Health Monitoring and Vibration Analysis of Nuclear Industry Centrifuges

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Abstract. In the field of nuclear energy civil engineering and construction field, spent fuel reprocessing is a crucial issue that cannot be bypassed, involving various process equipment that requires more effective health monitoring. A health monitoring system was designed and built for the sedimentation centrifuge used in spent fuel reprocessing, successfully capturing the main vibration issues encountered during its operation. Through vibration analysis, it was confirmed that flow-induced instability vibration is the primary factor affecting machine performance and threatening process safety. This article provides a health monitoring guarantee scheme for the safe operation of the centrifuge, as well as data guidance and support for its structural optimization.

Keywords: health monitoring, nuclear energy civil engineering, flow-induced instability, centrifuge, vibration

1 Introduction

From the outset of its nuclear power development, China established the strategy of "closed nuclear fuel cycle [1]", which entails the reprocessing of spent fuel to maximize the reuse of nuclear materials and solidify high-level radioactive waste. The clarification of the spent fuel solution is a crucial step in the spent fuel reprocessing process [2]. In both the existing pilot plants and the large plants under construction in China, centrifuges are utilized to complete this process [3]. The unique characteristics of the working medium impose high demands on the centrifuges [4]. In complex and demanding application scenarios, health monitoring is essential [5][6]. Additionally, for the rotor filled with liquid in the centrifuge, there is often a significant issue of flow-induced instability [7][8]. Flow-induced instability is a type of self-excited vibration, typically accompanied by a sudden surge of intense vibration [9], which greatly tests the safety and reliability of machines. It often necessitates optimizing machine design or employing passive [10] or active [11] vibration suppression methods to mitigate the adverse effects.

This article designs and builds a health monitoring system for centrifuges, successfully capturing the main vibration issues in the use of centrifuges, namely the phenom-

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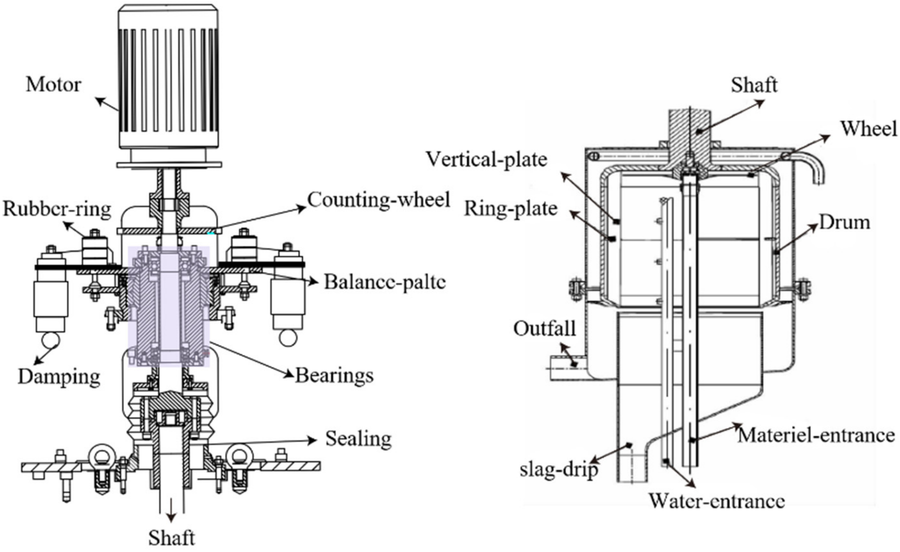
enon of unstable vibration. The research conducted in this article can provide a guarantee for the safe operation of centrifuges, as well as effective data support for understanding, insight into, and ultimately optimizing the structure of centrifuges.

2 Centrifuge Health Monitoring System

The structure of the centrifuge is shown in Figure 1. For ease of description, components such as the frame, base, and pipelines are omitted in Figure 1; in practical applications, only the above-ground part is the monitorable area, serving as the power input end of the rotor. This section of the rotor is supported by a pair of ball bearings and equipped with a passive vibration absorption unit consisting of a ball joint, a damping spring (rubber ring & diaphragm), and a damper; the underground part is the process section, where the core component, the rotor drum, is an inverted cup structure. The feed liquid enters from the bottom, and the insoluble particles will be separated by supergravity on the inner wall of the rotor drum under the action of centrifugal force.



