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RESEARCH ARTICLE

VIBRATION CHARACTERISTICS AND FAULT ANALYSIS OF HELICOPTER PEDALS

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ABSTRACT

Helicopters have numerous rotating components, and the vibrations generated during flight are significant, which negatively affects the pilot's flight control and physical and mental health. Therefore, vibration reduction and noise attenuation of helicopters are crucial research areas. Pilots complete flight missions through the flight control system, and the usability and comfort of the control system directly affect flight quality and safety. For a certain type of helicopter where excessive pedal vibration caused a "pedal-kick" fault, this paper employed a real-time vibration monitoring system to test and monitor the helicopter pedal vibration. Based on the flight test data, a spectral analysis was conducted on the helicopter pedal vibration signal to determine the abnormal vibration frequency. Then, by combining the comfort decrease limits and evaluation criteria for whole-body vibration exposure, the helicopter's aft cabin pedal vibration was diagnosed for faults. The source of the pedal "kick" vibration was accurately located, and after implementing relevant measures, the fault was successfully resolved.

KEYWORDS

Real-time vibration monitoring system, helicopter tail rotor control system, pedal, comfort decrease limit, spectral analysis

1. INTRODUCTION

Compared to fixed-wing aircraft, helicopters have more mechanical components and a more complex structure, resulting in much greater vibrations and noise. The driving environment of a helicopter pilot is relatively harsher, making fatigue more likely. To ensure the controllability and riding experience of helicopters, more effort needs to be invested in vibration reduction and noise attenuation during design (Taymaz, 2022). A group researchers studied the impact of high-level vibrations on helicopter pilots and found that excessive vibrations can cause a decrease in pilots' vision, making it difficult to read instruments, which in turn affects flight safety (Tamer et al., 2021). A group researcher measured the vibration characteristics of structures such as seats, steering wheels, and pedals, studying their impact on various parts of the human body (Nishiyama et al., 2021). Their research results can be used to improve ride comfort, operability, and safety. Andrew Law and colleagues examined the effect of whole-body vibrations on the heads and necks of helicopter pilots under different conditions, such as hovering and cruising (Law, 2017). They found that the weight of the head (including helmets, night vision devices, etc.) combined with flight conditions jointly influenced pilot neck muscle fatigue and injuries. This paper will study the impact of tail rotor control system vibrations on pilots. The tail rotor control system is an essential component of the helicopter control system. This system conveys the pilot's operations via the cockpit control device through the booster to the tail rotor blade, achieving attitude and state control of the helicopter (Jia, 2013). The tail rotor control system includes pedals, rods, rocker arms, boosters, etc. The tail booster shell is connected to the end face of the tail rotor through a flange, and the piston rod drives the tail rotor control mechanism for linear reciprocating motion. The structure of the tail rotor control system is shown in Figure 1. During the flight of a particular helicopter, there is often excessive vibration in the aft cabin pedals, especially at high speeds. The pedal vibration causes numbness in the pilot's legs, affecting the execution of flight tasks and the overall flight safety of the aircraft. Real-time vibration monitoring of the helicopter's power unit, transmission system, and control system is an essential means to ensure the flight safety of helicopters (Chen and Song, 2002; Wasser and Reber, 2005). This paper uses a self-developed vibration real-time monitoring system for real-time monitoring of helicopter pedal vibrations to ensure test flight safety. At the same time, pedal vibration data under different flight conditions is obtained to analyze the characteristics of pedal vibrations and the possible causes of excessive pedal vibrations, providing data and theoretical support for troubleshooting.

2. REAL-TIME VIBRATION MONITORING SYSTEM FOR HELICOPTER TRANSMISSION SYSTEM

The hardware of the real-time vibration monitoring system for the helicopter transmission system adopts the standard CPCI card structure design, mainly including signal acquisition and processing boards, control, and data recording boards. Its structure is shown in Figure 2, and its working mode is shown in Figure 3. The vibration monitoring system automatically starts when the helicopter is powered on. It converts the original high-sampling-rate vibration monitoring signal into a low-sampling-rate quasi-steady signal, which is then transmitted to the ground through a telemetry transmitter. The received processed quasi-steady data is used for real-time vibration monitoring.

