2011 3rd International Conference on Signal Processing Systems (ICSPS 2011)
IPCSIT vol. 48 (2012) © (2012) IACSIT Press, Singapore
DOI: 10.7763/IPCSIT.2012.V48.8

Application of HHT for Aerodynamic Instability Signal Analysis in Compressor

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Abstract. The phenomenon of aerodynamic instability in compressor including stalls and surges is very complicated, and the mechanism is still not clearly understand by researchers. For disclosing characteristics of the phenomenon better, the Hilbert-Huang transform (HHT) was introduced in this paper. The outlet total pressure of a compressor was adopted as the indicate signal of aerodynamic instability. In the HHT, firstly, the pressure signal was decomposed into several intrinsic mode functions (IMFs) with the empirical mode decomposition (EMD) method. Then, the Hilbert transform was carried out on each IMF. Finally, the time-frequency chart of the outlet total pressure was constructed. The analysis disclosed that: 1) the EMD method can decompose the outlet total pressure signal into the noise component, the stall component, the surge component and the others IMFs; 2) when the compressor operates in a steady state, the energy of the signal distributes evenly on the frequency band, while in aerodynamic instability state, the energy concentrates on the surge frequency and the stall frequency, the signal pulse intensity increasing significantly; 3) the type of aerodynamic instability of this compressor is surge companied with rotating stall.

Keywords: Hilbert-Huang transform; compressor; stall; surge; aerodynamic instability

1. Introduction

Aerodynamic instability of a compressor is a very complicated three-dimensional inner side unsteady flow phenomenon, which including rotating stall and surge. It not only decreases the performance of a compressor very seriously, but also increases the vibration badly [1]. While aerodynamic instability happens, a compressor can not keep operating in a steady state, moreover, may be destroy in a very short time. So, many attentions and research were made on aerodynamic instability. But until now, the mechanisms of this phenomenon are not clearly understood by researchers. The analysis of the signals collected in compressor instability experiments is of great significance to further study the mechanisms of aerodynamic instability, to carry out active control [2] and to develop alarm devices [3] of aerodynamic instability.

Signals of compressor aerodynamic instability are non-stationary signals. The classic Fourier transform spectral analysis method is based on the basis of stationary signals. It takes a global view of signals. The time information of signals is no longer included in the frequency domain. So, it can not be used to analyze the development process of signals. The time-frequency analysis is the main processing techniques for non-stationary signals. The time-frequency analysis methods include short-time Fourier transform (STFT), wavelet transform (WT) [4-5], Wigner-Ville distribution (WVD) and so on. Above mentioned methods take the signal as a whole to transform it into time-frequency domain, and are not the true sense of the instantaneous time-frequency analysis [6-8].

In this paper, the outlet total pressure of a compressor was taken as the characteristic signal for aerodynamic instability analysis. The Hilbert-Huang transform (HHT) [9] was used to analysis the time-frequency characteristics of signals.

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2. Signals of Aerodynamic Instability

An axial flow compressor is a very important part in an aircraft engine. It also often can be seen in the industry fields, for using to provide high pressure flow materials. The axial flow compressor (Figure 1) is a multistage unit employing alternate rows of rotating blades and stationary vanes, to accelerate and diffuse the air until the required pressure rise is obtained [10].

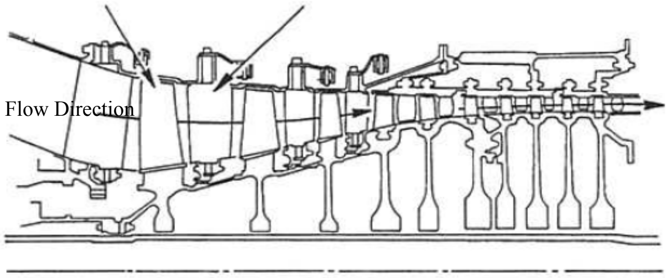

Figure 1. An axial flow compressor

If the operating conditions imposed upon the compressor blade departs too far from the design intention, breakdown of airflow induce aerodynamic instability. There are two styles of aerodynamic instability in axial flow compressors named surge and stall. When the attack angle of flow is too large, the flow separation is produced on the suction side of blades. Then it forms to stall cells. Relative to the rotor, stall cells run in the opposite direction along the rotor rotation. Rotation speed is generally 10% to 90% of the rotor speed, so it calls rotating stall (figure 2). The rotating stall has two types – progressive stall and sudden stall. Generally, the progressive stall is caused by parts of high of blades stall, and with multiple cells. While, the sudden stall is caused by the whole high blades stall, and often with a single cell. Because of the total pressure loss and almost no air flow through within the stall cells, the fluctuation amplitude of the wall static pressure and the outlet total pressure increase significantly.

