{22}P_2 \int_{x_0}^{\infty} f(x/D_2)dx, \quad (4)$$

where C_{21} — cost of false alarm; C_{12} — cost of undetected defect (first index — assumed condition, second — actual condition), usually $C_{12} \gg C_{21}$.

If it is assumed that right decisions are not evaluated, i.e. $C_{11}=C_{22}=0$, an expression is obtained for the average risk of making a wrong decision:

$$R = C_{12}P_{UD} + C_{21}P_{FA} = C_{12}P_2 [F(x_0/D_2)] + C_{21}P_1 [1 - F(x_0/D_1)]. \quad (5)$$

The obtained expression makes it possible to evaluate the risk of decision making on the basis of a known probability distribution functions of the criterion values for the good condition and the faulty condition, a priori probabilities of the conditions, and the costs of an undetected default and a false alarm.

4. Experimental the results

4.1. Experimental Data

In accordance with the schedule of planned turnarounds, the run length between turnarounds of a typical diesel hydrotreater is 2 years. Heat-exchange equipment of the reactor section was cleaned in 2013, 2015, and 2017 (the period under review).

In 2013, all the heat exchangers were cleaned. Considerable surface fouling was found at the shell side, especially in heat exchangers pos. T-2 and T-4. The deposit thickness was 2 to 5 mm.

In 2015, all the heat exchangers were disassembled and cleaned. The condition of the heat exchangers was evaluated as fouled. The deposit thickness was about 2 mm at the shell side.

In 2017, all the heat exchangers were disassembled and cleaned. The condition of the heat exchangers: fouled. The deposit thickness was 2 to 3 mm at the shell side.

Results of condition monitoring of heat exchangers of the reactor section of a typical diesel hydrotreater during turnaround activities are shown in table 1.

In some cases, values of the condition assessment criterion did not reach the predefined critical value of 1.30, however, cleaning of tube bundles was required as a result of opening of heat-exchange equipment. Incorrect condition assessment of heat-exchange equipment can be explained by non-availability of reliable data for the initial period of comparison (heat exchangers pos. T-1, 3, 6 in 2013), since operational testing of the condition monitoring software started in 2012.

In accordance with the schedule of planned turnarounds, the run length between turnarounds of a diesel hydrotreater using UOP technology (UOP diesel hydrotreater) is 4 years. Due to high activity of the catalytic system and taking into account the fact that the unit was first commissioned in 2012, the first run length between turnarounds for train B was 5 years. However, in 2016 and 2017, heat-exchange equipment of the reactor section of the UOP diesel hydrotreater was cleaned because of an unsatisfactory condition of the heat-exchange surface (see table 2). In 2016 and 2017, all the heat exchangers of both trains A and B were cleaned. The surfaces showed significant fouling at the shell side. The deposit thickness was 2 to 5 mm (Figure 2, Figure 3).

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Table 1. Results evaluation of the condition monitoring for heat exchangers of a typical diesel fuel hydrotreatment unit

Heat Exchanger Position	Turnaround Year			
	Condition Assessment Criterion	Cleaning	Condition of Heat Exchange Surface	Condition Assessment Results
2013				
T-1	1.24	Performed	Fouled	Ineffective
T-2	5.00	Performed	Highly Fouled	Effective
T-3	1.21	Performed	Fouled	Ineffective
T-4	6.41	Performed	Highly Fouled	Effective
T-5	1.65	Performed	Fouled	Effective
T-6	1.21	Performed	Fouled	Ineffective
2015				
T-1	1.14	Performed	Clean	Effective
T-2	1.28	Performed	Fouled	Effective
T-3	1.61	Performed	Fouled	Effective
T-4	1.75	Performed	Fouled	Effective
T-5	1.48	Performed	Fouled	Effective
T-6	1.45	Performed	Fouled	Effective
2017				
T-1	1.03	Performed	Clean	Effective
T-2	1.24	Performed	Clean	Effective
T-3	1.55	Performed	Fouled	Effective
T-4	1.53	Performed	Fouled	Effective
T-5	1.44	Performed	Fouled	Effective
T-6	1.42	Performed	Fouled	Effective

Table 2. Results evaluation of heat exchanger condition monitoring at UOP diesel hydrotreater.

