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VIBRATION RESISTANCE, VIBRATION TESTING, VIBRATION MONITORING AND DIAGNOSTICS OF GYROSCOPES AND OTHER ROTARY SYSTEMS

Ua Дана стаття присвячена викладенню в історичному розвитку досягнутих результатів, започаткованих М.А.Павловським наукового напряму, пов’язаного з вивченням коливальних процесів в обертових системах.

En This article is devoted to the presentation in a historical development of the results achieved, founded by M.A. Pavlovsky scientific directions related to the study of vibration processes in rotary systems

Vibration resistance of gyroscopes

In the 70’s of the last century, developers of control and navigation systems for new highly maneuverable objects faced the problem of ensuring vibration resistance of gyroscopes. The increase in intensity and expansion of the frequency range of vibration loads required the solution of a whole range of new, diverse tasks. Scientific works of M. A. Pavlovsky and his students developed the theory of vibrational stability of gyroscopic instruments, taking into account non-linear factors.

M. A. Pavlovsky was one of the first to draw attention to the fact that:

– non-linear factors appear not separately, but in combination;
– energy dissipation occurs not only under the influence of dry and viscous friction, but also hysteresis-type friction;
– resonant vibrations of gyroscopes, as a rule, are spatial;
– energy dissipation during resonant vibrations occurs mainly due to hysteresis-type friction.

The problem of vibration resistance of gyroscopes was considered from the unified standpoint of the analysis of nonlinear spatial oscillations, taking into account imperfect elasticity and nonlinear elastic characteristics of structural elements. The results obtained were summarized in the monograph [1].

Below are some of them:

– the moment of elastic unbalance reaches its maximum values at the main resonance. The maximum value does not depend on the difference in stiffness, but is inversely proportional to the energy dissipation in the structure;

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- among the non-linear resonances observed in gyroscopic instruments, the most unfavorable mode is the non-linear resonance of the n=1 kind, upon occurrence of which a constant component of the moment of elastic unbalance is formed even under the action of external vibration along one of the linear coordinates;
- a phenomenon close in essence to the phenomenon of parametric regeneration of oscillations was experimentally discovered, which leads to a significant increase in the amplitudes of the main resonance due to compensation of viscous friction due to a nonlinear relationship between the coordinates.
- the influence of a nonlinear resonance of n=1 kind and a phenomenon essentially close to the phenomenon of parametric regeneration of oscillations [2] becomes decisive for the vibration resistance of equally rigid gyroscopes. Due to non-linear resonant oscillations, the errors in equally rigid gyroscopes exceed those in unevenly rigid gyroscopes.

Based on the conclusions reached, the following recommendations were developed:

- implementation of the principle of equal stiffness allows to reduce the errors of gyroscopes outside their own frequencies of oscillation. To reduce the probability of an increase in the errors of gyroscopes due to the development of resonant oscillations, it is inappropriate to ensure the uniform stiffness of the structure is less than 10%;
- effective methods for reducing the errors of gyroscopes during vibration are to reduce the input vibro-impact effect through the use of vibration protection systems, the use of vibration-absorbing materials in the supporting structures, and increasing the natural frequencies of the gyroscopes;
- the introduction of polymeric materials into the design of gyromotors increases the vibration resistance of gyroscopes under resonance conditions, but has limitations due to temperature and time instability;
- active diagnostics of gyroscopes using resonances is more sensitive to defects than static tests.

Development of methodology for gyroscopes vibration testing

Experimental studies carried out within the framework of R&D works have made it possible to improve the methodology of vibration tests.

A full-scale study of serial single-axis vibration stands of the VEDS series and their foreign analogues was carried out. The amplitude-frequency characteristics of vibration stands are obtained in the normalized and extended frequency ranges. Vibrations of vibration stands in the regions of low-purity and high-frequency resonances of their design are studied. The frequency ranges in which the vibration effects specified by the vibration stand can be considered as singlecomponent and monoharmonic are determined. The vibrational characteristics of the mounting systems for the gyroscope blocks and individual gyroscopes on the vibro tables were studied. The basic principles for the development of these systems were formulated.

The results obtained were formulated in guidelines and used to test serial products.

Testing gyroscopes under resonance conditions

The received recommendations for testing gyroscopes in non-resonant frequency regions did not take into account the new requirements for the developed gyroscopes.