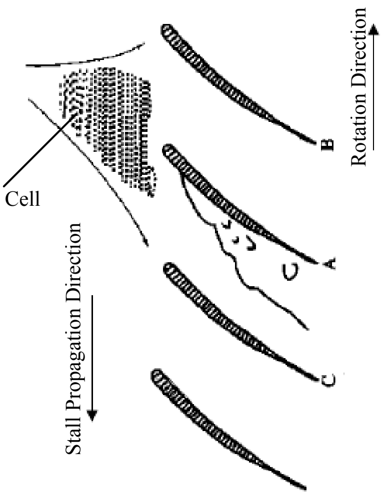

Figure 2. Stall in an axial flow compressor

Surge is an instability flow phenomenon in compression systems characterized by disruption of flow. The parameters of compression systems such as flow and outlet total pressure oscillate with time with low-frequency. In the surge cycles, the change of flow is often companied with the production, development and disappearance process of stall.

While an axial flow compressor operating in aerodynamic instability state, the outlet total pressure and the wall static pressure have strong pulse. It also shows a sharp decline in speed. In aircraft engines, the temperature after the turbine rises quickly and the thrust decreases sharply and even the vibrations excessive the standard levels. So, it should be avoid in compressor operations. The common character stall and surge is that the amplitude of dynamic pressure increases very significantly. In this paper, the outlet total pressure of the compressor is adopted as the signal to analysis the characteristics of aerodynamic stability.

3. Hilbert-Huang Transform

Hilbert-Huang transform includes two steps named the empirical mode decomposition (EMD) and the Hilbert transform. The EMD is based on that the amplitude of the signal itself can be decomposed into a finite number of signals with different characteristics of the intrinsic mode functions (IMFs), to solve the limits that the Hilbert transform can only operated on narrow bands signals. Then, the Hilbert transform is operated on IMFs respectively. Finally, the Hilbert time-frequency spectrum is obtained, which can characterize the frequency of signals in a very short time scales.

In the EMD procedure, IMF should meet two conditions. 1) in the entire data segment, the number of extreme points and the number of zero-crossing points must be equal or differ at most not more than one; 2) at any point, the mean of the up envelope formed by the local maximum points and the low envelope formed by the local minimum points is zero.

The EMD method assumes that any complex signal is composed by a number of different IMFs. In this way, any signal x(t) can be decomposed into IMFs based on the EMD method. The process of the EMD is actually a "sifting" process. In the "sifting" process, not only to eliminate the superposition of modal waveforms, but also to make the outline of waveforms more symmetrical.

The Hilbert transform is defined as the convolution of signal x(t) and the function h(t)=1/πt, expressed as following:

$$y(t) = H[x(t)] = x(t) * h(t) = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{x(\tau)}{t-\tau} d\tau \tag{1}$$

The analytic signal of x(t) is:

$$z(t) = x(t) + jy(t) = a(t)\exp[j\theta(t)] \tag{2}$$

Here, a(t) is the instantaneous amplitude; $\theta(t)$ is the instantaneous phase. So, the instantaneous frequency can be defined as:

$$f(t) = \frac{1}{2\pi}\frac{d\theta(t)}{dt} \tag{3}$$

The Hilbert spectrum can be obtained by getting a(t) and f(t) of each IMF.

$$H(t,f) = \mathrm{Re}\left\{\sum_{i=1}^{n} a_t(t)\exp\left[j\int 2\pi f_i(t)dt\right]\right\} \tag{4}$$

4. Experiments and Data Processing

4.2. Experiments

Stall and surge experiments were taken on an axial flow compressor using a compressor testing rig. Firstly, the speed of the compressor was kept steady at a value N. Secondly, the exhaust throttle was closed down slowly to push the compressor to the surge line. In this procedure, parameters such as pressures, vibrations, speed and air flow were monitored carefully. Then, when the aerodynamic instability phenomenon can be observed obviously from parameters, the exhaust throttle was opened quickly and the speed of the compressor was turned down. At last, the compressor returned to a normal operating state. In this way, a test cycle was completed [5]. In this experiment, the outlet total pressure was measure with a Kulite piezoresistive dynamic pressure sensor, and the sampling rate is 10kHz. The normalized waveform at the speed N=26200rpm is shown in figure 3. The time span is 12.025s.