Heat Exchanger Position	Turnaround Year			
	Condition Assessment Criterion	Cleaning	Condition of Heat Exchange Surface	Condition Assessment Results
2016				
100B-E1A/1,2	2.00	Performed	Highly Fouled	Effective
100B-E1A/3,4	2.72	Performed	Highly Fouled	Effective
100B-E1B/1,2	2.40	Performed	Highly Fouled	Effective
100B-E1B/3,4	2.44	Performed	Highly Fouled	Effective
2017				
100B-E1A/1,2	1.90	Performed	Highly Fouled	Effective
100B-E1A/3,4	2.47	Performed	Highly Fouled	Effective
100B-E1B/1,2	2.00	Performed	Highly Fouled	Effective
100B-E1B/3,4	2.62	Performed	Highly Fouled	Effective

4.2. Results of Processing of Experimental Data

Statistical analysis of all obtained data using known methods [25, 26] made it possible to obtain empirical and theoretical functions of probability distribution of the condition assessment criterion values and corresponding probability distribution densities of the assessment criterion for clean (1) and fouled (2) heat exchangers (Figure 4). The normal distribution law was used to approximate the random value distribution.



Figure 2. Condition of Heat Exchanger pos. 100B E1A3.



Figure 3. Condition of Heat Exchanger pos. 100B E1A2.

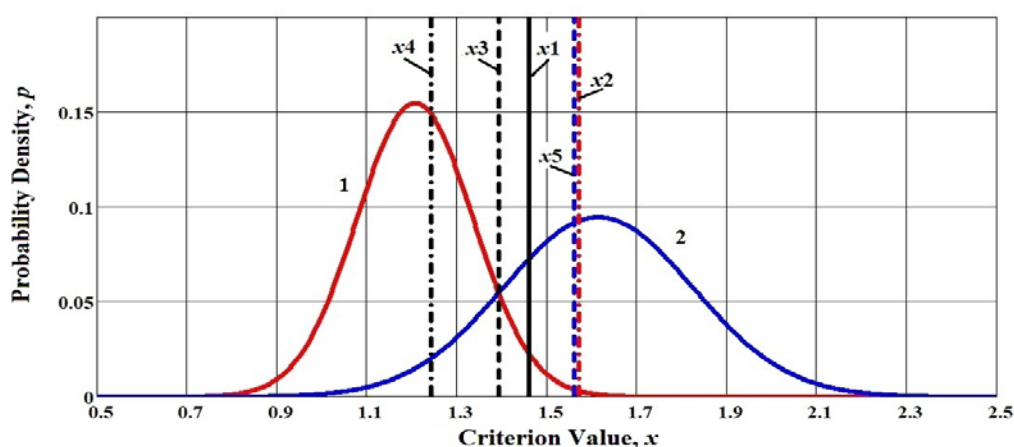


Figure 4. Probability density functions of values of condition assessment criterion for clean (1) and fouled (2) heat exchangers. Labels x_1 , x_2 , x_3 , x_4 , x_5 are criterion values calculated using minimum risk, minimum number of wrong decisions, maximum likelihood, minimax, Neyman-Pearson methods.

Minimum risk, minimum number of wrong decisions, maximum likelihood, minimax, Neyman-Pearson methods were used to determine the boundary value of the condition assessment criterion separating clean and fouled heat exchangers. Taking into account accumulated practical experience of condition check of heat-exchange equipment based on results of maintenance and pre-maintenance check of values of the condition assessment criterion, it is assumed that, if the value of the condition assessment criterion is less than 1.30, the a priori probability of a clean and operable heat exchanger is $P_1=0.970$. Therefore, the a priori probability of a fouled heat exchanger is $P_2=0.030$. The ratio of the cost of an undetected fouled heat exchanger to the cost of shutdown for its cleaning is assumed to be $C_{12}/C_{21}=10$.

