

Dynamic Reliability Analysis of Drum-Body Horizontal Screw Centrifuge

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Abstract: Taking the horizontal screw centrifuge drum as the research object, the structural dynamic reliability model with considering the randomness of time-varying load and structural parameters is established, and the reliability and failure rate of drum body are obtained. Firstly, the analytical dynamic model considering fluid-structure interaction is established by using Lagrange equations; Then, imposed the fluid-structure coupling load in Ansys simulation software, and by using random sampling, we obtain the statistical characteristics of the drum body stress distribution; Finally, the evaluation index of structural dynamic reliability is given by using stochastic process and stress-strength interference theory. The results show that: under normal working conditions, the maximum stress concentration area of the horizontal screw centrifuge drum occurs in the sediment area, and its equivalent force presents a time-varying normal distribution. After continuous working for 2000 hours, the probability of drum strength meeting the requirements is less than 80%, and the service life conforms to the characteristics of early failure in the "bathtub" curve, which lays a foundation for the dynamic optimization design of high-speed horizontal screw centrifuge.

Keywords: Horizontal screw centrifuge; drum; stress-strength; dynamic reliability; failure rate.

INTRODUCTION

The horizontal screw centrifuge [1] is an important separation equipment in the chemical industry, and the drum is a key structural part of the horizontal screw centrifuge. Practice [2] has proved that the strength and performance of the drum directly affect the production efficiency, service life and safety performance of the horizontal screw centrifuge. With the development of horizontal screw centrifuge towards high speed, light structure and high precision, the drum will be subject to more and more complex loads and generate vibration, and its dynamic problems will become more and more prominent. Due to the dynamic loading under working conditions and the random uncertainty of structural parameters caused by manufacturing and installation errors, so the horizontal screw centrifuge drum is actually a random structural system under the excitation of time-varying loads. Therefore, it is of great significance to study the reliability of the drum based on dynamic analysis to ensure the high stability and safe operation of the horizontal screw centrifuge.

At present, the reliability research of various centrifuges is mainly aimed at the static reliability of structural components. Gu [3] studied the stress distribution and static strength of the disc separator drum by finite element software; Zhou [4] et al. qualitatively analyzed the reliability of the main shaft and drum of the sedimentation centrifuge by using the fault tree method; Ren [5], Li [6], and Meng [7] studied the problem of avoiding resonance failure of centrifuge from the perspective of structural vibration frequency by using different simulation software; References [8-12] analyzed the mode of centrifuge vibration system through finite element software, and pointed out the structural parameters that have a greater impact. However, these studies are difficult to reflect the internal relationship between the dynamic performance of the centrifuge drum and its structural parameters, and ignore the dynamic stress reliability of the centrifuge drum under random parameters. In this paper, firstly, considering the fluid structure interaction, the discrete analytical dynamic model of the drum body is established based on the Lagrange equation of analytical mechanics; Then, the finite element software is used to solve the dynamic response of the drum body. Combining with experimental design and random simulation, the dynamic stress distribution and statistical characteristics of the drum body can be obtained; Finally, using the stress and strength interference theory in the time-varying reliability of mechanical structures, the dynamic reliability calculation problem of the drum body under the random uncertainty of its parameters is given, and the quantitative rules of the reliability and failure rate of the drum body with the service time are obtained.

DYNAMIC MODEL OF DRUM BASED ON FLUID STRUCTURE COUPLING

A horizontal screw centrifuge is a type of centrifuge that utilizes high-speed rotating mechanical components to drive internal fluids for swirling motion. The phases are separated by the density difference of each phase during high-speed rotation, and then classified by a screw feeder and discharged from each corresponding outlet. Its general internal structure is shown in Fig.1. The drum 2 and screw-conveyor 3 are connected by two concentric bearings, and the main motor 1 of the horizontal screw centrifuge can provide rotational power to the drum through

a pulley 5. The drum 2 is connected to the outer shell of the planetary differential mechanism 4 through a hollow shaft at the left bearing. The planetary differential mechanism 4 can convert the same direction and speed rotation between the screw-conveyor 3 and the drum 2 into rotation in the same direction but at different speeds. The drum is the core component of a horizontal screw centrifuge, and its main parameters include: drum half cone angle, drum rotation speed, liquid pool depth, aspect ratio, drum separation factor, etc.

