**Syllabus**
Course Program

# Dynamics of Rotors in Magnetic Bearings

Specialty
113 – Applied Mathematics

Institute
Institute of Computer Modeling, Applied Physics and Mathematics

Educational program
Computer and Mathematical Modeling

Department
Mathematical Modeling and Intelligent Computing in Engineering (161)

Level of education
Master's level (1 year 4 months)

Course type
Special (professional), Elective

Semester
1

Language of instruction
English

## Lecturers and course developers

**Gennadii Martynenko**
**(responsible lecturer and laboratory practical teacher)**
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Doctor of Engineering Sciences, Professor, Professor at the Department of Mathematical Modeling and Intelligent Computing in Engineering of NTU "KhPI"
Scientific and pedagogical work – 18 years. Author of more than 180 scientific and educational works.

Lecturer and laboratory workshop teacher of the discipline:
"Database organization", "Data Mining",
"Software systems for design and analysis",
"Software for simulation of physical processes",
"Modeling of objects and processes in CAD/CAE systems",
"Analysis of dynamic processes in CAD/CAE systems",
"Modeling in CAE systems",
"Approximate and numerical methods for solving nonlinear problems",
"Pedagogical and information technologies in applied mathematics".

More about the lecturer on the department's website

## General information

### Summary

The discipline is included in the block of selective disciplines in the direction of "Modeling of dynamic processes" and is devoted to the consideration of both general issues of modeling dynamic processes in rotor systems and machines for various purposes, namely linear and nonlinear phenomena of rotor dynamics, and highly specialized problems of modeling processes when used as supports passive and active magnetic bearings. The discipline is aimed at developing the knowledge, skills and abilities necessary for an analytical mathematical description of the dynamics of rotors in rigid, elastic, and, as a special case, magnetic supports. Approaches to the creation of analytical mathematical models applicable to the description of both rigid and flexible rotors, taking into account the rigidity of support in bearing

units, are considered. For passive and active magnetic bearings, information is provided to determine stiffness using analytical and numerical approaches. The practical use of the theoretical foundations of mathematical modeling of the dynamics of rotors, i.e. rotating shafts with attached elements (disks, impellers, trunnions, couplings, etc.), is demonstrated using modern multipurpose design and analysis packages, namely CAE (Computer-Aided Engineering) systems of finite element analysis of processes ANSYS Workbench. All stages of computer analysis of rotor dynamics are considered, taking into account possible nonlinearities of the power characteristics of magnetic bearings, including features of geometric modeling, applicable types of finite elements, mesh partitioning methods using various types of problem statements and corresponding types of finite elements, construction of a calculation model with boundary conditions and loads , output of calculation results, assessment of the quality of the finite element model and calculation results. This combination of theoretical and practical knowledge makes it possible to approach the solution of scientific and applied problems in the field of professional and research-innovative activities and mastering modern world trends in the development of methods for computer modeling of the class of objects under consideration and the processes occurring in these objects.

## Course objectives and goals

The goals of the discipline is: to develop students' knowledge of existing modern approaches to the theoretical methods of mathematical description and practical methods of computer modeling using computer CAE systems of engineering design and analysis of the dynamics of rotors of systems and turbomachines for various purposes, with an emphasis on the features of magnetic bearings of passive and active type.
The objectives of teaching the discipline are: to provide students with in-depth knowledge of methods and programs for solving problems of searching for the dynamic characteristics of rotor systems with various types of bearing supports (rigid, elastic, in particular magnetic) and simulation of the dynamic processes occurring in such systems under various types of load, in in particular due to the system's own imbalance. The practical solution of typical problems occurs using a modern specialized software package for modeling and finite analysis of processes ANSYS Workbench to create a procedure for analyzing and simulating processes and phenomena, which consists of constructing physical models of real objects, geometric modeling, and creating computational models. settings of the solution and the solution itself, displaying results in graphical and text form, assessing the accuracy of numerical results and their analysis with checking the operating conditions depending on the type of analysis. When solving most of these problems, the main labor involved is determining the parameters that characterize the state of the object depending on the formulation of the problem and the analysis performed, therefore increased attention is paid to solving problems based on the finite element method. At the same time, methods are considered for reducing the dimensionality of problems through the use of various types of finite elements, as well as through the use of lumped factors. The listed methods and techniques for studying the parameters of structures and mechanical systems are demonstrated by solving specific problems that are often encountered in practice, using the interactive mode of operation of the ANSYS Workbench software package.

