Research on Axial Flow Compressor Fault Diagnosis Based on Wavelet Analysis

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Abstract. The pressure signal of the axial compressor contains important information that reflects the working state of the compressor. The pressure signal in the compressor can be analyzed by wavelet analysis, which can provide an important basis for judging the working state of the compressor. In this paper, an axial-flow compressor fault diagnosis method based on wavelet analysis is proposed, which can be used to process the signal collected by the sensor in the compressor, and then to judge the state of the engine. The results show that the method can quickly and effectively identify the fault characteristics of the compressor and provide a new way for the rapid identification of the compressor fault.

1. Introduction

Aircraft engine is the core of the aircraft, and its working condition directly affects the safe and reliable operation of the aircraft. Compressor is an important component of the engine rotor, whose failure will cause a serious threat to the safety of the aircraft in the flight. Aircraft engine rotating parts mainly including blade, disk, shaft and bearings, have a high possibility of failure. However, due to the complexity of the working environment of the aircraft engine, the state changes frequently, making the work of fault diagnosis more difficult. How to get useful information from complex signals and take preventive measures plays an important role to improve the reliability of the engine. Therefore, it is necessary to carry out the fault diagnosis work for the compressor of the aircraft engine. The pressure pulsation signal can reflect the working state of the engine directly and quickly. The characteristic information of the signal can reflect the change of the working state of the system [1]. When the rotor breaks down, the pressure signal of compressor will have non-stationary time-varying characteristic, and the traditional Fourier transform cannot identify the fault feature in the time domain. The wavelet analysis method is used to deal with non-stationary time-varying signals, and the abrupt changes in the processed signals will not be lost and more obvious at some scales [2]. Therefore, based on the analysis of the characteristics of the engine compressor fault, this paper presents a method of characterizing the compressor fault based on the wavelet analysis method, which improves the efficiency of the feature extraction of engine rotor system fault, providing a new way for fault diagnosis of axial flow compressor.

2. Axial flow compressor fault wavelet identification

2.1 Wavelet transform.

Wavelet transform uses the time-frequency window shape method, which solves the contradiction between time resolution and frequency resolution [3]. It has good localized property in time domain and frequency domain. The low frequency components, using a wide time window, get a high
frequency resolution; The high-frequency components in the signal, using a narrow time window, get low frequency resolution[4]. This self-adaptability of wavelet transform makes it widely used in engineering technology and signal processing[5].

In the wavelet analysis, the main discussion of the function space is $L^2(R)$, which refers to the function space of the square integrable function on $R$, namely:

$$f(t) \in L^2(R) \Leftrightarrow \int_{R} \left| f(t) \right|^2 dt < +\infty$$

(1)

If $f(t) \in L^2(R)$, $f(t)$ is a signal with finite capacity while $L^2(R)$ is often referred as energy-limited signal space.

If $\psi(t) \in L^2(R)$, its Fourier transform is $\hat{\psi}(t)$ which satisfies the admissibility condition.

$$C_\psi = \int_{-\infty}^{\infty} \left| \omega \right| \left| \hat{\psi}(t) \right|^2 d\omega < \infty$$

(2)

That is to say $C_\psi$ is bounded, then $\psi$ is called a basis wavelet or mother wavelet. After the mother wavelet has been scaled and translated, a wavelet sequence is obtained.

$$\psi_{a,b}(t) = \left| a \right|^{-\frac{1}{2}} \psi\left(\frac{x-b}{a}\right)$$

(3)

Where $a, b \in R$, and $a \neq 0$. Let $a$ be the scaling factor and $b$ be the translation factor.

The essence of wavelet transform is to express an arbitrary function $f(t)$ in $L^2(R)$ space as its superposition of projections above $\psi_{a,b}(t)$ with different scaling factor $a$ and translation factor $b$. By adjusting $a$ and $b$, we can get the wavelet with different time-frequency width to match any position of the original signal to achieve the purpose of time-frequency localization analysis of the signal.

In practical application, discrete form of wavelet is often used. DWT can be obtained by the scaling factor $a$ and the translation factor $b$ in the discrete CWT. Usually take

$$a = a_0^{-j}, b = kb_0^{-j}a_0^{-j}, j,k \in Z$$

The corresponding wavelet function is as following.

$$\psi_{j,k}(t) = a_0^{-j} \psi(a_0^j t - kb_0), j,k \in Z$$

(4)

In practical applications, in order to make the calculation of wavelet more effective, usually wavelet function is constructed with orthogonality[6]. Theoretically, it can be proved that the continuous wavelet transform is discretized into discrete wavelet transform, and the basic information of the signal is not lost[5]. On the contrary, due to the orthogonality of the wavelet basis function, the correlation between the two points in the wavelet space due to the redundancy is eliminated. At the same time, the orthogonality makes the calculation error smaller, and the transformation time-frequency function can reflect the nature of the signal itself more accurately.