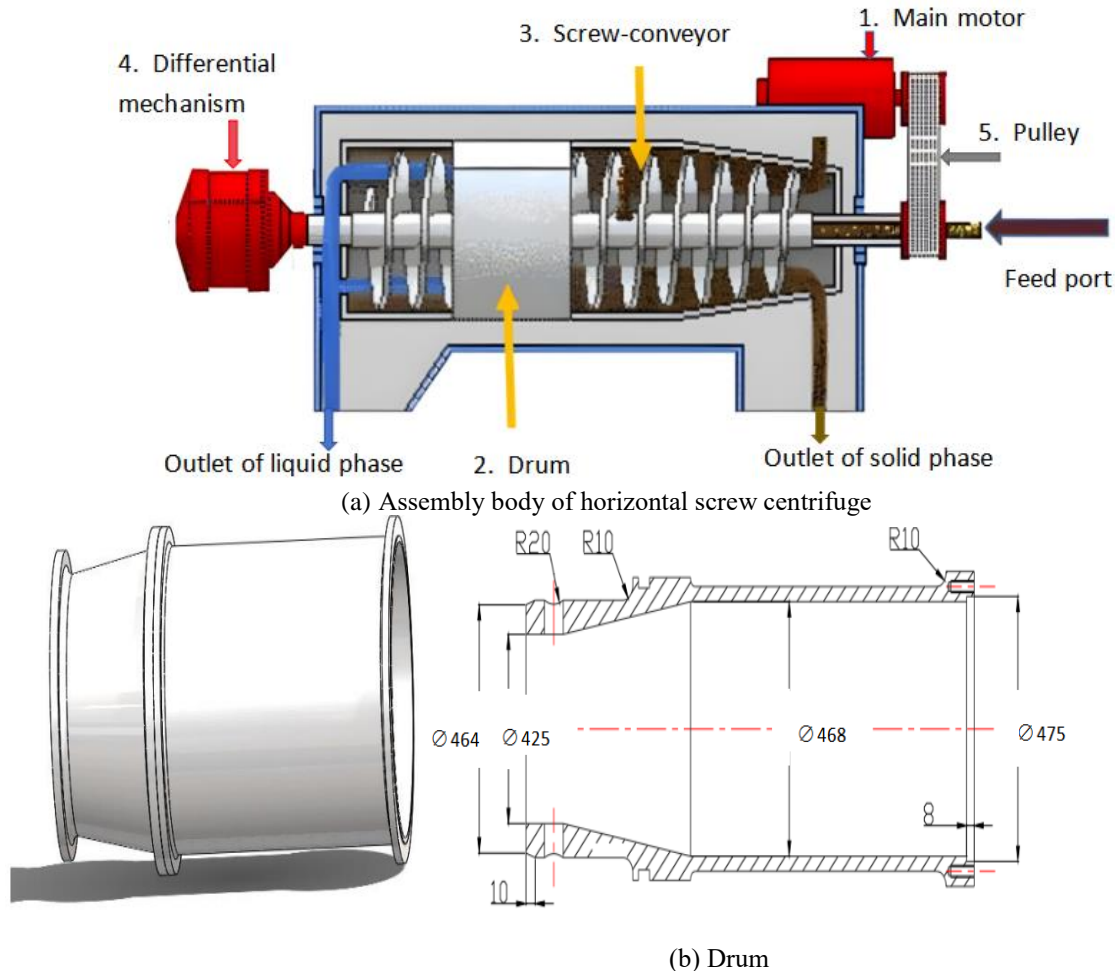


Fig. 1 3D structure of horizontal screw centrifuge and its drum

In terms of theoretical dynamic analysis, firstly, the drum barrel can be discretized with the triangular plate geometric unit. Considering the influence of liquid-solid coupling relationship, the dynamic model of drum can be established by using Lagrange equation as [13]:

