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Iaroslav Lavrenko[1], Tetiana Sydora[2], Maksym Sushchenko[3], Olena Chaikovska[4]

[1] Department of Dynamics and Strength of Machine and Strength of Materials, National Technical University of Ukraine "Ihor Sikorsky Kyiv Polytechnic Institute", Prospect Beresteiskyi (former Peremohy) 37, Kyiv, Ukraine, e-mail: lavrenko.iaroslav@gmail.com.ua, ORCID 0000-0002-4384-4866
[2] Department of Dynamics and Strength of Machine and Strength of Materials, National Technical University of Ukraine "Ihor Sikorsky Kyiv Polytechnic Institute", Prospect Beresteiskyi (former Peremohy) 37, Kyiv, Ukraine, e-mail: tania.sydora@gmail.com,
[3] Department of Dynamics and Strength of Machine and Strength of Materials, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Prospect Beresteiskyi (former Peremohy) 37, Kyiv, Ukraine, e-mail: speadcubing@gmail.com,
[4] Department of Theory, Practice and Translation of German, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Prospect Beresteiskyi (former Peremohy) 37, Kyiv, Ukraine, e-mail: chaikovska24@gmail.com, ORCID 0000-0001-9945-4296

SIMULATION OF THE STRESS-STRAIN STATE AND DETERMINATION OF THE NATURAL FREQUENCY OF THE LABORATORY CENTRIFUGE SHAFT VIBRATION USING ANSYS AND KISSSOFT

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Abstract. The rotor is a key element of high-speed mechanisms that are widely used in various industries, such as laboratory centrifuges used to separate mixtures of different fractions, gas turbines, industrial compressors, engines, and others. The main requirement for such mechanisms is reliability and safety during operation. To ensure the above requirements, it is necessary to determine the stress-strain state of the most loaded structural elements of the system and the dynamic characteristics. This paper presents an analysis of the stress-strain state of a rotor system using the example of a Pico21 laboratory centrifuge. The Ansys and KISSsoft software packages were used for 3D modelling of the finite element model. The system consists of a flexible shaft with a rotor, the rotor mass was changed during the simulation and supports, the role of which is performed by bearings. A comparative analysis of the obtained results of the stress-strain state is presented, which further makes it possible to carry out appropriate calculations taking into account stress concentrators to determine the durability and lifetime of high-speed mechanisms. The stresses are determined according to the von Mises and Tresca criteria. The paper also presents the results of the calculation and analyses the natural frequencies of the rotor system. Further studies, it is planned to determine the natural frequencies of vibration, taking into account gyroscopic effects, which are necessary to determine the resonant frequencies and zones of stable operation of the system.

Keywords: Centrifuge, stress, strain, vibration, frequency, Ansys, Kisssoft.

Introduction

Most structural elements of modern machines and mechanisms operate under variable loads that cause vibration. Vibrations cause cyclic stresses, which are the cause of damage and fatigue failure, especially in the case of resonance or other transient conditions. Unstable states, in turn, worsen the functional capabilities of structures.

The design of modern mechanisms and machines has developed in the direction of increasing power and high speeds while reducing weight. In this case, the dynamic loads increase, and the vibration impact on mechanisms, tools, and their structural elements increases accordingly.

Problem Statement

High-speed centrifuges are often designed as universal devices, where a single motor drives a wide range of different rotors with different masses, for example, Pico21 laboratory centrifuge, Fig. 1. Large rotors weighing up to 20 kg are used for specific centrifuges in blood banks, and even 60 kg are used in laboratories. As a rule, high-speed centrifuges operate at speeds of up to 10.000 rpm.

The moving parts of laboratory centrifuges create a potential risk of destruction during operation. During the operation of such structures, several requirements are imposed on them to ensure safety and reliability over the guaranteed lifetime. These requirements are ensured by the fact that the rotating structural elements must not be damaged during the guaranteed lifetime and by the presence of a protective shell.

Centrifuge manufacturers have to experimentally confirm that the centrifuge shell guarantees that all mechanical components and material samples will remain in the centrifuge in the case of the most dangerous failure, but such studies are quite expensive. Therefore, there is a need to study the strength and dynamic characteristics of the most stressed structural elements of laboratory centrifuges. One of these elements is the centrifuge shaft.

