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Dynamics analysis of rotor in disc centrifuge for separation of bioengineering

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Abstract: In order to reveal the influence of gyroscope effect and structure parameters on the modal frequency and critical speed of the rotor system in disc centrifuge for separation of bioengineering. Based on the rotor rigid body dynamics, the fixed-point gyroscope motion of the rotating spindle of the disc centrifuge was analyzed. Establishing a finite element dynamic model for the rotor system of a disc centrifuge, taking into account the gyroscopic moment caused by the rotational inertia of the rotor disk and the elastic support of the bearings. We calculated the gyroscopic moment and the analytical expression of critical speed. Analyzing the quantitative relationship between the gyroscope effect, bearing support stiffness, drum material density and the critical speed of the rotor system. The results show that the calculated value of finite element is close to the measured value. The influence of gyroscopic force on the vibration characteristics of rotor system for dish centrifuge cannot be ignored. The critical speeds of the rotor system increase with the increase of elastic support stiffness, while the first critical speed decreases with the increase of drum density, but the second critical speed increases with the increase of drum density. These studies provide a theoretical reference for the dynamic response, structural design and dynamic balance of disc centrifuge.

Keywords: disc centrifuge; rotor system; critical speed; gyroscopic effect

1. Introduction

Biological products include traditional biotechnology products (such as organic solvents, amino acids, organic acids, antibiotics produced by fermentation) and modern biotechnology products (such as medical peptides and proteins produced by recombinant DNA technology). Their production is different from that of general chemicals and has its own characteristics: (1) low concentration and small solid particle size. (2) Usually a mixture of multiple components. (3) Poor stability. (4) The requirements for the final product quality are very high. Therefore, in the development and research of most biological products, the research cost of downstream processing accounts for more than 50% of the total research cost; In the cost composition of the product, the separation and purification part accounts for more than 40-80% of the total cost; During the production process, the manpower and material resources for downstream processing account for 70-90% of the entire process.

The downstream processing of biotechnology can be divided into four steps [1]: (1) Pre treatment of fermentation broth and solid-liquid separation (removal of insoluble substances). Filtering and centrifugation are basic unit operations, sometimes requiring techniques such as coagulation, flocculation, cross flow membrane filtration, and cell lysis. (2) Preliminary purification (product extraction). There are many optional unit operations, such as adsorption, extraction, precipitation,

and ultrafiltration. (3) Highly purified (product refinement). Typical unit operations include chromatography, electrophoresis, precipitation, ion exchange, etc., but these techniques have high selectivity for the products. (4) Finished product processing. Concentration, crystallization, and drying are key. The culture medium (fermentation broth) in step (1) contains bacterial (cell) bodies, intracellular and extracellular metabolites, intracellular cellular substances, and remaining culture medium components. Regardless of whether the products people need are intracellular, extracellular, or the bacterial cells themselves, pre-treatment of the culture medium and recovery of the bacterial cells are the first steps. However, this is a difficult problem in solid-liquid separation, and there are not many practical and feasible recovery methods. Due to the consideration that recycling methods need to be cheap, simple, and reliable, as well as limited by technology and economy, recycling operations have become a bottleneck problem in downstream processing of biotechnology.

In biotechnology, disc centrifuges are mainly used in the following areas: (1) separation of biomolecules: Disc centrifuges are commonly used for separating DNA, RNA, Proteins and other biomolecules, as well as organelles and cellular debris. These separation operations are of great significance for fields such as biological research, genetic engineering, and biopharmaceuticals. (2) Cell culture and processing: During the cell culture process, a disc centrifuge can be used for cell collection, concentration, and washing operations. For example, in cell therapy and vaccine production, it is necessary to use a disc centrifuge for aseptic treatment and separation of cells. (3) Biopharmaceutical production: In the process of biopharmaceutical production, disc centrifuges can be used for the separation, purification, and concentration of drug components. By centrifugal separation, impurities in drugs can be removed, improving the purity and efficacy of drugs. The development trend of disc centrifuges in biotechnology: (1) Continuous technological innovation: With the continuous development of biotechnology, the technology of disc centrifuges is also constantly innovating and improving. For example, by improving the structure and materials of the disc, separation efficiency can be increased and energy consumption can be reduced; By introducing advanced control systems and sensor technology, more precise separation control and automation operations can be achieved. (2) The application fields are constantly expanding: With the widespread application and continuous development of biotechnology, the application fields of disc centrifuges are also constantly expanding. In addition to traditional biopharmaceuticals and cell culture fields, disc centrifuges are gradually being applied to emerging fields such as bioenergy and biological environmental protection. (3) Improvement of intelligence and automation level: In the future, disc centrifuges will pay more attention to the improvement of intelligence and automation level. By introducing advanced technologies such as artificial intelligence and big data, more intelligent separation control and automation operations can be achieved, improving production efficiency and product quality. In summary, the current application status of disc centrifuges in biotechnology shows characteristics such as high efficiency, high degree of automation, small footprint, and stable operation. With the continuous development of biotechnology, the application fields of disc centrifuges will be further expanded, and

the technology will continue to innovate and improve.

