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STUDY OF THE DYNAMICS OF SPINDLE SHAFT ON GAS-STATIC BEARINGS

This study delves into the complex dynamics of spindle shafts mounted on gas-static bearings, employing computational experiments and analysis to reveal crucial insights for optimizing high-precision machining processes. We identify natural frequencies and resonant tendencies of spindle vibrations through advanced Finite Element Method (FEM) simulations, highlighting their impact on operational stability and machining quality. Deliberately introduced imbalances further illuminate the dynamic behavior, displaying the detrimental effects of resonance on spindle performance. To mitigate these effects, we explore various technical solutions, including reducing rotor imbalances and intensifying acceleration through critical regions. Ultimately, this investigation provides a comprehensive understanding of spindle dynamics on gas-static bearings, guiding the development of robust and high-precision spindles for a range of industrial applications beyond just machining, such as precision robotics and microfabrication.

Keywords: *spindle dynamics, gas-static bearings, natural frequencies, computation*

Introduction: The exploration of natural frequencies in spindle shafts stands as a cornerstone in high-precision machining. This section elucidates the significance of understanding these frequencies in the context of spindle engineering, highlighting their impact on machining quality, operational efficiency, and the potential risks associated with resonances induced by external forces or imbalances within the spindle system.

The relentless pursuit of ever-increasing precision and efficiency in machining processes hinges on the flawless operation of high-speed spindles. Among the key players in this arena, spindles mounted on gas-static bearings have carved a unique niche by harnessing the remarkable properties of air itself [1]. Unlike their traditional counterparts – rolling or lubricated bearings – gas-static bearings employ a thin film of pressurized gas to levitate the spindle shaft, effectively eliminating the constraints of physical contact. This approach unlocks some benefits:

•Frictionless Movement: The absence of rubbing surfaces minimizes frictional losses, translating into reduced heat generation, lower power consumption, and extended spindle life.

•Exceptional Stiffness: The pressurized gas film provides remarkable rigidity, ensuring minimal shaft deflection even under intense machining forces, thereby contributing to unparalleled machining accuracy and surface finish.

•Superior Thermal Stability [5]: The inherent cooling effect of the flowing gas effectively maintains stable spindle temperatures, particularly crucial for high-speed operations and material machining with stringent thermal requirements.

•Clean and Environmentally Friendly: Unlike grease or oil-based lubrication systems, gas-static bearings operate in a closed loop, eliminating the risk of contamination and environmental hazards associated with lubricant leakage [6].

However, exploiting the full potential of this technology requires a profound understanding between spindle dynamics, gas film behavior, and external disturbances [2]. The seemingly invisible realm of spindle vibrations holds the key to unlocking optimal performance and avoiding catastrophic failures. Ignoring the intricate interplay of natural frequencies, resonant tendencies, and imbalance-induced forces can lead to detrimental consequences, impacting machining quality, jeopardizing spindle integrity, and potentially causing irreparable damage. This is where the present study delves deep into the heart of spindle dynamics on gas-static bearings, employing advanced computational tools and rigorous analysis to illuminate the invisible forces at play. Through meticulous simulations and meticulous experiments, we unveil the secrets of natural frequencies, resonance risks, and their impact on spindle behavior. By investigating the effects of deliberate imbalances and exploring potential mitigation strategies, we pave the way for designing and operating spindles that push the boundaries of precision and efficiency [3].

Methods. The process of identifying these natural frequencies involves complex computational Finite Element Method (FEM) experiments [7, 8]. These experiments leverage cutting-edge Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) techniques, employing a meticulously crafted 3D model that encapsulates the intricacies of the spindle shaft's structure and mechanics (Fig. 1, Fig. 2).

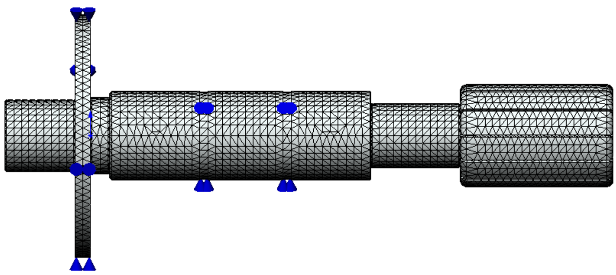
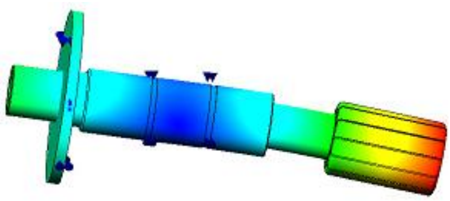
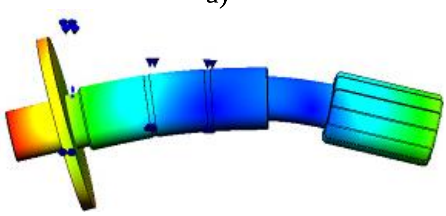


