ISBN: 978-981-18-5852-9
WCSE 2022 Spring Event: 2022 9th International Conference on Industrial Engineering and Applications
doi: 10.18178/wcse.2022.04.188

Fault Diagnosis of Axial Fan through Acoustic Signal Analysis

Zhuoyi Zhou [1 +], Honghai Xu [1], Jing Li [2], Keming Qiu [1], Jing Zhang [1] and Junchi Chen [1]

[1] Shaoxing Shangyu Institute of Quality Inspection and Metrology Testing
[2] China Coast Guard Academy

Abstract. Acoustic signal contains the characteristics of the structural vibration of the fan, and therefore can be used for its fault diagnosis. A method is proposed to detect the fault of the fan in non-stop state by analyzing its acoustic signal. The acoustic signal model is developed according to the relationship between acoustic signal and structural vibration, and the acoustic characteristics in Fourier spectrum of the axial flow fan is derived combined with the model. The theoretical analysis is validated through the field test, and the shaft misalignment fault is diagnosed. It provides new ideas for fan fault diagnosis under complex working conditions.

Keywords: fan, acoustic signal, fault diagnosis, spectrum, characteristic frequency.

1. Introduction

Fan is a kind of machinery which compresses and transports gas through mechanical energy. It is widely used in mines, tunnels, ships, industrial kilns, air conditioning, buildings and nuclear power plants [1]. The fan structure is relatively simple, and the motor of axial flow fan is connected with the blade through the coupling to transfer torque and power. Therefore, the fault types of the fan are relatively simple, mainly including shafting misalignment, rotor imbalance, base looseness, and blade damage. According to statistics, shaft misalignment, and rotor imbalance account for more than 60% of fan faults [2]. For the misalignment fault, the coupling deformation, bearing wear, shaft bending and other adverse phenomena will occur, which will cause the damage of the fan and lead to a series of production accidents such as equipment shutdown. In the event of a base looseness failure, some accidents such as severe fan vibration, loud noise or fan falling off may occur during operation. If blade damage fault occurs, the air volume may not meet the standard, and the fan cannot perform its due function, affecting the efficiency ofindustrial production and even causing certain safety hazards. Therefore, if the fan fails, it will seriously affect the operation of the industry and the daily life of residents. Since most fans work in relatively harsh environments such as tunnels and mines, it is not convenient for technicians to judge the types of faults through observation and experience. Therefore, it is of practical significance to study the technology of diagnosing fan faults via signal analysis.

At present, researchers have proposed some methods for fan fault diagnosis based on signal analysis. For example, Lauro [3] compared the power consumption information of the fan in the office building with the non-faulty fan, and carried out the fault diagnosis analysis of the fan based on the fuzzy set and fuzzy logic algorithm. Xu [4] collected the vibration signal of the centrifugal fans, and reconstructed it by the symmetric dot matrix technology. The single template, multiple templates and clustering fault templates were used for image matching to determine the types of fan faults. Yang [5] investigated the fault diagnosis theory of composite asynchronous sequential machine with cascade combination based on state feedback and output feedback, which provided a demonstration effect for fan fault diagnosis. Del Val [6] used micro-electromechanical systems microphone arrays in a semi-anechoic chamber to collect information about the fan's operating status for preliminary experiments, and applied acoustic image geometric parameters to support vector machine algorithms for classification to identify fan blade faults. Xie [7] collected the vibration signals of four fault states of the blade at rated speed and selected the effective intrinsic mode function (IMF) components through energy distribution and correlation coefficient according to the results of empirical mode decomposition. The multi-scale entropy, generalized multi-scale entropy and the refined generalized multi-scale entropy between the original signal and 1-8 IMF components were compared and

+ Corresponding author. *E-mail address*: zzy_ustb@foxmail.com.

analyzed, and then the kernel function and parameters optimized by particle swarm optimization method were selected to obtain the optimal support vector machine model to complete the accurate classification of centrifugal fan blade faults. Ranade [8] proposed a simplified fault diagnosis model based on polynomial regression, which used the residual error generated by the system to accurately diagnose the fault of the heating ventilating and air conditioning fan. Monkova [9] calculated the frequencies of the outer ring and inner ring damages of rotating machinery, evaluated the operating state of the bearing using Root Mean Square values, and monitored the condition of the machine in the frequency domain through fast Fourier transform. Islam [10] proposed a method based on improved adaptive filter, fuzzy logic and spectrum analysis to detect rotating fault features, established an adaptive filter based on entropy and fuzzy logic to select the step size and performed Hilbert envelope analysis to identify the fault characteristics of rotating machinery.