One of the new tasks of vibration testing of experimental gyroscopes was to determine their resonances. A necessary condition for carrying out such tests was to ensure the safety of the design of gyroscopes under conditions of dynamic loads increasing at resonances. The effect of the reverse action of a resonating gyroscope on a vibro table (moving part) of a vibrostand was discovered. At the same time, the level of vibration of a vibro table in the resonance of the gyroscope was significantly reduced, the so-called anti-resonance effect. The reverse effect depended on the ratio of a resonating mass and a vibro table mass, damping in the resonating system, and a frequency range of a resonance. Since most gyroscope designs had low energy dissipation, even if a resonating mass and a vibro table mass differed by more than an order of magnitude, the antiresonance effect significantly affected test conditions. In contrast to low-frequency oscillations, the mode of constant input disturbance was not always possible for resonances due to a limited power of a vibration stands and a critical increase in the load on the gyroscope’s bearings. Several original test methods were developed, which were described in the monograph [1].

A new direction of diagnostics - active vibration diagnostics of gyroscopes and their elements

The developed methods for testing gyroscopes under resonance conditions have found practical application for controlling the elastic-damping characteristics of gyromotors. The methods are based on the use of test harmonic excitation and analysis of the gyro motor response to this disturbance. This direction in diagnostics was called active diagnostics and was developed primarily for research purposes. One of the successful applications of active vibration diagnostics was the control of the axial preload of gyromotors, which has also found application in serial production. Increasing the stiffness of gyromotors and reducing their dimensions have made static methods for determining the axial interference ineffective. The technique was based on using the dependence of the components of the stiffness matrix of the ball-bearing bearings of the rotor on the magnitude of the axial interference force [3].

Given that the mass characteristics of the vibrating table-gyromotor system were known in advance, the resonance (or antiresonance) frequency was used to control the axial preload. The practical implementation of the method became possible after the creation of systems for mounting gyromotors on a vibration stands table (or vibrators), which did not change their elastic characteristics. The disturbance level was selected from the requirements of the minimum impact on the gyro motor and the repeatability of the measurement results. An example of such control is given in Copyright certificate No. 1130092 Method for determining the tightness of the rings of ball bearings of a gyromotor [4].

Vibration monitoring and diagnostics of gyroscopes with ball bearings

The problem of diagnosing bearings of gyroscope supports arose due to the need to solve a number of tasks:

– monitoring and norming of vibrational activity of navigation systems gyroscopes
– quality control of gyroscopes assembly, starting from the early stages of the technological process
– forecasting the resource of gyroscopes based on acceptance tests.

As studies have shown, the main contribution to the intrinsic vibration of gyroscopes was made by the bearings of the main axis of the gyroscope. The construction of generation models of not only vibration, but also stiffness oscillations has become the basis for developing the theory and practice of monitoring and diagnosing precision rotor systems.

Generation models of ball bearings of precision rotor systems

Rolling bearings are widely used as bearings for rotary systems. According to the type of rolling elements, roller and ball bearings are distinguished. Depending on the perceived load, radial, thrust (axial) and angular contact bearings are used. According to the assembly conditions, bearings with axial preload and with radial clearance are distinguished. The stability of the axial tension during operation is often ensured using axial expansion joints.

Each type of rolling bearing and design of the rotor system brings its own characteristics to the vibration pattern. In [5], a generating model was built for preloaded angular contact ball bearings. This is the most common case for gyroscopes. Based on large-scale studies of the state of the surfaces of precision ball bearings, it was found that the predominant defects are edging and waviness of raceways of the rings and rolling elements. (Distributed defects). The profile of the raceways of rings and balls can be represented as a set of harmonics of its expansion in a Fourier series. The prevailing defects are introduced at the stage of mounting ball bearings and are described by the first harmonics of the expansion of the raceways in the Fourier series: the first harmonic is the misalignment of the rings; the second harmonic is the ovality of the rings and balls etc.

Unlike plain bearings, the movement of ball bearing parts is very complex. So, the ball participates in orbital rotation with the frequency of the separator and at the same time around its own axis. To build a generating model, it is necessary to know four generating frequencies generating frequencies:

ω – angular velocity of rotation of the rotating ring;

ω_A – angular velocity of the separator rotation relative to the fixed race;

ω_B – angular velocity of the separator rotation relative to the rotating race;

ω_C – ball angular rotation velocity.