Fig. 1 The intricate mesh design and secure fastening mechanisms implemented within the Gas Static Pressure system

Meanwhile, Fig. 2 provides invaluable insights into the vibrational modes of the shaft, delineating the characteristics of the 2nd and 3rd harmonics (a) as well as the 4th and 5th harmonics (b).



a)



b)

Fig. 2 Shaft vibration modes of 2nd and ^{3rd} harmonics (a), 4th and 5th harmonics (b)

The derived values for the five harmonics of natural vibration frequencies provide following spectrum: 96 Hz, 435.3 Hz and 857 Hz. Notably, these frequencies often coincide with external disturbances that align with rotational speeds, rendering resonance at the first frequency unlikely, given its divisor relationship with the rotational speed at 1.18 RPM. However, resonance possibilities emerge notably at the 2^{nd} and 3^{rd} harmonics, correlating with a rotational speed of 5955.6 RPM or its multiples. Similarly, resonance tendencies are observed at the 4^{th} and 5^{th} harmonics, signifying possibilities at 26118 RPM or its multiples. The implications are most critical with the second and third harmonics, given their resonant frequencies lying within the operational speed range of the spindle.

Validation of these findings from natural vibration frequency calculations and critical rotation speeds is corroborated through the construction and analysis of the Campbell diagram. This diagram, formulated using a distinct CAE program and the 3D spindle shaft model (Fig. 3), visually delineates critical rotation speeds, denoted as dots, aligning with external disturbing forces mirroring the spindle shaft's rotational frequency.

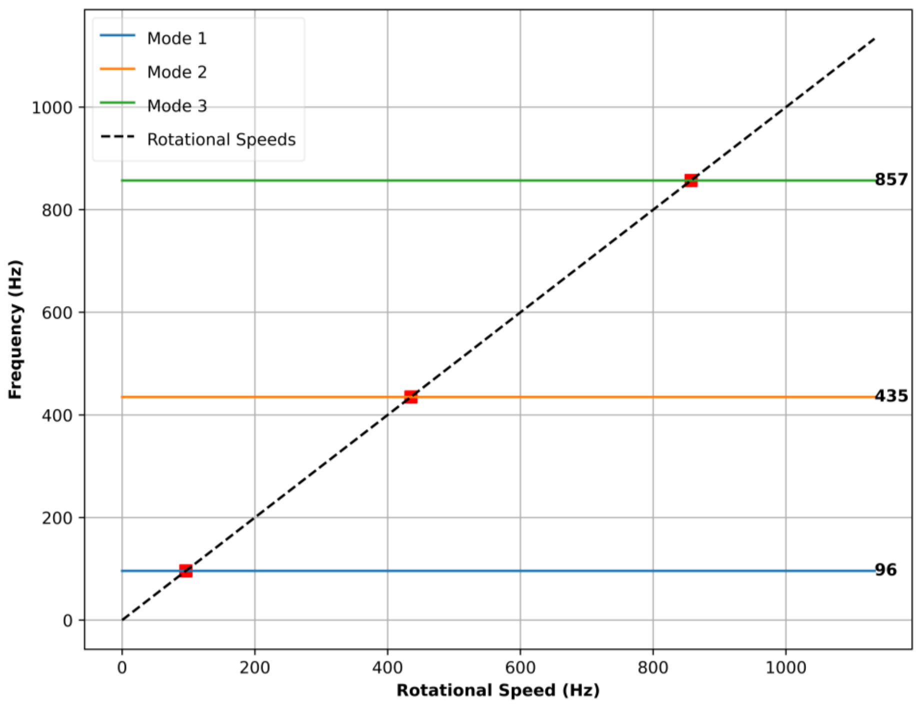


Fig. 3 The frequency diagram(Campbell diagram)

To delve deeper into the dynamic behavior, we introduce an artificial calibrated imbalance into the 3D shaft model (Fig.4). This deliberately induced imbalance, when subjected to rotation, engenders unbalanced inertial forces (centrifugal forces), fostering oscillations reminiscent of harmonic motion at the shaft's rotational frequency and amplitudes observed within the X0Y plane.

