Analysis and Application of Vibration Signals of Aerospace Servo Actuator

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Abstract. This paper analyzes the vibration signals of aerospace servo actuator and studies their applications. In the signal pre-processing, an adaptive filter based on genetic algorithm is added to improve the signal-to-noise ratio. Time domain analysis is used to monitor the vibration signals and determine the main vibration directions. Frequency domain analysis is used to extract the main vibration frequencies and perform preliminary fault analysis. The WT method with optional window function is used for time-frequency analysis, which can describe the relationship between vibration signal frequency and time, and decompose the signal characteristics required for the analysis. In the research, LabVIEW and MATLAB are used for data processing and analysis. The research lays the foundation of aerospace servo actuator vibration signal analysis and processing system.

1. Introduction
In recent years, the requirements for actuators used in the aerospace industry are increasingly demanding. As actuators, the aerospace servo-actuators participate in the work of the transmission and control system, and other devices cannot replace their role in the aerospace industry. Domestic evaluation and improvement of precision actuator performance requires more advanced measurement and control technology and instruments as the basis.

The actuator is bound to vibrate during operation, which affects the safety and reliability of the actuator operation to some extent \cite{1}.

The aerospace servo actuator under study has a maximum drive speed of 20,000r/min. Its maximum load reaches 50KN, the maximum input torque is 20NM, and the linear load stroke is 250mm.

The characteristics of high speed and large load mean that the vibration stability and working reliability of aerospace servo actuators need more attention, so vibration is used as one of the indicators to evaluate the working condition of aerospace servo actuators. Further, it can analyze the failure of aerospace servo actuators to reduce maintenance and repair costs. It also provide a reliable basis for the design of vibration dissipation, vibration damping, vibration isolation systems and the structural improvement of themselves.

To monitor and analyze the vibration signal of aerospace servo actuators and establish a vibration signal analysis and processing system for aerospace servo actuators, there are the following basic requirements.

(1) Real-time monitoring of vibration signals.
(2) Extraction of signal time and frequency domain features.
(3) Determination of the main direction of vibration of aerospace servo-actuators.
(4) Extraction of the main vibration frequencies of aerospace servo-actuators.
(5) Fault warning and fault analysis.

The vibration signals generated by aerospace servo-actuators during operation are non-smooth signals, which bring more difficulties for signal acquisition and analysis processing. In order to fully grasp the vibration signal characteristics, it is also necessary to design a joint function of time and frequency for time-frequency analysis [2]. With its unique superiority, the time-frequency analysis method has become the main research direction since recent years. STFT transform and wavelet analysis method are most widely used [5-8].

This paper analyzes the vibration signals of aerospace servo actuator and studies their applications. The adaptive filter based on genetic algorithm is added to improve the signal-to-noise ratio, and on the basis of time domain analysis and frequency domain analysis, further time-frequency analysis is performed to obtain more complete vibration signal characteristics, and analysis is carried out based on LabVIEW and MATLAB.

2. Pre-processing of vibration signals

The main body of the test is an aerospace servo actuator, and the signal acquisition tools are acceleration sensors with measurement points in the horizontal (X direction), vertical (Z direction) and axial (Y direction) directions. The structure of the signal acquisition and processing system is shown in Figure 1.

The vibration signals collected by the sensors during the operation of the aerospace servo actuator are complex and unstable. They are mixed with various interference signals, so that errors are inevitable and even the signal may be distorted. In order to obtain a more realistic and reliable vibration signal to analyze, the collected signal needs to be pre-processed.

2.1. Anti-aliasing filtering

If the sampling theorem is not satisfied during discretization sampling, it can cause high-frequency to low-frequency aliasing, resulting in modal frequency distortion. In order to eliminate the aliasing phenomenon to avoid distortion, the acquired signals should be low-pass filtered [6].

2.2. Data pre-processing

The assembly errors, sensor errors and noise interference can cause trend terms in the collected vibration signals, which can causing huge errors and even distorting the low frequency spectrum. Therefore, we use the least squares method for detrending to ensure the authenticity and reliability of the signal [6].

2.3. Adaptive filtering

The vibration signals collected contain a lot of noise, which makes the signal feature extraction more difficult. For effective analysis, it is necessary to improve the signal-to-noise ratio.