Analytical model of kinematic vibration of a precision rotor system on angular contact ball bearings with axial preload

Building analytical vibration models is a complex and time-consuming task. The problem can be correctly solved under certain assumptions, for example, in the so-called quasi-static setting. In this case, it is assumed that the frequencies of the disturbing forces generated by non-ideal bearings are significantly lower than the natural frequencies of the rotor system. This assumption is valid for most gyroscopes. This approach, used by the author of this article, made it possible to obtain the coefficients of the influence of defects on the vibration of the rotor system, the change in the coefficients of the stiffness matrix and the moment of resistance to rotation.

The obtained composition of the spectrum of disturbing forces and oscillations of the stiffness matrix components made it possible to build generation models that explained most of the phenomena observed during testing of gyroscopes.

On the basis of these studies, the practical problem of reducing the vibrational activity of gyromotors by eliminating resonant oscillations caused by bearing vibration was solved.

Another, perhaps more important, application of these results was the development of a new direction in gyroscope diagnostics. It was shown that in order to solve diagnostic problems, it is sufficient to confine ourselves to the analysis of the first two approximations of stiffness oscillations and perturbing forces. Table 1. shows the vibration spectrum in the first approximation.

As can be seen from Table 1, as a first approximation, the vibration of a ball bearing is caused by a limited number of harmonics of ring defects. Therefore, to describe the impact on the vibration of the rotor system of such significant errors as assembly defects, constant and variable loads, it is necessary to consider the second approximation.

***Table* 1.**

Vibration of radial-and-thrust ball bearings, in the full contact mode (1st approximation)

Direction	The type of defect the number of the expansion harmonics	Harmonics frequency
Axial	Waviness of non-rotating race $e_A = \lambda n,\ \lambda = 1,2...$	$\lambda n \omega_A = \lambda \omega_{nA}$
	Waviness of rotating race $e_B = \lambda n,\ \lambda = 1,2...$	$\lambda n \omega_B = \lambda \omega_{nB}$
	Lack of the roundness of the ball $\begin{cases} e_C = 2,4,6 \\ e_C = 3,5,7 \end{cases}$	$\begin{cases} e_C \omega_C \\ 2e_C \omega_C \end{cases}$
Radial	Waviness of non-rotating race $e_A = \lambda n \pm 1,\ \lambda = 1,2...$	$\lambda n \omega_A$
	Waviness of rotating race $e_B = \lambda n \pm 1,\ \lambda = 1,2...$	$\lambda n \omega_B \pm \omega$
	Unequal balls $e_C = 0$	ω_A
	Lack of the roundness of the balls $\begin{cases} e_C = 2,4,6 \\ e_C = 3,5,7 \end{cases}$	$\begin{cases} e_C \omega_C \pm \omega_A \\ 2e_C \omega_C \pm \omega_A \end{cases}$

The second approximation describes the occurrence of vibration from the interaction of two defects. Moreover, these defects can enter into the expression for the disturbing forces both directly and through one or two generalized displacements obtained as a result of solving the equation of the first approximation.

The author showed that in order to explain the observed phenomena, it was necessary to study the complete nonlinear model of the SHP, which takes into account the nonlinear relationships between the coordinates and changes in the contact angle during deformation of the ball bearings.

It has been shown that for diagnostic purposes the spectrum of axial vibration and axial stiffness is most suitable for diagnostics. The movement of the separator does not affect the formation of the spectra of these quantities, which is why they coincide.

From the analysis of the amplitudes in the spectrum of axial vibration and axial stiffness, other things being equal, the harmonics given in Table 2 will prevail.

***Table* 2.**

The basic components of the axial vibration
(2nd approximation)

Defect	Mismatched non-rotating race		Con-stant radial loading	Une-qual balls	Lack of the roundness of balls	Edging of ro-tating race $e_B \geq 3$
Mismatched non-rotating race Axial run-out	$\omega^{*)}$	---	---	---		---
Mismatched non-rotating race Ellipticity	---	2ω	---	$2\omega_A$	$2e_c\omega_c \pm 2\omega_A$	---
Mismatched rotating race Ellipticity	---	---	---	$2\omega_B$	$2e_c\omega_c \pm 2\omega_B$	---
Mismatched rotating race Axial run-out		$\omega^{*)}$				
Edging of the rotating race $e_A \geq 3$	---	---		---	---	$e\omega$, $e = e_A = e_B$

Practical issues of vibration diagnostics of gyroscopes with ball bearings

The obtained theoretical results have made it possible to create methods for diagnosing precision rotor systems on angular contact ball bearings with axial preload. A qualitative leap in the development of vibration diagnostics was the transition from measuring the overall level of vibration to the analysis and normalization of individual harmonic components of the vibration spectrum [6]. It took several years of efforts to develop information-measuring systems that allow diagnosing gyromotors in pilot production.