Review of Modern Information Sources on the Subject of the Paper

In the last few years, scientists have made progress in studying the dynamic processes of rotor systems. The dynamics of a flexible rotor with active magnetic bearings were studied in [1, 2] using the finite element method (FEM) with the help of Ansys Workbench. The results of modelling and analysis of a stepped rotor shaft made of a composite, using loads and boundary conditions, vibration studies, and a Campbell diagram are presented in [3]. The results of the study of the stress-strain state (SSS) of the shaft using Ansys are presented by the authors in [4]. In [5], the authors demonstrate the modelling of an engine shaft (EN24) using CATIA, and the results of static, dynamic analysis, and fatigue calculations were carried out using Ansys.

Calculations for the strength and stiffness of a shaft for automotive and marine equipment under high torque loading are presented in [6]. To timely detect structural failure points, the authors analyzed studies of the static behavior of the pump shaft model at the design stage based on the finite element method (FEM) under the influence of various types of loading [7]. In [8, 9, 10], free transverse vibrations of an injection pump shaft with a complex geometry were investigated using analytical methods and numerical modelling. The modelling was carried out taking into account stress concentrators. The results of optimizing the shaft dimensions and strength calculations using the FEM are reported in [11].

The authors investigated the effect of a crack on the dynamic behavior and strength of a rotating stepped shaft using the FEM in [12]. The results of analytical and numerical calculations of the stress-strain state of hydraulic unit shafts, taking into account design features, are presented in [13]. The authors of [14, 15] discuss the modelling and optimization of the SSS of a high-strength rotor and shaft structure of high-speed machines. As a result of the modelling analysis of a bevel spur gear shaft, the authors determined its static strength, fatigue strength, and bending stiffness [16]. A study of the behavior and calculation of the strength of a steel coil shaft as a drive shaft in the process of wire rope winding under conditions of increasing load is presented by the authors in [17].

Objectives and Problems of Research

To predict the lifetime of structural elements, it is necessary to more accurately determine their stress-strain state (SSS) and study their dynamic characteristics. Since full-scale testing is quite expensive, numerical modelling using software products is an actual task.

The purpose of this work is to study the stress-strain state on the example of a real shaft design of the Pico21 laboratory centrifuge, taking into account the influence of rotors of different masses to determine the weakest points at the design stage and reduce manufacturing time.

Since centrifuges operate at high rotational speeds, the calculation of natural frequencies and their analysis is important to determine the resonance frequencies, which make it possible to identify the zones of stable and unstable operation of the system, leading to a decrease in the functionality of the centrifuge and a decrease of separation.

Main Material Presentation

Laboratory centrifuges are designed to separate mixtures into fractions of different densities. In this paper, we consider the shaft of a Pico 21 laboratory centrifuge manufactured by Thermo Scientific Electron Corporation, to which rotors of different configurations and weights are attached, Fig. 1.

a *b*

Fig. 1. Laboratory centrifuge with rotor: a – Pico 21 centrifuge; b – different rotor configurations

The centrifuge, a sketch of which is shown in Fig. 2, consists of a rotor 1 rotating about a vertical axis 2, driven by an electric motor, the anchor of which 3 is on the same axis, and the stator and shell 4 are fixed on elastic supports 5. The supports are designed to allow the centrifuge to rotate about the fixed axes ξ, η, with the same rotational stiffness.

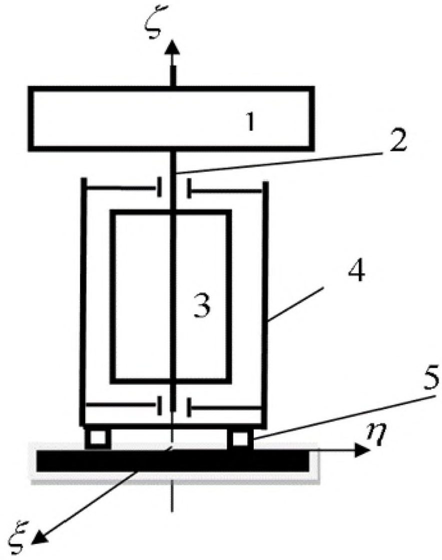


Fig. 2. Sketch of the laboratory centrifuge Pico 21

In the paper, the problem of determining the stress-strain state (SSS) of a centrifuge shaft with different rotor weights (0.3 kg, 0.4 kg, 0.5 kg, 0.6 kg, 0.7 kg) was studied by numerical methods using the popular software packages Ansys and KISSsoft.