$$\frac{d}{dt} \left(\frac{\partial T}{\partial \dot{\mathbf{u}}_i} \right) - \frac{\partial T}{\partial \mathbf{u}_i} + \frac{\partial N}{\partial \mathbf{u}_i} = \mathbf{F}_i + \mathbf{q}_i. \quad (1)$$

Here, \mathbf{u}_i is the displacement vector of the drum node i , T is the kinetic energy of the drum, N is the sum of the elastic deformation energy and fluid pressure energy of the drum, therefore, equation (1) has the characteristics of fluid structure coupling. \mathbf{F}_i is the generalized force vector of the external load (including the centrifugal force of the drum wall mass, the unbalanced excitation force transmitted by the main shaft system and the concentrated stress between the disc set and the horn tube assembly), \mathbf{q}_i is the force vector of the connection structure on the drum body (such as the contact binding force of the lock ring, the top cover and the thread).

Setting the drum barrel be divided into the m units, and the generalized coordinate vector of the whole is $\mathbf{U} = (\mathbf{u}_1, \mathbf{u}_2, \dots, \mathbf{u}_m)^T$, then expanding equation (1), we get the matrix form of all nodes for dynamic differential equation and the stress response $\boldsymbol{\sigma}$ as follows:

$$M\ddot{U} + C\dot{U} + KU = Q, \tag{2}$$

$$\sigma = DBU.$$

Here, M , C , K are the mass matrix, the damping matrix and the stiffness matrix respectively, Q is the load matrix, D , B are the elastic matrix and the strain matrix respectively. Due to limited space, the detailed expressions of each matrix can be found in Reference [18].

It can be seen from equation (2) that the strength analysis of the drum should be a dynamic process during the disc separator operation under various working conditions. Using equation (2), we can carry out the modal analysis on the drum and calculate the natural frequencies and modes of each order of vibration. In order to avoid resonance, we can optimize the structural parameters and spindle speed. However, due to the large degree of freedom, numerical integration is more complex to calculate the node displacement and stress response of the drum. Therefore, we use finite element software simulation to replace the numerical calculation of equation (2).

STRESS STATISTICAL CHARACTERISTICS OF DRUM BASED ON FINITE ELEMENT SIMULATION

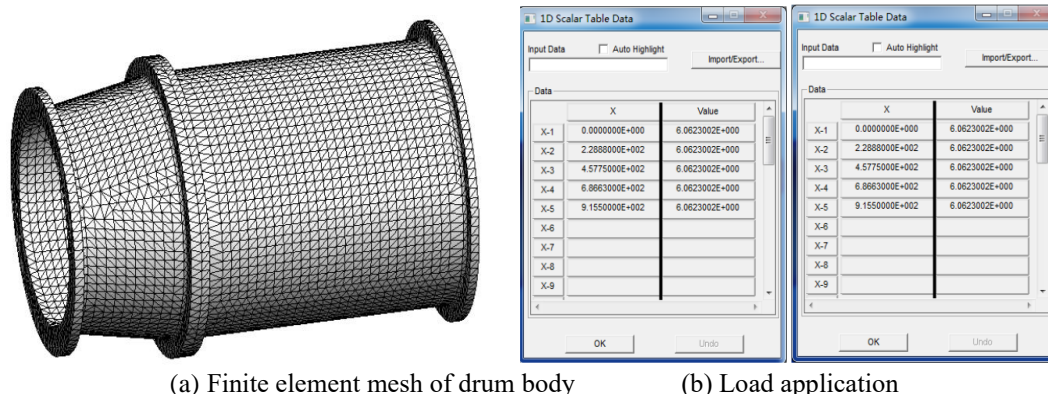
The main steps of ANSYS finite element structural analysis include pre-processing, applying loads, setting solution parameters and solving, and post-processing [14]. Pre-processing is the starting stage of the entire analysis process, aimed at establishing a structural finite element analysis model that conforms to the actual situation. This stage includes analyzing environmental settings, defining elements and material types, establishing geometric models, and performing mesh partitioning and defining boundaries and constraints. Applying loads, setting solution parameters, and solving involve defining load information, specifying analysis types and options, and performing solution calculations. Post-processing involves visualizing and analyzing the computed data, including entering the post-processing unit and reading in the computed results.