The development of this direction faced the following limitations, which were associated with:

– spatial nature of the vibration;
– commensurate weight of vibration sensor and gyro motor:
– lack of non-contact methods for measuring the vibration;

– ensuring repeatability of test results (mounting errors, change in gyro motor temperature).

It should be borne in mind that this method could be used primarily for fully assembled products, which often precludes dismantling to correct defects.

The foregoing stimulated the search for alternative solutions in the field of active vibration diagnostics, which was used and developed to control the stiffness characteristics and axial preload of gyro motors. The experience of controlling the axial preload has shown that when measuring the dynamic stiffness, its values depend on the angular position of the rotor. The average value of the dynamic stiffness characterized the value of the axial preload, and its spread was the error in manufacturing and assembling the precision rotor system. Spectral analysis of oscillations of the axial resonance frequency of the gyro motor made it possible to control the main errors in the manufacture and assembly of its ball bearings. A detailed method for determining the defects of the ball-bearing bearings of the rotor is described in the Copy right certificate No. 1597661[7]. At the same time, a measuring complex was created to implement a new method of active vibration diagnostics, for which a copyright certificate No. 1627874 was obtained [8]. This method has found wide application in a number of industrial enterprises to diagnostic gyro motors weighing from 7 rams to 5 kilograms

The created complex made it possible, in addition to active diagnostics, to evaluate the vibrational activity of the gyromotor and micropower fluctuations. Comprehensive diagnostics of gyroscopes at all stages of their assembly made it possible to implement a method for predicting the resource of devices based on the results of ground tests.

Development of a monitoring and diagnostics system for rotating equipment of nuclear power plants (NPPs)

The sharp reduction in defense orders required the search for new areas of application for the developed diagnostic methods. With the direct participation of M. A. Pavlovsky, the Scientific and Technical Center of NAEK Energoatom "Diagnostics of Technological Equipment of NPPs" (STC DIATOS) was created at the Kiev Polytechnic Institute. At the request of the industry, the Concept of a monitoring and diagnostics system (SMD) for rotating equipment of NPPs was developed. The SMD was designed to provide not only control over the safe operation of rotating equipment, but also to reduce the cost of its maintenance and repair. Vibration monitoring has been used as the most versatile and practical way to obtain information about the technical condition of rotating equipment.

According to the developed concept, the SMD had to solve two main tasks:

– create a diagnostic base for switching to maintenance according to the actual state, i.e. ensure reliable monitoring of the actual state and forecasting of the residual life of the equipment in operation.
– ensure the determination of the causes of vibration failures for the subsequent elimination of the operating conditions of the equipment that caused them.

The created software package provides SMD with the following operation modes:

– *Periodic monitoring*. This is the main mode of operation of the SMD. In this mode, the following is carried out: measurement of the vibrational and technological parameters of the unit according to a predetermined schedule or as needed, depending on the actual state of the industrial equipment in operation. Processing and analysis of the measured parameters and assessment of the current state of the unit mechanisms are carried out. The software package issues a warning and alarm when the specified limits are exceeded.
– *Adaptive monitoring*. The adaptive monitoring mode is designed for flexible restructuring of the measurement and analysis system to improve the signal-to-noise ratio. This reduces the risk of misdiagnosis and recognizes defects at earlier stages of their inception. The depth and frequency of testing can be changed depending on the following factors:
  – current vibration and technical condition of the equipment;
  – condition of pumping units after repair;
  – modes of operation of pumping units and classes of technological processes.

In class-based adaptive monitoring, the operating mode is divided into classes depending on the process parameters.

– *Diagnostics of the state of the equipment*. In this mode, the software package will perform:
  – express diagnostics of equipment condition;
  – evaluation of the sufficiency of the amount of information for diagnosis.

  Preparation of recommendations for an extended inspection of equipment.
– *Multi-channel research complex for searching for the causes of defects*. It is used for:
  – analysis of special modes of equipment operation and extended testing in the event of the “Alarm” state;
  – carrying out complex diagnostics of the technical condition;
  – identification of the mutual vibrational influence of the units.
– Balancing. This mode, depending on the tasks to be solved, is divided into two functional levels: two-plane balancing and multi-plane balancing.