To model the shaft, we used steel 45, the characteristics of which are shown in Table 1.

Table 1

Material properties

Parameter	Units of measure	Value
Density	kg/m^3	7850
Thermal expansion coefficient	C^{-1}	$1{,}2 \cdot 10^{-5}$
Young modulus	Pa	$2 \cdot 10^{11}$
Poisson's ratio		0,3
Shear modulus	Pa	$7{,}6923 \cdot 10^{10}$

A drawing of the shaft, which was calculated in Ansys and Kisssoft software packages, is shown in Fig. 3.

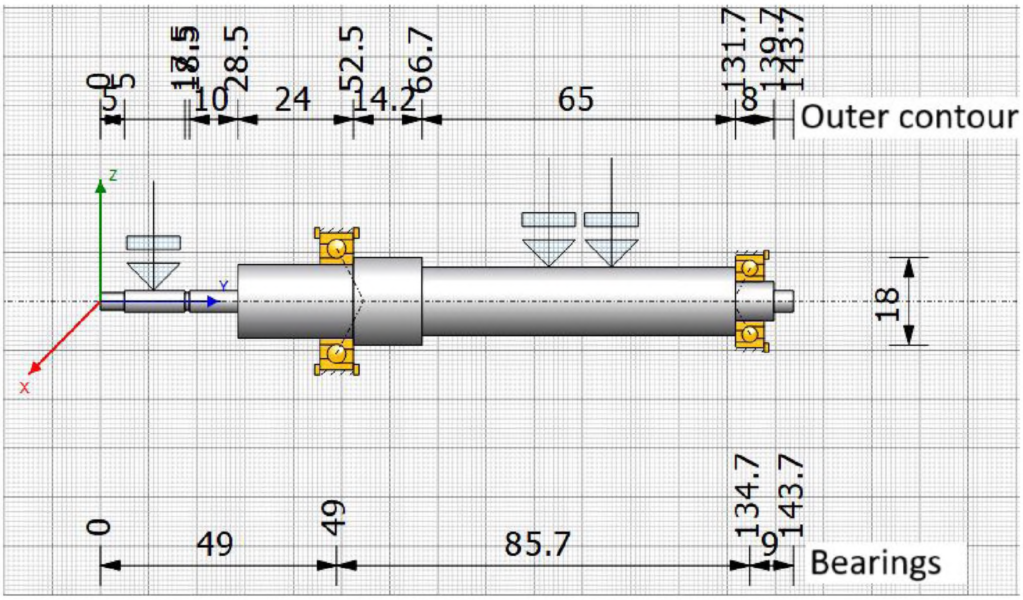


Fig. 3. Centrifuge shaft drawing in the KISSsoft software package

The equivalent stresses according to the von Mises criterion are calculated according to Eq. (1).

$$\sigma_{eq} = \sqrt{\frac{1}{2}\left(\left(\sigma_{11}-\sigma_{22}\right)^2+\left(\sigma_{22}-\sigma_{33}\right)^2+\left(\sigma_{11}-\sigma_{33}\right)^2+6\cdot\left(\sigma_{12}^2+\sigma_{23}^2+\sigma_{13}^2\right)\right)}, \quad (1)$$

where σ_{ij} – components of the stress tensor, $i, j = \overline{1,3}$.

To study the effect of different rotor weights (0.3kg, 0.4kg, 0.5kg, 0.6kg, 0.7kg) on the stress-strain state of a laboratory centrifuge shaft, numerical simulations were performed using the Ansys software package. The results of the calculations are shown in Fig. 4.

