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Wavelet Analysis of the Shaft Order Perturbation and Stall Inception in an Axial Compressor

HE Xiang, MA Hongwei, ZHANG Jun, Wei Wei

National Key Laboratory of Science and Technology on aero-Engines, School of Energy and Power Engineering, Beihang University, Beijing, 100191, China

An experiment was carried out in a low-speed large-scale axial-compressor. Dynamic pressure signals were measured and analyzed with a wavelet transform. At all stable operating condition, a shaft order perturbation was observed from the dynamic pressure signals and wavelet power spectrums. By measuring the tip clearance, blade pitches and blade thickness distributions, a rotor asymmetry was identified in this compressor, which is strongly linked to the shaft order perturbation. Modal wave appears at the near-stall operating point. The propagation speed of the modal wave is about 20% rotating speed. At the peak of the modal wave, the intensity of the shaft-order-perturbation increases obviously, while it decays very fast at the trough of modal wave. By throttling the compressor, modal stall occurs in several seconds and only one stall-cell was detected. The stall cell grows smoothly out of the modal wave and its propagation speed is increased to 30% rotor speed. In several revolutions before stall, the intensity of the modal wave is increasing and a shaft order perturbation produced by modal-wave grows into stall inception which indicate stall onset but not trigger stall.

Keywords: axial compressor, stall inception, modal wave, wavelet analysis, shaft order perturbation

Introduction

Compressor stall/surge usually leads to significant loss in performance, engine flameout, even serious mechanical failure. Therefore, the attempts of extending the stable operating range of compressor have always been investigated since the early development of the gas turbine engine. In the past two decades, many efforts were devoted to reveal the triggering mechanisms of compressor stall. The flow disturbances that appear before fully developed rotating stall play an important role in stall development, and some are believed to trigger stall, namely stall inception[1]. Two distinct stall-inception patterns have been identified. The first, referred to as modal was initially predicted by Moore-Greitzer [2]. The existence of the modal inception was first validated in the single and multi-stage compressors by McDougall et al. [3] and Garnier et al. [4] respectively. The second is usually called spike which was observed initially by Day [5].

Mailach et al. [6] clarified the instability disturbance as two types. a) The first one is the long-length-scale/modal disturbance. b) The second one is the short length-scale disturbance including the spike inception and multi-cell configurations.

The multi-cell configuration could happen at stable operating point, which is obviously distinct from the spike inception. The high-frequency disturbance observed by Day et al. [7] belongs to the stable multi-cell disturbance

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or multi-cell rotating stall. Inoue et al. [8] discuss the multi-cell disturbance and the results suggest that the number and the size of the cells are constant. Cumpsty believed that the 'rotating instability' observed by Mailach et al. [6, 9] and Marz et al. [10] is a special case of multi-cell disturbance. Therefore, there is a lot of controversy whether it should be referred to as 'rotating stability'.

Moreover, Day et al. [7] observed another kind of disturbance, i.e., the shaft order perturbation, which is present to a greater or lesser extent in all compressors. This is because the concentricity of rotor and casing, the size of the tip clearance gaps, and the uniformity of the blade angles are never absolutely perfect throughout the entire compressor. Feng Lin [1] discussed such unsteady disturbances in a low speed compressor at the near stall condition. The same phenomenon was observed by Hyung-Soo [11] at stable operating condition far away from stall.

In this paper, an experiment was carried out in Low-speed Large-scale Axial Compressor (LLAC) test rig to study the shaft order perturbation and stall inception. In addition, a wavelet transform code was developed to analyze the raw pressure data. The details about the wavelet analysis refer to [1, 12].

Experimental Facility and Measurement Layout

The LLAC test rig is a single-stage axial compressor with inlet guide vanes (IGV). The rotor and stator blades with C4-series airfoil are designed in terms of the free vortex law. More detailed design parameters are summarized in Table 1.