## Format of classes

Lectures, laboratory classes, consultations, self-study. Final control in the form of a credit

## Competencies

Program competencies according to the educational program:
PC1: Ability to solve tasks and problems that can be formalised, require updating and integrating knowledge, in particular in conditions of incomplete information;
PC2: Ability to conduct scientific research aimed to develop new and adapt existing mathematical and computer models to study various processes, phenomena and systems, conduct appropriate experiments and analyse the results;
PC4: Ability to develop and research mathematical and computer models, conduct computational experiments and solve formalised problems using specialised software;
PC9: The ability to mathematically formalise the formulation of scientific and practical problems, to choose a mathematical analytical or numerical method of its solution, which ensures the required accuracy and reliability of the result;

PC10: Ability to develop mathematical methods and algorithms for computer modelling of nonlinear physical phenomena and processes in innovative technological systems;
PC11: Ability to mathematically describe various dynamic processes that can occur in systems of design objects.

### Learning outcomes

Program learning outcomes according to the educational program:
LO4: Build mathematical models of complex systems and choose methods of their research, implement the built models in software and check their adequacy using computer technologies;
LO14: To have the knowledge to mathematically formalise the formulation of scientific and practical problems, to choose a mathematical analytical or numerical method of its solution, which ensures the required accuracy and reliability of the result;
LO17: Possess knowledge of the mathematical description of various dynamic processes that can occur in systems of design objects.

### Student workload

The total volume of the course is 120 hours (4 ECTS credits): lectures - 32 hours, laboratory classes - 16 hours, self-study - 72 hours.

### Course prerequisites

The study of the course is based on the knowledge acquired during the completion of the bachelor's educational program in specialty 113 - Applied Mathematics, in particular the educational program "Computer and Mathematical Modeling", namely: concepts, formulations, approaches and methods of mathematical analysis, modeling, theoretical and analytical mechanics, mechanics of a deformable solid and the theory of vibrations, and on the information considered in the disciplines of the curriculum: Discipline in the profile direction “Special Numerical Methods”.

### Features of the course, teaching and learning methods, and technologies

As part of the author's course "Dynamics of rotors in magnetic bearings", lectures are conducted interactively using multimedia technologies. In laboratory classes, a practically oriented approach to learning is used, general and individual tasks are performed, allowing one to gain knowledge and skills in the use of software tools and applications for modeling dynamic linear and nonlinear processes in rotor systems and machines, namely the dynamics of rotors in different bearings, to evaluate strength and stable state of these objects. When conducting a laboratory workshop, freely licensed software for training (Free Student Software) is used, in particular the student version of the ANSYS Mechanical APDL and ANSYS Workbench packages, which is freely available on the ANSYS, Inc. website for download.

## Program of the course

### Topics of the lectures

MODULE #1. Lecture classes (LCs) 2 credits / 32 hours “THEORETICAL FOUNDATIONS FOR MODELING LINEAR AND NONLINEAR DYNAMICS OF ROTORS IN RIGID, ELASTIC AND MAGNETIC BEARINGS” (*one class covers 1 topic in 2 hours*)
Topic 1. Introduction to linear and non-linear dynamics of rotors.
1. Historical foundations of the theory of rotor dynamics. 2. Modern rotary machines and systems. 3. Types of bearing supports. 4. Approaches to modeling and analysis of rotor dynamics.
Topic 2. Magnetic bearings (types and operating principles).
1. Principles of magnetic levitation and types of magnetic bearings (MBs). 2. Passive magnetic bearings (PMB) with permanent magnets. 3. Active magnetic bearings (AMBs). 4. Systems and algorithms for AMBs control. 4. Methods and methodologies for calculating force and stiffness characteristics.
Topic 3. Tools for analyzing rotor dynamics in different types of bearing arrangements.
1. Existing analytical and numerical approaches to modeling the dynamics of rotors in bearings of various types and means of their implementation. 2. Promising directions of scientific research in the field of rotor dynamics in magnetic bearings.

