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THE METHOD OF NON-CONTACT VIBRATION CONTROL OF ENERGY DEVICE DETAIL STATE BASED ON THE USE OF INFORMATIVE FREQUENCIES OF OWN VIBRATIONS RELATED TO CERTAIN TYPES OF DEFECTS

[a]O.V. VLADIMIROV, [b]R.R. GIBADULLIN, [c]N.V. DENISOVA, [d]I.V. IVSHIN, [e]M.F. NIZAMIEV

[a]Associate Professor, PhD in Technical Sciences, Kazan State Power Engineering University, Kazan, Krasnoselskaya str., 51
[b]Teacher, PhD in Technical Sciences, Kazan State Power, Engineering University, Kazan, Krasnoselskaya str., 51, Russia
[c] Associate Professor, Candidate of Physical and Mathematical Sciences, Kazan State Power Engineering University, Kazan, Krasnoselskaya str., 51, Russia
[d] The head of the department, doctor of technical sciences, Kazan State Power Engineering University, Kazan, Krasnoselskaya str., 51, Russia
[e] Teacher, PhD in Technical Sciences, Kazan State Power Engineering University, Kazan, Krasnoselskaya str., 51, Russia
e-mail:[a] info@ores.su, [b]russia@prescopus.com,[c]global@ores.su, [d]editor@prescopus.com ,[e]editor@ores.su

Abstract: They performed the theoretical studies in the software complex ANSYS to determine the information frequencies of the natural oscillations of gas engine parts associated with certain types of defects. A new method of non-contact vibration control (MNCVC) was developed for the state of complex details based on the use of informative natural vibration frequencies associated with certain types of defects. The developed and created a new instrumentation-measuring and software complex to implement a new MNCVC of complex-shaped parts using laser vibrometry methods. Experimental studies of the natural oscillation parameters of the gas engine parts have been carried out and the working capacity of the new MNCVC state for the power plant parts was confirmed.

Keywords: Instrument-measuring complex, software, noncontact vibration control method, gas engine, laser vibrometer, TKR turbine body, ANSYS.

1 Introduction

Power plants (PP) of various purposes, type and operation principle should be effective and reliable in operation. Timely and accurate control of the technical condition of products is one of the ways to improve product reliability and reduce operating costs. Modern methods of power plant state monitoring allow to detect a defect at an early stage of its generation in time, to predict its development, and to determine the scope of maintenance or repair. Among many existing methods of state monitoring the vibrational method is the most objective, accurate and sensitive to defects, which allow to apply non-contact measurement methods and computer technologies.

Vibration characteristics contain sufficiently large information about the technical state of a power plant, its nodes, parts and mechanisms (Randall, 2011; Girdhar, 2004; González & Villalobos Antúnez, 2016). At the same time, the existing methods of vibration control require further development and improvement. The development and the improvement of non-contact vibration control methods to determine the state of parts, working units and the mechanisms of power plants is an urgent task.

Numerous works by domestic and foreign authors have been devoted to the problem of vibration control method improvement (Kazakov, 2012; Ivshin, 2009). In these works, the control of complex shape object state is performed by the analysis of the spectra in the frequency range from 0 to 20 kHz, their comparison with the reference spectrum developed in the same frequency range. However, theoretical and experimental studies showed that the defects affect the natural frequencies of the product oscillations in a certain frequency range (Nizamiev, 2017; Mamedov, 2017). The analysis of the spectra over the entire frequency range under study reduces the probability of a defect detection, which can be seen in the analysis of informative parameters characterizing the state of control objects.

As a defect develops, the degree of its influence on the product own oscillations changes, and only significant defects can affect the change of most modes of natural oscillations, and this can be determined by the signal spectrum designed over the entire range of studied frequencies.

In this regard, it is expedient to develop the method of product vibration control, based on the analysis of those frequencies of natural oscillations that are most sensitive to a product state change and a defect presence.

2 Theoretical Substantiation for The Development of A New Method of Non-Contact Vibration Control for The Condition Of Energy Unit Details

With the purpose of a new MNCVC development for power plant components, theoretical studies have been carried out to determine the informative frequency interval that allows to detect the defects in a turbine compressor (TC) turbine casings by analyzing the spectrum of natural vibrations.

The examination of the available methods related to the modeling of defects for complex shape parts has shown that it is expedient to use finite element method (FEM) based on computer modeling in ANSYS Workbench to determine the informative harmonics of spectra (Barulina, 2011).

In the ANSYS Workbench finite element simulation software, the frequencies of turbine shell natural vibrations were calculated, which made it possible to determine the informative frequency intervals of the research object associated with certain types of manufacturing defects (Repin, 2013; Nizamiev et al, 2010).

The objects of the study are turbine housing of TC of a prospective gas engine, 20 standard defect-free and 5 control ones: case No. 1 of the serial version (without a defect); cases No. 2, 3, 4, 5 with the most typical artificial defects (Table 1), which are not detected by visual inspection.

Table 1. Production Defects of TC cases

TC body No	Description of defects
2	"Shrinkage porosity" inside one of the inner rods
3	"Shrinkage porosity" inside both inner rods
4	"Growth" inside both inner rods
5	«Shrinkage shell»

Three-dimensional model and a finite-element grid of the object under study are shown on Figure 1.

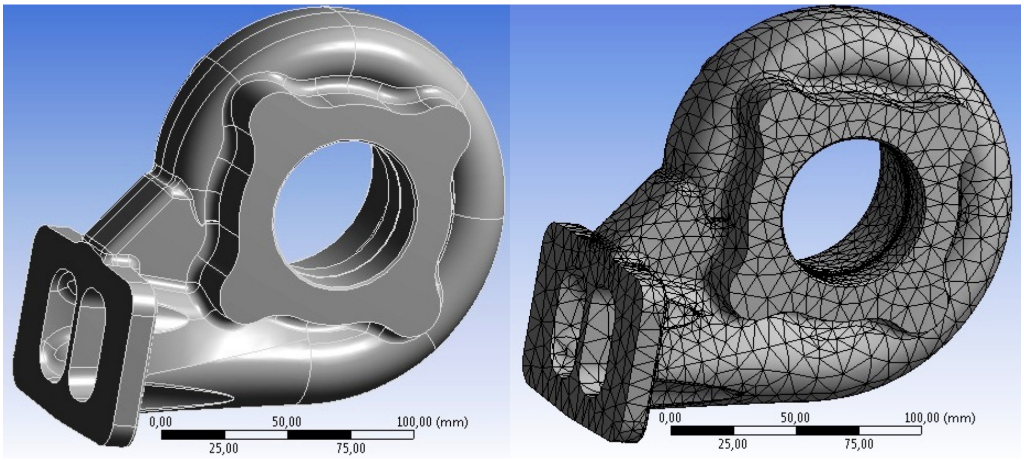


Fig 1. Three-dimensional model (on the left) and a finite-element grid (on the right) of TC turbine body

In order to conduct a modal analysis of the research object (defective and defect-free), it was decided to simulate the production defect of TC turbine body # 4, that is, to apply "growths", as shown on Fig. 2.

