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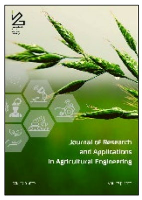

The new method for balancing an assembly of rotating elements with variable dynamics

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The study presents an analysis of both passive and active balancing systems, with active balancing systems considered more effective, especially for devices with variable rotational speeds and imbalance dynamics. The focus was placed on the balancing mechanism of a centrifuge used for mineral particle sedimentation studies. The analysis of available solutions revealed that ready-made electronic and mechanical systems were not suitable for direct adaptation, necessitating the development of a new solution. An innovative active balancing mechanism was designed, based on two cooperating discs, one of which can move relative to the other along two axes. The mechanism works by detecting centrifugal force and automatically adjusting the relative position of the discs, bringing the rotating system to a balanced position. The built prototype confirmed the effectiveness of the solution up to 800 rpm. The developed design has been submitted for patent protection.

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1. Introduction

In mechanical systems, rotating assemblies, subassemblies, and components are widely used, especially in machine tools, industrial machinery, engines, and turbines. The symmetrical distribution of rotating masses relative to the axis of rotation results in the mutual balancing of centrifugal forces. However, imbalance can occur, and in some cases, it is unavoidable [1].

At higher speeds, when mass asymmetry of the rotating element occurs (e.g., due to wear or operational use), and the principal inertia axis of the rotor does not coincide with its geometric axis, an imbalance arises. The causes of this phenomenon may include design inaccuracies, defective materials, machining and assembly errors, as well as external factors such as temperature, humidity, or improper operating parameters [2].

Imbalance leads to a significant unbalanced centrifugal force strongly associated with angular velocity, which can manifest as intense vibrations, oscillations, or, at higher speeds, noise. Such irregularities can negatively affect the reliability of machinery, potentially leading to fatigue failure of structural components regardless of their position relative to the vibration source. This ultimately results in a significant reduction in service life or even system failure.

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Additionally, vibrations pose a safety risk to operators handling these devices and may cause excessive strain. Thus, there is an increasing demand for precise balancing methods, especially for rotating machinery and components with variable physical properties, geometries, and rotational speeds [3].

The balancing of rotating components can be achieved through both passive and active methods [1, 4]. In passive methods, balancing is often accomplished by positioning additional fixed masses around the rotation axis or by using flexible elements and dampers. These methods are limited to devices operating with uniform rotational motion at low speeds. In contrast, active balancing systems can be adjusted to the vibration characteristics during operation, making them significantly more effective than passive vibration control [1].

Currently, two types of active balancing solutions for rotating systems are used: electronic and mechanical. Electronic balancing methods are applied, e.g. in machine tools (grinders), where they compensate for uneven grinding wheel wear at high speeds. These methods use electromagnetic fields for balancing [5, 6]. The most common type of active damper utilizes electromagnetic force or eddy currents generated by alternating current applied to rotating shafts. The magnetic flux can be generated by electromagnets or permanent magnets. Electrorheological and magnetorheological fluids are also used to balance forces, as these fluids can modify their damping (rheological) properties depending on the applied electric or magnetic field, which may be induced by electric current flow through a coil [7].

Mechanical methods are more commonly used in low-speed devices. The balancing of the rotating system is achieved by changing the position of the correction mass through the displacement of a fixed element or by delivering fluid to specifically designed chambers [8, 9]. One example includes the use of balls or rollers moving relative to the axis of rotation [10, 11] or adjustable compensatory flaps [12].

In practice, achieving perfect balance in rotating devices is challenging. In engineering, a rotor is considered balanced if it operates stably, meaning that the rotor's vibration amplitude is minimized within an acceptable range. Unfortunately, most active balancing methods described in the literature pertain to rotational motion at a constant angular velocity [13]. In the case of variable rotational speeds, the effectiveness of these methods decreases. Thus, the aim of this study is to evaluate the possibility of adapting existing solutions or developing a new method for balancing rotating assemblies in equipment designed for accelerated sedimentation of mineral particle suspensions under variable rotational speed conditions and dynamic imbalance formation.

2. Subject of the study and methodology

The subject of this study is the description and characterization of the balancing mechanism for a rotating centrifuge assembly designed to investigate the sedimentation rate of solid particles in fluids. During the centrifuge design phase, some fundamental assumptions were defined:

a) The minimum capacity of the rotating vessels should not be less than 1 dm^3.

b) The vessels containing the suspension should have a cylindrical shape with a maximum height of 250 mm.

c) The minimum number of vessels attached to the rotating head should be no fewer than four.

d) The rotating vessel assembly should achieve a final rotational speed of 900 rpm.

e) The rotating head should reach its final speed gradually, with uniform acceleration, over a period of 20 minutes.