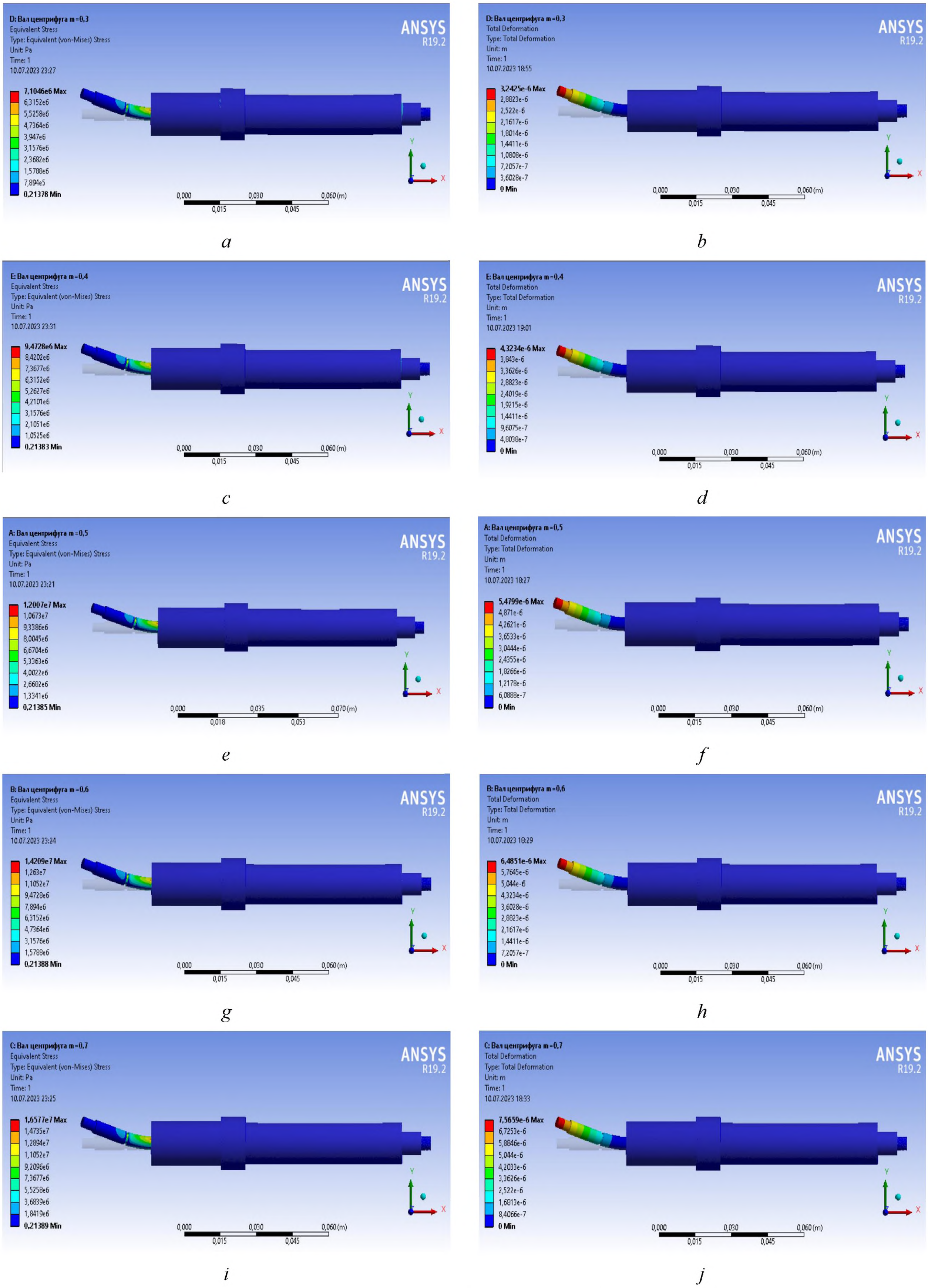


Fig. 4. Equivalent stress (a, c, e, g, i) and total deformation (b, d, f, h, j) distribution using ANSYS

To examine the results shown in Fig. 4, the stress-strain state of the centrifuge shaft with different rotor masses (0.3 kg, 0.4 kg, 0.5 kg, 0.6 kg, 0.7 kg) was modelled using the Kisssoft software package. The results of calculating the maximum stresses and displacements that occur on the centrifuge shaft are shown in Fig. 5.