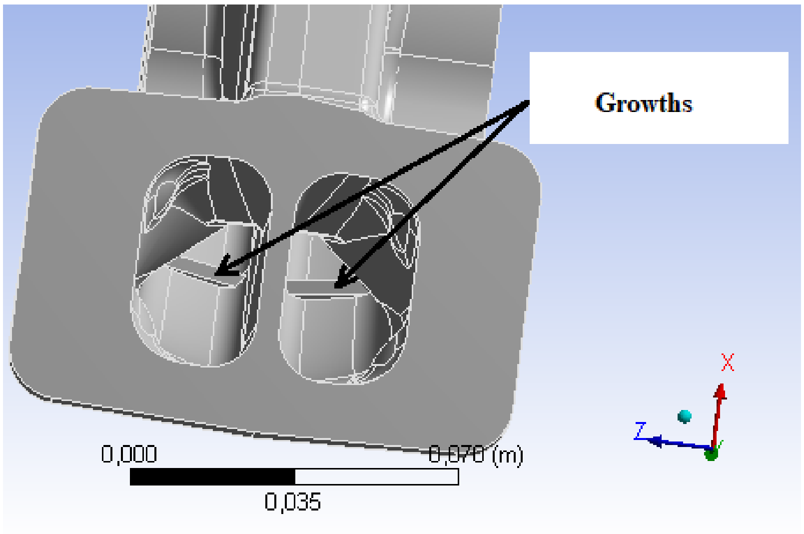


Fig 2. Defective body of TC turbine

Modal analysis was applied, the calculation was carried out using the Lanczos algorithm. The block diagram of the calculation is shown on Figure 3 (Kotov, 2008; Nizamiev et al, 2014).

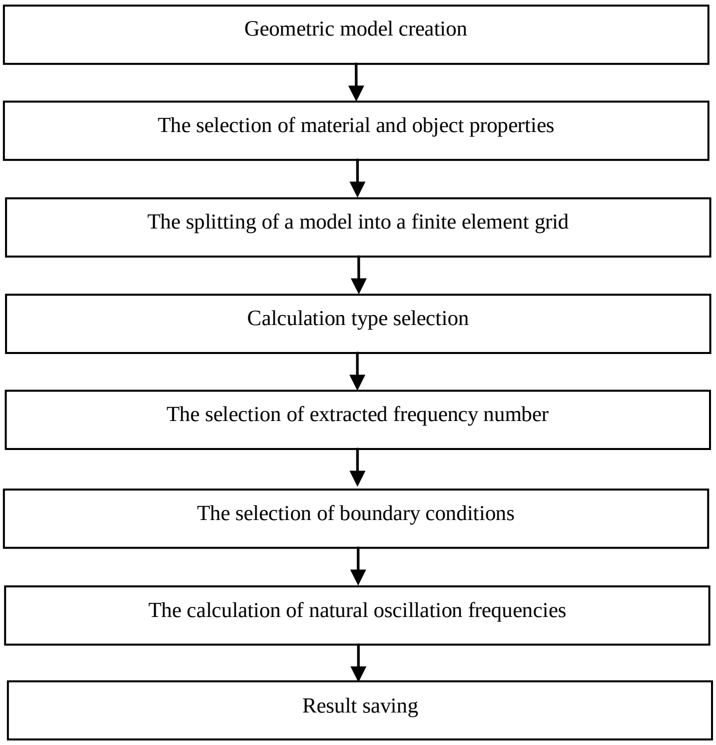


Fig 3. Calculation flowchart

The properties of the material used in the calculation are presented in Table 1.

Table 2. The properties of TC turbine body material

Design part	Material	Density, kg/m^3	Young's modulus, GPa	Poisson's ratio
TC turbine housing	Gray cast iron	7200	110	0,28

At the stage of the boundary condition setting, the movement restrictions were applied to the design model in the places where the body is in contact with the vibration-proof surface shown on Fig. 4.

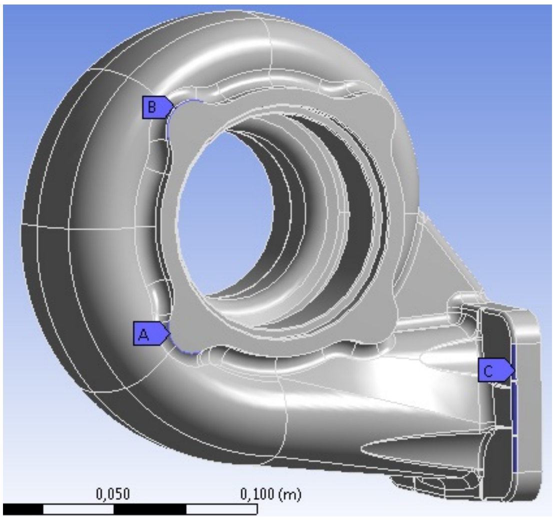


Fig 4. Places for TC turbine body installation on a vibration-proof surface (marked on the model in blue (A, B, C))

The main differences between the modes (the region of difference) in the frequencies of a defect-free and defective TC turbine body natural oscillations are shown in Table 2.