Topic 4. Rotor dynamics analysis in ANSYS APDL/Workbench.
1. Introduction to rotor dynamics analysis using numerical finite element method. 2. General equations of dynamics. 3. Advantages of the finite element method for modeling rotating structures. 4. Overview of the rotor dynamics analysis process. 5. Rotor dynamics analysis tools. 6. Commands used in rotor dynamics analysis. 7. Finite elements used in rotor dynamics analysis. 8. Terminology used in the analysis of rotor dynamics (gyroscopic effect, whirl - precession, elliptical orbit, stability, critical speed, Critical Speed Map, Campbell Diagram).
Topic 5. Rotor dynamics analysis in ANSYS APDL/Workbench.
1. Stages of rotor dynamics analysis. 2. Building a model. 3. Modeling of parts. 4. Modeling of bearings using finite elements COMBIN14, COMBI214, FLUID218, MATRIX27 and MPC184, their purpose, differences and settings. 5. Modeling tips and examples (adding a stationary part, turning non-axisymmetric parts into equivalent axisymmetric mass, defining multiple rotating parts, validating the model by printing a rotor mass summary). 6. Application of loads and boundary conditions (constraints) in rotary dynamics analysis (quasi-static loads, rotating forces in Harmonic and Transient Analysis). 7. Distributed forces arising from an unbalance in the model of a solid body or shell.
Topic 6. Rotor dynamics analysis in ANSYS APDL/Workbench
1. Solution of rotor dynamics analysis. 2. Adding damping. 3. Setting the rotation speed and taking into account the gyroscopic effect. 4. Solution procedure for further Campbell Analysis of prestressed structure using Linear Perturbation. 5. Solving a Harmonic Analysis using rotating synchronous or asynchronous forces (using OMEGA, CMOMEGA commands). 6. Selecting a suitable solution for Modal, Harmonic and Transient Analysis. 7. Using Modal Analysis of Linear Perturbation.
Topic 7. Rotor dynamics analysis in ANSYS APDL/Workbench
1. Postprocessing of the rotor dynamics analysis results. 2. Postprocessing of complex results in postprocessors POST1 and POST26. 3. Visualization, printing of characteristics and animation of orbits after Modal or Harmonic Analysis. 4. Visualization of orbits after analysis of transient actions. 5. Postprocessing of support and reaction forces in COMBI214 and FLUID218 finite elements. 6. Campbell Diagram (visualization of the evolution of frequencies with changes in rotation speed, checking stability and precessional rotation in each mode, determining critical speeds and stability thresholds).
Topic 8. Construction of analytical mathematical models to describe the dynamics of rigid rotors in magnetic bearings of various types.
1. Description of rotors in magnetic bearings as dynamic electromagnetomechanical systems. 2. Mathematical description of the dynamic behavior of the rotor in the MB depending on the adopted simplifications ("mechanical" part of the mathematical model). 3. Statement of the problem and nonlinear equations of motion describing the vibrations of rigid bodies in a potential field of forces. 4. Design diagram of a rigid rotor in magnetic bearings. 5. Determination of inertial forces. 6. Non-inertial forces acting on a rigid rotor in magnetic bearings. 7. Linearized equation of motion of a rigid rotor in magnetic bearings. 8. Nonlinear equation of motion of a rigid rotor in magnetic bearings..
Topic 9. Construction of analytical mathematical models to describe the dynamics of rigid rotors in magnetic bearings of various types.
1. Principles and specifics of the mathematical description of rotor dynamics using the AMB (electromagnetic part of the mathematical model). 2. Disadvantages of simplified approaches. 3. Construction of a linearized multidimensional coupled model of a rotor with controlled electromagnetic bearings. 4. A method for analyzing electromagnetic circuits of active magnetic bearings in order to find refined analytical expressions of magnetic energy and forces.
Topic 10. Construction of analytical mathematical models to describe the dynamics of rigid rotors in magnetic bearings of various types.
1. Complete nonlinear dynamic model of a rigid rotor in an MP. 2. General principles of forming a model of the dynamics of rigid rotors in an MP. 3. Features of mathematical models in the presence of passive MFs in the system for the implementation of combined magnetic suspensions. 4. Methodology for finite element calculation of force and rigidity characteristics of passive and active MPs taking into account the control law.
Topic 11. Analytical mathematical models of the dynamic behavior of flexible rotors in MBs.
1. The priority and sufficiency of the analysis of the dynamics of rigid rotors in an MBs. 2. Features of constructing mathematical models of flexible rotors. 3. Computer and software tools for calculating the parameters of the MBs and rotor dynamics, taking them into account
Topic 12. Control systems and monitoring of dynamic characteristics of rotor systems with active magnetic bearings.