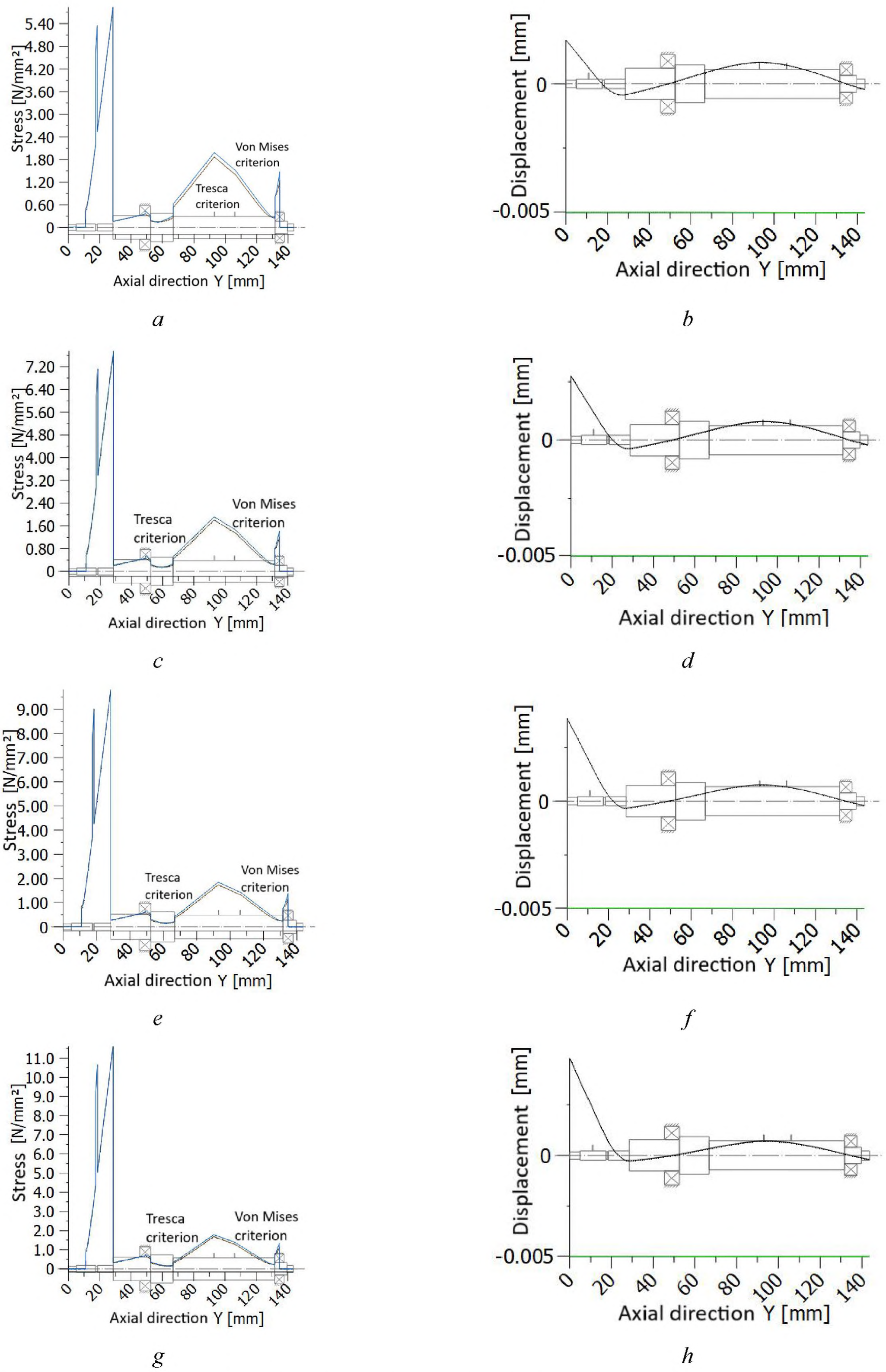
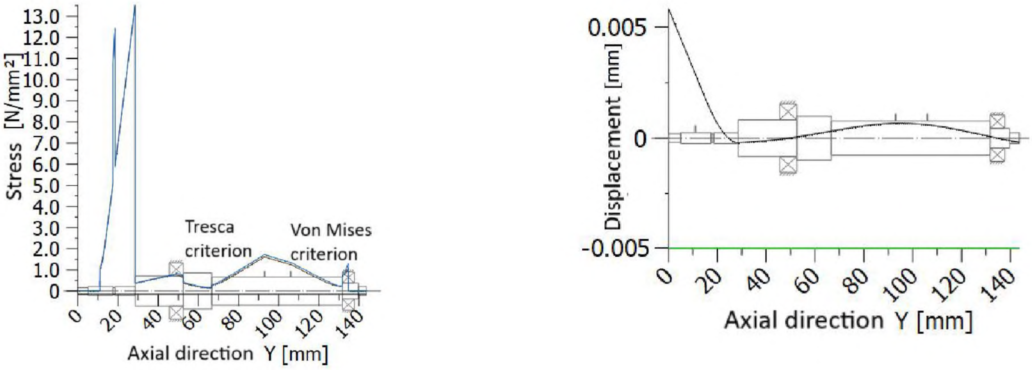