Table 3. The frequencies of TC turbine body natural oscillations

Mode	Frequencies of a defectless TC turbine housing,	Frequencies of a defective TC turbine No.4	Difference in frequencies,	Mode	Frequencies of a defectless TC turbine housing,	Frequencies of a defective TC turbine No.4	Difference in frequencies,

	Hz	housing, Hz	Hz		Hz	housing, Hz	Hz
1	2	3	4	1	2	3	4
1	907,53	909,31	1,78	31	10079	10081	2
2	1507,5	1508,7	1,2	32	10169	10174	5
3	1939	1936,5	-2,5	33	10428	10431	3
4	2044,3	2046,2	1,9	34	10528	10529	1
5	2813,3	2817,2	3,9	35	10705	10711	6
6	3105,4	3105,8	0,4	36	11235	11238	3
7	4617,7	4615,7	-2	37	11298	11300	2
8	4788,4	4794,1	5,7	38	11585	11584	-1
9	4937,8	4939,3	1,5	39	11753	11758	5
10	5409,2	5408,7	-0,5	40	12186	12199	13
11	5501,6	5501,8	0,2	41	12298	12308	10
12	5612	5612,9	0,9	42	12399	12413	14
13	5757,2	5761,8	4,6	43	12604	12616	12
14	6305,6	6318,5	12,9	44	12703	12723	20
15	6443,2	6454,6	11,4	45	12870	12884	14
16	6510,3	6525,8	15,5	46	13055	13063	8
17	6922,2	6937,4	15,2	47	13150	13160	10
18	7007,5	7025,9	18,4	48	13437	13449	12
19	7193,6	7212,5	18,9	49	13503	13512	9
20	7294,7	7314,4	19,7	50	13685	13700	15
21	7478,4	7489,7	11,3	51	13848	13868	20
22	7791,8	7800,2	8,4	52	13994	14016	22
23	8269,8	8271	1,2	53	14185	14200	15
24	8463	8467	4	54	14445	14442	-3
25	8846,1	8846,3	0,2	55	14656	14661	5
26	9063,9	9061,8	-2,1	56	14790	14788	-2
27	9219,8	9218,4	-1,4	57	14856	14854	-2
28	9518,3	9519,1	0,8	58	14976	14981	5
29	9687,9	9685,3	-2,6	59	15158	15153	-5
30	9846,9	9850,6	3,7	60	15316	15313	-3

Figure 5 and 6 show the differences in the frequencies of a defect-free and a defective TC turbine casing, as well as the zones of the largest and smallest differences are singled out by modes in the frequencies of a defect-free and defective TC turbine housing. The abscissa shows the ordinal number of the mode, the ordinate represents the frequency difference in hertz, the points denote the differences in the frequencies of natural oscillations by the modes of a defect-free and a defective TC turbine body (column 4 of Table 2). The dashed line corresponds to the frequency difference of 7 Hz. The frequencies above the dashed line are the most different ones.

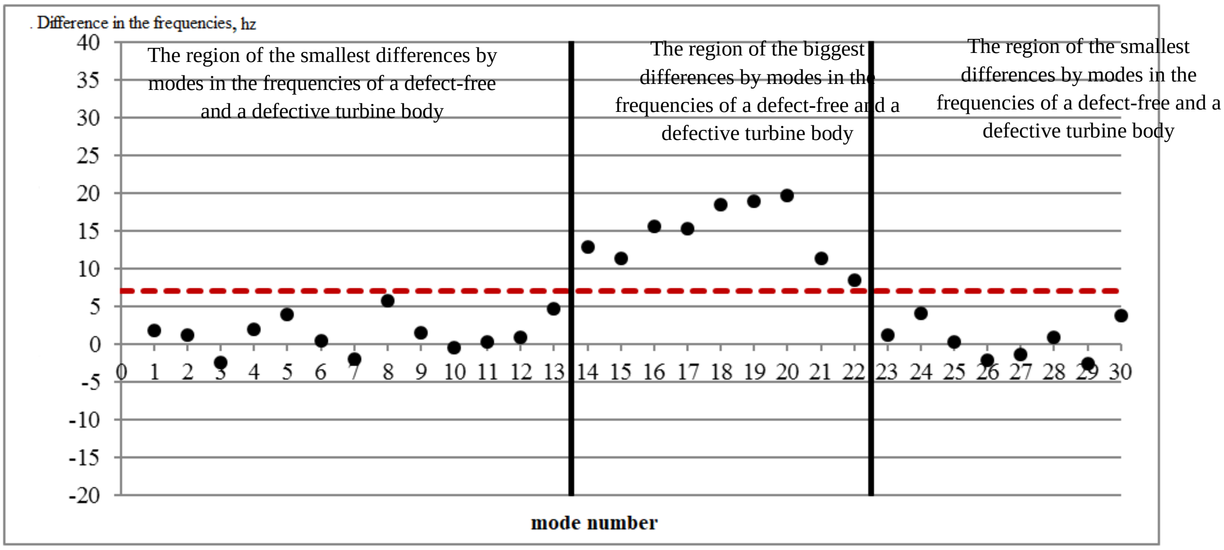


Fig 5. Difference in the frequencies of a defect-free and a defective TC turbine body from the mode 1 to 30

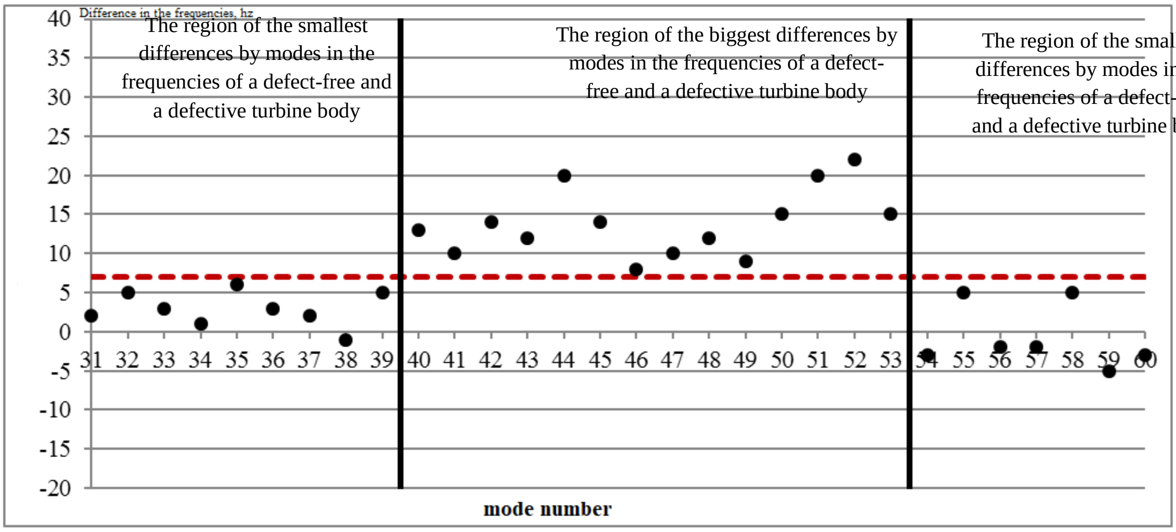


Fig 6. Difference in the frequencies of a defect-free and a defective TC turbine body from the mode 31 to 60

The analysis of the modal analysis results showed that the greatest differences by modes in the frequencies of a defect-free and a defective body of TC turbine are available at the intervals of 6-8 kHz (mode 14-22) and 12-14.2 kHz (mode 40-53 mode). Theoretical calculations were carried out for three defective bodies of TC turbines, shown in Table 1.