So far, most scholars have collected and analyzed the vibration signal during the operation of the fan to diagnose their faults. However, in the actual work process, the installation position of the fan may be in a place that is difficult to operate manually, and it is also difficult to collect vibration signal data in the three directions of X, Y, and Z at the same time. Therefore, the method of diagnosing fan faults through vibration signal analysis has certain limitations in industrial production. Considering that the acoustic signal is radiated during the operation of the fan, it is usually regarded as noise. The collection of the acoustic signal is very convenient and fast, and is not limited by the installation position of the fans. Therefore, it is more feasible to analyze acoustic signals to monitor the status and diagnose faults of the fan on the actual site. In the previous research, the authors of this article [11] successfully diagnosed the fault gears by analyzing the acoustic signal of the planetary gearbox, verifying the feasibility of the rotating machinery fault diagnosis through acoustic signal analysis. This paper will study the fan fault diagnosis technology based on acoustic signal analysis, which has strong application value for monitoring fan status and guiding technicians to diagnose fan faults in industrial engineering.

2. Characteristics analysis of fan's typical faults

According to the classification of the sound source, the noise radiated during the operation of the fan belongs to the structure noise [12]. The acoustic signals come from the overall structural vibration of the fan, that is, the sound signal is generated by the vibration of the blades, shaft system, base and other components when the fan is running. According to the vibration theory, the vibration signal can be expressed as a set of cosine functions containing amplitude modulation (AM)-frequency modulation (FM) terms, and the vibration signal model can be expressed as [13]

$$p(t)=\sum_{k=0}^{K}a_{\mathrm{k}}(t)\cos[2\pi kf_{\mathrm{r}}t+b_{\mathrm{k}}(t)+\theta_{\mathrm{k}}] \tag{1}$$

$$\begin{aligned} a_k(t) &= c\sum_{n=0}^{N}A_{kn}\cos(2\pi nf_{\mathrm{r}}t+\phi_{kn}) \\ &= c[1+\sum_{n=1}^{N}A_{kn}\cos(2\pi nf_{\mathrm{r}}t+\phi_{kn})] \end{aligned} \tag{2}$$

$$b_k(t)=\sum_{l=1}^{L}B_{kl}\sin(2\pi lf_{\mathrm{r}}t+\varphi_{kl}) \tag{3}$$

where $p(t)$ is vibration signal model, f_{r} is characteristic frequency, $a_k(t)$, $b_k(t)$ are AM term and FM term, A_{kn}, B_{kl} are AM and FM coefficient, c is a dimensionless constant, and ϕ_{kn}, φ_{kl}, θ_k are initial phases.

Given the acoustic signal has the same amplitude-frequency characteristics as the vibration signal, the vibration signal model listed above is also effective for the acoustic signal, so it can be inferred that different type of faults correspond to different types of fault characteristic frequencies, and the dominant spectral lines in the spectrum are also different. Therefore, the collected acoustic signal can be Fourier transformed, and the main characteristic spectral lines or modulation sidebands in the Fourier spectrum can be extracted to determine the fault type of the fan. Then the corresponding fault characteristic frequencies will be introduced [14] and the corresponding spectrum characteristics will be analyzed and derived in accordance with the following four types of typical fan faults: rotor imbalance, shaft misalignment, base looseness, and blade damage.

2.1. Analysis of Rotor imbalance

In the process of fan manufacturing, due to manufacturing or assembly errors, there may exist mass eccentricity in the original rotor system of the produced fan, which may cause rotor imbalance faults. Besides, during the long-term operation of the fan, the rotor parts may be worn and fatigued, which cause damage to the rotor system, thereby exacerbating the rotor imbalance failure. According to the characteristics of its mechanical structure, the rotor system of the axial flow fan is directly connected by the motor and the blades, so the characteristic frequency of the rotor imbalance should be related to the motor rotation frequency:

$$f_{\mathrm{r}} = n / 60 \tag{4}$$

where n is motor speed.