Fig. 5. Equivalent stress (a, c, e, g, i) and total deformation (b, d, f, h, j) distribution using KISSsoft



i *j*

Fig. 5. (continuation) Equivalent stress (a, c, e, g, i) and total deformation (b, d, f, h, j) distribution using KISSsoft

Fig. 5 shows a comparison of the stresses calculated by the von Mises and Tresca criteria. The Tresca stress criterion is more conservative. However, the von Mises criterion gives more accurate values when considering plastic materials. The numerical values of stresses obtained by the Tresca and von Mises criteria are given in Table 2.

Table 2

Comparison of stress calculations according to Tresca and von Mises criteria in KISSsoft software

Rotor masses, kg	Stresses (Tresca criterion), MPa	Stresses (von Mises criterion), MPa
0,3	5,83	5,8249
0,4	7,7555	7,7487
0,5	9,6810	9,6724
0,6	11,6065	11,5962
0,7	13,5320	13,52

Since the von Mises criterion gives more accurate calculation results, Fig. 6 and Fig. 7 show graphical dependences of stresses and displacements on rotor mass obtained in Ansys and Kisssoft, accordingly.

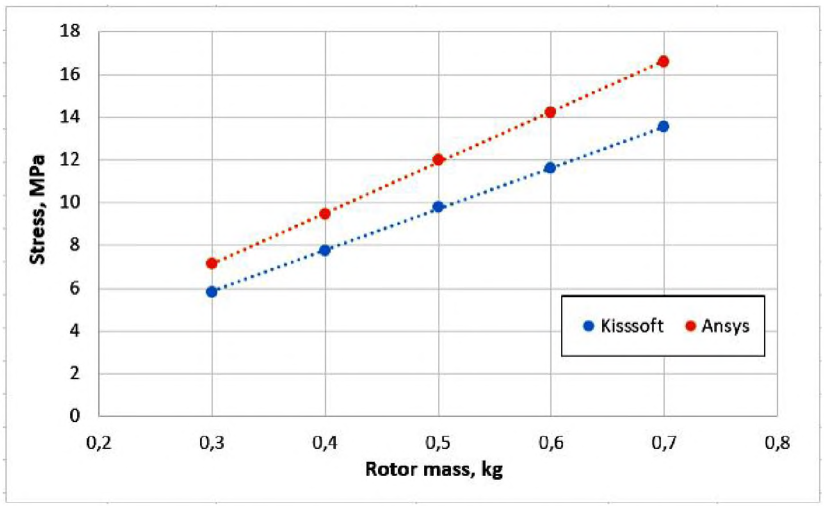


Fig. 6. Equivalent stresses calculated for rotors of different masses using KISSsoft and ANSYS

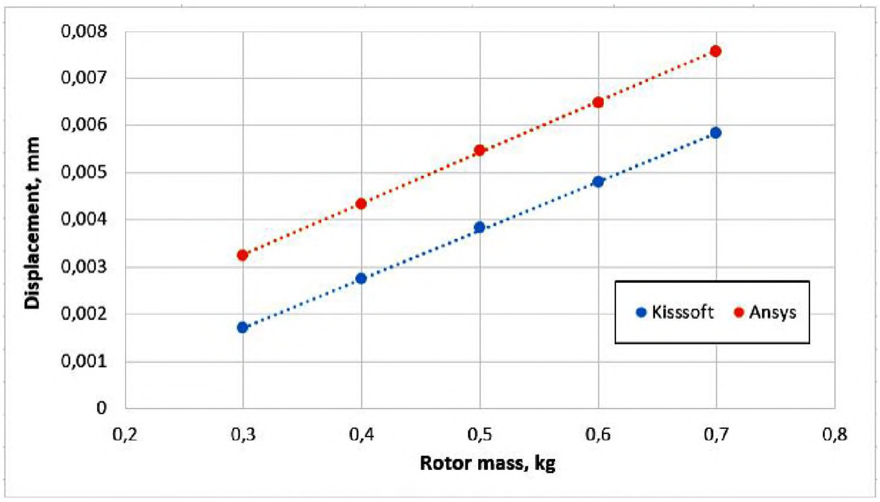


Fig. 7. Total deformations calculated for rotors of different masses using KISSsoft and ANSYS