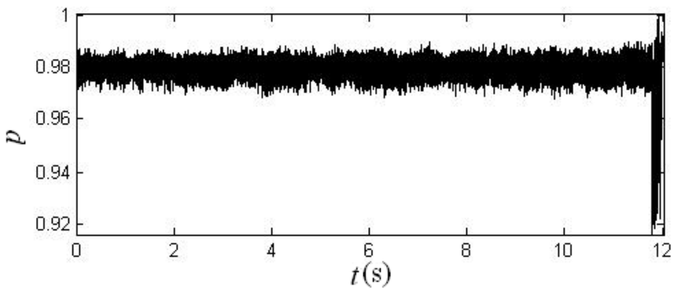

Figure 3. The waveform of the outlet total pressure

4.3. Data Processing

In this section, the outlet total pressure was decomposed into 4 levels with the EMD method. The IMFs and coarse signal (C) are shown in figure 4. It can be seen that the IMF1, IMF2 and IMF3 are low-amplitude high-frequency noise signals. The IMF4 and C are signals characterized the aerodynamic instability features.

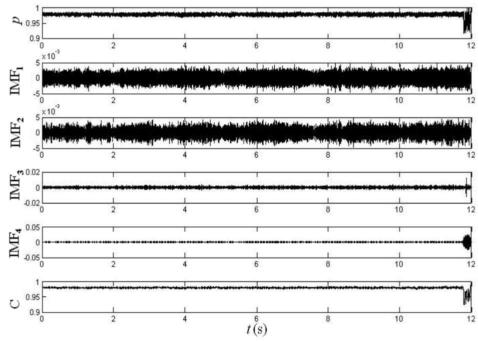

Figure 4. The EMD of the outlet total pressure

The Hilbert spectrum is shown in figure 5. In this figure, the segment with time t=11~12.025s and frequency f=0~500Hz is selected. It can be seen that the energy of signal concentrated in the low frequency band from about 11.8s. It can be considered as the precursor of aerodynamic instability.

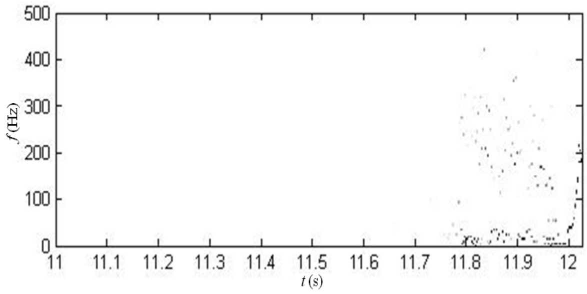

Figure 5. The Hilbert spectrum of the outlet total pressure

5. Discussion

To further analyze the characteristics of IMF4 and C, the spectrum analysis are made on two segments of the signals, t=1.0000~1.4095s as aerodynamic steady state and t=11.7800~11.9920s as aerodynamic instability state. The results are shown in figure 6 and 7, with the frequency band f=0~500Hz.