Disc centrifuge [2,3] is an efficient centrifugal separation equipment widely used in the chemical, food, and environmental industries. Importantly, the rotor system mainly consists of the drum, disc, and drive device components. The high-speed rotation of the drum generates inertial centrifugal force in the gap between the discs, thereby achieving multiphase flow separation. The dynamic characteristics of the rotor system directly affect the separation accuracy, lifespan, and efficiency of the disc centrifuge. With the development of the disc centrifuge towards high speed, light structure and high accuracy, the force between the rotor turntable and the bearing is growing, and its dynamic problems will become more and more prominent [4–6]. Therefore, calculating the critical speed of the rotor is crucial for the vibration of a disc centrifuge, and it is necessary to avoid resonance during normal operation of the disc centrifuge.

At present, the transfer matrix method [7,8], the modal synthesis method [9,10], and the finite element method [11–13] are usually used for the calculation of critical speed. The simulation calculation has also some mature and stable general commercial softwares, such as ANSYS and SAMCEF [14,15]. For the gyroscopic effect of rotor system, in references [16,17], the influence law of gyroscopic moment on rotor critical speed and unbalance response was given by using hybrid modeling and finite degree of freedom discrete method. For the influence of sliding bearing support form on rotor dynamics, in references [18,19] they found that the support dynamic coefficient was different under different rotor speeds. For disc centrifuges, Xue et al. [20] used the finite element software to study the dynamic characteristics of high-speed rotor for the latex separation. He et al. [21] studied the influence of the structural parameters of vertical shaft system in disc centrifuge on the critical speed. However, these finite element models are simplified and have certain limitations. However, there is currently relatively little research on the critical speed of the rotor system in disc centrifuges. Studying the vibration modes and critical speeds of rotor system can lay an important foundation for optimizing the dynamic performance of disc centrifuge.

It should be pointed out that there are few literature studies on the critical speed of disc centrifuge under considering both elastic support in structural parameters and gyroscopic effects simultaneously. The research objective of this article is: Firstly, we derive the gyroscopic moment, and we add the gyroscopic moment and the elastic support to the rotor dynamics equations. Secondly, we use software to create three-dimensional structural solid models of disc centrifuge, and apply loads and constraints to obtain the modal analysis in ANSYS module. Finally, we draw a Campbell diagram of the rotor of disc centrifuge and obtain the critical speed of rotor system, at the same time, by changing the level of structural parameters, we quantitatively analysis the variation law of critical speed. The research results provide theoretical reference for the structural optimization design and dynamic control of disc centrifuge.

2. Finite element model of rotor system considering gyroscopic effect

As shown in **Figure 1**, the typical rotor system [22–25] can generally be discretized into disk, rotating shaft, bearing and fixed support. The cross-sectional

position of rotor is expressed by the axis coordinates x, y of rotating shaft and the deflection angle θ_x, θ_y of cross-section.

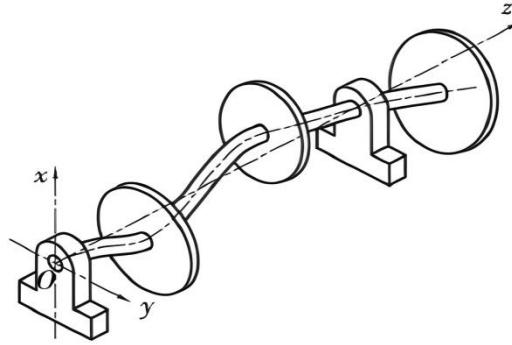


Figure 1. Diagrammatic sketch of rotor system.

For a rigid disk of lumped mass, the Langrange kinetic equation [26] of rotor is:

$$\begin{cases} [M_d]\{\ddot{u}_{1d}\} + \Omega[J]\{\dot{u}_{2d}\} = \{Q_{1d}\}, \\ [M_d]\{\ddot{u}_{2d}\} - \Omega[J]\{\dot{u}_{1d}\} = \{Q_{2d}\}. \end{cases} \quad (1)$$

Here, $[M_d] = \begin{bmatrix} m & 0 \\ 0 & J_d \end{bmatrix}$, $[J] = \begin{bmatrix} 0 & 0 \\ 0 & J_p \end{bmatrix}$, $\{u_{1d}\} = \{x, \theta_y\}^T$, $\{u_{2d}\} = \{y, -\theta_x\}^T$, m is disk mass, J_d is moment of inertia for diameter, J_p is polar moment of inertia, Ω is self-rotational angular velocity, $\{Q_{1d}\}, \{Q_{2d}\}$ are generalized forces on disk.

It needs to be emphasized, $G = \Omega \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & J_p \\ 0 & 0 & 0 & 0 \\ 0 & -J_p & 0 & 0 \end{bmatrix}$ is gyroscopic effect matrix.