Table 1 Parameters of the compressor stage

Parameter	Value
Outer diameter (m)	1
Hub-to-tip ratio	0.6
Design Speed (r/min)	1200
Design mass flow rate (kg/s)	22.4
Re_{chord}	7.5×10^5
Number of blades	36+17+20
Blade chord (mm)	100, 180, 180
Rotor tip clearance (mm)	3

The measurements were conducted at the 50%, 75% and 92% design rotor speed. Because the phenomena discussed here are almost the same at these three rotor speed, the discussions are focused on the results at 75% rotor speed. The overall compressor performance in terms of the static-to-static pressure rise coefficient ($\Psi=\triangle Ps/0.5\rho U^2$) and the flow coefficient ($\Phi=V_x/U$) was measured with circumferential array of four static pressure taps on the casing at both inlet and outlet of the compressor as shown in Figure 1. Four dynamic sensors are located around the annulus on the casing in front of the first rotor (Figure 2). The sampling rate is 10 kHz.

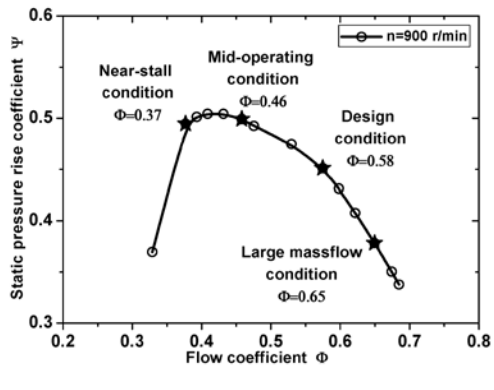

Fig. 1 Overall static pressure rise characteristic

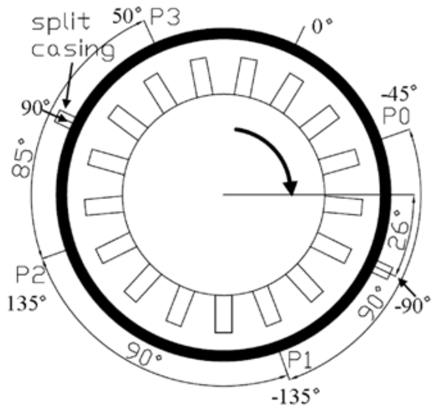

Fig. 2 Measurement layout

Result and discussion

The shaft order perturbation at the stable conditions in the 1.5-stage compressor

The pressure trace obtained from P1 is given in Figure 3(a) at the condition of Φ=0.65 far away from the stall. The disturbances are observed from pressure traces in the same rotor passages of every revolution, which means it propagates around the annulus at 100% rotor speed.

Actually, the disturbances happens at all operating conditions, such as design operating condition of Φ=0.58 and mid-operating condition of Φ=0.46. Feng Lin [1] has observed such similar disturbance, which occurs at the early pre-stall period, while in this paper such disturbance happen at all stable operating conditions. Day et al. [7] called it as the shaft order perturbation.

There are four distinct energy bands in the wavelet power spectrum as shown in Figure 3(b), which is corresponding to the frequency components of $1f_{rot}$, $2f_{rot}$, $3f_{rot}$ and $17f_{rot}$ in the FFT amplitude spectrum of Figure 3(c).