Based on the results of theoretical studies on the determination of natural oscillation information frequencies of gas engine parts associated with certain types of defects, the following conclusions can be drawn:

1. According to the results of natural oscillation frequency calculation in the ANSYS Workbench software complex, the frequency ranges were determined to study the parameters of the natural oscillations for TC turbine body. The analysis of modal analysis results showed that the most informative frequency ranges characterizing the presence of production defects such as "growth", "shrinkage porosity", "shrinkage shell" in TC turbine housings are the frequency ranges of 6-8 kHz and 12-14 kHz.
2. The frequency ranges of 0-6 kHz, 8-12 kHz, 14-15 kHz of a defect-free and a defective research object did not show any differences in the modes of natural oscillations and the record of these ranges in the general analysis of spectra may adversely affect the results of TC turbine body state monitoring.
3. According to the results of numerical simulation, it can be concluded that in order to determine the presence of a defect effectively, it is advisable to analyze the spectra not on the entire frequency interval, but only in the informative frequency range, which makes it possible to detect the defects in complex shape details.
4. According to the results of theoretical studies, a new method of vibrational control for the state of complex shape products is proposed, based on the analysis of the informative frequency range of the amplitude spectrum associated with certain types of defects (Bruyaka et al, 2010).

In order to implement the proposed MNCVC of complex shape part state, they developed the instrument-measuring complex and software using the contactless methods of laser vibrometry, and the experimental studies of natural oscillation parameters of gas engine parts have been carried out.

3 Instrument-Measuring Complex To Implement A New Method Of Non-Contact Vibration Control For The Condition Of Energy Unit Details

A new instrument-measuring complex (IMC) was developed and created for the implementation of the new MNCVC for the state of power unit parts (Figure 7) (Nizamiev et al, 2015)

IMC includes the laser vibrometer 1, the matching device 2, the multifunction input/output module 3, the personal computer 4, and software 5 developed in a graphical programming environment LabVIEW 13.0 (Morris Alan & Langari, 2012), Pat. 160989. Rus. Federation: IPC G01M 15/02, G01M 15/05). A patent for IMC utility model was obtained (Zhuravlev, et al, 2006; Nizamiev et al, 2016).

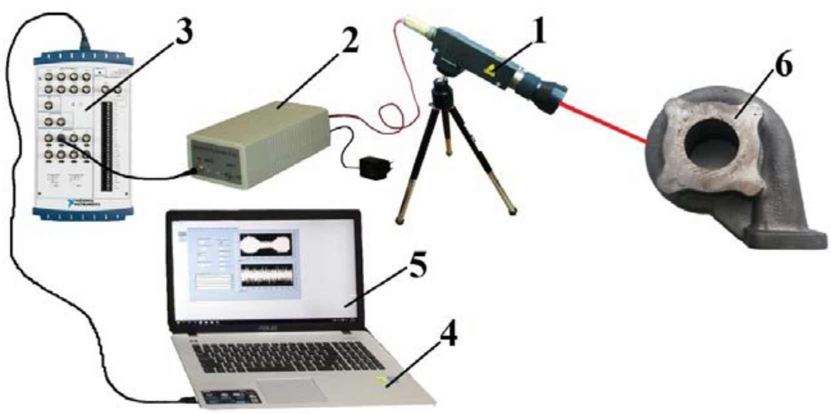


Fig 7. The diagram for the instrument-measuring complex: 1 - laser vibrometer; 2 - matching device; 3 - multifunctional input-output module; 4 - personal computer; 5 - software; 6 - the object of the study

A special feature of the developed complex is the use of non-contact laser vibrometers as the measuring sensors. Contact vibration sensors have a number of significant disadvantages (unsatisfactory repeatability of a signal when a sensor is installed on the same object in "remove-set" mode, the impossibility of measuring the vibration parameters of small-sized products, complex shapes, high-temperature objects, the need for a special surface preparation for sensor mounting, a reliable fixing of a sensor on a control object, etc.) and are not fully suitable to determine the state of gas engine parts. Laser measuring systems, characterized by a high accuracy, informative and noncontact nature, do not have these drawbacks and allow to measure the vibration parameters of complex shape parts of a gas engine (Nizamiev M.F. 2015).

Laser vibrometers allow to make oscillation measurements in the studied points of the working engine at the distance of up to 5 meters, and also to exclude the influence of numerous noises of operating engine mechanisms on the oscillations under study.

The laser vibrometer registers vibrations and converts them into an electrical signal proportional to the vibration speed of a research object that is connected to the multifunction input-output module, where it is digitized and transferred to a personal computer with installed software (Figure 8).

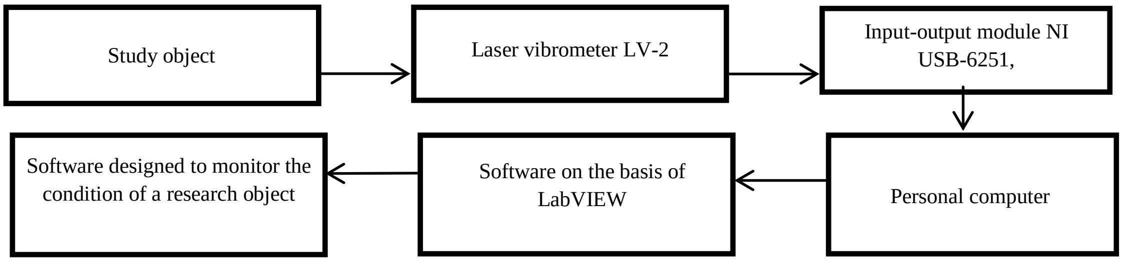


Fig 8. IMC structural scheme

The digitized signal received from the multifunction input-output module is converted into the amplitude spectrum using the Fast Fourier Transformation (FFT) procedure and analyzed by software.