When the rotating shaft makes synchronous forward precession, the gyroscopic torque Γ in rotor is:

$$\Gamma = -(J_p - J_d)\Omega^2 \sin \alpha \cos \alpha \quad (2)$$

Here, α is the angle between the axis of disk and the line connecting the two fulcrums.

From the above equations, it can be seen that the presence of gyroscope torque can reduce the deformation of the shaft and improve its rigidity, thus increasing the critical speed of the shaft.

When rotating at high speed, the shaft needs to be regarded as an elastic shaft, and its mass has distribution, the displacement of any element nodes A, B are $\{u_{1s}\} = \{x_A, \theta_{Ay}, x_B, \theta_{By}\}^T$, $\{u_{2s}\} = \{y_A, -\theta_{Ax}, y_B, -\theta_{Bx}\}^T$, according to the Lagrange equation, the structural dynamics of the shaft unit is:

$$\begin{cases} [M_s]\{\ddot{u}_{1s}\} + \Omega[J_s]\{\dot{u}_{2s}\} + [K_s]\{u_{1s}\} = \{Q_{1s}\}, \\ [M_s]\{\ddot{u}_{2s}\} - \Omega[J_s]\{\dot{u}_{1s}\} + [K_s]\{u_{2s}\} = \{Q_{2s}\}. \end{cases} \quad (3)$$

Here, $[M_s]$ is uniform matrix including translational inertia matrix, $[J_s]$ is rotation matrix, $[K_s]$ is stiffness matrix, $\{Q_{1s}\}, \{Q_{2s}\}$ are generalized forces on shaft unit.

The displacement of disk and each node of shaft unit is composed the generalized coordinates of rotor. Since the disk is connected with the shaft, so at the joint, the force

and moment acting on the disk and the force and moment acting on the shaft unit are the relationship between the acting force and the reaction force. The rotor motion equation is:

$$\begin{cases} [M_1]\{\ddot{U}_1\} + \Omega[J_1]\{\dot{U}_2\} + [K_1]\{U_1\} = \{Q_1\}, \\ [M_1]\{\ddot{U}_2\} - \Omega[J_1]\{\dot{U}_1\} + [K_1]\{U_2\} = \{Q_2\}. \end{cases} \quad (4)$$

Here, $[U_1] = [x_1, \theta_{1y}, x_2, \theta_{2y}, \dots, x_N, \theta_{Ny}]^T$, $[U_2] = [y_1, -\theta_{1x}, y_2, -\theta_{2x}, \dots, y_N, -\theta_{Nx}]^T$ represent the displacement vector for the rotor contains N nodes, $[M]_1$ is overall mass matrix, $\Omega[J]_1$ is rotation matrix, $[K]_1$ is stiffness matrix, and $\{Q_1\}, \{Q_2\}$ are the corresponding generalized forces.

For the bearing unit with stiffness and damping, the center displacement of bearing seat j is x_{bj}, y_{bj} , then the Lagrange kinetic equation of bearing seat is:

$$\begin{bmatrix} M_{bx} & 0 \\ 0 & M_{by} \end{bmatrix} \begin{Bmatrix} \ddot{x}_b \\ \ddot{y}_b \end{Bmatrix}_j + \begin{bmatrix} c_{bxx} & c_{bxy} \\ c_{byx} & c_{byy} \end{bmatrix} \begin{Bmatrix} \dot{x}_b \\ \dot{y}_b \end{Bmatrix}_j + \begin{bmatrix} k_{bxx} & k_{bxy} \\ k_{byx} & k_{byy} \end{bmatrix} \begin{Bmatrix} x_b \\ y_b \end{Bmatrix}_j = \begin{Bmatrix} Q_{1b} \\ Q_{2b} \end{Bmatrix}_j. \quad (5)$$

Here, $[M_{bx}], [M_{by}]$ are projection quality for x, y direction of bearing seat, $[k_b], [c_b]$ are stiffness and damping coefficient matrix of support, Q_{1b}, Q_{2b} are generalized oil film forces on bearing.

If the system has S supports in total, the oil film force acting on the rotor is the sum of the oil film forces of each support. Then the overall motion equation of the rotor-bearing system is the superposition of Equations (4) and (5), and its general form is:

$$[M]\{\ddot{q}\} + ([C] + [G]_{gyr})\{\dot{q}\} + ([K] + [K]_{spc})\{q\} = \{F(t)\} \quad (6)$$

Here, $[M], [C], [K]$ are generalized mass matrix, generalized damping matrix and generalized stiffness matrix respectively, q, \dot{q}, \ddot{q} are displacement, velocity and acceleration vectors of Generalized coordinates respectively, $F(t)$ are generalized external excitation forces, $[G]_{gyr}$ is generalized gyroscopic effect matrix, $[K]_{spc}$ is generalized rotational damping matrix.