The core content of the software design for the real-time vibration monitoring system of the helicopter transmission system is the vibration signal processing algorithm, which is the key technology in the development of the entire vibration monitoring system. It directly affects whether the vibration monitoring system can meet the model

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requirements. The vibration components that the transmission system vibration amplitude algorithm needs to extract correspond to a fixed frequency, so the extraction difficulty is relatively low. However, because the vibration source frequencies of the transmission system are relatively close, the algorithm is required to have a high resolution (Si, 2010; Xu, 2012; Xiong, 2011).

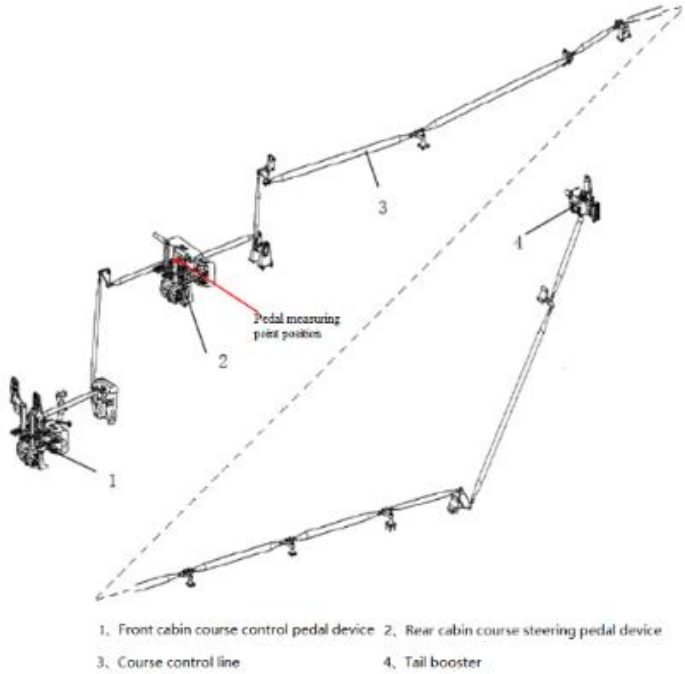

Figure 1: Schematic diagram of the helicopter tail rotor control system

To achieve a higher frequency resolution, a common method is to increase the data length of the Fourier transform algorithm. However, this method can result in issues such as long latency and, under the condition of speed fluctuation, the calculated result being less than the actual value. Based on the model requirements, improvements have been made to the Fourier transform algorithm, proposing a new algorithm (Lei et al., 2017). This involves first truncating the vibration data according to the frequency corresponding to the transmission system vibration source for a complete cycle. The frequency resolution corresponding to this point is frequency-shifted so that the frequency corresponding to the vibration source is precisely on the point of the frequency resolution. This not only can reduce the energy leakage within the spectrum line but also simultaneously reduce the influence of the nearby vibration source on the vibration amplitude calculation result of this frequency point. The specific algorithm flowchart is shown in Figure 4.

The helicopter has many rotating parts that might cause increased pedal vibrations, including the main rotor, transmission system, tail rotor, engine, and related accessories. An analysis of the pilot's subjective perception of pedal vibrations can first rule out high-frequency vibrations caused by engine vibration sources. Therefore, the focus of the real-time monitoring system for transmission system vibrations is on real-time processing and monitoring of the vibration components of the rotor, transmission system, and tail rotor at the pedal location.