IMC software (Nizamiev M.F. 2015; Hampel et al, 1989). consists of the following components combined into one user package:

- the programs for the generation of reference spectra;
- the programs for spectrum comparison with a standard;
- technical condition monitoring programs.

All these components are combined in one integrated shell, the logging of work is provided with the possibility of further viewing the results of record and signal processing modes. The conclusion about a product state is performed automatically without a user's participation, which excludes subjectivity in et al, 2014).

The program for the generation of reference spectra is designed to form the reference product spectrum of a serviceable product and a confidence interval for the comparison with a confidence level of 0.95. The reference spectrum is formed from the results of testing a sufficiently large batch of serviceable products that are the sample from a general population, and includes the most common characteristics of the product's own oscillations. The

robust weighing method is used to form the reference spectrum (Hastings & Peacock, 1980). The development of the reference spectrum is the process of frequency transition from the set of amplitudes of the original spectra at a given frequency (a_1, a_2, a_3, ..., a_m) to a single (generalized, reference) value a_s. It is assumed that a standard will contain only general data typical for the whole set of spectra and should not contain any (random) features of a particular spectrum. In the software, they implemented the possibility of the spectrum "normalization". This function divides each harmonic of the spectrum into the largest amplitude, thus the influence of the mechanical impact force on the results of the experimental data is excluded.

The program for the comparison of spectra with a standard (Fig. 9) is designed to assess the differences of each initial spectrum of the recorded signals from the reference spectrum.

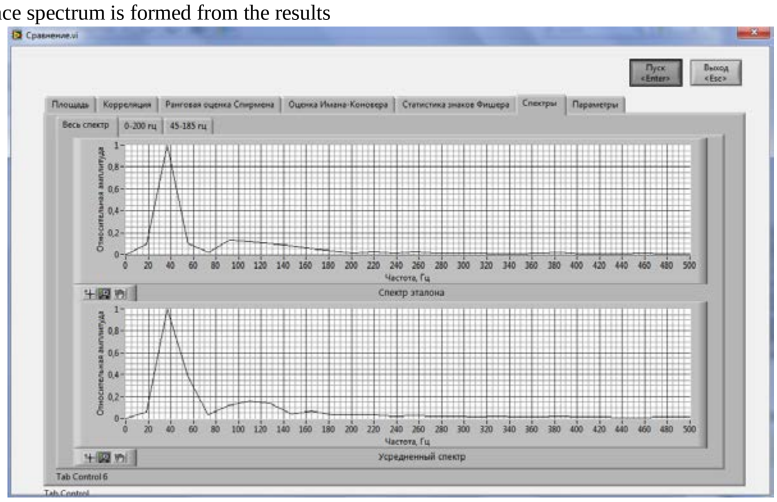


Fig 9. The appearance of the program front panel to compare the spectra with a standard.

The program works in the following sequence:

- a reference file and sensor signals are read;
- a spectrum is formed for each signal;

- the values of target functions are calculated for each spectrum using target comparison functions;
- it is determined whether the values of the objective functions are within the limits of the confidence interval.
- They use the following as the target functions for vibration signal spectrum comparison in the developed programs:
- correlation coefficient;
- Spearman's non-parametric rank estimate;
- Iman-Konover estimate (Orlov, 2004).

The technical state control program is designed to evaluate the differences between the current signal spectrum and the reference spectrum in the automatic mode.

When the program is started, the vibrational responses of the beats are recorded from the measuring channels (a product number and code are put into a file name, the file format is .txt). After the end of a record, the program generates the spectrum for each signal by the FFT algorithm automatically, calculates the target comparison functions of the reference and the current spectra, and compares them with the confidence interval boundary.

In the software, in order to implement the proposed method for complex shape product state control, the possibility of reference and controlled object spectrum comparison is implemented by the means of objective functions, not only over the entire frequency range of the spectrum, but also in its informative areas characterizing the presence of a defect in a monitoring object.

In order to determine the products as "suitable" or "defective" (Figure 10), the approach is used that is typical for the procedures of anomaly rejection: the program interprets the set of computed values of some statistics (p_1, p_2, ..., p_m) as a set of measured values of an abstract parameter and applies the following procedure to this set of values (The certificate of the computer program state registration № 2014613692.):

1) to calculate the median value estimate $\overline{p}$;

2) to calculate the spread estimate S as the mean absolute deviation;

3) to develop a confidence interval for a given level of significance α:

$$\overline{p} \pm S \cdot t(1-\frac{\alpha}{2}, m-2),$$

where $t(\alpha, m)$ – α -quantile of the Student's distribution with m degrees of freedom.

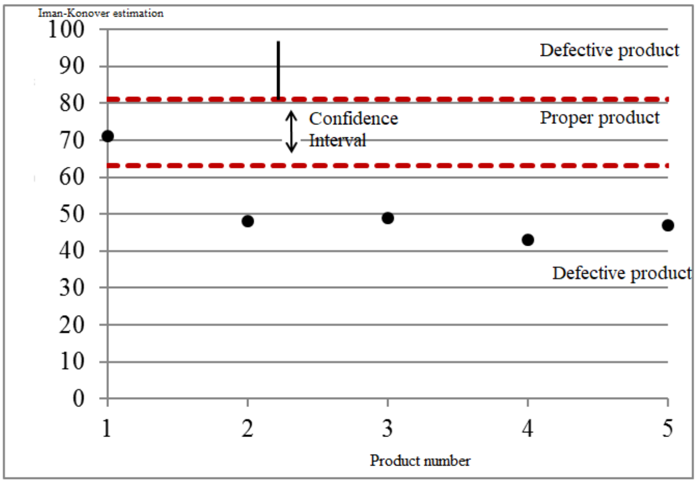


Fig 10. The principle of decisive "proper - defective" rule development by the example of Iman-Konover estimate

If the comparison coefficients are within the limits of the confidence interval, then the object of the study is considered as "proper", if they exceed the limits of the confidence interval, then the product is recognized as "defective".

Thus, using the developed software, the spectra of gas engine parts are analyzed, not only over the entire frequency range of the spectrum, but also on its informative areas characterizing the presence of a defect in a control object.