According to the design drawings, we give the specific structure and process parameters of the simulation, as shown in Table 1. Importantly, the boundary constraint conditions are: no friction constraint on both sides and axial constraint on top.

For finite element simulation analysis, mesh division is crucial. The quality of mesh division directly affects the accuracy of finite element simulation analysis and also affects the solving speed of computer simulation analysis. The more precise the mesh division, the higher the accuracy of finite element simulation analysis, and the slower the speed of computer simulation solving. ANSYS Workbench software has the nonlinear adaptive region for mesh division, which can adjust the quality of mesh division according to geometry. Using Solid45 units, the mesh division of the drum is shown in Fig. 2(a).

The loads include the torque of the fluid and the centrifugal force of the drum wall rotation, the unbalanced excitation force transmitted by the main shaft system is added to the drum in the form of prestressing. The constraint limits are the translational degrees of freedom along the X, Y, and Z axes, as well as the rotational degrees of freedom around the X and Z axes. Selecting the Load/BCs>Cream>Pressure>Element Uniform in the ANSYS Workbench software to create a new load name, and then select the corresponding p1 and p2 from the spatial fields in the pressure column of the input data tab to define the size of the pressure load, as shown in Fig. 2(b).

In finite element pre-processing, constraints, also known as boundary conditions, need to be applied. The boundary conditions should be determined according to the installation requirements of the drum. The two end covers of the drum are connected to the two shaft necks, and the bearings at both ends are fixed at one end and move at the other end. Therefore, the large end face of the drum constrains all degrees of freedom, while the small end face constrains radial and circumferential degrees of freedom.



(a) Finite element mesh of drum body (b) Load application
Fig. 2 Finite element model of drum

Table 1 Working conditions of drum barrel

Parameter	Value	Name	Value
Speed (r/min)	7250	Separated mixture	Natural rubber latex
Material of drum barrel	2Cr13	Surface pressure of liquid centrifugation (N/m ²)	10.4*10 ⁶
Poisson's ratio	0.3	Pre tightening force of thread (N)	50000
Density (kg/m ³)	7730	Centrifugal force of mass (N/m ²)	11.1*10 ⁶
External diameter (m)	0.468	Surface pressure excited by vertical shaft (N/m ²)	8.7*10 ⁶
Height (m)	0.2675	Surface pressure of internals (N/m ²)	2.4*10 ⁶
Wall thickness (m)	0.0305	Boundary	The wall is Moving Wall
Modulus of elasticity (N/m ²)	2*10 ¹¹		

Using finite element software ANSYS Workbench, the stress distribution obtained by finite element simulation under the condition that the load is applied once is shown in Fig. 3. We find that the surface stress distribution of the drum barrel is uneven, and the maximum stress peak appears on the surface of the sediment area, therefore, the equivalent stress value here is the largest, which is the concentration area of structural stress and is most prone to fatigue failure. The equivalent maximum stress of drum barrel is $493.95 \times 10^2 \text{ N/m}^2$.