1. Principles for the construction of AMBs control systems. 2. Analog and discrete control methods and algorithms. 3. An example of the implementation of a control method for a laboratory model of a rotor in a combined magnetic suspension. 4. Demonstration of the phenomena of nonlinear rotor dynamics based on experimental studies of the dynamics of a model rotor.

Topic 13. Dynamics of rotors in a combined passive-active magnetic suspension using the example of a model rotor..

1. Laboratory rig of a rotor in a combined magnetic suspension. 2. Calculation of the characteristics of linear oscillations of the rotor. 3. Construction of a nonlinear analytical model, its linearization and determination of natural frequencies, as well as critical rotation speeds. 4. Solution of the problem of nonlinear rotor dynamics of a laboratory model. 5. Construction of a nonlinear model. 6. Analysis of nonlinear dynamics of the rotor of a laboratory installation. 7. Assessment of the stability of a rotating rotor in a combined magnetic suspension.

Topic 14. Examples of calculating characteristics and modeling the dynamics of rotors of turbomachines with magnetic bearings.

1. Design of the rotor of an expander-compressor unit (ECU) in a combined magnetic suspension.
2. Determination of natural frequencies, as well as critical rotation speeds using a numerical finite element approach. 3. Radial passive MBs for the ECU rotor. 4. Axial active MBs for the ECU rotor.
5. Construction of a nonlinear analytical model, its linearization and linear analysis of the dynamics of the ECU rotor. 6. Analysis of nonlinear dynamics of the ECU rotor. 7. Assessment of the stability of a rotating ECU rotor in a combined magnetic suspension.

Topic 15. Examples of calculating characteristics and modeling the dynamics of rotors of turbomachines with magnetic bearings.

1. Design of the rotor of a power gas turbine unit (GTU) with active magnetic bearings. 2. Characteristics of the GTU shafting. 3. Analysis of linear vibrations of GTU rotors using a numerical finite element approach. 4. Construction of a nonlinear analytical simulation model to study the dynamics of GTU rotors in the AMBs. 5. Analysis of the dynamics of the compressor and generator rotors of the gas turbine unit in the AMBs at operating modes.

Topic 16. Resume of the course “Dynamics of rotors in magnetic bearings”.

1. Brief overview of the main points of the course (linear and nonlinear dynamics of rotors of various systems and machines with different bearing supports, including passive and active magnetic bearings).
2. Summary for modeling the dynamic behavior of rotors and calculating rotor dynamics characteristics in the CAE system ANSYS APDL/Workbench.

## Topics of the workshops

There are no classes.