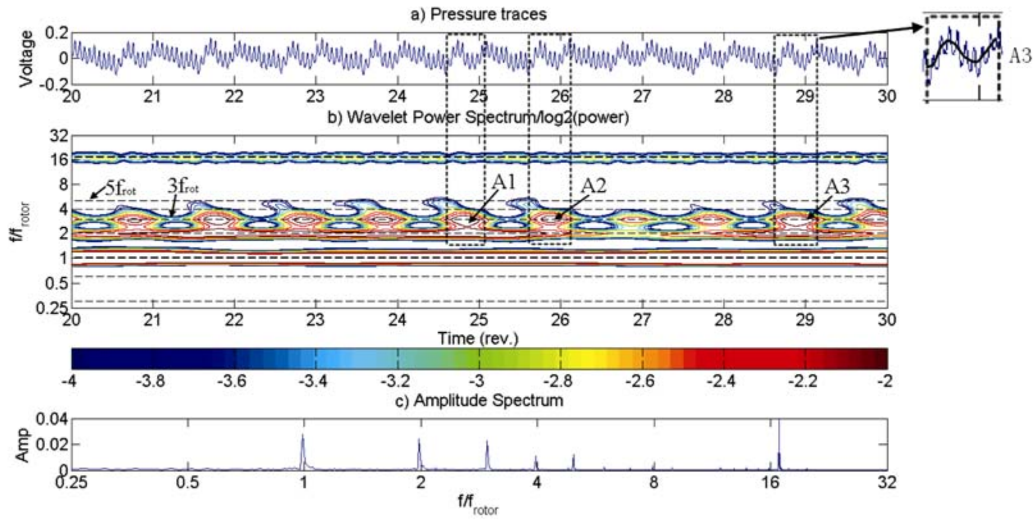

Fig. 3 Wavelet analysis of the pressure trace at the condition of Φ=0.65 far away from stall

There are 10 spots of $3f_{rot}$ in 10 rotor revolutions in the subplot (b), such as A1, A2 and A3. The enlarged plot of A3 illustrates the perturbation occupies about 9 blade passages out of 17 blades on this rotor. The wavelength of the disturbance is about 6 blade passages, i.e., about 1/3 of the rotor blades number.

The shaft order perturbation in an isolated rotor

In order to validate that the shaft order perturbation is induced by the rotor asymmetry, the IGV and stator blades were removed and the repeated test was carried out. In addition, the tip clearance of each blade and blade pitch of each rotor passages is measured.

Figure 4(a) shows the tip clearance of each blade in the rotor. Tip clearance is almost uniform and is about 3mm at 50% chord. However, compared with the 50% chord, the tip clearance become larger and is no longer uniform at leading-edge, especially at trailing-edge. It views the tip clearances of 17 blades as a time series signal and then the FFT spectrum can be obtained as shown in Figure 4(b). The frequency components of $1f_{rot}$, $2f_{rot}$, $3f_{rot}$ and $4f_{rot}$ are induced by the tip-clearance asymmetry. Actually, the blade pitch and the blade thickness at tip are also non-uniform and their FFT spectrums are similar to Figure 4(b).

The FFT spectrum of pressure signal indicates that the shaft order perturbation also happens in the isolated rotor at large mass-flow operating condition, as seen in Figure 5. Actually, it occur at all stable operating condition in this isolated rotor. These results validate Day's conclusions [7] that the shaft order perturbation is induced by the rotor or casing asymmetry.

Propagation of the disturbances at the near-stall condition

At the near-stall condition of Φ=0.37, the modal wave is observed from the pressure trace in Figure 6. The modal frequency is centered on the $0.2f_{rot}$. In the energy band between $2f_{rot}$ and $5f_{rot}$, the intensity of the shaft order perturbations becomes larger at the peak of the modal-wave, such as M1, M2, M3 and M4 as shown in Figure 6(b).