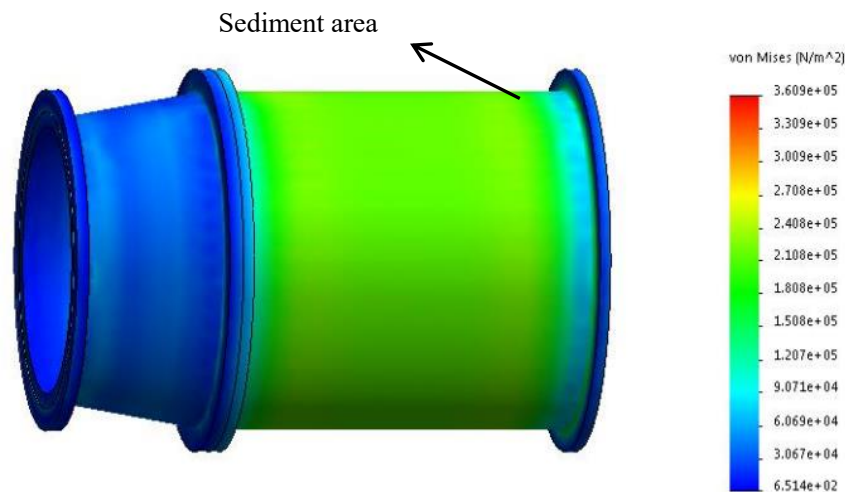
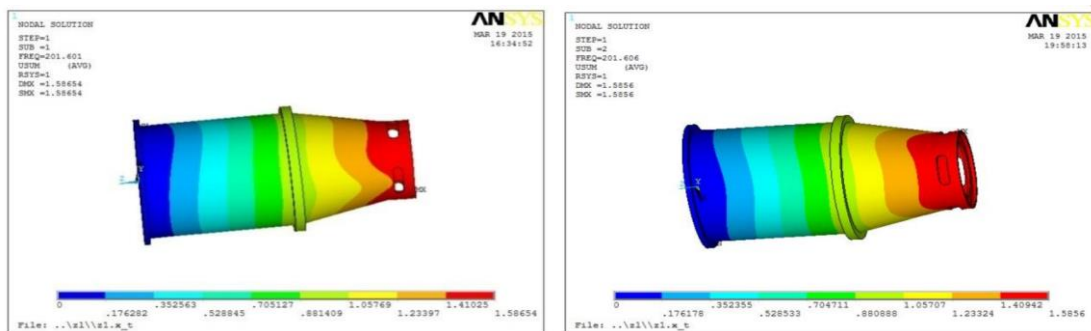


Fig. 3 Equivalent stress distribution of drum

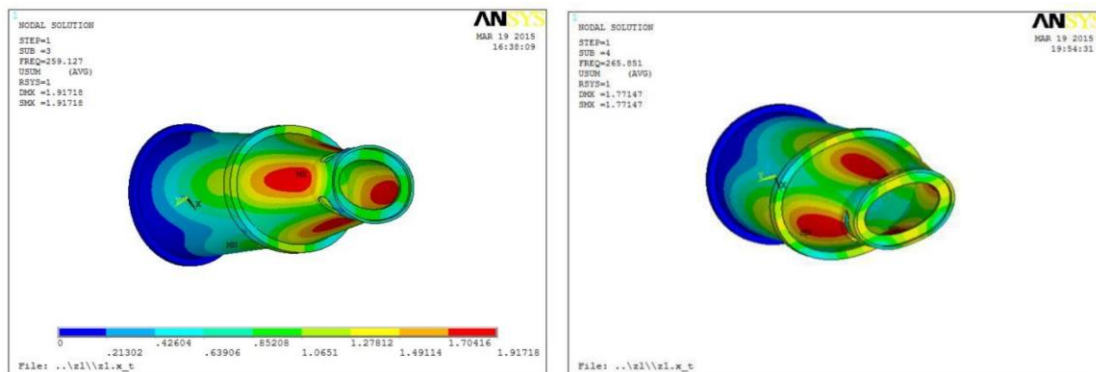
Importantly, the Fig.3 shows that the maximum stress distribution on the drum is located in the sediment area. From the perspective of multiphase flow, a large number of solid particles flow into the sediment area, which has a strong impact on the drum wall, therefore, it is necessary to open holes or slots in the sediment area to facilitate the smooth discharge of sediment.