When solving the vortex frequency and critical speed [27], only the homogeneous equation corresponding to the Equation (5) needs to be considered, so the vortex frequency ω equation without damping is:

$$\left| -[M - (J_d - J_p \frac{\Omega}{\omega})] \omega^2 + K \right| = 0 \quad (7)$$

Further, when calculating the critical speed of rotor system, the critical speed of synchronous forward vortex can be calculated by substituting $\Omega = \omega$ into the Equation (7).

3. Finite element operation of rotor system in disc centrifuge

The rotor system structure in disc centrifuge is shown in **Figure 2**. The specific assembly is as follows: the drum is connected with the vertical shaft through the conical surface, the copper gear on the horizontal shaft drives the spiral gear on the vertical shaft, the spring seat is fixed on the engine seat, the upper bearing of vertical shaft is supported by the six springs evenly distributed in spring seat through the

sliding sleeve, and the lower bearing of vertical shaft is hinged on the engine seat.

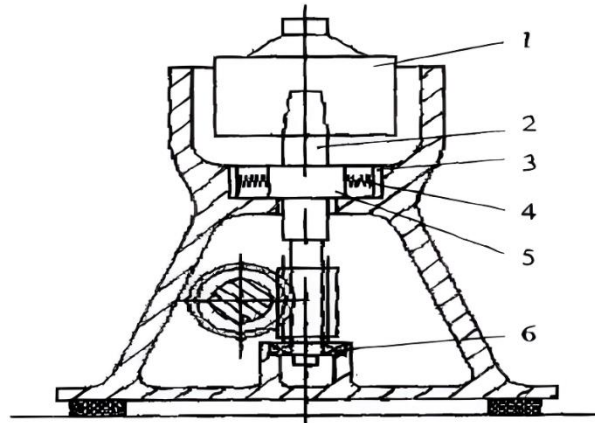


Figure 2. Structure of rotor system in disc centrifuge.

Note: 1. Drum; 2. Vertical shaft; 3. Spring seat; 4. Radial spring; 5. Upper bearing; 6. Lower bearing.

In the Ansys16.0 software, the SOLID185 of geometric elements is used to divide the drum and the vertical shaft, the parameters are Elastic modulus $E = 2.01 \times 10^{11}$ n/m, Poisson's ratio $\mu = 0.3$, density is $\rho = 7730 \text{ kg/m}^3$. The six springs at the upper end of drum and the lower bearing are simplified as elastic supports, which are divided by COMBIN14 of geometry geometric, the parameters are stiffness coefficient $K_{up} = 4.95768 \times 10^6$ N/m, $K_{under} = 1.8 \times 10^8$ N/m. The rotating components on the vertical shaft are divide by MASS21 of geometric elements, and the gyroscopic effect should be imposed by CORIOLIS command. The finite element mesh generation adopts the mapping mesh generation method, which has high accuracy. The finite element mesh is divided into 25,527 nodes and 22,963 units, including 22,946 SOLID units, 12 COMBIN14 units and 5 MASS21 units. The three-dimensional finite element model of rotor system in disc centrifuge is shown in **Figure 3**.

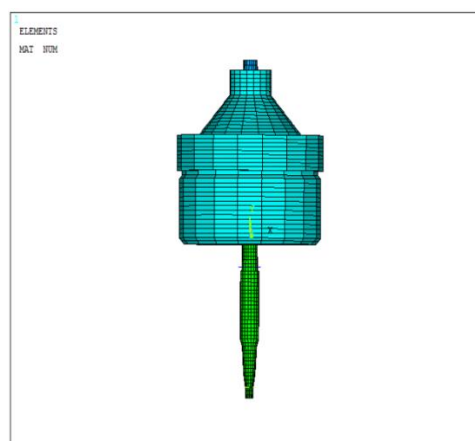


Figure 3. Finite element model of rotor system.

4. Calculation and analysis of critical speed

4.1. Calculation of critical speed

The constraints at the upper and lower bearings of rotor system in disc centrifuge

are axial displacement at one end and fixation at the other end. The degree of freedom in the axial direction of vertical shaft is zero, and the centrifugal force caused by eccentric mass is applied in the form of rotational angular velocity. QRDAMP method in ANSYS is selected to calculate the critical speed, finally, the Campbell law is obtained in **Figure 4**.

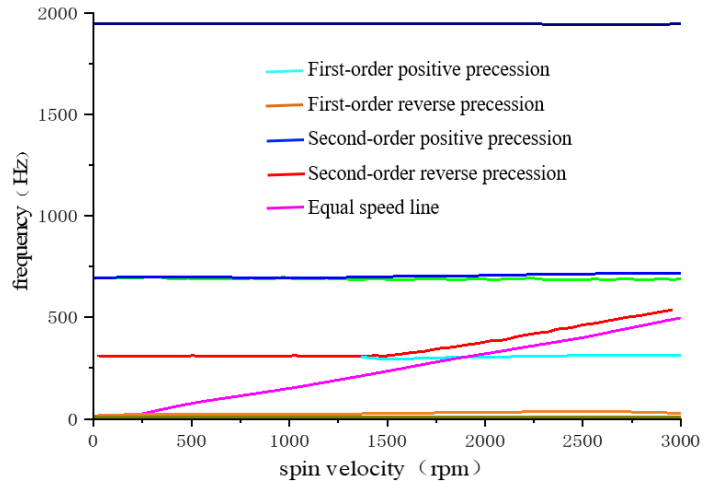


Figure 4. Campbell diagram of rotor system in disc centrifuge.