Probabilities of an undetected faulty condition and a false alarm, as well as risk curves (Figure 5) for different methods and boundary values are calculated based on the following decision-making conditions:

- minimum risk method — minimum average risk is determined;
- method of minimum number of wrong decisions — it is assumed that an undetected defect and a false alarm have the same cost;
- maximum likelihood method — the cost and probability of an undetected defect are assumed equal to the cost and probability of a false alarm;
- minimax method — the minimum risk value is determined among the maximum values at “unfavorable” value of P_1 resulting in the highest risk value;

- Neyman–Pearson method – the probability of an undetected defect is minimized at a given acceptable level of probability of a false alarm.

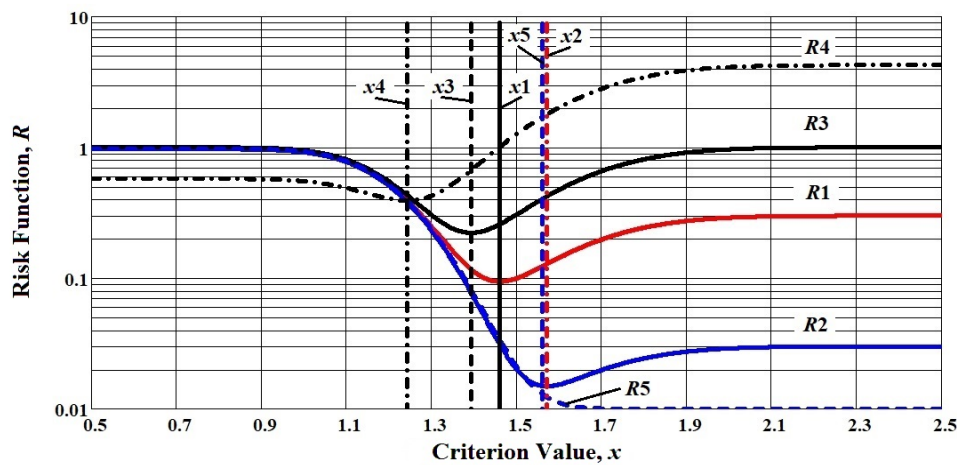


Figure 5. Risk functions of decision making and labels of values of condition assessment criterion calculated using methods of minimum risk ($R1$ and $x1$), minimum number of wrong decisions ($R2$ and $x2$), maximum likelihood ($R3$ and $x3$), minimax ($R4$ and $x4$), and Neyman–Pearson ($R5$ and $x5$).

Table 3 Results evaluation of heat exchanger condition monitoring at UOP diesel hydrotreater.

Method	Minimum Risk	Minimum Number of Wrong Decisions	Maximum Likelihood	Minimax	Neyman-Pearson
x	1.46	1.57	1.39	1.24	1.56
P_1	0.970	0.970	0.970	0.970	0.970
P_2	0.030	0.030	0.030	0.030	0.030
P_{FA}	0.024	0.002	0.072	0.225	0.003
P_{UD}	0.007	0.013	0.004	0.017	0.012
R	0.094	0.128	0.117	0.392	0.123

5. Discussion of results

The analysis of obtained data (see table 3) showed that the risk of decision making is minimized ($R=0.094$) by the boundary value ($x1=1.46$) of the condition assessment criterion obtained using the minimum risk method. At the same time, the probability of an undetected fouled condition of a heat exchanger is $P_{UD}=0.007$ (i.e. below 0.70%), and the probability of a false alarm is $P_{FA}=0.024$.

The magnitude of the risk of a wrong decision obtained using the methods of minimum number of wrong decisions, maximum likelihood, Neyman–Pearson is approximately the same and lies in the range from 0.117 to 0.128, i.e. the variation range of the values is 1.00% maximum. The probability of an undetected fouled condition ($P_{UD}=0.004$) is minimized by the boundary value of $x3=1.39$ which was obtained using the maximum likelihood method. The minimum probability of a false alarm ($P_{FA}=0.003$) with the probability of an undetected fouled condition $P_{UD}=0.012$ is achieved by the boundary value of $x3=1.56$ calculated using the Neyman-Pearson method.