(a) Overground (b) Underground

Fig. 1. Structure of the centrifuge [4].

The final monitoring scheme (measurement points & software functions) is shown in Figure 2 (the balance plate vibration and bearing status analysis content are omitted in Figure 2).

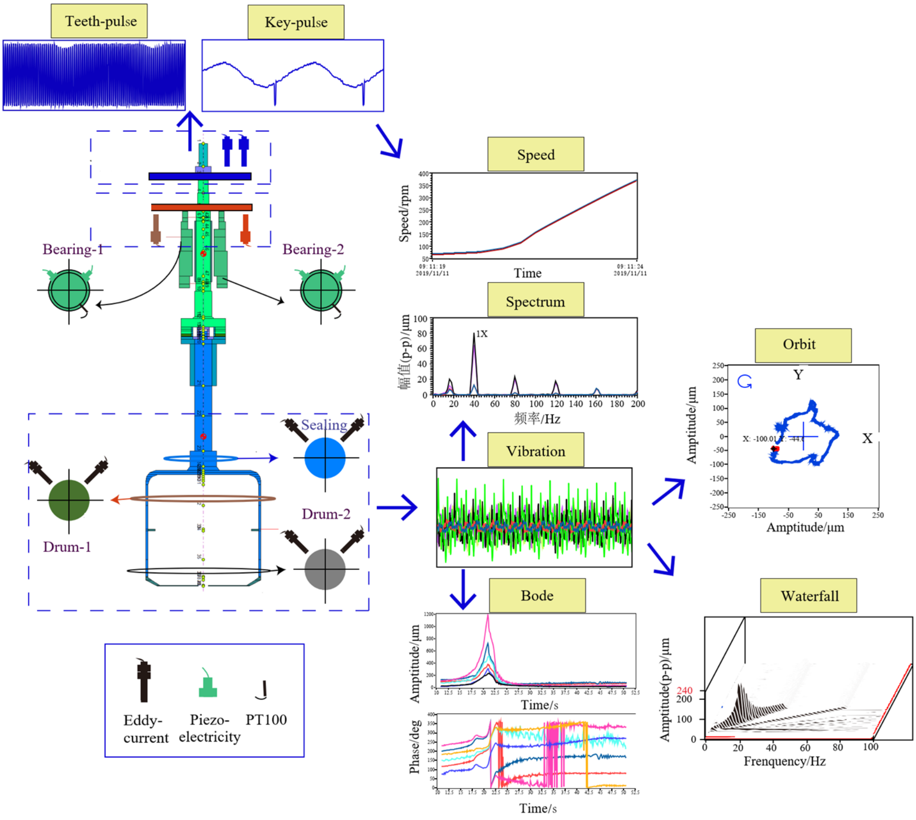


Fig. 2. Function classifications.

Eddy current sensors, piezoelectric sensors, and temperature sensors (PT100) were used; the acquisition/analysis terminals were the NI CompactRIO series and Advantech UNO industrial computers. The voltage module (vibration) sampling rate was 21.56 kHz, and a human-machine interface was developed based on LabVIEW software, with an analysis (refresh) frequency of 2 Hz.

Based on the existing structure of the centrifuge, key measurement points were selected. In addition to 1) monitoring the vibration (acceleration) and temperature of the bearing assembly, 2) the “sway” of the balance plate was also monitored to explore the potential relationship with the radial bending vibration of the rotor. 3) Keyway holes were drilled on the counting wheel disc to measure tooth pulses for speed identification, while obtaining key phase references for order analysis, rotor dynamic balancing, etc. 4) Two holes were drilled orthogonally at the end of the ground part - the sealing sleeve - for installing eddy current sensors to monitor the radial vibration of the rotor tail end above ground. 5) During the commissioning phase, two radial sections were selected on the drum to monitor orthogonal rotor vibrations.