Figure 4 illustrates a designed cutout intended to create a calibrated imbalance. This meticulously calibrated imbalance, set at 30 gmm, introduces an element within the rotor that mirrors the mass and symmetry of the cut-out component, facilitating oscillations in the spindle shaft aligned with the rotational speed.

According to the fundamental principles of theoretical mechanics, centrifugal forces and vibration amplitudes exhibit a direct proportionality to the square of the angular velocity of rotation. This theoretical foundation finds practical affirmation through comprehensive computational experiments conducted within the CAE program, vividly represented in *Fig.5*.

The calculations further reinforce that at rotational speeds up to 10000 RPM the amplitudes induced by the calibrated imbalance remain well below 0.06 μm. This minute amplitude range comfortably complies within the stringent thresholds required for high-precision machining processes utilizing the spindle, such as grinding or polishing.

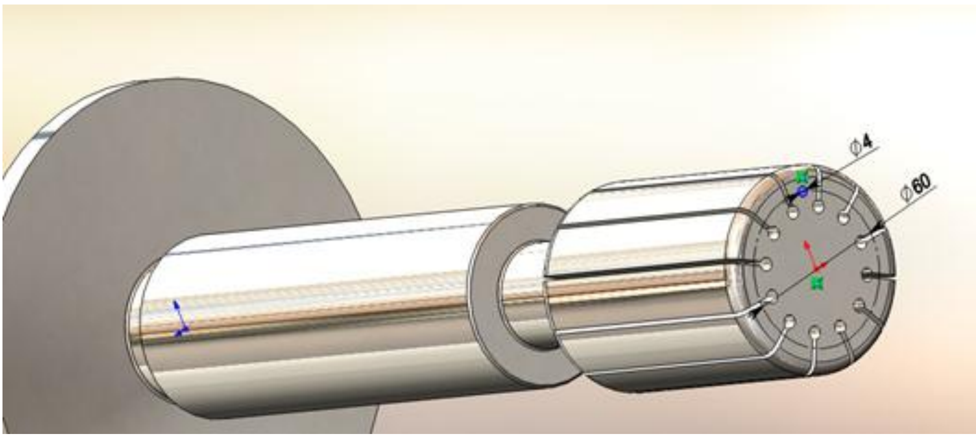


Fig. 4 Sketch of a cutout to create a calibrated imbalance

However, the frequency of 10000 RPM proves to be supercritical, necessitating passage through the resonance region at a shaft speed of 5955.6 RPM. A computational experiment was conducted to study the slow acceleration typical of drives that accelerate under load and with a limited reserve of propulsion power.

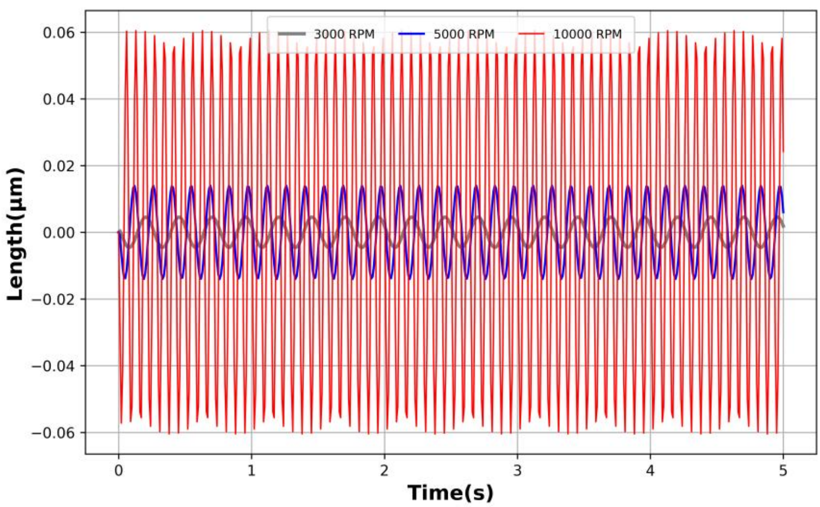


Fig. 5 Amplitudes of vibration in an unbalanced spindle shaft during steady motion at rotational speeds of 3000, 5000 and 10000 RPM.