According to the definition of critical speed, the intersection point between the is rotational speed line drawn from the origin in the Campbell diagram and the vortex frequency curve is the critical speed. **Figure 4** shows that the first-order critical speed of the rotor is 720.6 r/min, and the second-order critical speed is 19,908.4 r/min. The working speed of this model of disc separator is 7250 r/min, which is much higher than its first-order critical speed but much lower than its second-order critical speed. Therefore, the dynamic characteristics of this rotor only consider the first-order and second-order critical speeds and corresponding vibration modes.

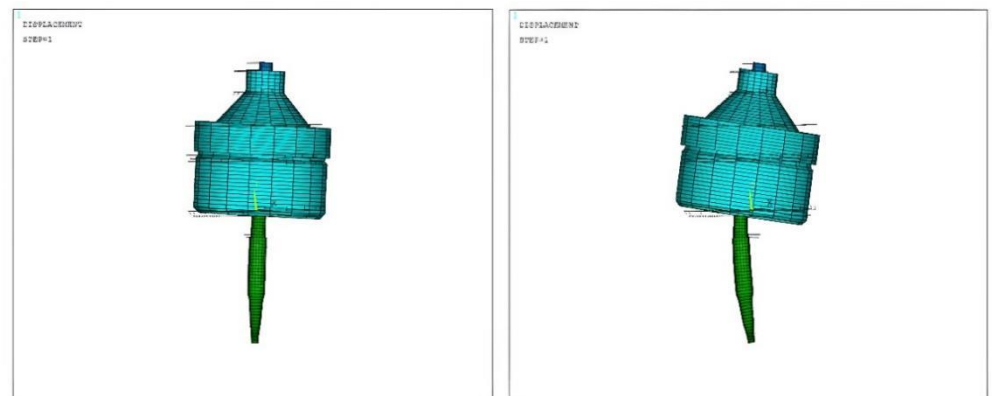


Figure 5. Vibration mode diagram of rotor system: (a) first-order vibration mode; (b) second-order vibration mode.

From the **Figure 5**, it can be seen that the deformation of the second-order vibration mode is much more pronounced than that of the first-order, and the top of drum is the maximum displacement of the vibration for the first-order and second-

order vibration mode. Meanwhile, when the vertical rotor system is in the first-order vibration mode, the vertical shaft remains basically unchanged, and the deflection deformation generated by the shaft is mainly caused by the support spring at the upper support. The second-order vibration mode is the swinging of the typical first order cantilever beam bending characteristics.

4.2. Influence of gyroscopic effect on critical speed

In ANSYS, the gyroscopic torque is changed to 0 by CORIOLIS command settings, so the calculation results of the critical speed of rotor in disc centrifuge without considering the gyroscopic effect are shown in **Table 1**.

Table 1. Effect of gyroscopic moment on the critical speed of rotor system.

Name	Without gyroscopic moment	With gyroscopic moment	Error/(%)
First-order critical speed (r/min)	671.3	720.6	6.84
Second-order critical speed (r/min)	5813.85	19,908.4	70.88

It can be seen from the **Table 1** that the gyroscopic torque increases the first-order and second-order critical speeds, especially the second-order is a more pronounced increase. At the same time, the references [20] and [28] have done some practical test on the same type of disc centrifuge by using dynamic balancing technology. The actual data show that the first-order resonance speed of disc centrifuge of fluctuates within the range of 710–750 r/min. Therefore, to some extent, the first-order critical speed value considering gyroscopic effect is closer to the actual measured value.

4.3. Influence of upper support stiffness on critical speed

The upper support springs on disc centrifuge has the ability of automatic centering and good vibration damping performance to the rotor system, which can reduce the rigidity of the system and make the machine run smoothly. When the upper support stiffness is increased from 1.0×10^5 (N/m) to 1.0×10^{11} (N/m), the change law of critical speed is shown in **Figure 6**.

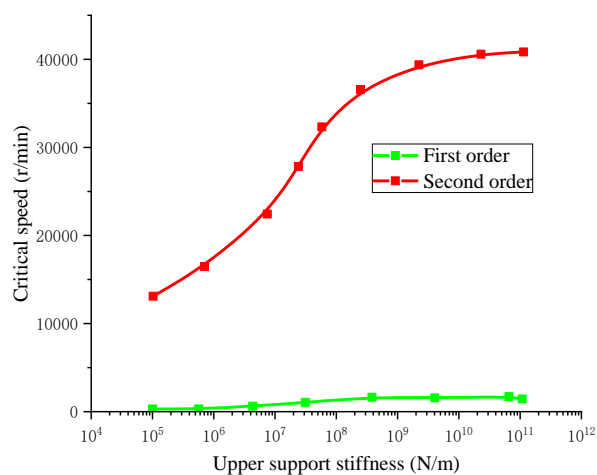


Figure 6. Effect of upper support stiffness on critical speed.