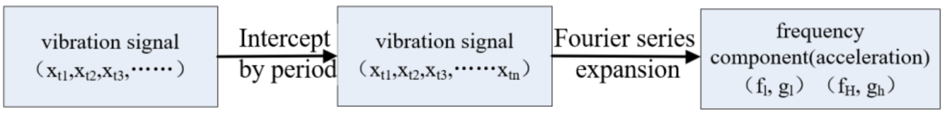

Figure 4: Flowchart of the transmission system algorithm

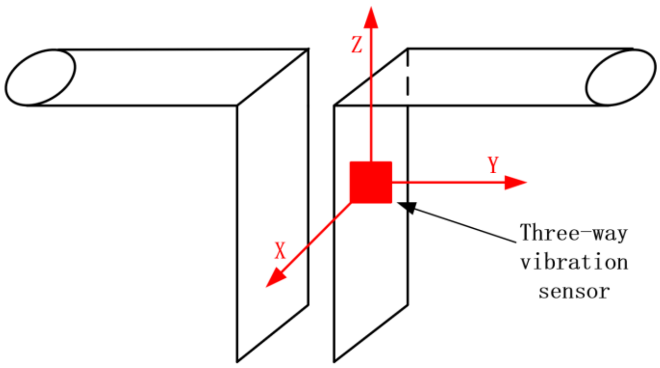

Figure 5: Schematic diagram of the helicopter pedal measurement point

The installation position of the aft cabin pedal vibration sensor is shown in Figure 5. A triaxial vibration sensor is adhered to the pedal bracket to measure the vibration amplitude in three directions of the pedal.

3. Analysis of Pedal Vibration Data

A spectrum analysis was conducted on the pedal vibration data during the helicopter's acceleration flight process. Waterfall charts of vibrations in all directions of the pedal during the helicopter's acceleration flight are shown in Figures 6 to 8. From the figures, it can be seen that the main frequency components appearing in the pedal vibration data are: 25.5Hz, 26.8Hz, 53.6Hz, 75.7Hz, and 78Hz. Among them, the vibration amplitudes at 25.5Hz and 53.6Hz are relatively large, while the vibration amplitudes of other frequency components are smaller. Moreover, the vibration amplitude of the pedal at 25.5Hz and 53.6Hz clearly increases with the increase in speed.

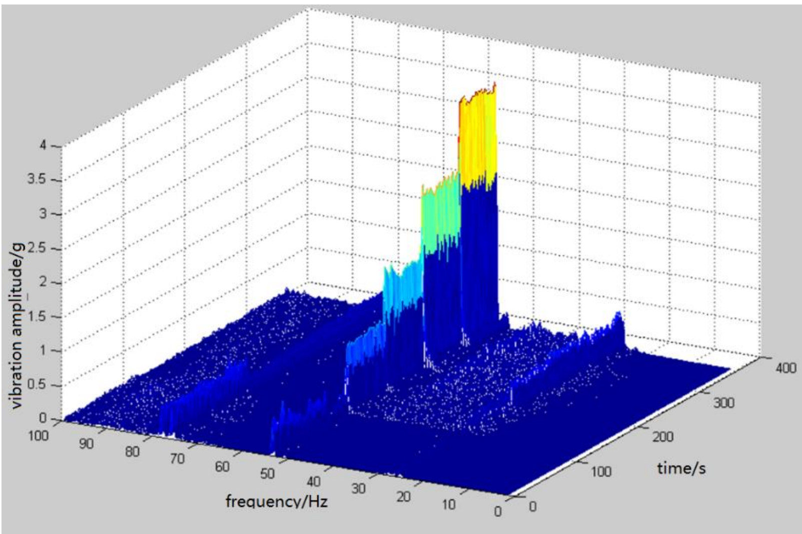

Figure 6: Waterfall chart of pedal X-direction vibration during airplane acceleration flight