2.2 Data processing.

The dynamic pressure signals we get are collected by pressure probes. The pressure probe collects regular pressure pulsation signal with noise signal during normal operation. In the event of a compressor failure, a pressure fluctuation occurs in the compressor. These fluctuations are mixed in the original pressure signal. If this singularity point can be detected, the fault signal of the compressor can be detected. The dynamic pressure in the engine compressor is composed of three parts: the boost pressure $p_0$, the pressure pulsation $p_n$ caused by the measurement noise, and the pressure pulsation $p_s$ at the time of failure, ie, $p=p_0+p_n+p_s$. The frequency characteristics of the above three pressure components are different, the stage pressure $p_0$ is caused by the engine rotor work with the frequency
of the engine rotor frequency; \( p_n \) is caused by the measurement noise with high-frequency; \( p_s \) is caused by the failure of the pressure pulsation with low frequency. The three pressure signals are mixed together, and it is difficult to separate them by using the waveform analysis method in the time domain.

3. Example analysis

3.1 De-noising
Take the pressure signal of a compressor as an example. The data used in this experiment is the pressure value corresponding to 11000 time points collected by a certain axial-flow engine compressor sensor. As shown in Figure 1, the data values have been processed, but the dynamic properties of the signals are not changed. Time is from 0 ~ 11 seconds with the sampling frequency of 1000Hz.

![Figure 1. The compressor sensor signal](image1)

It can be seen from Figure 1 that the compressor is still in normal work from the time domain. We first denoise the compressor sensor signal to suppress the useless part of the signal to enhance the useful part of the signal. We use one-dimensional wavelet denoising method to remove the high-frequency noise \( p_n \).

The original signal and the processed signal are compared in Figure 2.

![Figure 2. The compressor sensor signal after denoising process](image2)

It can be seen that in about 8 seconds, a collapse and a great pulse of the pressure occurred can be seen from the processed signal, it is likely that the compressor failure, which may be stall or surge according to the general situation.

3.2 FFT analysis.
Use the FFT on the signal frequency domain analysis, the result is shown in Figure 3.

It can be seen that at frequencies around 60 Hz and 298 Hz, the energy of the signal suddenly becomes large, and at this time the compressor is likely to fail, possibly as a stall or surge which need further analysis.

![Figure 3. The spectrum of original signal after FFT](image3)

![Figure 4. Multi resolution analysis of Original Signal](image4)
3.3 Wavelet analysis

The wavelet multiresolution analysis is used to analyze the signal to decompose it into different scales under the approximate signal $a$ and detail signal $d$, of which each scale has different time and frequency resolution. The multi-layer resolution analysis is only a further decomposition of the low-frequency part $a$, while the high-frequency part $d$ is not considered. For the dyadic wavelet, the frequency band of the approximation signal and the detail signal is $fs/2^k$, $fs/2^k ~ fs/2^{k-1}$, where $f_s$ is the sampling frequency[6].

Then divide the signal into five layers, and extract the detail signals and the approximate signal $a_5$ for analysis.

| Number of layers | $a_5$ | $d_5$ | $d_4$ | $d_3$ | $d_2$ | $d_1$ |
|------------------|-------|-------|-------|-------|-------|-------|
| Frequency band (Hz) | 0-15.625 | 15.625-31.25 | 31.25-62.5 | 62.5-125 | 125-250 | 250-500 |

It can be seen from Figure 4, the pressure pulsation is mainly in $d_3$ and $d_4$ layer, while pulsation occurs for about 8.2 seconds. By FFT processing it can be seen that the pressure fluctuation is at around 62Hz. As the boundary frequency of $d_3$ and $d_4$ is 62.5Hz, the frequency of the pulsation can be set at 62.5Hz.

It can be seen from Figure 4, the frequency of 300Hz does not have obvious pulsation, so we do not analyze it here.

Then more research is done about $d_3$ and $d_4$ to excavate more information.

By spectral analysis of $d_3$ in Figure 5, the amplitude of the pulse maximum can be seen at 65.3Hz, but on average, but the range is about 63Hz.

By spectral analysis of $d_4$ in Figure 4, the amplitude of the pulse maximum can be seen at 59.5Hz, but the average the range is about 62Hz.

Now it can be seen that the energy mutation point is at about 8.2s with frequency of about 62.5Hz. It is known that the main cause of the abrupt change in the capacity of the compressor is stall or surge, while the surge is mainly at low frequency (usually only a few hertz or ten hertz) of the airflow along the axis of the compressor, with high amplitude (strong pressure and flow fluctuation). Therefore, it can be inferred that a stall fault occurred around 62.5 Hz at about 8.2s.

4. Conclusion

The axial-flow compressor fault diagnosis method based on wavelet analysis proposed in this paper can detect the stall signal quickly which can be used as a powerful tool to detect the engine stall fault. Based on the multiresolution property of the wavelet transform, this method can select the wavelet decomposition level according to the frequency characteristic of the stall signal with high accuracy. Based on this, the method of axial flow compressor fault diagnosis can be further developed to engineer application, to provide a powerful method and tools of improving the reliability of the engine.
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