Fig. 6 illustrates the acceleration from 4170 RPM to 9000 RPM in 10 seconds and the passage through the critical (resonant) frequency region.

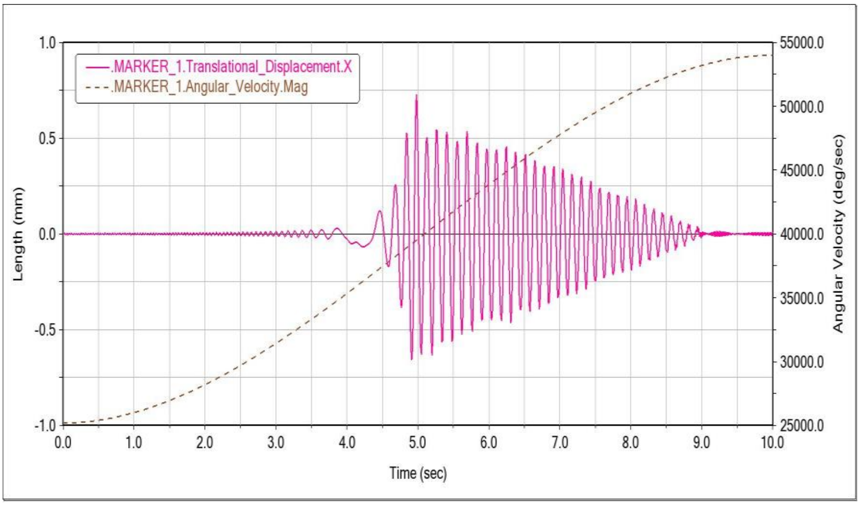


Fig. 6. Slow acceleration of the shaft and passage of the resonant frequency

The experiment vividly depicts the increase in shaft oscillation amplitudes upon entering the resonance region and the extended period for exit during the slow, near-uniform acceleration. At resonance, the oscillation amplitude sharply rises to an unacceptable value of 0.75 mm, potentially leading to damage and disruption of the Gas Static Pressure (GSP) system, rendering the attainment of a 10000 RPM speed unfeasible with a rotor imbalance of 30 g mm (refer to Fig. 5).

Subsequent to this observation, the movement of the spindle shaft's center of mass in the X0Y plane, termed as orbital movement, was studied via a computer experiment. Trajectories around characteristic time values (3, 6, 7, 8 s) were defined to highlight significant changes in oscillation amplitudes during acceleration (Fig. 7).

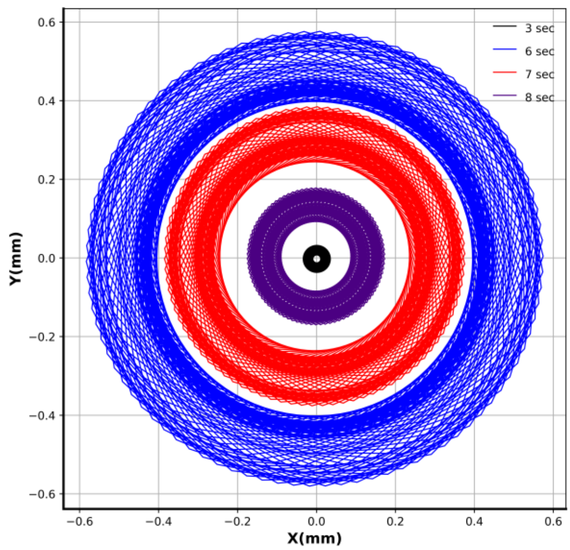


Fig. 7 Shaft orbital movement at around 3, 5, 7, 8 seconds of acceleration

Orbital motion analysis demonstrates the symmetry of amplitudes concerning the shaft's axis of rotation.

Further exploration into more intense acceleration and passage through the resonant region was undertaken. A computational experiment aimed to avoid a critical increase in oscillation amplitudes by increasing angular acceleration near the resonant region is depicted in Fig. 8.