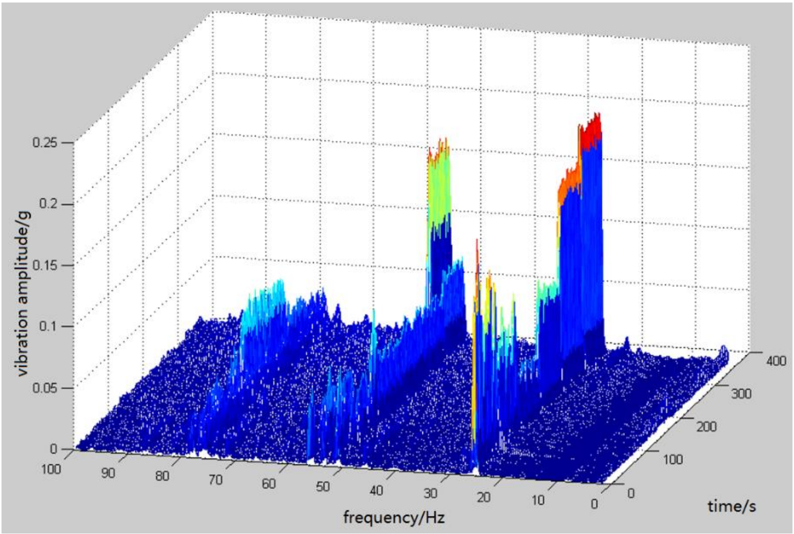

Figure 7: Waterfall chart of pedal Y-direction vibration during airplane acceleration flight

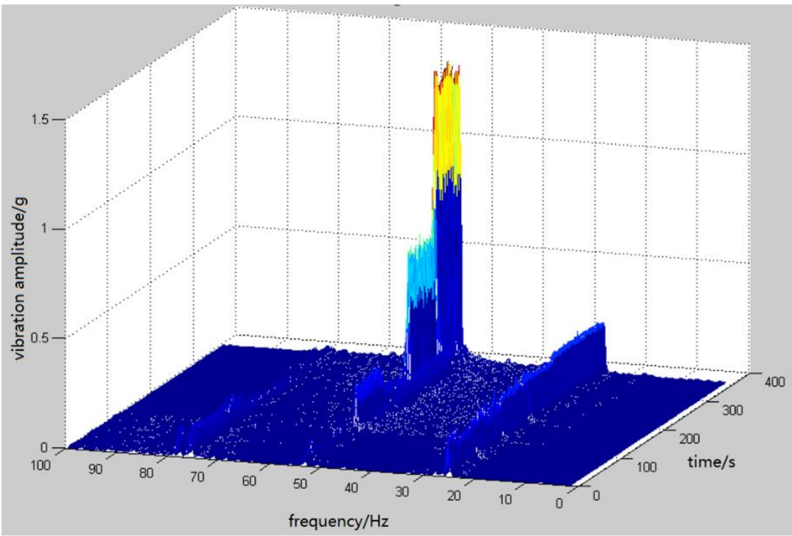

Figure 8: Waterfall chart of pedal Z-direction vibration during airplane acceleration flight

Under different flight speeds, the variation curves of vibration amplitude for each frequency component in the three directions of the pedal with speed are shown in Figures 9 to 11. From the figures, it can be observed:

(1) In all three directions, the vibration amplitude at a frequency of 53.6Hz on the pedal significantly increases with increasing flight speed. The vibration amplitude at a frequency of 53.6Hz in the X direction reaches 3.2g at the highest speed, and in the Z direction, it reaches 1.2g at the highest speed. Additionally, the vibration amplitude in the Y direction at a frequency of 25.5Hz first decreases and then increases with the increase in flight speed, reaching a maximum value of 0.22g at the highest speed. Vibration amplitudes at other frequencies are relatively small and do not show noticeable changes with flight speed.

(2) Based on feedback from pilots that "at high-speed flight states, pedal vibrations cause numbness in the feet," it is preliminarily judged that the vibration frequency components causing this problem are mainly 25.5Hz and 53.6Hz. Therefore, subsequent focus will be on analyzing and troubleshooting the two corresponding vibration sources.