The software registration certificate for PC was received (24).

4 Experimental Studies Of Own Vibration Parameters For Gas Engine Parts With The Use Of A New Method Of Non-Contact Vibration Control

In order to approbate the proposed state of MNCVC for power plant components based on the analysis of amplitude spectrum informative frequencies and the development of the technique to monitor the state of power plant parts, the series of experimental studies were carried out with TC turbine shells of a gas turbine engine using IMC.

Prior to the experimental studies, they performed the preparation, the adjustment and the tuning of the equipment used in the measuring system in accordance with the requirements set forth in the technical documentation, the operating instructions for specific instruments and GOST. The laser vibrometer was installed at the distance of 1 - 2 m from the study object, the laser beam was directed to the point of TC turbine body, as was shown on Fig. 11, without a preliminary preparation of an object surface.

The location of free oscillation excitation and the point of the laser vibrometer beam aiming is chosen on the basis of the initial experimental studies and the possibilities of the studied object placement on a vibration-proof surface. The proposed method of excitation and guidance makes it possible to determine a defect of TC turbine body. The peculiarities of experimental study performance were taken into account during the modal analysis of the finite element ANSYS modeling during the determination of the spectrum informative frequencies, which make it possible to detect a defect in the control object.

Fig 11. The body of TC turbine with the laser sensor beam guidance point and the place of free oscillation excitation

In order to record a signal, the following parameters were set:

- time interval for signal recording - 20 seconds (5 beats);
- sample rate - 60,000 countings;
- the parameters of the detected signal pulses (sensitivity 10, pulse start minus counts - 10, multiplication of height - 0.4, height addition - 0).

The body of TC turbine experienced 5 mechanical impacts with a shock hammer from the height of 5 cm without an effort, under the action of gravity. The vibration parameters were recorded by a laser vibrometer.

The first series of experiments was conducted in order to develop a reference spectrum. One measurement was performed for each defect-free body, in which 5 mechanical shocks were performed. The reference spectrum is designed around 21 defect-free body parts of power plants for TC turbines of a gas engine, that is, according to 100 mechanical shocks (signals) (Figure 12).

In order to develop the reference spectrum and the confidence interval, the following parameters were set:

- zero reference number;
- signal sampling length for spectrum acquisition - 16,384 counts;
- frequency intervals, in which the processing of spectra will be performed, were selected on the basis of theoretical studies in ANSYS Workbench, and made 6-8 kHz and 12-14.2 kHz;
- Confidence level - 0,95;
- Normalization of the spectrum into the "on" mode.

The second series of experiments was conducted to obtain the spectra of control (defect and defect-free) shells and compare them with the reference spectrum. TC control bodies were used as the object of the study, the defects of which are described in Table 1. The spectrum of a defective control product (TC body No. 4) is shown on Figure 13.

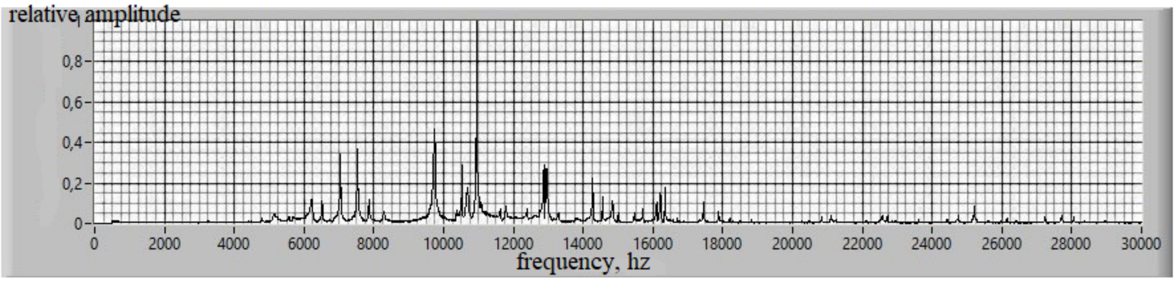


Fig 12. The reference spectrum of TC turbine bodies

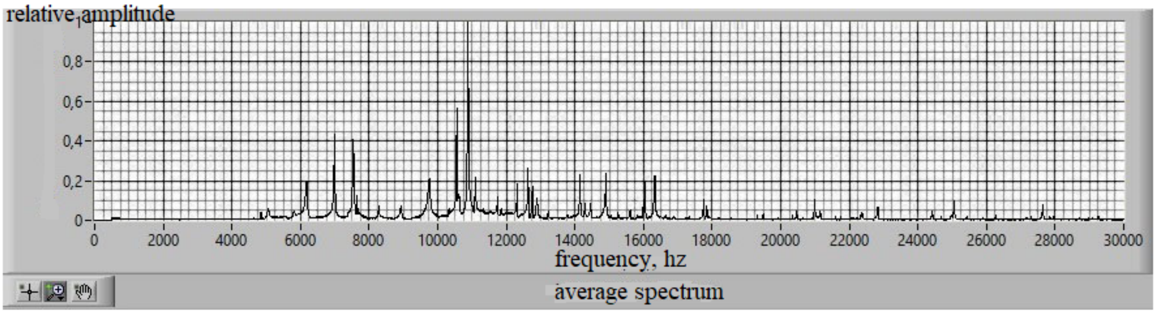


Fig 13. The spectrum of TC №4 defective body

The spectra were compared over the entire frequency range from 0 to 30 kHz and in the frequency range from 6 to 8 kHz and from 12 to 14 kHz.

The results of the reference and control spectrum comparison of TC No. 4 body are shown on Figure 14.