Combined with the fan acoustic signal model, it can be inferred that for the acoustic signal radiated by the fan, in its Fourier spectrum, there are a series of spectral lines with frequency f_{r} and its octave frequencies nf_{r}, which can reflect the rotor unbalance fault of the fan.

2.2. Analysis of shaft misalignment

The shaft of the axial flow fan is connected with the main shaft of the motor through a coupling to form a shaft system. There may also exist some installation errors and abrasion deformation in the process of production and operation, which may cause the shaft connection displaced, and then this leads to the shaft misalignment failure of the fan. Similarly, according to the characteristics of the shafting connection structure, the characteristic frequency of the shafting misalignment can be expressed as

$$f_{\mathrm{r}} = 2n / 60 \tag{5}$$

It can be deduced that in the Fourier spectrum of the acoustic signal, the characteristics of the shaft misalignment are mainly manifested as the notably existence of $2f_{\mathrm{r}}$ and a series of high-order harmonics $4f_{\mathrm{r}}$, $6f_{\mathrm{r}}$, $8f_{\mathrm{r}}$, $10f_{\mathrm{r}}$, etc. Therefore, it is possible to determine the shaft misalignment fault by detecting the presence or absence of the lager amplitudes of the even frequency components in the acoustic signal spectrum.

2.3. Analysis of base looseness

The signal characteristic of base looseness is mainly nonlinear. In the Fourier spectrum, in addition to characteristic frequency f_{r} and its multipliers, there are also multiple fractional harmonics (0.3~0.5) f_{r} and sub-harmonics $1.5f_{\mathrm{r}}$, $2.5f_{\mathrm{r}}$ existing in the spectrum, and the amplitude of the high octave frequencies are greater than that of the low octave frequencies. Thus, when analyzing the spectrum, it is feasible to match whether there are obvious fractional harmonics, sub-harmonics and their higher frequency components, which is the basis for determining the base looseness fault of the fan.

2.4. Analysis of blade damage

During the operation of the fan, if there exist the blade damage fault, the modulation phenomenon will occur in the acoustic signal radiated by the fan. Its acoustic signal model can be expressed as

$$p(t) = \underbrace{\left[1 + A_{\mathrm{r}}\cos\left(2\pi f_{\mathrm{r}} t + \phi\right)\right]}_{\text{AM by balde damage}} \cos\left[2\pi N f_{\mathrm{r}} t + \underbrace{B_{\mathrm{r}}\sin\left(2\pi f_{\mathrm{r}} t + \varphi\right)}_{\text{FM by balde damage}} + \theta\right] \tag{6}$$

where N is the number of blades, and A_{r}, B_{r} are AM and FM coefficients of the blade damage fault.

According to the acoustic signal model of blade damage, it can be inferred that in the Fourier spectrum, the dominant frequencies are the lines of Nf_{r}, which have higher amplitudes and will be modulated by the characteristic frequency of the blade damage fault, showing that there are a large number of modulation sidebands $(N \pm m)f_{\mathrm{r}}$ (m=1,2,⋯) near the characteristic frequency line, and it can be determined that there exist the blade damage fault.

3. Test and result analysis

An axial fan was sent to our testing center for routine aerodynamic performance testing. The parameters are shown in Table 1, and the installation and testing of the fan is shown in Figure 1.

Table 1. parameters of the fan

Fan		**Motor**	
Specification	GXF-I-9A	Specification	Y180L-6
Air volume (m^3/h)	41684	Speed(r/min)	960
Number of blades	8	Power(kW)	15

Fig. 1. Test fan.

During the test, it was found that the vibration was severe and the noise was high, so the acoustic signal was collected and analyzed to diagnose the fan. Through intuitive analysis of Figure 2, the time-domain waveform of the acoustic signal of the axial flow fan, it was observed that the sound pressures of the radiated acoustic signal were generally 0.6 Pa, which is 89.5 dB, and the highest sound pressure level within 10 seconds was 97.2 dB, thus it was preliminarily determined that the fan may be malfunctioning. From the motor speed curve in Figure 3, it could be seen that the motor kept running at a speed of 960r/min, and the fan's characteristic frequency f_r=16Hz could be calculated. The Fourier transform was performed on acoustic signal of the fan, and the spectrum including the fault characteristics was obtained as shown in Figure 4. Affected by environmental noise, there existed a large number of irregular lines in the low frequency range of 0-50Hz in the figure, but the characteristic frequency f_r and its higher harmonics2f_r, 3f_r, 4f_r, 5f_r, 6f_r of the fan could also be clearly extracted from the spectrum. No spectral lines such as fractional harmonics and sub-harmonics were found, so the base looseness fault was preliminarily ruled out. No corresponding modulation sidebands were found in the spectrum. Meantime, since the fan blades were inspected all intact before the test, the blade damage was excluded. Then, it is extracted that the amplitudes of even-numbered harmonics 2f_r, 4f_r, and 6f_r in the spectrum were larger than that of others, and it could be determined that they were dominant. Therefore, the shaft misalignment fault was preliminarily diagnosed.