For the analysis of available solutions, an algorithm for examining balancing systems of rotating assemblies was developed, as shown in Figure 1. The methodology for studying balancing mechanisms consists of two distinct phases. The first phase focuses on the technical analysis of the balancing mechanism, which includes evaluating the scalability of the solution, the market availability of components and subsystems, functionality, and adaptability. After meeting all four criteria, the second phase assesses the economic feasibility of the proposed solution. The key boundary condition in this phase is the cost of adapting the balancing mechanism for the centrifuge. The cost considerations include either purchasing ready-made components or subsystems for the balancing mechanism or manufacturing selected components or assemblies based on the adopted solution.

The presented methodology not only enables the selection of an appropriate solution but also provides insight into the technical and economic limitations of existing balancing mechanisms for rotating machine assemblies. It also served as a foundation for developing new or modifying existing balancing mechanisms.

3. Results of research and design work

In accordance with the presented methodology, some structural solutions for the balancing system were analysed, assessing their adaptability in both technical and economic terms.

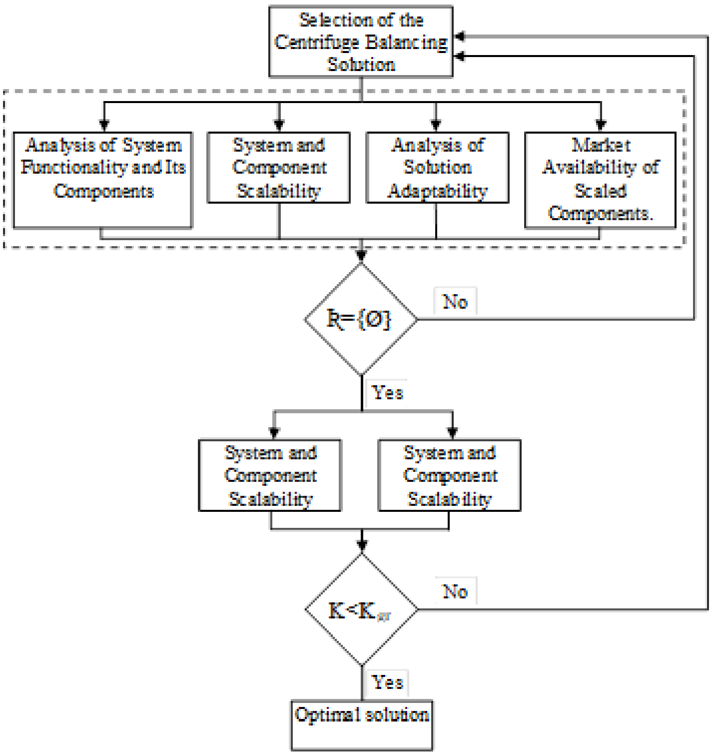

Fig. 1. Algorithm for analysing the adaptation of existing solutions for centrifuge applications.

Although balancing methods based on electronic systems were technically acceptable, they posed limitations due to the complexity of data analysis associated with processing sensor signals. This necessitated advanced control and analysis algorithms, which, due to their complexity, could introduce additional errors [14]. Unfortunately, this limitation of electronic balancing systems could also lead to additional costs during implementation and ongoing maintenance. Given the significant costs associated with implementation and potential regular maintenance, advanced electronic systems were rejected at the analysis stage.

The study also examined the adaptation of mechanical active balancing systems, including counterweight masses, magnetorheological fluid-based systems, active magnetic bearings, and adjustable balancing rings [15, 16]. However, these active balancing systems could not be directly applied to the centrifuge in question. The primary reason was the lack of ready-made, scalable solutions available on the market, regardless of the chosen balancing system. Adaptation of any solution required designing a custom system with numerous modifications, mainly within the rotor hub or the entire rotor itself, which would necessitate a fundamental redesign of the entire device.

The conducted analysis of various balancing systems, in relation to the defined design assumptions, did not allow for the use of an off-the-shelf structural solution available on the market. Transferring design solutions from high-speed balancing assemblies would excessively increase the complexity of the centrifuge system. However, as a result of the conducted analyses and design-conceptual work on adapting existing balancing solutions, a new concept for a dynamic balancing system was developed. This system is based on two rotor disks that can move relative to each other. A conceptual schematic of this system is presented in Figure 2.

As a result of the centrifugal force, plate 6 moves relative to plate 5, causing the deflection of levers 4 and 10 along axes 1 and 2, which are mutually perpendicular. The levers shift the sliders 3 and 9, respectively, activating the switching mechanism in the control modules of motors 1 and 7. Depending on the direction of deflection of levers 4 and 10, the control modules operate motors 1 and 7 in such a way that the displacement caused by the centrifugal force, identified along axes 1 and 2, returns to a balanced state (equilibrium). By shifting sliders 3 and 9 and deflecting levers 4 and 10, plate 6 moves in two independent axes relative to plate 5, ensuring that the centrifugal force from the rotating plate 6 reaches the preset minimum value in modules 2 and 8. The initial setting of modules 2 and 8 is adjusted by the tension of springs, which also regulate the sensitivity and accuracy of the balancing process.

According to the description above, a prototype of the described active balancing system for the rotor assembly has been constructed, with an axonometric view of the assembly presented in Figure 3.