## Topics of the laboratory classes

MODULE #2. Laboratory practical classes (LPCs) 1 credit/16 hours “COMPUTER MODELING OF LINEAR AND NONLINEAR DYNAMIC BEHAVIOR OF ROTORS IN RIGID, ELASTIC AND MAGNETIC BEARINGS IN THE CAE SYSTEM ANSYS APDL/WORKBENCH” (*one class covers 1 topic in 2 hours*)

Topic 1. Analysis of linear and nonlinear rotor dynamics in ANSYS APDL/Workbench:

*Task 1* – Campbell Diagram Analysis of a Simply Supported Beam in ANSYS APDL/Workbench.

Topic 2. Analysis of linear and nonlinear rotor dynamics in ANSYS APDL/Workbench:

*Task 1* – Unbalance Harmonic Analysis in ANSYS APDL/Workbench.

*Task 2* – Mode-Superposition Harmonic Response to Base Excitation in ANSYS APDL/Workbench.

Topic 3. Analysis of linear and nonlinear rotor dynamics in ANSYS APDL/Workbench:

*Task 1* – Mode-Superposition Transient Response to an Impulse in ANSYS APDL/Workbench.

*Task 2* – Transient Response of a Startup in ANSYS APDL/Workbench.

Topic 4. Analysis of linear and nonlinear rotor dynamics in ANSYS APDL/Workbench:

*Task 1* – Geometric modeling of turbomachinery rotors and calculation of mass characteristics of attached components for constructing beam- or volume-mass calculation models of rotors..

*Task 2* – Critical Speed Map Generation (for an eight-stage centrifugal compressor supported by two inclined pad bearings using a beam-mass (or volumetric-mass) analysis model) in ANSYS APDL/Workbench.

Topic 5. Analysis of linear and nonlinear rotor dynamics in ANSYS APDL/Workbench:

*Task 1* – Calculation of a Plain Cylindrical Journal Bearing Characteristics in ANSYS APDL/Workbench.

*Task 2* – Calculation of a Squeeze Film Damper Characteristics in ANSYS APDL/Workbench.
*Task 3* – Transient Analysis of a Plain Cylindrical Journal Bearing in ANSYS APDL/Workbench.
*Task 4* – Transient Analysis of a Plain Cylindrical Journal Bearing (3D Approach)in ANSYS APDL/Workbench.
Topic 6. Analysis of linear and nonlinear rotor dynamics in ANSYS APDL/Workbench:
*Task 1* – Calculate the force characteristics of passive magnetic bearings made of annular permanent magnets using a series of magnetostatic analyzes in ANSYS APDL/Workbench.
*Task 2* – Calculate the force characteristics of active magnetic bearings taking into account the control law analytically and using a series of electromagnetostatic analyzes in ANSYS APDL/Workbench.
*Task 3* – Campbell Diagram Analysis and Harmonic Analysis of unbalanced turboexpander rotor in passive radial and active axial bearings in ANSYS APDL/Workbench.
Topic 7. Results of the course "Dynamics of rotors in magnetic bearings".
*Modular control #1.* The computer test (40 random short questions) is devoted to the theoretical foundations of mathematical modeling of rotor dynamics in rigid, elastic and magnetic bearings and its numerical analysis in the CAE system ANSYS APDL/Workbench.
Topic 8. Results of the course "Dynamics of rotors in magnetic bearings".
*Modular control #2.* Presentation and defense of an individual calculation problem devoted to the analysis of the dynamics of one of the rotor design options in ANSYS APDL/Workbench.

### Self-study

1. Basic concepts, equations and methods of the theory of forced linear and nonlinear oscillations of discrete systems when solving problems of different classes under various types of dynamic load – 12 hours.
2. Basic concepts, equations and methods of electromagnetism theory and methodology for performing Magnetostatic Analysis in ANSYS APDL/Workbench – 11 hours.
3. Basic concepts, equations and methods of the theory of free and forced oscillations of discrete systems – 11 hours.
4. Basic concepts, equations and methods of control theory – 16 hours.
5. Providing individual tasks (performing an individual calculation task and completing it) – 12 hours.
6. Providing semester control (preparation for module control) – 10 hours.