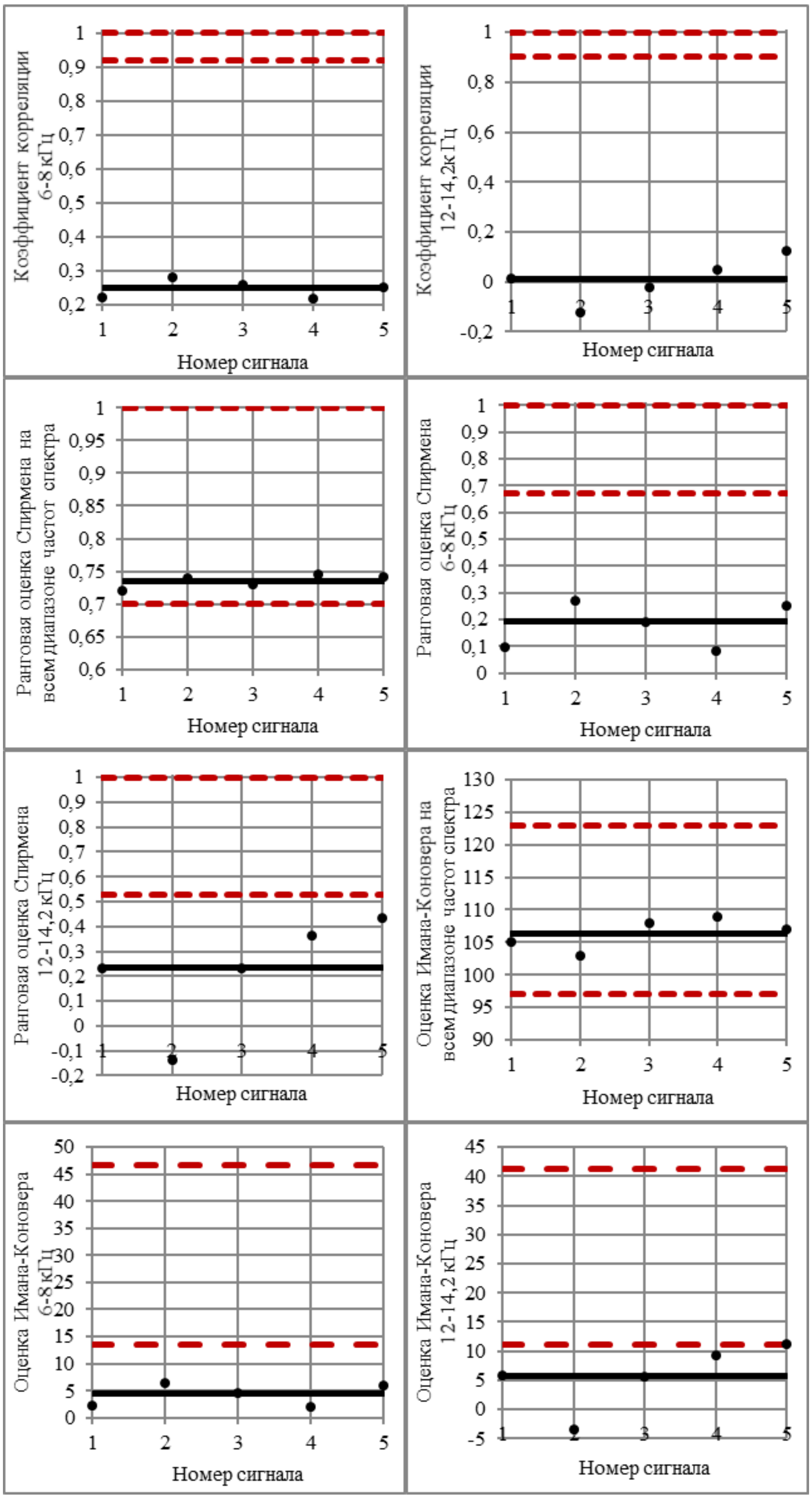


Fig 14. The results of reference and control spectrum comparison for TC № 3

The numbers of mechanical shocks (signal number) are presented on Figures 14 within the abscissa axis, the values of the target comparison functions are plotted along the ordinate axis, the dashed lines are the confidence interval boundaries, the solid line is the median value for all measurements of the control (defective) case.

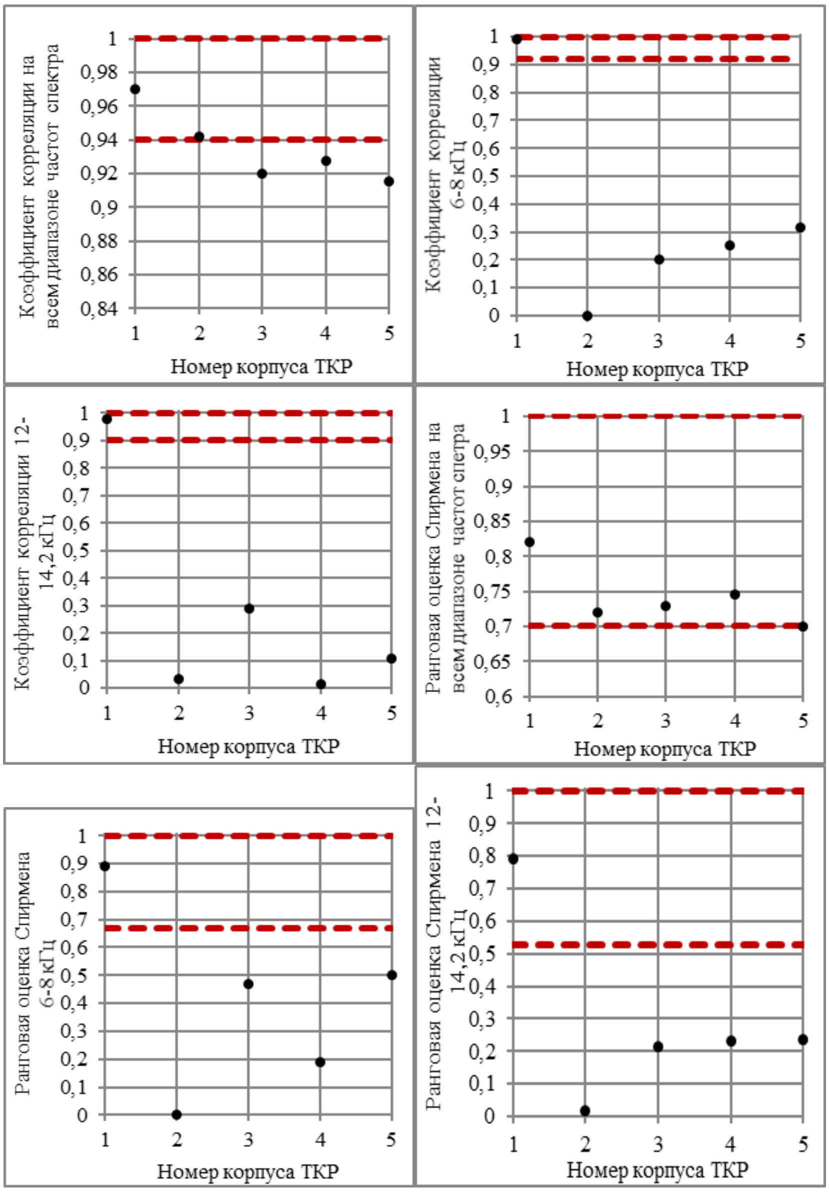
The values of the objective functions during the comparison of the spectra over the entire frequency range (0-30 kHz) are either near the boundaries or within the confidence interval, which indicates that a defect ("growth") of TC turbine body is not detected.