Meanwhile, the modal shape diagram for the first several orders of natural frequencies of the drum under the effect of fluid structure coupling is shown in Fig. 4.



(a) The first order of vibration mode

(b) The second order of vibration mode



(c) The third order of vibration mode (d) The fourth order of vibration mode
Fig. 4 Modal analysis of drum

From Fig.4 of the vibration mode, it can be seen that the first order and two order of the drum vibration mode are all bending vibrations, while the third order and fourth order of the drum vibration mode are mainly vibrations in X-Y two directions. The first several orders of natural frequencies of the drum are: 201.60Hz, 201.60Hz, 259.132Hz and 265.85Hz respectively. Considering that the working speed of the drum is 7250r/min, so the working frequency is 128.33Hz. Therefore, the natural frequency of the drum does not coincide with the working frequency, so the resonance of the drum will not occur.

Wei [15] et al used the finite element analysis software ANSYS to analyze the stress of the upper suspended centrifuge drum under normal working conditions □ explored the influence of various parameters on strength □ identified the danger point of the drum rotation □ and Optimized drum structure. By changing the level of structural parameters, we can obtain that the main parameters affecting the stress distribution of the horizontal screw centrifuge drum are: composition of emulsion, spindle speed, drum height, drum external diameter, drum wall thickness. According to mechanical materials science [16], it is generally considered that the main design parameters of the structural system obey the normal distribution. The probability characteristics are shown in Table 2.

Table 2 Probability distribution of drum random parameters

Random variable	Distribution type	Mean value	Variance
External diameter /m	Normal distribution	0.46	0.46×10^{-3}
Height /m	Normal distribution	0.2675	0.2675×10^{-3}
Wall thickness /m	Normal distribution	0.0305	0.305×10^{-4}

Using the hypercube Latin sampling based on the experimental design method, repeat the calculation steps above, change the structural parameters of the finite element software simulation model for 64 times, and the statistical results of the stress response sample values in the drum sediment area are shown in Fig. 5.

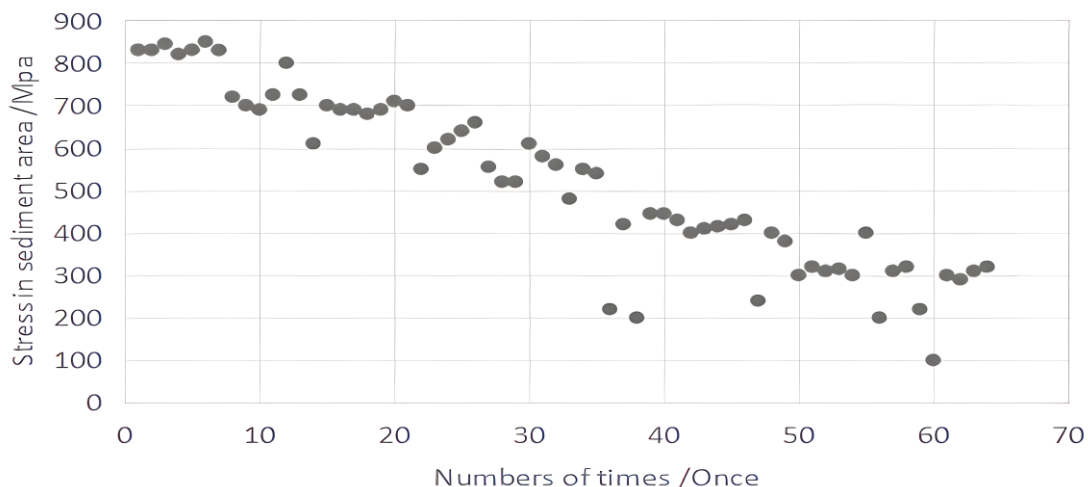


Fig. 5 Distribution of maximum dynamic stress calculated by finite element method

We can see from Fig. 4 that the load is applied once, and the equivalent stress distribution for the maximum

stress in the drum sediment area conforms to the normal distribution, with the mean value is 493.95 Mpa and the standard deviation is 6.6667.