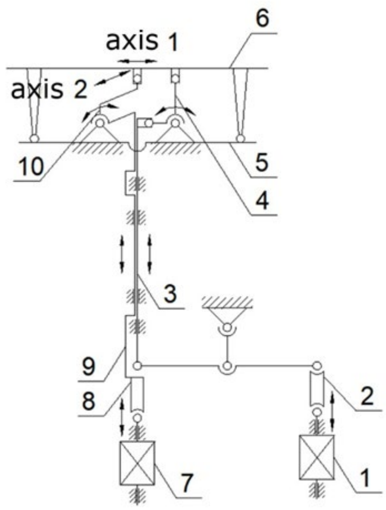

Fig. 2. Conceptual schematic of the developed active balancing mechanism for the rotating centrifuge assembly; 1 – axial shift motor, 2 – motor 1 control module, 3 – linkage of lever 4, 4 – axial shift lever 1, 5 – fixed plate, 6 – balanced plate, 7 – axial shift motor 2, 8 – motor 2 control module, 9 – linkage of lever 10, 10 – axial shift lever 2.

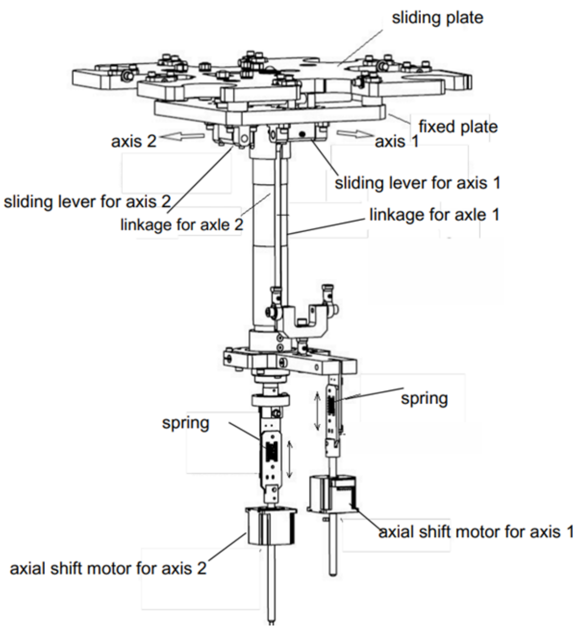

Fig. 3. Axonometric assembly drawing of the balancing mechanism.

A prototype of the centrifuge, designated as "0", was constructed with the following dimensions: width 800 mm, depth 800 mm, and height 950 mm. The device was equipped with a 450 W brushless BLDC motor with an encoder. Through a belt transmission, the motor drove a rotor on which a head was mounted to hold four cylinders arranged at 90° intervals. This motor and belt system enabled the rotating assembly to reach a maximum speed of 800 RPM. Each cylinder used for the centrifugation had a capacity of 800 ml. According to the design specifications, the target imbalance between two opposing cylinders was set at approximately 100 g. To identify the imbalance, an accelerometer was used with the following specifications:

- Measurement range: ±100 g,
- Sensitivity: 20 mv/g (millivolts per 1 g of gravitational acceleration),
- Operating bandwidth: 0.5 Hz to 1 kHz,
- Noise floor: <100 μg/√Hz.

These parameters ensured sufficient sensitivity to detect imbalance levels exceeding 0.2 g. Only startup tests were conducted on prototype "0", and the results were satisfactory. The target rotational speed of 800 RPM was achieved, and the imbalance correction system effectively compensated for a designed differential of 100 g between opposing cylinders. The solution is the subject of a complex patent application (Patent Office of the Republic of Poland, P.449180).

6. Conclusions

The conducted studies on the availability of active balancing solutions and their analysis of adaptation possibilities as a balancing system for a centrifuge for accelerated sedimentation of mineral deposits, both in terms of variable rotational speed and the dynamics of the resulting imbalance due to processes occurring in the rotating elements of the device, did not allow for the application of existing solutions available on the market. Balancing systems and their constructions are typically designed for specific devices and the balancing of the rotating assembly of that device. The work led to the development of a new solution dedicated to the rotating assembly of a centrifuge for accelerated sedimentation of mineral deposits. Commonly used methods for determining the particle size distribution of mineral deposits and soils are based on the sedimentation process. Internationally accepted standard methods for determining the granulometric composition of soils and other mineral formations are characterized by high labor intensity and time consumption. These analyses also require appropriate qualifications and experience of the personnel conducting the measurements. The use of a centrifuge enables the determination of the particle size distribution of soils or other mineral materials using the same physical principles (Stokes' law) as the traditional sedimentation method, but in a significantly shorter time. The main challenge in construction of a sedimentation centrifuge is the relatively large sample volume and the mass of the tested material, which necessitates an innovative solution for balancing the rotating mass.

The structural solution, which has been filed for a patent, is based on two disks that can move relative to each other along two axes. One of these disks is fixed, while the other moves relative to it using linkages connected to drive elements. Based solely on the startup tests of prototype '0', it was confirmed that the design functioned correctly at rotational speeds of up to 800 RPM.

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