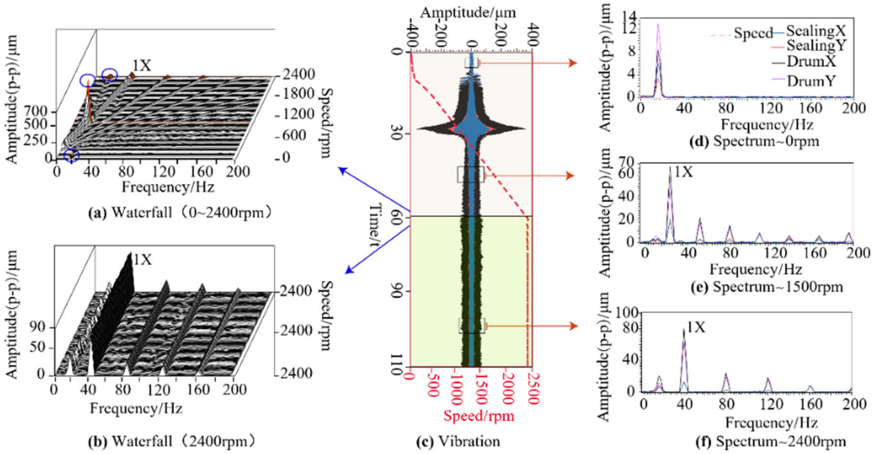
3 Experimental Analysis

3.1 Real-Machine Testing

Based on the centrifuge health monitoring system established above, full-cycle condition monitoring was conducted on the centrifuge for fault diagnosis and countermeasure design. This section analyzes and summarizes the typical vibration responses observed during real-machine testing, aiming to reveal the essential vibration characteristics of the centrifuge (especially the nonlinear and asynchronous vibrations under complex flow field effects). Furthermore, based on a comprehensive understanding of the mechanism of flow-induced instability, potential means to avoid instability are proposed. In actual experiments, a large amount of test data was accumulated to test the impact of different component parameters on the performance of the centrifuge. This section only presents a set of typical results from no-load and load tests for illustration.

3.1.1 No-Load Testing. To achieve centrifugal separation of different feed liquid components, the centrifuge is designed with several operational speeds, including the operational speed that passes through the first-order critical speed. Therefore, the system is required to have the ability to pass through the critical speed, which is not easy for a centrifuge with a support point far away from the drum and a center of gravity biased towards the drum. A strong vibration reduction (damping) unit is needed to assist. At the same time, a suspended drum is more susceptible to external excitation, and an excessively long damping path can make vibration dissipation difficult, which has been confirmed through no-load testing.

The results of a no-load test experiment are shown in Figure 3, corresponding to a start-up process through the critical speed.



(a) Waterfall（0~2400rpm）

(b) Waterfall（2400rpm）

(c) Vibration

(d) Spectrum~0rpm

(e) Spectrum~1500rpm

(f) Spectrum~2400rpm

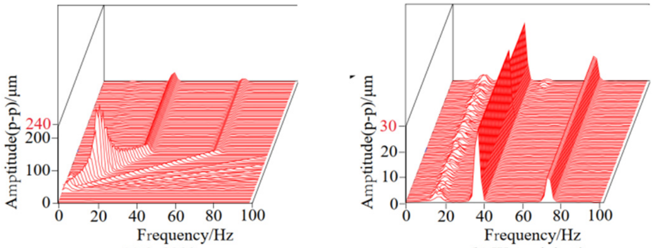
Fig. 3. Results of a no-load test.

The final speed was maintained at the design speed of 2400 rpm. Figures 3(a) and 3(b) analyze the vibration displacement in the X direction of the lower drum, forming waterfall charts under various operating conditions. The "1X" used in the figure represents the fundamental frequency vibration, and "p-p" represents the peak-to-peak value, the same as below; Figure 3(c) is the measured vibration waveform, including the vibration displacement in the X/Y orthogonal directions of the sealing sleeve and the lower drum (specific color representation is described in the label in Figure 3(d)). Three segments of vibration were extracted: at rest (0 rpm), during acceleration (≈1500 rpm), and when reaching the design speed (2500 rpm). FFT transformation was performed on each segment, and the frequency spectra shown in Figure 3(d)~(f) were obtained in turn.