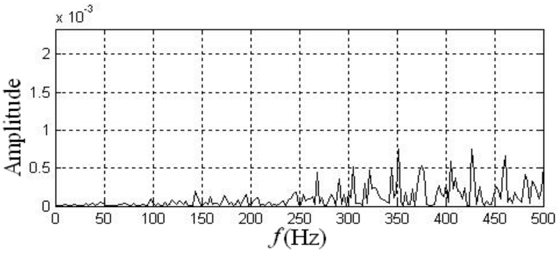

Figure 6 (a). The spectrum of IMF_4 in steady state

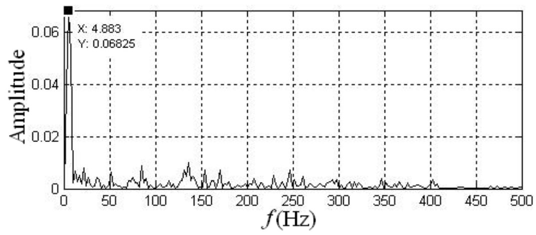

Figure 6 (b). The spectrum of *C* in steady state

Figure 6. The spectrum of IMFs in steady state

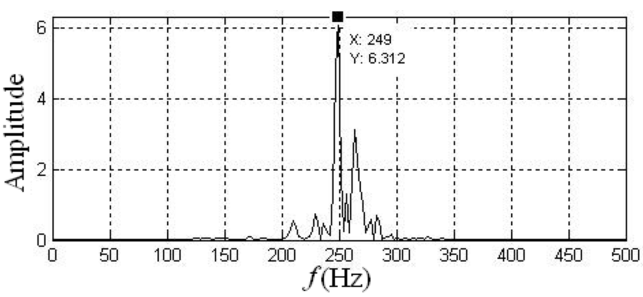

Figure 7 (a). The spectrum of IMF_4 in instability state

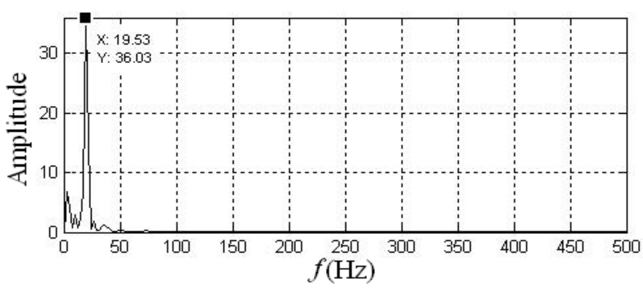

Figure 7 (b). The spectrum of *C* in instability state

Figure 7. The spectrum of IMFs in instability state

It can be seen from the figure 6, in the steady state, IMF4 is a stationary random noise. The coarse signal contains 4.9 Hz small amplitude (a=0.07) pulse component, which is the pressure fluctuation caused by adjusting the throttle on the export of the compressor. While in unsteady state (figure 7), the main frequency component of IMF4 is 249.0Hz, which is 57% of the rotational speed (N=26200rpm=436.7Hz). The main frequency component of the coarse signal is 19.5Hz. It can be concluded that the frequency of 249.0Hz is the rotating stall and 19.5Hz for the surge frequency. In this compressor, the phenomenon of aerodynamic instability characterized by the surge accompanied with the rotating stall. The IMF4 characterized stall signal and the coarse signal characterized the surge signal.

6. Conclusion

In this paper, the HHT is used to analysis the outlet total pressure of a compressor. The time-frequency spectrum is obtained. The original signal is decomposed into several IMFs. The physical meaning of IMFs are disclosed by the spectrum analysis. Then main conclusions are as follows:

1) With the EMD method, the outlet total compressor of the compressor can be decomposed into the noise, the surge, the rotating stall and others IMFs. In this paper, the IMF1~IMF3 are noise signals; the IMF4 is the rotating stall signal; the coarse signal (C) is the surge signal.

2) It can be drawn from the time-frequency and the spectrum chart that when the instability occurs, the amplitude of the outlet total pressure is increased significantly and the energy of the signal concentrate on the frequency of surge and stall.

3) The type of aerodynamic instability of the compressor is surges accompanied with rotating stalls. The frequency of rotating stall is 249.0Hz and the frequency of surge is 19.5Hz.

7. References

[1] D.X. Liu, P.L. Ye, J. Hu, and et al, “Design and evaluation technology of stability of aircraft turbine engine”, Aviation Industry Press, Beijing, 2004.

[2] Y. Liu, M. Dhingra, and J.V.R. Prasad, “Active compressor stability management via a stall margin control mode”, J. Engineering for Gas Trubines and Power, vol. 132, 2010, pp. 051602-1-10.

[3] N. Tahara, M. Kurosaki, Y. Ohta, and et al, “Early stall warning technique for axial-flow compressor”, Transactions of the ASME, vol. 129, 2007, pp. 448-456.

[4] F.K. Lu, and A.A. Ortiz, “Determining shock and detonation wave propagation time using wavelet methods”, 39th AIAA Fluid Dynamics Conference, 22-25 June, 2009, San Antonio, Texas.

[5] H Zhang, and Q H Pu, “Aerodynamic Unsteadiness Detection in Compressor Based on Wavelet Analysis”, Gas Turbine Experiment and Research, vol. 18, pp. 38-40, 2005.

[6] C. Li, and H.X. Cheng, “Research of no-stationary stochastic signals based on time-frequency analysis methods”, Automatic Measurement and Control, vol. 26, 2007, pp. 83-85.

[7] Z. Meng, G.P. Dai, and B. Liu, “Charactreristics study on time-frequency analysis method based on empirical mode decomposition”, Chinese J. Sensors and Actuators, vol. 19, 2006, pp. 1029-1032.

[8] J.H. Dong, H.M. Gu, and X. Zhang, “A comparison of time-frequency analysis mothods and their applications”, Chinese J. Engineering Geophysics, vol. 4, 2007, pp. 312-316.

[9] N.E. Huang, S. Zheng, S.R. Long, and et al. “The empirical mode eecomposition and the Hilbert splectrum for nonlinear and non-stationary time series analysis”, Proc. R. Soc. Lond. A, vol. 454, 1998, pp. 900 -995.

[10] Rolls-Royce plc, “The jet engine”, The Technical Publications Department, Rolls-Royce plc, Derby, England, 1996.