## Course materials and recommended reading

### Main literature

1. Matsushita O., Tanaka M., Kanki H., Kobayashi M., Keogh P. Vibrations of Rotating Machinery: Volume 1. Basic Rotordynamics: Introduction to Practical Vibration Analysis. Springer Japan, Tokyo, 2017 (https://books.google.co.ve/books?id=wNQkDwAAQBAJ&printsec...).
2. Matsushita O., Tanaka M., Kanki H., Kobayashi M., Keogh P. Vibrations of Rotating Machinery: Volume 2. Advanced Rotordynamics: Applications of Analysis, Troubleshooting and Diagnosis. Springer Japan, Tokyo, 2019.
3. Schweitzer G., Maslen E.H. eds. Magnetic Bearings. Theory, Design, and Application to Rotating Machinery. Springer, 2009. (https://books.google.co.ve/books?id=1Kyg5dWyBasC&printsec...)
4. Lee H.H. Finite Element Simulations with ANSYS Workbench 2021.-SDC Publications, 2021. (https://www.sdcpublications.com/Textbooks/Finite-Element-Simulations-ANSYS-Workbench/ISBN/978-1-63057-456-7/)
5. ANSYS 2023R1. Mechanical User's Guide. ANSYS Inc., Southpointe, 2600 Ansys Drive, Canonsburg, PA 15317, 2023. (Magnetostatic Analysis) (https://ansyshelp.ansys.com/Views/ Secured/corp/v231/en/pdf/Workbench_Users_Guide.pdf)
6. Rotordynamic Analysis Guide. ANSYS, Inc., 2023, Southpointe, 2600 Ansys Drive, Canonsburg, PA 15317. (http://www.ansys.com)

### Additional literature

1. Zienkiewicz O.C., Taylor R.L. and Zhu J.Z. The Finite Element Method: Its Basis and Fundamentals. Butterworth-Heinemann, Sixth edition, 2013. 802 p.
2. Ansys Student - Free Software Download. ANSYS, Inc., 2023. URL: https://www.ansys.com/academic/students

## Assessment and grading

### Criteria for assessment of student performance, and the final score structure

*Content module 1 (LCs)* – maximum 50 points: computer test (40 random short questions with 4 answer options, of which 1 is correct - 1.25 points for each correct answer) or exam (1 theoretically detailed question and a practical task to solve an engineering problem for modeling processes in a structure) - maximum 25 points for correct answer to each of two questions).
*Content module 2 (LPCs)* – maximum 50 points:
14 laboratory work tasks (maximum 3.0 points for each completed and submitted laboratory work task) and 1 individual calculation task (maximum 8.0 points for completed and defended calculation task).
*Total* – maximum 100 points.

### Grading scale

| Total points | National | ECTS |
|---|---|---|
| 90–100 | Excellent | A |
| 82–89 | Good | B |
| 75–81 | Good | C |
| 64–74 | Satisfactory | D |
| 60–63 | Satisfactory | E |
| 35–59 | Unsatisfactory (requires additional learning) | FX |
| 1–34 | Unsatisfactory (requires repetition of the course) | F |

## Norms of academic integrity and course policy

The student must adhere to the Code of Ethics of Academic Relations and Integrity of NTU "KhPI": to demonstrate discipline, good manners, kindness, honesty, and responsibility. Conflict situations should be openly discussed in academic groups with a lecturer, and if it is impossible to resolve the conflict, they should be brought to the attention of the Institute's management.
Regulatory and legal documents related to the implementation of the principles of academic integrity at NTU "KhPI" are available on the website: http://blogs.kpi.kharkov.ua/v2/nv/akademichna-dobrochesnist/

## Approval

| Approved by | Date<br>August 30, 2023 | Head of the department<br>Oleksii VODKA |
|---|---|---|
| | Date<br>August 30, 2023 | Guarantor of the educational and professional program (1 year 4 months)<br>Oleksiy LARIN |