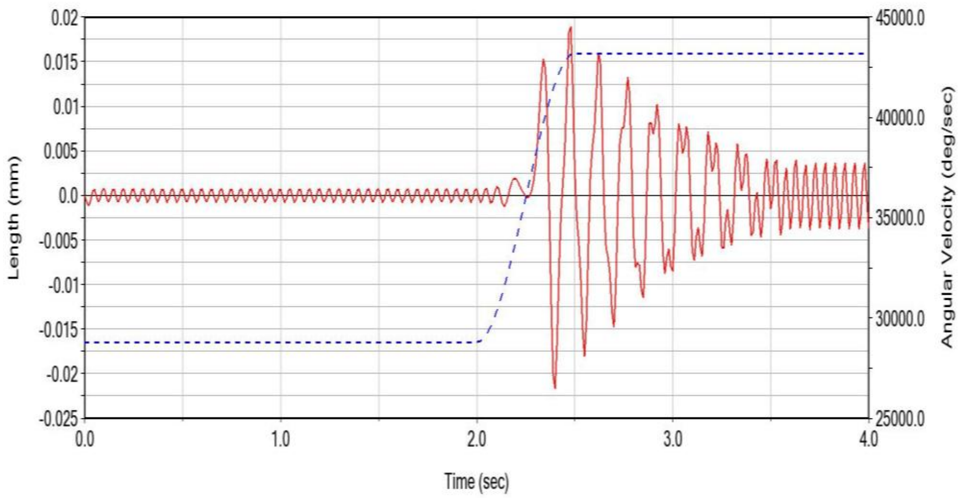


Fig. 8 Intensive acceleration of the shaft and passage of the resonant region

This experiment resulted in significantly decreased amplitudes in the resonant region, reaching only 0.19 mm or 190 µm, still exceeding the average clearance of 15 microns in the gas-static bearings, thereby impacting functionality. Hence, the spindle with this imbalance should only operate at subcritical rotation speeds, up to 5500 RPM.

For scenarios necessitating supercritical rotation speeds, potential technical solutions were proposed:

- Reducing the permissible value of rotor imbalance.
- Increasing damping forces, such as viscous resistance friction, for enhanced absorption of oscillatory movement energy.
- Augmenting the intensity of shaft acceleration.

Reducing the permissible spindle shaft imbalance emerges as a relatively straightforward and effective solution for further study. Additionally, intensifying the acceleration of the spindle rotor to navigate through the resonant region and attain supercritical frequencies stands as an effective method to mitigate maximum oscillation amplitudes. An accelerated passage through the critical region illustrated in Fig. 9 involved an angular acceleration of 2618 rad/s².

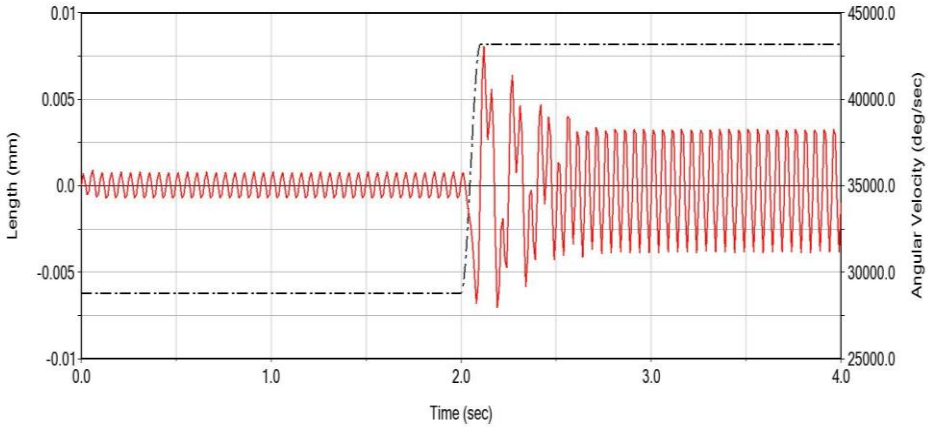


Fig. 9 Passage of the resonant region with increased shaft acceleration intensity to an acceleration of 2618 rad/s²

Accelerated passage through the resonance region: By increasing the angular acceleration to 2618 rad/s², we achieved a significant reduction in oscillation amplitudes within the critical zone, diminishing them to a mere 7-8 μm. This remarkable reduction surpasses the average clearance of 15 μm in the gas-static bearings, effectively enabling the spindle to safely traverse the critical oscillation region of the 2^{nd} and 3^{rd} harmonics without jeopardizing performance. Figure 10 further strengthens this claim, vividly displaying the stable orbital motion of the rotor during steady-state operation, even after traversing the critical speed zone. This visual evidence underscores the efficacy of accelerated passage as a viable mitigation strategy for resonance effects in gas-static spindle systems.