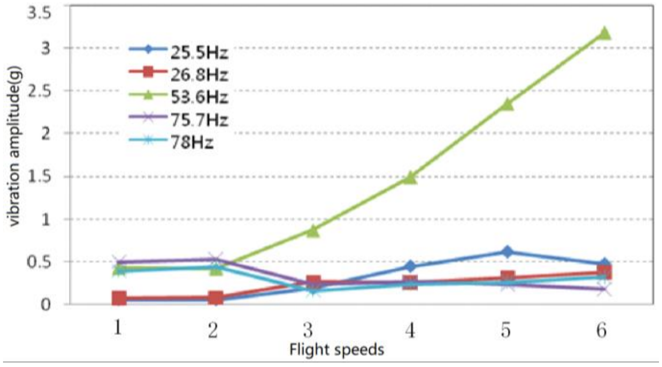

Figure 9: Variation curve of pedal X-direction vibration with flight speed for each frequency

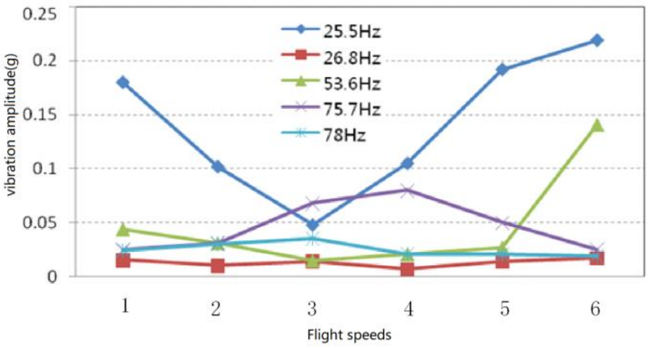

Figure 10: Variation curve of pedal Y-direction vibration with flight speed for each frequency

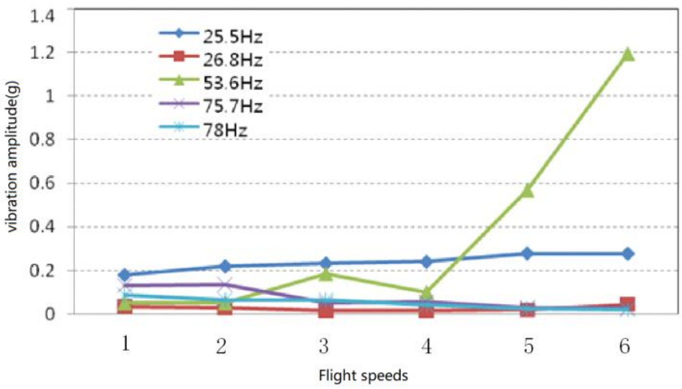

Figure 11: Variation curve of pedal Z-direction vibration with flight speed for each frequency

4. Analysis of Pedal Vibration Problems

4.1 Comfort Reduction Limits and Evaluation Criteria for Human Whole-body Vibration Exposure

People have different subjective feelings to vibrations of different frequencies (Harsha, 2014; Yong and Sebastian, 2017; Chen et al., 2017). Experiments have shown that, under the influence of not very strong vibration sources, vibrations at frequencies of 0-1Hz mainly affect the head, causing discomfort after continuous exposure for a few minutes; 1-2Hz vibrations tend to make people drowsy; 3-4Hz vibrations cause significant vibrations in the waist and chest; 5-8Hz feels uncomfortable and the vibration feels strong; 9-30Hz causes significant face and neck vibrations, interfering with vision, with the vibration feeling most pronounced at 30Hz; from 30-80Hz, the vibration feeling gradually diminishes, and at high frequencies, there's a numb feeling in the feet.

The military standard GJB 966-90 and literature provide a detailed explanation of comfort reduction limits and evaluation criteria for human whole-body vibration exposure (Oliveira et al., 2001; Guoqing et al., 2016). The comfort reduction limit refers to the vibration parameter boundary that maintains human comfort. Exceeding this limit causes a reduction in comfort. The standard characterizes this using the root mean square value of acceleration, related to vibration frequency, exposure time, and vibration direction. Figure 12 shows a schematic diagram of the body-axis coordinate system describing the effects of human vibration, where the x-axis is from back to chest, the y-axis is from right side to left side, and the z-axis is from feet to head.