Given the large number of controlled units at NPPs, to perform the preventive monitoring functions listed above, a mobile (of-line) SMD based on a portable data collector and a multi-channel portable research complex was chosen.

Data collectors performed the following functions:

- determination of the overall vibration level in the frequency band required by international and national vibration control standards;
- spectral analysis of vibration;
- analysis of the spectrum of the envelope of a random high-frequency vibration signal;
- analysis of vibration signal form (operation in oscilloscope mode);
- storage of measured information.

Several modifications of the mobile SMD were created on the basis of the developed portable analyzers of the DC series. Most Ukrainian NPPs were equipped with these SMDs.

The created multi-channel research complexes were introduced at KhNPP and South Ukraine NPP both for multi-plane balancing and for researching alarm situations. A great contribution to the development and implementation of multichannel research complexes was made by O. A. Cherdyntsev. The multichannel monitoring systems for buildings and building structures developed under his leadership are widely used in SE “STATE RESEARCH INSTITUTE OF BUILDING CONSTRUCTIONS”. The implemented modal analysis functions made it possible to use the mentioned complexes to control the technological process of pile driving

More than 10 years of experience in the study of rotating equipment of nuclear power plants was summarized in the standard STP SE NAEK “ENERGOATOM” Norms of the vibration state of rotating mechanisms of nuclear power plants”, developed by STC DIATOS at NTTU KPI.

Condition monitoring and diagnostics of critical power equipment [9]

The positive results of mobile systems implementation for preventive monitoring and diagnostics became the basis for the implementation of these systems in related energy sectors, in particular, in the oil and gas sector. The implementation of domestic gas turbine engines at the compressor stations of the Ukrainian gas transmission system required the development of methods and means for condition monitoring gas compressor units. SMD were supposed to provide not only protective monitoring, but also preventive (predictive) monitoring.

Protective monitoring should provide:

- protecting equipment from primary failure and reducing the risk of secondary damage to equipment, danger to personnel and the environment;
- operational information to ensure that the equipment is operating within the limits prescribed by the designer and/or manufacturer of the controlled equipment.

Protective monitoring should immediately respond to any identified change in the state of the equipment under control. The response speed is determined by the relevant standards for the particular type of equipment. The requirement for system speed dictates the use of simple measurements in protective monitoring. These requirements can only be met in stationary systems using permanently installed primary information sensors and data collectors implemented on industrial computers. These systems must operate in on-line monitoring mode.

Preventive (predictive) monitoring aims to identify potential problems. Condition monitoring alone cannot prevent a failure, but timely warning of a problem can saves cost and time, since scheduled repairs (replacing a defective node) are incommensurably easier and cheaper than fixing a failure with secondary

Thus, increasing the efficiency of equipment use, reducing the costs of its operation, maintenance and repair is the main incentive for predictive monitoring programs implementation. This type of monitoring does not require an immediate response, but it requires high sensitivity to detected anomalies and the reliability of the generated assessment of the current technical (vibration) condition and the forecast of its development. Since no immediate reaction is required, the interval between subsequent measurements can range from a few hours to weeks and months.

Therefore, periodic predictive monitoring, as shown in the previous paragraph, can be performed using mobile or portable data collectors using temporarily installed sensors. The undoubted advantage of this approach is its relative cheapness, which justifies its use for a wide class of general-purpose equipment. The second advantage is the flexibility and ease of increasing computing resources (especially when using mobile computers), which makes it indispensable for additional diagnostic studies of equipment.

Until recently, on-line monitoring has been associated with protective monitoring. Regulatory organizations in various countries are expanding the list of equipment that must be covered by continuous protective monitoring systems, which leads to an increase in the cost of equipment operation. On the other hand, the rapid growth in productivity and the decrease in the cost of industrial computers has led to the fact that the share of sensors and measurement channels has become prevalent in the total cost of a monitoring system.

In this regard, it has become cost-effective to supplement protective equipment systems with predictive monitoring functions in order to reduce the cost of maintenance and repair of this equipment. As a rule, the cost of installing a complex multi-channel and multi-parameter predictive monitoring system is a small part of the cost of the equipment under control and is commensurate with one day of forced downtime for this equipment.