As mentioned above, resonant frequencies and the transient processes caused by them impair the functionality of the laboratory centrifuge, in this regard, the calculation of the first three natural frequencies was carried out using the Ansys and Kisssoft software packages, taking into account different rotor masses. The results of the calculations are shown in Table 3 and Fig. 8, respectively.

Table 3

Comparison of natural frequencies from ANSYS and KISSsoft

	ANSYS			KISSsoft		
Rotor masses, kg	1, Hz	2, Hz	3, Hz	1, Hz	2, Hz	3, Hz
0,3	54	77,21	410,43	24,09	88,3	363
0,4	54	76,84	355,88	24,08	88,3	321,41
0,5	54	76,47	318,54	24,06	88,3	291,1
0,6	54	76,1	290,93	24,05	88,3	268,86
0,7	54	75,74	269,45	24,04	88,3	253,92

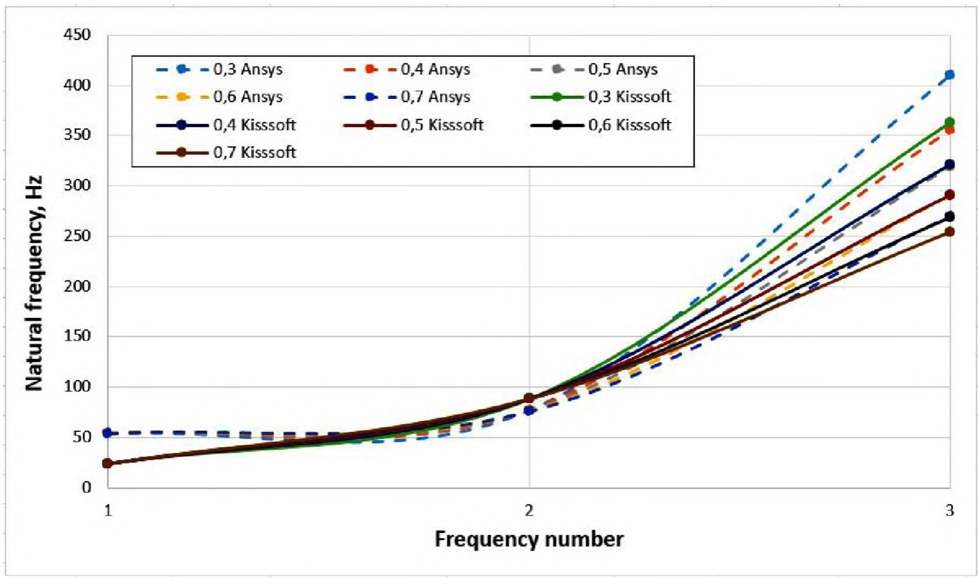


Fig. 8. Natural frequencies calculated for rotors of different masses using KISSsoft and ANSYS

Conclusions

The use of FEM allows for a significant reduction in calculation time compared to the known methods of shaft design and calculation outlined in the engineering literature, and to avoid calculation failures and increase their accuracy. The stresses occurring on the shaft are within acceptable limits. The stress values were calculated using the Tresca and von Mises criteria. In all cases of stress-strain state modelling, the maximum stresses occur at the point of contact between the rotor and the shaft of the laboratory centrifuge. The numerical simulations showed that the deformations obtained in Ansys and Kisssoft packages have similar values.

As a result of numerical modelling in the Ansys and Kisssoft software packages, the first three natural frequencies of the laboratory centrifuge shaft were determined, taking into account different masses of the rotors. The results showed a strong correlation.

In further studies, it is planned to carry out calculations taking into account stress concentrators to determine the durability and service life of the most loaded structural elements and optimise the shaft design. Determination of natural oscillation frequencies taking into account gyroscopic effects.

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