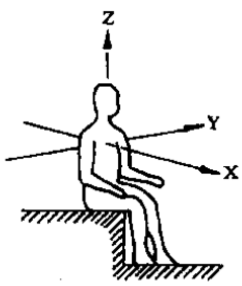

Figure 12: Schematic diagram of the body-axis coordinate system describing human vibration effects

During helicopter flight, to obtain stable test data under a certain flight state, a typical flight task requires maintaining this state for 3 minutes. Therefore, it's necessary to obtain acceleration limits for exposure at different frequency components for 3 minutes. According to the relationship between acceleration limits and exposure time introduced in GJB 966-90 (Formula 1), the acceleration limit for 3 minutes of exposure is consistent with the acceleration limit for 1 minute of exposure.

$$a_t = a_1 \quad t \leq 10\text{min}$$
$$a_t = a_1\sqrt{\frac{t_0}{t}} \quad 10\text{min} \leq t \leq 480\text{min} \tag{1}$$

Where a_1—— the boundary value of 1min vibration, a_t—— the boundary value of vibration for t minutes, t_0——10min;t——exposure time (minutes).

According to formula 1 and referring to the limit values corresponding to different vibration frequencies, exposure times, and vibration directions in the National Military Standard GJB 966-90, the comfort reduction limit values for the key frequency components exposed for 3min are calculated and shown in Table 1.

4.2 Fault Analysis

The comparison of vibration amplitude values in all three directions of the pedal at different frequencies to the comfort reduction limits is shown in Figures 13 to 14. From the figures, we can deduce:

(1) The vibration amplitude at 25.5Hz is much lower than the comfort reduction limit, so the pilot will not feel discomfort due to the vibration at this frequency.

(2) At maximum flight speed, the vibration amplitudes of the pedal in the X and Z directions at 53.6Hz are both higher than the 1min exposure comfort reduction limit, causing discomfort to the pilot during flight.

Table 1: Comfort reduction limit values for other frequency components exposed for 3min (acceleration peak value)

	Z-direction Vibration	X or Y-direction Vibration
25.5Hz	0.43g	1.17g
53.6 Hz	0.91g	2.60g

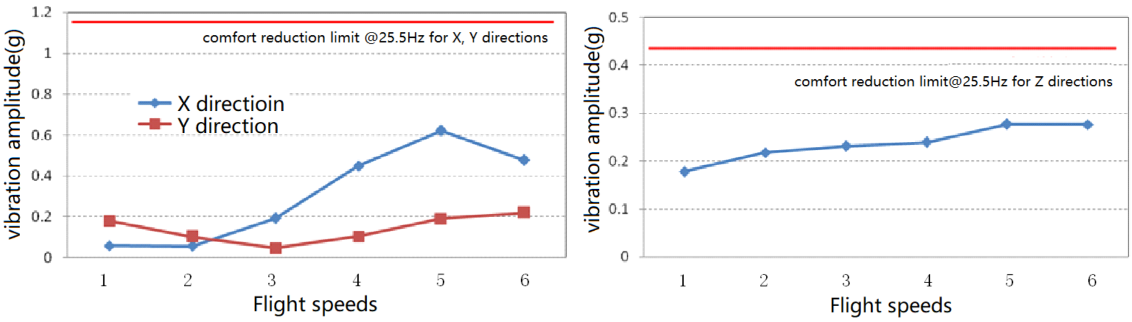

Figure 13: Comparison of vibration amplitude vs comfort reduction limit at 25.5Hz for X, Y (a), and Z (b) directions.