The values of function objective comparison in the frequency range of 6-8 kHz and 12-14 kHz go beyond the confidence interval of defect-free (reference) cases. Thus, the spectra on these ranges have significant differences, that is TC turbine body is recognized as a defective (a defect is detected).

By the technique described above, 5 control objects (4 faulty ones (Table 1) and 1 defect-free TC body) were studied. The results of the reference spectrum comparison and the spectra for 5 control objects are shown on Fig. 15. The dots denote the median values (of five signals) of the objective comparison functions for a corresponding TC body.

The median values during spectrum comparison over the entire frequency range (0-30 kHz) of TC № 1 defect-free body lie within the confines of the confidence interval (dashed lines), respectively, the body is recognized as a defect-free, the median values of the body No. 2, No. 3, No. 4, No. 5 (table 1 - defects) are either near the boundaries or within the confidence interval, which indicates that the manufacturing defects of the bodies are not detected.

Median values during spectrum comparison at the frequency intervals of 6-8 kHz and 12-14 kHz of TC No. 1 body (defect-free) lie within the confines of the confidence interval (dashed lines), respectively, the body is recognized as a defect-free one. The defective bodies No. 2, No. 3, No. 4 and No. 5 were uniquely identified using the developed IMC with the confidence level of 0.95 on the frequency bands of 6-8 kHz and 12-14 kHz.



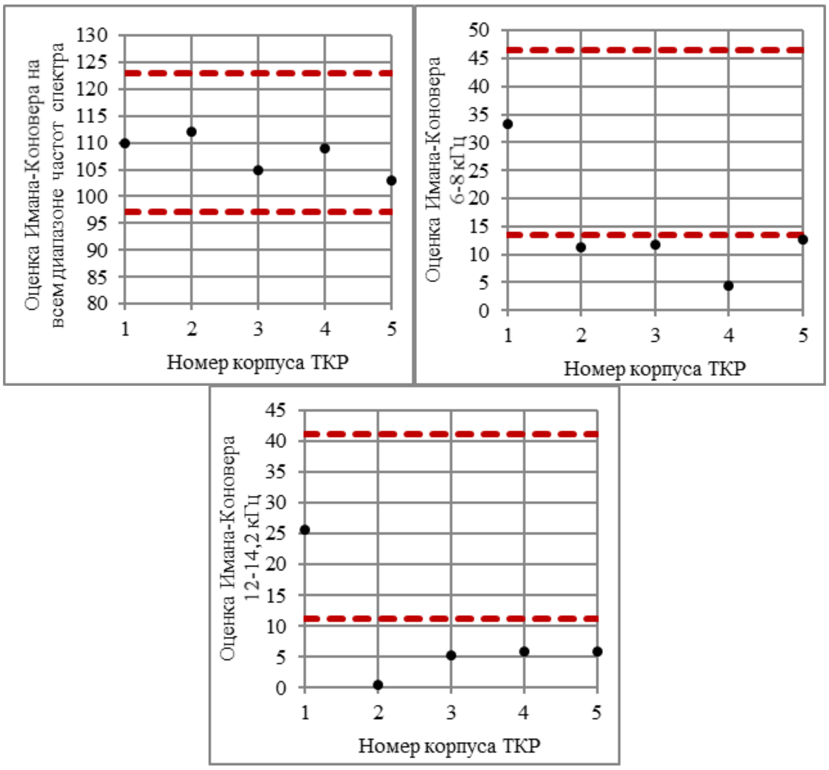


Fig 15. The comparison results of reference spectrum and the spectra of five TC control bodies

The defects described in Table 1 are detected on a narrow frequency band of 6-8 kHz and 12-14 kHz, which is determined by the output of the objective function values beyond the limits of the confidence interval with the confidence level of 0.95.

The analysis of the experimental data showed a stable defect detection in TC turbine body using a laser vibrometer according to 3 objective comparison functions at the frequency range of 6-8 kHz and 12-14 kHz and confirmed the possibility of this method use and the IMC to control the state of power plant parts in an automatic mode.

Based on the results of experimental studies, they tested the method for complex shape detail state control, based on the analysis of the informative frequency interval of the amplitude spectrum. The results of experimental studies confirm the theoretical studies on the effect of defects on the natural vibration frequencies of TC turbine engine bodies of a gas engine in the ANSYS Workbench software package. The most informative frequency intervals characterizing the presence of defects in TC turbine housings make 6 - 8 kHz and 12 - 14 kHz.

5 Conclusions

1. Theoretical studies were carried out to determine the informative frequencies of gas engine part natural oscillations associated with certain types of defects. The informative frequency intervals were determined after finite element modeling in the ANSYS Workbench software package, which allow to detect the defects in the turbine body of a gas turbine engine by analyzing the natural frequency spectrum.
2. A new method of non-contact vibration control of complex shape part state was developed, based on the analysis of the amplitude spectrum informative frequencies of natural oscillations associated with certain types of defects. The method is tested as the result of experimental studies using IMC.
3. A new IMC was developed and created for the implementation of a new method of non-contact vibration control of complex detail state using laser vibrometry methods. The developed complex allows to control contactless the state of gas engine parts, both during production and during operation.
4. The software was developed that allows to implement a new method of non-contact vibration control of power unit part state using non-contact laser vibrometry methods.
5. The experimental studies of natural oscillation parameters for gas engine parts have been carried out. The analysis of the experimental data showed a stable determination of the defect in a control object and confirmed the possibility of IMC use and the method of noncontact vibration control of defects in engine parts within automatic mode

6 Summary

After the theoretical and experimental research given in the work, the actual scientific and technical problem is solved in the field of nondestructive testing, which consists in a new method development for contactless vibration control of the state for complex shape parts, as well as in the development, the creation and the testing of an instrumental-measuring complex that implements a new method.

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