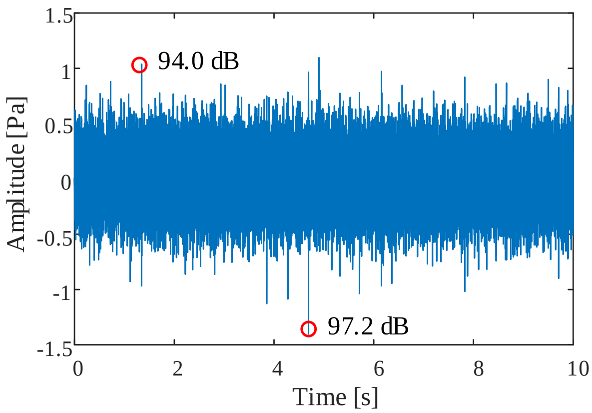

Fig. 2: Time domain waveform.

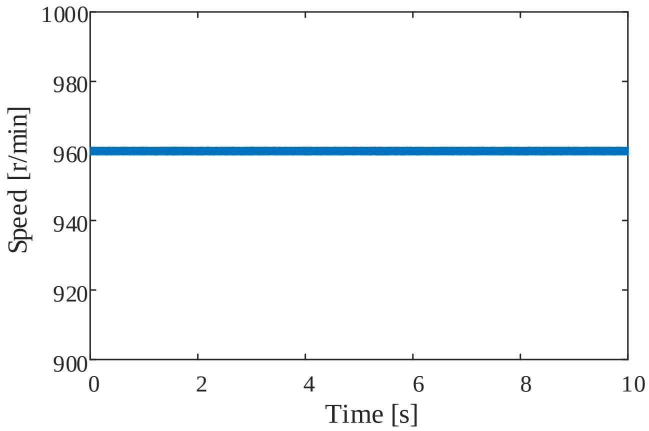

Fig. 3: Motor speed.

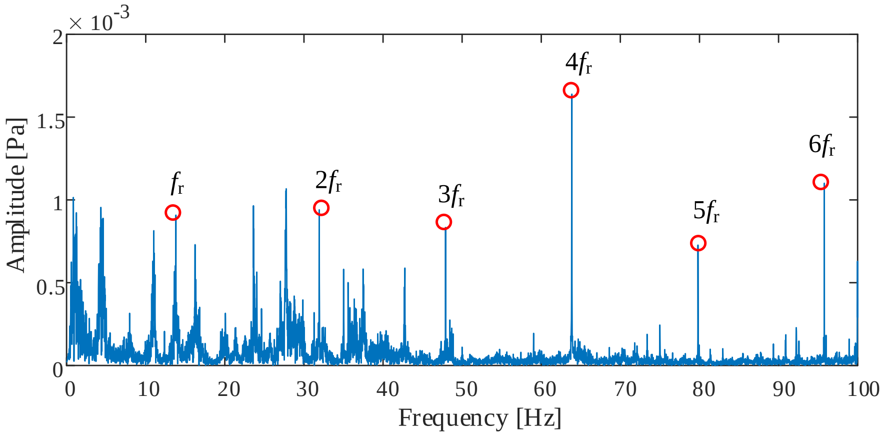

Fig. 4: Fourier spectrum of the acoustic signal.

The axial flow fan was shut down to be inspected, and it was found that the main shaft of the fan connected by the coupling and the main shaft of the motor were not on the same horizontal line. In fact, the main shaft of the motor was about 1mm lower. In the actual installation process, considering the thermal expansion and contraction, the motor spindle should be slightly higher than the fan spindle to ensure that the two axes remain the same level when the fan is running. After re-aligning and running the fan again, its vibration and noise radiation returned to normal. Therefore, this diagnostic test successfully verified fan's shaft misalignment fault.