From **Figure 6**, it can be seen that as the stiffness of the upper support increases along the order of magnitude, both the first and second critical speeds increase, and the second-order change rate is significantly larger. When the stiffness increases from 1.0×10^6 (N/m) to 1.0×10^8 (N/m), the second-order critical speed undergoes a step change and then tends to slow down. At this point, due to the excessive stiffness, it can be approximated as a fixed support, and the impact on the critical speed gradually reaches its upper limit.

4.4. Influence of drum material density on critical speed

Generally, changing the weight of disk can change the critical speed of rotor system. By changing the weight of the disc, the critical speed of the rotor system can be altered. As the density of the drum increases from 6800 kg/m^3 to 8600 kg/m^3 , the change law in critical speed is shown in **Figure 7**.

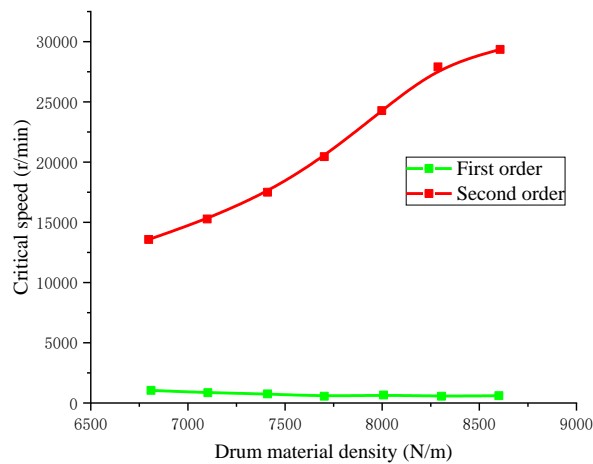


Figure 7. Effect of drum material density on critical speed.

From **Figure 7**, it can be seen that the first-order critical speed of the rotor gradually decreases with the increase of conversion density and eventually stabilizes, while the second-order critical speed gradually increases with the increase of conversion density and finally slows down. Compared to the first order, the amplitude change rate of the second order is larger. Therefore, in the design of the drum structure, it is possible to consider increasing the weight of the drum to achieve the goal of moving the working speed away from the critical speed.

5. Conclusion

For fermentation broth pretreatment, blood separation, and restricted component recovery, centrifuges provide a non-invasive separation method while maintaining biological activity. Referring to the Powerfuge series centrifuges from Carl Separators Co., Ltd. in the United States, this article designs and develops a fully automatic high-speed bio disc separator to achieve the coupling of fermentation and separation processes. This series of separators has a drum separation factor of up to 20,000 G, and the whole machine runs smoothly with low vibration, achieving fully automatic operation and on-site cleaning. The separation effect is good and the processing capacity is large. Especially suitable for the clarification and separation of suspensions

with solid phase density greater than liquid phase, small solid-liquid density difference, and low solid phase concentration (< 5%), widely used in fields such as biotechnology, biopharmaceuticals, blood products, traditional Chinese medicine preparations, fine chemicals, food and beverage, ultrafine powders, etc.

The gyroscopic effect of a disc centrifuge (also known as a disk centrifuge) refers to the mechanical effects generated by the mass and rotational speed of the rotor during high-speed rotation. The gyroscopic effect refers to the phenomenon where the rotation axis of a rotating object produces a moment perpendicular to both the rotation axis and the direction of the external torque when subjected to an external torque, causing the rotation axis to deflect. In a disc centrifuge, when the rotor rotates at high speed, significant gyroscopic effects are generated due to the mass and rotational speed of the rotor. The impact of gyroscopic effect: (1) Rotor stability: The gyroscopic effect can affect the stability of the rotor. During high-speed rotation, the rotor is subject to various external forces such as air resistance and unbalanced forces. The torque generated by the gyroscope effect can resist the interference of these external forces, keeping the rotor relatively stable. However, if the gyroscopic effect is too large or external interference is too strong, the rotor may lose stability, leading to vibration or stall. (2) Bearing wear: The gyroscopic effect can also exacerbate bearing wear. Due to the effect of gyroscopic torque, the rotor will generate a gyroscopic motion trend. When this trend cannot be offset by the friction torque of the bearing, it will cause the ball to slide along the raceway of the ring, thereby increasing heat generation and bearing wear. (3) Separation effect: The gyroscope effect also has a certain impact on the separation efficiency of disc centrifuges. Although the gyroscopic effect itself does not directly participate in the separation process, it can affect the motion state of the rotor, which in turn affects the flow and separation effect of the suspension between the discs. Calculation and analysis of gyroscopic effect: In engineering practice, finite element analysis software (such as ANSYS) is commonly used to calculate and analyze the gyroscopic effect of disc centrifuges. These software can consider the influence of gyroscopic effects on the dynamic characteristics of rotors, including rotor vibration, deformation, and stability. By calculation and analysis, the design parameters of the rotor, such as speed, mass distribution, and bearing type, can be optimized to reduce the impact of gyroscopic effects on the performance of disc centrifuges. Measures to reduce gyroscopic effects: (1) Optimize rotor design: By optimizing the mass distribution and shape design of the rotor, the generation of gyroscopic effects can be reduced. For example, a symmetrical disc layout and uniform mass distribution can be used to reduce gyroscope torque. (2) Improving bearing performance: Choosing high-performance bearings and lubricants can reduce bearing friction and wear, thereby reducing the impact of gyroscopic effects on rotor stability. (3) Controlling the speed: Reducing the speed appropriately within the allowable range can reduce the generation of gyroscopic effect. However, it should be noted that reducing the rotational speed may affect the separation efficiency and production capacity of the disc centrifuge. (4) Strengthen monitoring and maintenance: Regularly monitor and maintain the disc centrifuge to promptly identify and address potential issues such as bearing wear, imbalance, etc., which can maintain the stability of the rotor and extend the service life of the equipment. In summary, the gyroscopic effect of a disc centrifuge is an important mechanical phenomenon that has a certain