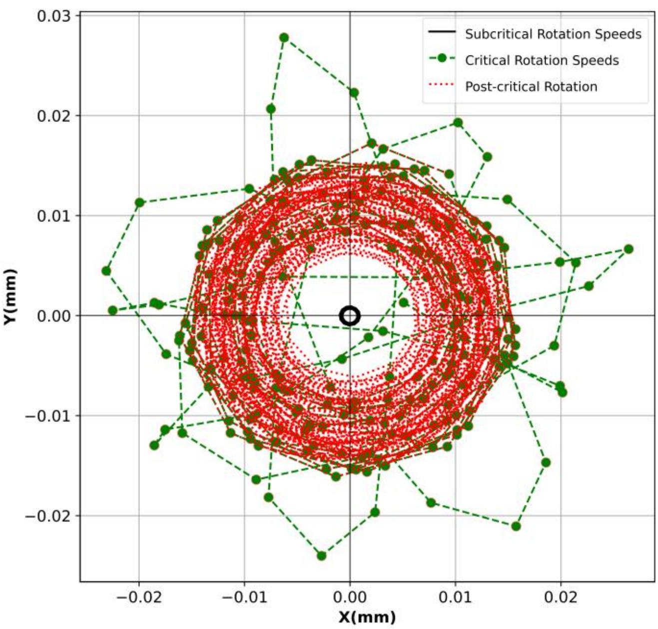


Fig. 10 Shaft orbital movement with critical rotation speeds

This section critically evaluates the implications of the investigation findings on spindle functionality and precision machining operations. It analyzes the resonance tendencies observed, in conjunction with the induced imbalances, concerning their potential impact on spindle performance, operational safety, and the implications for high-precision machining processes.

Conclusions. This study unveils a novel approach for comprehending and optimizing the dynamics of gas-static spindle systems under deliberate imbalance conditions. Our rigorous computational experiments and analyses have demonstrably identified critical resonance-prone rotational speeds and quantified their detrimental influence on spindle performance. By introducing calibrated imbalances, we illuminate the system's dynamic behavior, showcasing the significant amplification of vibration amplitudes within resonance regions. To mitigate these effects and enable safe operation beyond critical speeds, we propose a range of technically viable solutions. Notably, our investigation highlights the efficacy of intensified acceleration strategies, allowing for swift passage through critical frequencies while minimizing oscillation amplitudes. This groundbreaking approach paves the way for utilizing gas-static bearing technology in diverse, demanding applications beyond traditional machining, including precision robotics, microfabrication, and other fields where exceptional accuracy and control are paramount. In conclusion, this study establishes a new paradigm for understanding and mitigating resonance effects in gas-static spindle systems, paving the way for the development of next-generation spindles capable of pushing the boundaries of precision and efficiency across a range of critical industries.

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ДОСЛІДЖЕННЯ ДИНАМІКИ ВАЛУ ШПИНДЕЛЯ НА ГАЗОСТАТИЧНИХ ПІДШИПНИКАХ

Це дослідження розглядає складну динаміку валу шпинделя, встановленого на газостатичних підшипниках, використовуючи обчислювальні експерименти та аналіз, щоб виявити ключові моменти для оптимізації процесів високоточної обробки. Ми визначаємо власні частоти і резонансні тенденції коливань шпинделя за допомогою передових методів моделювання методом скінченних елементів (МСЕ), підкреслюючи їх вплив на стабільність роботи і якість обробки. Спеціально введений дисбаланс додатково ілюструє динамічну поведінку, демонструючи негативний вплив резонансу на характеристики шпинделя. Щоб пом'якшити ці ефекти, ми досліджуємо різні технічні рішення, включаючи зменшення дисбалансу ротора та інтенсифікацію прискорення на критичних ділянках. Зрештою, це дослідження допомагає краще зрозуміти динаміку шпинделів на газостатичних підшипниках, керуючи процесом розробки надійних і високоточних шпинделів для цілого ряду промислових застосувань, що виходять за рамки виключно машинобудування, таких як прецизійна робототехніка та мікропроцесорне виробництво.

Ключові слова: динаміка шпинделя, газостатичні підшипники, власні частоти, розрахунок

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