For non-stationary signals, the conventional digital filter cannot effectively filter and eliminate noise. The adaptive algorithm can automatically adjust the filter parameters and structure according to the environment to achieve optimal filtering. Compared with the classical LMS adaptive algorithm based on gradient most rapid descent search, the genetic algorithm based on biological evolutionary rules solves the problem of local optimum and is more global in nature.

3. Signal analysis methods

3.1. Time domain analysis

Time-domain analysis responds to the time-domain characteristics of the vibration signals generated by aerospace servo-actuators. Real-time monitoring can be used to determine whether their operation is smooth and for fault warning. It can also discern the main vibration directions and provide a basis for improving structural design and vibration damping system design.
3.1.1. Time domain statistical analysis

Time domain statistical analysis is mainly to process sample amplitude $X_s$, average amplitude $\bar{X}$, peak value $X_p$, period $T$, root mean square value $X_{rms}$, variance $\sigma^2$, standard deviation $\sigma$ and other parameters to obtain waveform metrics, pulse metrics, cliff coefficients, and other metrics [4].

The algorithm flow for the time-domain statistical processing of the aerospace servo-actuator vibration signal is shown in Figure 2.

![Figure 1 Structure of the signal acquisition and processing system](image1)

![Figure 2 Algorithm flow for time domain statistical analysis](image2)

3.1.2. Autocorrelation analysis

The autocorrelation function $R_\tau(t)$ describes the similarity between the signal $x(t)$ and itself in the time domain. It is related to the signal lag time $\tau$ and observation time $T_0$ as the following formula.

$$R_\tau(t) = \lim_{T_0 \to \infty} \frac{1}{T_0} \int_{-T_0}^{T_0} x(t)x(t+\tau)dt$$

(1)

Obviously, a smooth and periodic random signal $x(t)$ has the same periodic component as $R_\tau(t)$.

3.2. Frequency domain analysis

By analyzing the distribution characteristics of the amplitude and energy of the vibration signal at each frequency, the main vibration frequencies can be obtained, which can be used for the preliminary fault diagnosis of the aerospace servo actuator. It can also provide the basis for the vibration damping and anti-resonance design of its working system.

3.2.1. Fast Fourier Transform

The DFT transform decomposes complex signals into multiple sinusoidal superpositions and describes their frequency, amplitude and other characteristics in the frequency domain. It is the basis of Fast Fourier Transform.

The forward and inverse DFT of the discrete signal $x(n)$ is

$$X[k] = DFT\{x[n]\} = \sum_{n=0}^{N-1} x[n]e^{-j2\pi kn/N}$$

(2)

$$x[n] = IDFT\{X[k]\} = \frac{1}{N} \sum_{k=0}^{N-1} X[k]e^{j2\pi kn/N}$$

(3)

Where: $N$ - time series length; $k$ - spectral line number, and $k = 0,1,\ldots,N-1$; $j = \sqrt{-1}$.

It can be seen that the DFT involves a huge amount of computation. To simplify the computation, FFT is derived.

$$X[k] = DFT\{x[n]\} = \sum_{n=0}^{N-1} x[n]W_N^{kn}$$

(4)

Where: $W_N = e^{-j2\pi/N}$, thus simplifying the DFT algorithm.

3.2.2. Power spectrum analysis

The power spectrum reflects the energy distribution of the signal by the power variation of the vibration
signal. The power spectrum analysis can strengthen the strong signal and weaken the weak signal, thus obtaining the main vibration frequencies.

First, the signal \( x(t) \) is processed to obtain \( X(f) \).

\[
\lim_{T \to \infty} \frac{1}{T} \int_{-T}^{T} x^2(t)dt = \lim_{T \to \infty} \frac{1}{2\pi T} \int_{-\infty}^{\infty} |X(f)|^2 df = \frac{1}{2\pi} \lim_{T \to \infty} \int_{-\infty}^{\infty} \frac{|X(f)|^2}{T} df
\]  

(5)

The signal density function \( S_s(f) \) can be obtained as follows.

\[
S_s(f) = \lim_{T \to \infty} \frac{|X(f)|^2}{T}
\]  

(6)

Then the average power of the vibration signal \( \psi_s^2 \) can be found as follows.

\[
\psi_s^2 = \lim_{T \to \infty} \frac{1}{T} \int_{-T}^{T} x^2(t)dt = \frac{1}{2\pi} \int_{-\infty}^{\infty} S_s(f)df
\]  

(7)

3.3. Time-frequency analysis

For the non-smooth vibration signal, the signal characteristics can be completely grasped only when the regular pattern of signal frequency changes with time is understood \(^2\).