DYNAMIC RELIABILITY CALCULATION OF DRUM

In the process of emulsion liquid separation, the horizontal screw centrifuge should be a long-term dynamic process and its working conditions are random and uncertain. As various loads are repeatedly applied, the fatigue cracks will appear in the sediment area of the drum. Significantly, it is conservative and inaccurate to evaluate the safe life of the drum body only according to the strength theory under single load (i.e. static reliability model). Therefore, in the reliability modeling of the drum, the influence of the number of load actions on the fatigue life of the drum should be considered.

According to the method in the references [17-18], the random variable of the maximum stress σ_{\max} in the design reference period T is taken as the equivalent load of the dynamic stress random process $\sigma(t)$ according to the sequential statistical method. If the distribution of the equivalent stress for the maximum stress in drum sediment area is normal $N(\mu, \sigma)$ under each load, so the random variable of the maximum stress follows the extreme value I distribution after the load is applied for n times, and its mean value E and variance Var are:

$$E(\sigma_{\max}) = \mu + m\sigma + 0.5772a\sigma, Var(\sigma_{\max}) = \pi^2(a\sigma)^2 / 6. \quad (3)$$

Here, μ, σ are the mean and standard deviation of the normal distribution of a load respectively.

And the definitions of parameters m, a are:

$$m = \sqrt{2 \ln n} - \frac{\ln \ln n + \ln 4\pi}{2\sqrt{2 \ln n}}, a = \sqrt{2 \ln n}. \quad (4)$$

Here, n is the number of times the load acts within the design reference period.

If the number of load occurrences per unit time is one, that is $t = n$, the dynamic reliability $R(t)$ and failure rate $\lambda(t)$ of drum body are:

$$R(t) = P(\sigma_{\max} \leq s) = \Phi\left(\frac{E(s) - E(\sigma_{\max})}{\sqrt{\text{var}(s) + \text{var}(\sigma_{\max})}}\right) (0 < t \leq T), \quad (5)$$

$$\lambda(t) = -\frac{R'(t)}{R(t)}.$$

Here, s is the yield limit strength of the material, Φ is the standard normal distribution function, $R'(t)$ is the derivative of $R(t)$.

When the load is applied once, the mean value $\mu = 493.95$ Mpa of the equivalent stress for the maximum stress in sediment area of the drum, and the standard deviation $\sigma = 6.6667$ are substituted into equation (3), and then the mean value 577.057 Mpa and the variance 24.64 of the material yield limit are substituted into equation (4), so we can get the change rule of the drum reliability as shown in Fig. 6 and the change rule of the drum failure rate as shown in Fig. 7.