- Firstly, it can be inferred from the spectral characteristics that the system exhibits poor convergence in free vibration under continuous environmental excitation, indicating that the system damping may be inadequate. This results in significant vibration in a certain frequency band (≈17.5 Hz, non-synchronous). It has been confirmed that the synchronous use of multiple units in the experimental plant exacerbates environmental excitation. Once other units are shut down, this excitation effect will significantly decrease, and in actual measurements, non-synchronous vibration is almost undetectable;
- Secondly, in conjunction with the waterfall plot analysis, it can be seen from the annotations in Figure 3(a) that the non-synchronous frequency that exists from the beginning to the end is approximately equal to the resonant frequency, which is consistent with the rotor system stability theory;
- Finally, the system exhibits a relatively large transient critical peak, while the steady-state vibration at the design speed is relatively small. However, the "surge" of non-synchronous vibration poses a hidden danger, indicating that the system is continuously subjected to environmental excitation. The interaction between system damping and this excitation demonstrates a dynamic stability, rather than a complete suppression of it.

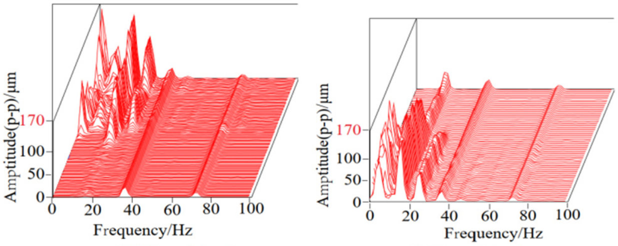
3.1.2 Load Tests. As a typical liquid-filled rotor system, centrifuges are also prone to the risk of flow-induced instability. The complex fluid-structure coupling effect between the feed liquid and the rotor drum will result in complex, nonlinear, and stochastic vibration responses in the centrifuge, with the most significant being the initiation, growth, and even uncontrollability of asynchronous vibrations. This situation was confirmed during the load test of the centrifuge. It was also found during the test that the damper will play an important role in resisting fluid excitation, but not necessarily mean the larger it is, the better it will be; different structural parameters will also affect the actual effect of fluid excitation, resulting in vibrations with different frequency domain characteristics, but there will basically be a common trend.

After optimizing the basic component parameters of the centrifuge (such as adjusting the vibration reduction spring for large differences in orthogonal vibration or adjusting the damper for excessive critical vibration peak/amplification factor), a load test was conducted on the centrifuge, including water load test and simulated feed solution load test. Here, we only analyze and describe some typical experimental data from the water load test, aiming to present the typical effects and influence patterns of fluid on the centrifuge. The results of a water load test experiment are shown in Figure 4, including a complete water filling process and a characteristic condition of passing through the critical speed reduction with liquid. Among them, each waterfall plot is obtained based on the vibration analysis of the sealing ring in the X direction.



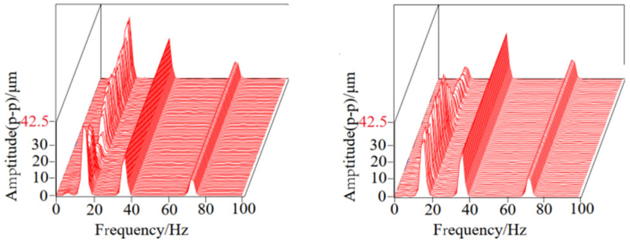
(a) 0~2200rpm run-up

(b) Water-injection



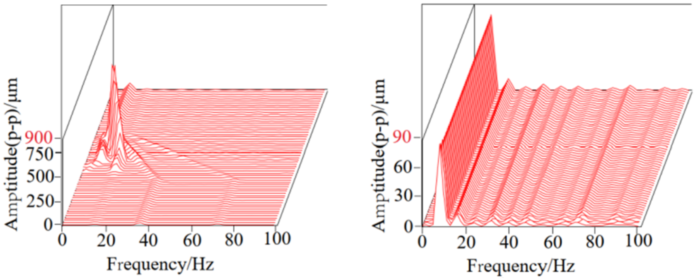
(c) Water-injection-1

(d) Water-injection-2



(e) Water-injection-3

(f) Water-full



(g) Passing-through-the-critical-speed

(h) Operate at 500rpm

Fig. 4. Typical vibration response history of water-loading test.