4. Conclusion

This paper analyzes the characteristics that the acoustic signal radiated by the fan during operation contains its structural vibration information, and then given the advantages of the convenience of acoustic signal acquisition over vibration signal, proposes a method of axial fan fault diagnose through acoustic signal analysis. The Fourier spectrum characteristics of the acoustic signal of the four typical faults of axial fan, rotor imbalance, shaft misalignment, base looseness, and blade damage, are derived. The collected acoustic signal is analyzed and the characteristic frequencies are successfully extracted through the spectrum analysis in the field test. The shaft misalignment fault of the fan is successfully diagnosed, which verified the feasibility of the theoretical method of diagnosing the axial flow fan through acoustic signal analysis, and it is helpful for the fan fault diagnosis through the acoustic signal analysis in the industrial field under the non-stop state.

5. Acknowledgements

Thanks go to the anonymous reviewers and the editor for their suggestions and comments, which have helped improve the quality of this paper.

6. References

[1] F. P. Bleier. *Fan handbook: selection, application, and design: McGraw-Hill*. 2018.

[2] H. P. Jagtap, A. K. Bewoor, and R. Kumar. Failure analysis of induced draft fan used in a thermal power plant using coordinated condition monitoring approach: A case study. *Engineering Failure Analysis*. 2020, 111: 104442.

[3] F. Lauro, F. Moretti, A. Capozzoli, I. Khan, S. Pizzuti, M. Macas, and S. Panzieri. Building fan coil electric consumption analysis with fuzzy approaches for fault detection and diagnosis. *Energy Procedia*. 2014, 62: 411-420.

[4] X. Xu, H. Liu, H. Zhu, and S. Wang. Fan fault diagnosis based on symmetrized dot pattern analysis and image matching. *Journal of Sound and Vibration*. 2016, 374: 297-311.

[5] J. M. Yang. Fault Diagnosis for Composite Asynchronous Sequential Machines with Cascade Composition. *International Journal of Mechanical Engineering and Robotics Research*. 2017, 6(6): 502-505.

[6] L. del Val, A. Izquierdo, J. J. Villacorta, L. Suárez, and M. Herráez. First steps on fan matrix condition monitoring and fault diagnosis using an array of digital MEMS microphones. *Proceedings of Meetings on Acoustics 173EAA*. 2017, 30: 030014.

[7] X. Xie, W. Chen, B. Chen, J. Cheng, and L. Tan. Comprehensive fatigue estimation and fault diagnosis based on Refined Generalized Multi-Scale Entropy method of centrifugal fan blades. *Measurement*. 2020, 166: 108224.

[8] A. Ranade, G. Provan, A. El-Din Mady, and D. O'Sullivan. A computationally efficient method for fault diagnosis of fan-coil unit terminals in building Heating Ventilation and Air Conditioning systems. *Journal of Building Engineering*. 2020, 27: 95-105.

[9] K. Monkova, P. P. Monka, S. Hric, D. Kozak, M. Katinić, I. Pavlenko, and O. Liaposchenko. Condition monitoring of Kaplan turbine bearings using vibro-diagnostics. *International Journal of Mechanical Engineering and Robotics Research*. 2020, 9(8): 1182-1188.

[10] M. S. Islam, and U. Chong. Rotating Machine Fault Detection based on Fuzzy Logic and Improved Adaptive Filter. *International Journal of Mechanical Engineering and Robotics Research*. 2021,10(2): 79-86.

[11] Z. Zhou, and Z. Feng. Planetary Gearbox Fault Diagnosis via Acoustic Signal Analysis. *2017 International Conference on Sensing, Diagnostics, Prognostics, and Control (SDPC)*. 2017, pp. 29-34.

[12] J. W. S. B. Rayleigh, *The theory of sound: Macmillan*. 1896.

[13] Z. Feng, and M. J. Zuo. Vibration signal models for fault diagnosis of planetary gearboxes. *Journal of Sound and Vibration*. 2012, 331(22): 4919-4939.

[14] B. H. Ahn, Y. H. Kim, J. M. Lee, J. M. Ha, and B. K. Choi. Signal-Processing Technology for Rotating Machinery Fault Signal Diagnosis. *Progress in Clean Energy: Springer*. 2015, 1: 933-943.