Wavelet analysis method can adjust the time domain resolution and frequency domain resolution of the signal according to the requirements, and better reflect the multi-scale characteristics of the signal.

The Mallat algorithm is commonly used to implement wavelet decomposition, and the algorithm is as follows.

\[
c^0_j = y_k, \quad c^j_n = \sum_{k} c_{n-2^j k} h_{n}, \quad d^j_n = \sum_{k} c_{n-2^j k} g_{n} \quad n = 0,1,...,P - 1
\]  

(8)

Where: \( y_k \) - signal waveform; \( c^j_n \) - approximation coefficient; \( d^j_n \) - detail coefficient; \( j \) - number of decomposition layers; \( P \) - number of samples; \( h(n) \) - impulse response of H the filter. \( g(n) \) - impulse response of the G filter \(^5\).

Using wavelet decomposition, complex unstable signals can be decomposed in multiple layers to extract the required feature information, such as fault characteristics.

4. Results & Discussion

An aerospace servo actuator is rotating at 2000r/min without load, and the sampling frequency of the test system is 1000HZ. The vibration signals generated in the X, Z and Y directions are analyzed. Here, we use MATLAB and LabVIEW for joint analysis.

4.1. Time domain analysis

The acquired signal waveforms are shown in Figure 3. The signals are disorganized and contains many meaningless signals, so it should be processed initially.

The parameters of the signal after filtering and denoising are identified, and the results are shown in Table 1. From the time domain waveform diagrams of the vibration signals, it is easy to see that the main vibration directions of the aerospace servo actuator are X and Y directions.

The vibration in the Y direction is more severe, so the vibration signal in the Y direction will be further analyzed below.

| Direction | Peak-to-peak (m/s²) | Mean (m/s²) | Root mean square (m/s²) | Standard deviation (m/s²) | Kurtosis (m/s²) |
|-----------|---------------------|-------------|------------------------|--------------------------|----------------|
| X         | 0.658               | 0.004       | 0.098                  | 0.098                    | 0.925          |
| Y         | 0.976               | 0.002       | 0.176                  | 0.176                    | 1.893          |
The results of the autocorrelation analysis are shown in Figure 4, and it can be seen that the autocorrelation tends to decay.

4.2. Frequency domain analysis
The frequency and power spectra are obtained as in Figure 5. The results obtained from the FTT agree with the power spectrum analysis, which shows that the main vibration frequencies are about 22Hz, 24Hz, 26Hz and 28Hz.

4.3. Time-frequency analysis
Comparing the performance index of each window function, the Hemming window in the cosine window is selected for data processing. The wavelet decomposition results are shown in Figure 6.

The figure shows that after 5 layers of wavelet decomposition, the time-frequency characteristics of the vibration signal can be identified. It is inferred that for complex unstable signals, the desired signal characteristics can always be obtained in the appropriate number of layer decompositions. This method is widely used in fault analysis to extract the fault signal and determine where the fault source is based on its characteristics.
5. Conclusions
This paper analyzes the vibration signals of aerospace servo actuators.

Adaptive filters based on genetic algorithms are added to signal processing to improve the signal-to-noise ratio, overcoming the inefficiency and local optimum of traditional filters and making them more global and effective.

When window function processing is performed, the window function is selectable rather than established, which improves the reliability and universality of the algorithm to a certain extent. The appropriate window function is selected for different signal characteristics in order to obtain reasonable analysis results.

Research and experimental results show that:

1) The time domain analysis methods can monitor the working condition of the aerospace servo actuator and determine the main vibration direction. They can also provide early warning of the failure of its working system, improve safety and reliability. The main vibration directions of this aerospace servo actuator are the X and Y directions.

2) The frequency domain analysis methods can extract the main vibration frequencies. They can be used in preliminary fault analysis. The main vibration frequencies of this aerospace servo actuator are 22Hz, 24Hz, 26Hz and 28Hz in the Y direction.

3) The time-frequency analysis methods characterize the energy density of the vibration signals at different frequencies and times, and can extract the fault characteristic signal for further fault analysis to determine the type and exact location of the fault.

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