impact on the stability and separation efficiency of the rotor. By optimizing rotor design, improving bearing performance, controlling speed, and strengthening monitoring and maintenance measures, the impact of gyroscopic effects can be reduced, and the performance and stability of disc centrifuges can be improved.

The main conclusions of this article are:

(1) According to the theory of rigid body dynamics, the gyroscopic moment was calculated, and the motion equation of the rotor system was derived using the discrete method. Using ANSYS software to simulate and calculate the dynamic characteristics of the rotor system of a disc centrifuge, the critical speed and model vibration mode were calculated in detail, and the influence of the drum gyro effect, bearing support stiffness, and drum material density on the critical speed was discussed in detail.

(2) Theoretical calculations and finite element simulation results indicate that the rotor system of the disc centrifuge has synchronous positive precession, and its critical speed within the second order has practical significance. The software calculation value of the first-order critical speed when considering the gyroscope torque is close to the measured first-order resonance speed of the separator, which verifies the effectiveness of the finite element model. Moreover, the gyroscope torque increases the critical speed, especially with a significant impact on the second-order critical speed; When the stiffness value of the upper support varies from 1.0×10^5 (N/m) to 1.0×10^{11} (N/m), the numerical change of the second-order critical speed is significant; The increase in drum weight will increase the second-order critical speed of the rotor system and decrease the first-order speed. Therefore, when designing the dynamic performance of the rotor system of a disc centrifuge at a certain speed, the influence of the above parameters should be comprehensively considered in order to obtain the optimal design.

(3) Due to the drum and the vertical shaft are fixedly connected as a whole in dynamic model, so it ignores the stiffness and damping in the joint between the drum and the vertical shaft. Because of this, there is a certain slight error between the calculation results and the actual situation.

In addition, this article ignores the influence of the meshing between the small helical gear on the vertical axis and the copper gear on the horizontal axis on the lateral stiffness of the vertical axis system. Furthermore, we can consider more precise rotor system dynamics and apply artificial intelligence technology to the rotor system dynamics of disc centrifuge.