- As can be seen from Figures 4(b) to 4(f), with the water filling process from no filling to full filling, under the same dynamic composition (damping & stiffness, etc.), the asynchronous vibration response of the system will also exhibit different frequency domain characteristics. One is the frequency variation characteristic of single frequency → multiple frequencies → single frequency, and the other is the amplitude characteristic of small to large, then large to small. This indicates that different filling states of the drum correspond to different stability margins. In the no-fluid or fully-filled state, it is in a relatively stable state, while partial filling often has a more pronounced destabilizing effect;
- As shown in Figure 4(b), the introduction of fluid may affect the existing vibration of the centrifuge itself. In Figure 4(b), there is a noticeable decrease in the amplitude of the fundamental frequency, especially compared to the situation before the water was added (this has occurred in most experiments across different test units);
- Flow-induced instability may exhibit frequency domain characteristics that differ from those of common rotor instability. As in this set of experiments, high-amplitude vibrations not only occur near the natural frequency but also accompany the appearance of its harmonic and fractional vibrations. This often indicates a collective high amplitude in the instability frequency band, as shown in Figure 4(c)-(d);
- Due to the high damping effect of the damper, when the force between the liquid in the rotating drum and the drum enters a steady state, the vibration response of the system will exhibit a relatively stable trend. Although non-synchronous vibration may still exist, it will not diverge and is often significantly lower than synchronous vibration, as shown in Figure 4(f);
- The biggest challenge faced by centrifuges using flexible rotors may be the liquid passing through the critical zone. During the short deceleration process, the destabilizing effect of the fluid will maximize at the moment of passing through the critical zone, as shown in Figure 4(g). To cope with this condition, the system must have sufficient destabilizing force, which usually requires the assistance of a damper;
- The centrifuge that has passed the critical point will quickly return to a steady state, as shown in Figure 4(h). Although the liquid had not completely fallen off at this time, the non-synchronous components were almost invisible in the spectrum.

4 Conclusion

This article takes the design of a health monitoring system for centrifuges as an opportunity to recognize the significant challenges faced by liquid-filled rotors and analyzes and summarizes their typical vibration characteristics. The specific conclusions are as follows.

1) In practical applications, special attention should be paid to the potential risk of flow-induced instability in liquid-filled rotor systems. Due to the complexity of fluid-structure coupling, the vibration response often exhibits a certain degree of randomness, but under certain conditions, there is often a high degree of commonality. For flexible liquid-filled rotors, this commonality is reflected in the trend that the influence of the liquid filling amount on the system stability margin first increases and then decreases,

and partial liquid filling often poses a higher risk. The biggest challenge faced by liquid-filled rotors operating in the supercritical regime is the transient vibration caused by passing through the critical point with liquid, which often represents a huge transient vibration. Generally, sufficient vibration reduction measures are required to assist in safely navigating through this transient process.

2) Implementing active vibration reduction measures such as electromagnetic actuators will aid in achieving active vibration control of the liquid-filled rotor system. To address more complex fluid-induced vibrations, it is necessary to adopt adaptive control algorithms. On the one hand, by analyzing the fluid-structure coupling mechanism, we can establish a quantitative relationship between fluid excitation and the modes of the rotor system, thereby assisting in the synthesis of advanced controllers. On the other hand, by accumulating experimental data under various operating conditions and utilizing convergence control methods, we can find an estimation model corresponding to the fluid and rotational speed, establish an offline library, and form a gain scheduling algorithm.

Acknowledgments

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