6. Summary and Conclusion

Processing of experimental data obtained as a result of condition monitoring of heat-exchange equipment during its maintenance and repair, process simulation, and determination of the condition assessment criterion made it possible to obtain new results in evaluating the boundary value for condition assessment criterion of heat exchangers using probabilistic-statistical methods of decision making.

As a result of the studies performed, it was found that if a certain value of the criterion for the condition assessment of heat-exchange equipment is exceeded, it indicates quality degradation of heat exchange and the necessity for maintenance or repair of heat exchangers.

Processing of experimental data made it possible to obtain probabilistic characteristics of the condition assessment criterion, in particular, probability density of the condition assessment criterion values for clean and fouled heat exchangers. The probabilistic characteristics enabled calculation of probabilities of an undetected fouled condition and a false alarm, the risk of making a wrong decision using such decision-making methods as the minimum risk method, method of minimum number of wrong decisions, maximum likelihood method, minimax method, Neyman–Pearson method. Boundary values of the condition assessment criterion were obtained based on risk functions of decision-making using various methods.

Depending on the absolute value of the cost of an undetected fouled condition and a false alarm, two solutions to the problem of selection of the boundary value of the condition assessment criterion can be recommended:

1. The boundary value $x_1=1.46$ of the condition assessment criterion obtained using the minimum risk method ensures the minimum probability of an undetected fouling condition of a heat exchanger $P_{UD}=0.007$ with the probability of a false alarm $P_{FA}=0.024$, which warrants its application if the cost of an undetected fouled condition is high;
2. The boundary value $x_3=1.56$ calculated using the Neyman–Pearson method ensures the minimum probability of a false alarm ($P_{FA}=0.003$) with the probability of an undetected fouled condition $P_{UD}=0.012$; this criterion value can therefore be used if the cost of a heat exchanger shutdown for repair is high.

7. References

- [1] Randall R B 2011 *Vibration-based Condition Monitoring: Industrial, Automotive and Aerospace Applications* (West Sussex: Wiley)
- [2] Goyal D and Pabla B S 2016 The Vibration Monitoring Methods and Signal Processing Techniques for Structural Health Monitoring: A Review *Archives of Computational Methods in Engineering* **23(4)** 585–594
- [3] Juan P A-S and Hojjat A 2016 Signal Processing Techniques for Vibration-Based Health Monitoring of Smart Structures *Archives of Computational Methods in Engineering* **23(1)** 1–15
- [4] Sizarev V D, Sokolova A and Balitsky F 2014 Rotary machinery condition monitoring technique based on stochastic methods of vibration signal analysis *1th Int. Conf. on Condition Monitoring and Machinery Failure Prevention Technologies* vol. 1 (Manchester: Curran Associates, Inc.) pp 270–275
- [5] Cajas Muñoz, Franco David, Torres Díaz, Cristian Paúl 2018 *Adquisición de Señales Acústicas y de Vibración Para el Diagnóstico de Fallos en un Compresor Reciprocante de Doble Etapa* (Cuenca – Ecuador: Universidad Politécnica Salesiana)
- [6] Kostyukov V N and Naumenko A P 2015 Naumenko Standardization in the sphere of vibrodiagnostic monitoring of piston compressors *Procedia Engineering* vol **113** pp 370–380
- [7] Rossi G. 2012 Vibration analysis for reciprocating compressors *ORBIT magazine* **32(2)** 34–41
- [8] Naumenko A P, Kudryavtseva I S and Odinets A I 2018 Evaluation of peak values of the oscillation processes parameters, *2018 Dynamics of Systems, Mechanisms and Machines (Dynamics)* pp 1–5
- [8] Tran V T, Thobiani F Al and Ball A D 2014 An approach to fault diagnosis of reciprocating compressor valves using Teager–Kaiser energy operator and deep belief networks *Expert Syst. Appl.* **41(9)** 4113–4122
- [9] Ahmed M, Baqqar M, Gu F and Ball A D 2012 Fault detection and diagnosis using Principal Component Analysis of vibration data from a reciprocating compressor *Proc. of 2012 UKACC Int.l Conf. on Control* pp 461–466
- [10] Smith A, Gu F, Ball A D 2019 An Approach to Reducing Input Parameter Volume for Fault Classifiers *International Journal of Automation and Computing* **16(2)** 199–212