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References

1. Mouat Aidan R. Sustainability in food-waste reduction biotechnology: a critical review[J]. *Current opinion in biotechnology*, 2022, 77:102781.
2. E. A. Parvaneh, H. Monireh. Optimization of industrial-scale centrifugal separation of biological products: comparing the performance of tubular and disc stack centrifuges[J]. *Biochemical Engineering Journal*, 2022, 178:108281.
3. Fu Shuangcheng, Zhu Jie, Zhou Faqi, et al. Study on the characteristics of flow field in disc partition in disc centrifuge[J]. *Asia - Pacific Journal of Chemical Engineering*, 2021, 16(4):1-9.
4. Shi Kai. Research on Assembly High-speed Rotary Drum Stress and Optimization Based on Fluid Dynamic Characteristics[D]. Zhanjiang: Guangdong Ocean University, 2015, 34-45.
5. Ofuchi E.M., Silva H.L.V., Bertoldi D., et al. Study of the bubble motion in a centrifugal rotor based on visualization in a rotating frame of reference[J]. *Chemical Engineering Science*, 2022, 259:117829.
6. Yang Mengyan, Liu Xiaolin, Howell John A, et al. Analysis and estimation/prediction of the disk stack centrifuge separation performance-Scaling from benchtop fixed rotor type to disk stack centrifuges[J]. *Separation Science and Technology*, 2020, 55(14):2615-2621.
7. Gao Chaoqi, Xiang Yiqiang, Yang Yunshen, et al. Transfer matrix method for analyzing dynamic response of multi-span elastically supported SFT under moving load[J]. *Applied Mathematical Modelling*, 2022, 112:238-261.
8. Deng Hao, Fang Xi, Wu Huachun, et al. Dynamic Analysis of Flexible Rotor Based on Transfer Symplectic Matrix[J]. *Shock and Vibration*, 2019,1:1-11.
9. Zhang Yiming, Tang Jiqiang, Xu Xueping. Modal analysis and multidisciplinary optimization of disk-shaped rotor in MSCMG[J]. *International Journal of Mechanical Sciences*, 2022, 226:107387.
10. Tarkashvand A., Golmohammadi A., Safizadeh M. S.. Stability and modal analysis of an unbalanced asymmetric multi-disk rotor system on bearings as viscoelastic substrate[J]. *Archive of Applied Mechanics*, 2022, 92(8):2247-2271.
11. Seyed R. M., Mahmood H. A., Shahram J.. Analytical calculation and finite element evaluation of electromagnetic leakage field distribution in surface-mounted permanent magnet synchronous motors taking the rotor eccentricity effect into account[J]. *COMPEL-The international journal for computation and mathematics in electrical and electronic engineering*, 2021, 41(1):96-124.
12. Shen Zihan, Chouviou Benjamin, Thouverez Fabrice, et al. Enhanced 3D solid finite element formulation for rotor dynamics simulation[J]. *Finite Elements in Analysis and Design*, 2021, 195:103584
13. Chen Y. S., Cheng Y. D., Liao J. J., et al. Development of a finite element solution module for the analysis of the dynamic behavior and balancing effects of all induction motor system[J]. *Finite Elements in Analysis and Design*, 2008, 44:483-492.
14. Sun Hongyan, Zhang Xiaolong. Rotator Critical Rotational Speed and Modal Analysis Based on ANSYS[J]. *Machine Building & Automation*, 2008, 4: 53-54.
15. Jetteur P., Bruyneel M.. Advanced capabilities for the simulation of membrane and inflatable space structures using SAMCEF[J]. *Computational Methods in Applied Sciences*, 2008, 8:211-231.
16. A Farshidianfar, S Soheili. Effects of rotary inertia and gyroscopic momentum on the flexural vibration of rotating shafts using hybrid modeling[J]. *Mechanical Engineering*, 2009,16(1):75-86.
17. Wang Meiling, Han Qingkai. The gyroscopic effect on dynamic characteristics of dual-disk rotor system[J]. *Advanced Engineering Forum*, 2011, 2(3):942-947.
18. Z Yaacob, M K Hasan, J Sulaiman. On the dynamics behaviors of a cylindrical journal bearing[J]. *International Symposium on Information Technology*, 2008,4:1-7.
19. Huang Manliang, Liu Changjun, Zhang Guangye, et al. Analysis about critical rotate speed of cantilever single-rotor centrifugal machine[J]. *Oil Field Equipment*, 2006, 35(S):27-28.
20. Xue Xiaoning, Chen Jingchao, He Zhen. Dynamics characteristics analysis on high-speed rotor of latex centrifuge separator[J]. *Journal of Mechanical Design*, 2014, 31(4):84-89.

21. He Shizheng, Wang Donghui, Yang Jian, et al. Influence of structural parameters on critical speed of vertical shaft system of a dish centrifuge[J]. *Transactions of The Chinese Society of Agricultural Machinery*, 2005, 36(7):57-60.
22. Hong Jie, Jiang Liming, Wang Yongfeng, et al. Nonlinear Dynamics of an Elastic Stop System and Its Application in a Rotor System[J]. *Applied Sciences*, 2022,12(10):5103-5111.
23. S. D. Sovan. Dynamics of a Non-Ideal Gyroscopic Rotor System with Translational-Rotational Coupling Effect of External and Internal Damping[J]. *Mechanics of Solids*, 2022, 57(3):604-616.
24. Han Qingkai, Yu Tao, Wang Deyou, et al. Nonlinear vibration analysis and diagnosis method of fault rotor system[M]. Beijing: Science Press, 2010.
25. Mohammad R. M., Peiman M.. Prediction of chatter in high speed milling including gyroscopic effects[J]. *International Journal of Machine Tools & Manufacture*, 2006, 46: 996-1001.
26. Densborn Simon, Sawodny Oliver. Flexible multibody system modelling of an aerial rescue ladder using Lagrange's equations[J]. *Mathematical and Computer Modelling of Dynamical Systems*, 2021, 27(1):322-346.
27. S Huaitao, Z Jizong, Z Yu, H Gang. Calculation and analysis of critical speed of high speed motor spindle rotor system[C]. *IOP Conference Series: Materials Science and Engineering*, 2018, 399(1):012025.
28. Zhang Qiong. Calculation of dynamic characteristics and dynamic balance of disc screw centrifuge[D]. Hangzhou: Zhejiang University, 2008, 45-53.