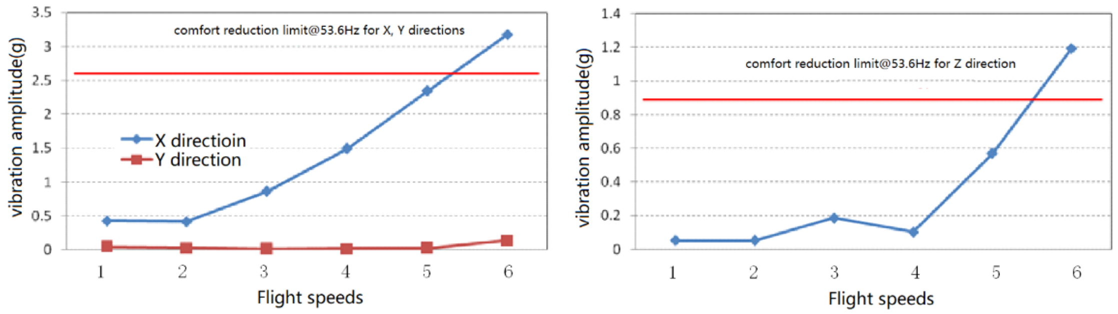

Figure 14: Comparison of vibration amplitude vs comfort reduction limit at 53.6Hz for X, Y (a), and Z (b) directions.

Through the pedal vibration data analysis, it was found that the vibration amplitude at 53.6Hz is relatively large, and there is a clear increasing trend with the increase in flight speed. When the flight speed is at its maximum, the vibration amplitude exceeds the comfort reduction limit of 1min exposure. According to the National Military Standard GJB 965-90, "People perceive vibrations of different frequencies differently. Experiments have shown that, under the action of a weak vibration source, the vibration sensation gradually decreases from 30-80Hz, and there's a numbness in the feet in the high-frequency area." This means that vibrations larger than the comfort reduction limit at 53.6Hz might cause numbness in the pilot's feet. Through vibration data analysis, it was determined that the uncomfortable vibration frequency for the pilot was 53.6Hz. As the helicopter's tail rotor control system is a rod system structure, vibrations are directly transmitted to the pedals through the operating rods. The 53.6Hz vibration of the pedal mainly comes from the tail rotor. The fault reason is located at the vibration source tail rotor and the transfer path tail rotor control system's rod structure. The troubleshooting work can be carried out on the tail rotor or the tail rotor control system.

4.3 Pedal Vibration Troubleshooting Plan

According to the fault analysis, checks were conducted on the tail rotor and the tail control tie rod. An external inspection of the tail rotor showed no abnormalities. A dynamic balance check met the usage requirements, indicating that there was no vibration problem with the tail rotor itself. Therefore, it was necessary to check the vibration transfer path tail control tie rod. There was no jamming or abnormal wear on the tail control tie rod bearing, and the installation torque and assembly clearance of the tail control tie rod and rocker arm bolts met the manual requirements. This indicated that there was no structural damage to the tail control tie rod, but there was a vibration coupling problem. Ultimately, the solution chosen was to add weights to the control tie rod to offset the coupling frequency, which involved installing counterweights to the tie rod assembly. After adding weights to the tail control system, a verification flight was conducted. The results showed that the pedal kicking issue had completely disappeared. In the high-speed flight state, the vibration amplitude at 53.6Hz decreased from 3.2g to 0.96g, a reduction of about 70%.

5. Conclusion

This article implemented real-time monitoring of the pedal vibration response through the real-time vibration monitoring system of the helicopter transmission system. By utilizing a vibration component algorithm for real-time data processing of the vibration data, we identified the vibration amplitude of multiple frequency components that might cause the pedal kicking issue. Any vibration abnormalities were promptly detected during the flight process, ensuring the safety of test flights. Through spectral analysis of the pedal vibration data and a comparison with human body vibration comfort reduction limits, we discovered that the vibration amplitude at the 53.6Hz frequency was excessive, leading to numbness in the foot. The cause of the pedal vibration fault was ultimately traced to the control rod system's vibration coupling. Based on this, an appropriate troubleshooting solution was formulated, addressing the pedal vibration and kicking issue.

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