- [11] Sokolova A and Balitsky F 2013 S-discriminants. New approach to machinery condition monitoring and defects occurrence and development detecting *10th Int. Conf. on Condition Monitoring and Machinery Failure Prevention Technologies* vol 1 (Krakow: Curran Associates, Inc.) pp 387–398
- [12] Balitsky F, Sokolova A, Dolaberidze G and Ivanova M 2013 Serial-cascade demodulation approach for machinery faults identification in nonlinear vibration diagnostics *10th Int. Conf. on Condition Monitoring and Machinery Failure Prevention Technologies* vol 1 (Krakow: Curran Associates, Inc.) pp 98–195.
- [13] Kostyukov V N and Naumenko A P 2016 About the experience in operation of reciprocating compressors under control of the vibration monitoring system *Procedia Engineering* **152** (201) pp 497–504
- [14] Naumenko A P 2009 Real-time condition monitoring of reciprocating machines *6th Int. Conf. on Condition Monitoring and Machinery Failure Prevention Technologies* vol 1 (Dublin: Curran Associates, Inc.) pp 1201–1212
- [15] Naumenko A P 2011 Modern methods and means of on-line monitoring of parameters and real-time health monitoring of piston machines *8th Int. Conf. on Condition Monitoring and Machinery Failure Prevention Technologies* vol 1 (Cardiff: Curran Associates, Inc.) pp 809–821
- [16] Kostyukov V N and Naumenko A P 2012 The Piston Compressor: The Methodology of the Real-Time Condition Monitoring *J. Phys.: Conf. Ser.* **364** 012130
- [17] Kostyukov V N and Naumenko A P 2016 Regulatory-methodical guidelines on real-time vibroacoustic monitoring of piston compressors *Advances in Technology to Support End User Mission – Proc. of the 2016 Joint Conf./Symp. of the Society for Machinery Failure Prevention Technology and the Int. Society of Automation* (Dayton: Dayton Convention Center, OH, USA)
- [18] Kostyukov V N and Naumenko A P 2012 Designing and operation experience of real-time monitoring systems *9th Int. Conf. on Condition Monitoring and Machinery Failure Prevention Technologies* vol 1 (London: Curran Associates, Inc.) pp 1053–1060
- [19] Lemos J C, Costa A L H and Bagajewicz M J 2017 Linear method for the design of shell and tube heat exchangers including fouling modeling *Applied Thermal Eng.* **125** 1345–1353
- [20] Demin A M, Gorchakova A A, Naumenko A P and Odinets A I 2019 Condition monitoring of heat-exchange equipment of the diesel fuel hydrotreatment processes *AIP Conf. Proc.* **2141** 050002
- [21] Kostyukov V N, Naumenko A P and Kudryavtseva I S 2017 Assessment of Characteristic Function Modulus of Vibroacoustic Signal Given a Limit State Parameter of Diagnosed Equipment *J. Phys.: Conf. Ser.* **944** 012063
- [22] Kostyukov V N, Naumenko A P, Kudryavtseva I S and Boychenko S N 2016 Formation of diagnostic features vector based on characteristic function of vibroacoustic signal *Thirteenth Int. Conf. on Condition Monitoring and Machinery Failure Prevention Technologies* vol 1 (Charenton-le-Pont: Curran Associates, Inc.) pp 171–181
- [23] Kazarin D V, Bazakin V V, Zaytsev A V, Teterin A O and Kudryavtseva I S 2015 The research of rotation frequency influence and technical state condition upon the level of vibration spectrum components of rolling bearings *Procedia Engineering* vol **113** pp 332–336
- [24] Kostyukov V N, Naumenko A P and Kudryavtseva I S 2016 Usage of characteristic function as informative diagnostic feature *Procedia Engineering* **152(201)** pp 521–526
- [25] Kudryavtseva I S, Naumenko A P and Odinets A I 2019 Diagnostic signs on the basis of characteristic functions of vibroacoustic oscillations *AIP Conference Proceedings* **2141** 050007