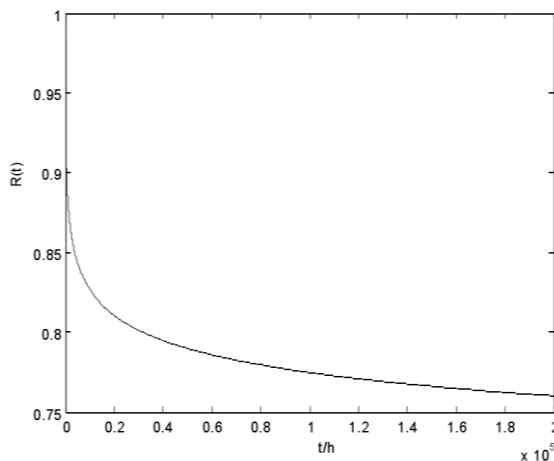


Fig. 6 The time-varying reliability of the drum

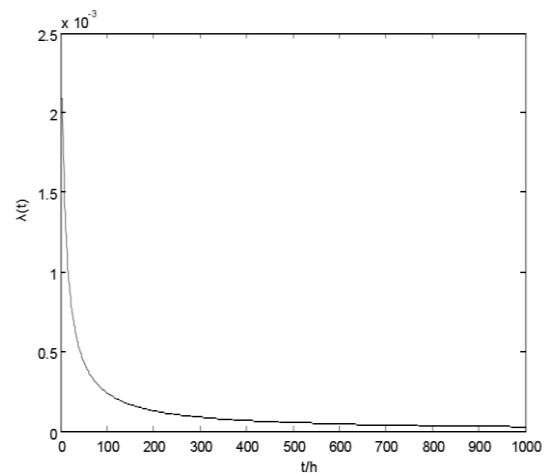


Fig. 7 The failure rate of the drum

It can be seen from Fig. 5 that the reliability of the drum decreases gradually with the increase of service time, and the reduction is relatively fast in the early stage, and gradually tends to be gentle in the later stage. The speed of reliability reduction is gradually decreasing, and the reliability of the 20000h service life index is more than 80%, which can basically meet the requirements of continuous work. It can be seen from Fig. 6 that the failure rate of the drum shows a decreasing trend with the increase of time, and has the early characteristics of the "bathtub" curve (early failure period), which is consistent with the failure rule of common mechanical structures when the strength degradation is not considered in the reliability modeling process. Therefore, the calculation in this paper is practical and effective.

In order to verify the accuracy of the calculation results, Monte-Carlo method is used to calculate the reliability of gear and bearing respectively, and according to the reliability formula of series system [19-20], the reliability of gearbox system is obtained in the Table 3.

Table 3 The result of Monte-Carlo simulation

Number of times t	Reliability
One hundred thousand	0.865442
Two hundred thousand	0.865421
Five hundred thousand	0.865386
One million	0.865342
Two million	0.865321
Five million	0.865321

As can be seen from the Table 3, with the increase of number of times, the reliability tends to be stable numerically, and the larger the number of simulation time is, the closer the result of reliability is to the reality. When the number of times reach two million, that is, the time t is 56h, the reliability value is close to the calculation result of the formula (4) (when the time t is 56h, the value of the integral formula is 0.8653), so the above calculation model is effective.

DISCUSSION

This paper studies the dynamic reliability of the horizontal screw centrifuge drum by combining theory with simulation. The main conclusions are as follows:

- (1) The fluid-structure coupling analytical dynamic model of the horizontal screw centrifuge drum contains not only the randomness of the structural parameters of the system but also the dynamic action process of the load. Based on this equations, the influence of different parameters on the natural frequency of the drum can be obtained.
- (2) Based on the finite element simulation calculation, the stress distribution diagram of the drum under the actual working condition is obtained, and the statistical characteristics (mean value and variance) of the dynamic equivalent stress in the stress concentration area of the drum are obtained by using random sampling and simulation methods, which provides a necessary basis for the quantitative calculation of dynamic reliability. The finite element software simulation shows that the maximum stress distribution on the drum is located in the sediment area.
- (3) By using the dynamic stress sequence statistics method and the stress strength interference theory, the specific expressions of the dynamic reliability and the dynamic failure rate of the horizontal screw centrifuge drum are obtained. The life index calculated with this formula conforms to the engineering practice law, in which the rate of reliability reduction is first large and then small, and the failure rate reduction is first severe and then gentle. The two are in good agreement.

Using this method, the next step can continue to study the dynamic reliability of each component of the horizontal screw centrifuge drum considering strength degradation and the reliability calculation of the whole system with failure correlation.

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