Another trend in the creation of integrated monitoring and diagnosing systems for critical equipment is to provide the ability to work with data obtained from both stationary and portable (mobile) data collectors. This allows using one program to assess the technical condition of the enterprise equipment, regardless of the type of collector (stationary or portable) and, if necessary, increase the amount of information received and the depth of its processing on the problem unit by installing additional sensors and carrying out additional measurements by portable (mobile) means.

An integrated multifunctional monitoring and diagnostic system was developed and implemented for a gas compressor units (GCU). The developed monitoring and diagnostics system for GCU (hereinafter referred to as the System) is designed for continuous protective and periodic preventive (predictive) monitoring and analysis of the causes of changes in the vibration state of the GCU. The system provided:

– protection of equipment in terms of vibration parameters and axial displacement of GCU;
– automation of the processing of current and archived information to search for and identify deviations from the normal operation of the mechanical units of GCU for timely warning of personnel about the origin and development of possible malfunctions;
– the possibility of diagnosing GCU defects and analyzing their causes.

The expert level is an automated place of an expert-diagnostician, on which the software package “Detailed diagnostic monitoring of GCU of compressor station “DD-MONITORING_G” developed by STC DIATOS is installed. The program of detailed diagnostic monitoring “DD-Monitoring G” or “DD-Monitoring *G* plus” allows you to implement the chosen strategy of preventive (predictive) monitoring and provides a wide range of diagnostic tools. The system was installed on the GPA-25 gas compressor units of the Barskaya, Sofievskaya and Grebenkovskaya compressor stations, and the diagnostic engineer's remote workplace was implemented at the Cherkasytransgaz department of main pipelines.

Using methods of the technical condition assessment for technical audit of oil and gas facilities

The created methodology for the technical condition assessment of equipment was used to carry out several international projects:

The TACIS project ATA 2000/014 “Technical audit of Sea Oil Terminal Pivdenny”. Dr. Petrenko led the Technical audit team that conducted:

– development of methodology of integrated assessment of technical condition of Sea Oil Terminal Pivdenny
– diagnostics of main and auxiliary pumps, valves, electrical, control and metering equipment, tank farm, and piping etc;
– assessment of Terminal technical condition of Sea Oil Terminal Pivdenny;
– development of Recommendation to improve Safety Management System of Terminal, Condition Monitoring and Diagnostic System.

The TACIS project EuropeAid/119460/C/SV/UA, Reform of the Operation System of Gas Transit in Ukraine, Phase III. Dr. Petrenko led the Technical audit team that conducted:

– development of the Procedure of integrated assessment of technical condition of key elements of Gas Transit Network (GTN) of Ukraine;
– technical audit of key elements of GTN, according to the applicable legislative and normative framework;
– analysis of management process: the construction management, rehabilitation process (rehabilitation of gas compressor units), the operation – Maintenance Process, Training Process, Purchasing, Quality process;
– analysis of efficiency of Operating System of GTN of Ukraine, including Quality Management System and Safety Management System;
– development of recommendations for the reform of Operating System and maintenance of GTN of Ukraine including harmonization standards and technical regulation.

Based on the results obtained, plans were made to reform and modernize the gas transit infrastructure. One of the main goals of reforming the Ukrainian gas infrastructure was its integration into the European one.

To eliminate technical barriers between gas transmission systems, it was necessary to harmonize Ukrainian gas standards with European and international ones. It took several international assistance projects, in which the author took an active part, for the adoption in Ukraine of European gas functional standards, as well as related standards. In general, about 100 European and international standards were adopted, which ensured the target level of harmonization.

Conclusion

– Works by M. A. Pavlovsky and his students made it possible to make a qualitative leap in vibration testing of complex mechanical systems with rotating elements.

- Created in the 28th building of NTTU KPI, a unique experimental base made it possible to carry out vibration tests of a wide range of objects, including resonance modes.
- The developed methods of vibration diagnostics of precision rotor systems have no analogues and allow not only to control the assembly process, but also to predict the operation of the product based on ground tests.
- Adaptation of the developed methods of monitoring and diagnostics for critical equipment made it possible to create monitoring and diagnostic systems for rotating equipment of nuclear power plants and gas compressor units.
- The created methodology for assessing the technical condition of critical energy infrastructure facilities was successfully applied for the technical audit of several of critical energy system, in particular, Ukrainian GTN.

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