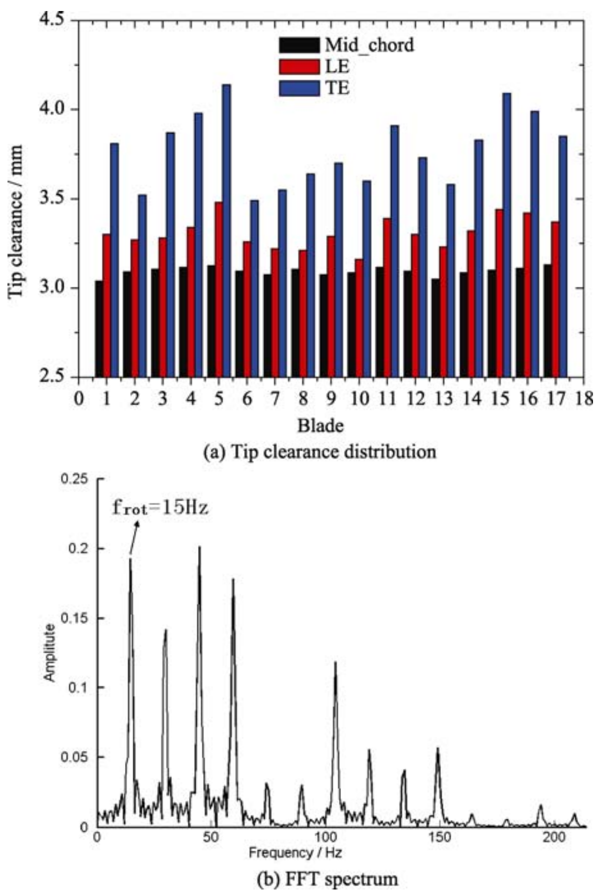

Fig. 4 Rotor asymmetry in the compressor

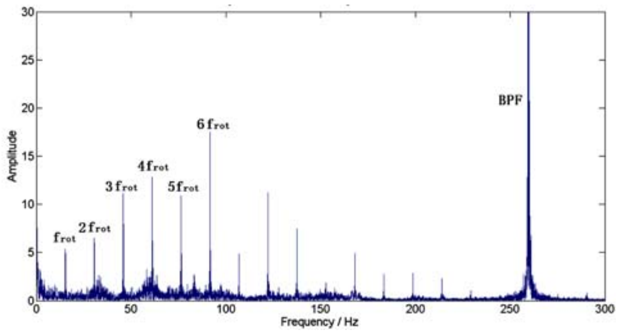

Fig. 5 FFT of pressure signal at large mass-flow condition

Figure 7 shows propagation of the modal waves around the annulus. The wavelet power spectrums only show the energy band from 1f_{rot} to 8f_{rot}. The dashed arrow illustrates the propagation of the modal wave around the annulus with 20% rotor speed (0.2f_{rot}). The shaft order perturbations marked with solid-arrow propagates around the annulus at 100% rotor speed. The intensity of the shaft order perturbations becomes larger just at the modal peaks, while it decays very fast at the trough of the modal wave. Although some disturbances can propagate more than one revolution, the intensity is not enough to grow into an inception at the near-stall condition.

The stall behaviors in the 1.5-stage compressor

Figure 8 show that the pre-stall period from −40 to 0 revolutions experiences the similar process as the near-stall condition. The disturbances of M5 to M10 aroused by the modal-wave are increasing in intensity. In the following, the compressor enters into a region, namely 'the frequency mixing region' (FMR) suggested by NIE Chaoqun [13], from 0 to 6 revolutions marked with red dashed-line. From 6 to 20 rotor revolutions, the compressor enters into full stall. Figure 9(c) and (d) indicates the 30% and 60% f_{rot} are corresponding to stall-cells passing frequency and its double frequency.

The peak of the modal wave is located at P0 at revolution -6.5 as seen in Figure 9. Then, the peak moves to P2 at revolution -4. In this period, the shaft order perturbations, C1, C2 and C3, are generated by the modal-wave. However, the perturbations decay very fast. At rotor revolution -2.5, a shaft order perturbation B is also produced marked with solid-circle. The most significant is that it does not decay after the peak of the modal-wave passing through and the amplitude of disturbance B is keeping on growing. The disturbance B indicates that the compressor enters into 'the frequency mixing region' and it should be regarded as a stall inception. The propagation speed of disturbance B slows down to 80% rotor speed from 100%.

At rotor revolution 0, another disturbance D1 appears at P2 as shown in Figure 9 and Figure 10. Subsequently, more and more disturbances appear and increase in size and amplitude in the frequency mixing region. At last, these disturbances are merged into a large stall cell at revolution 6 and the compressor comes into the full stall condition. The propagation speed of the stall cell is 30% rotor speed. It should be noted that the modal wave grows into the stall cell smoothly, which agrees well with the conclusions obtained by NIE Chaoqun [13]. That means the stall is triggered by modal wave rather than shaft order perturbation.

Conclusions

1. The shaft order perturbation was observed at all stable conditions in the low-speed large-scale axial-compressor. This disturbance is strongly linked to the rotor asymmetries.

2. A modal wave appears at the near-stall condition.

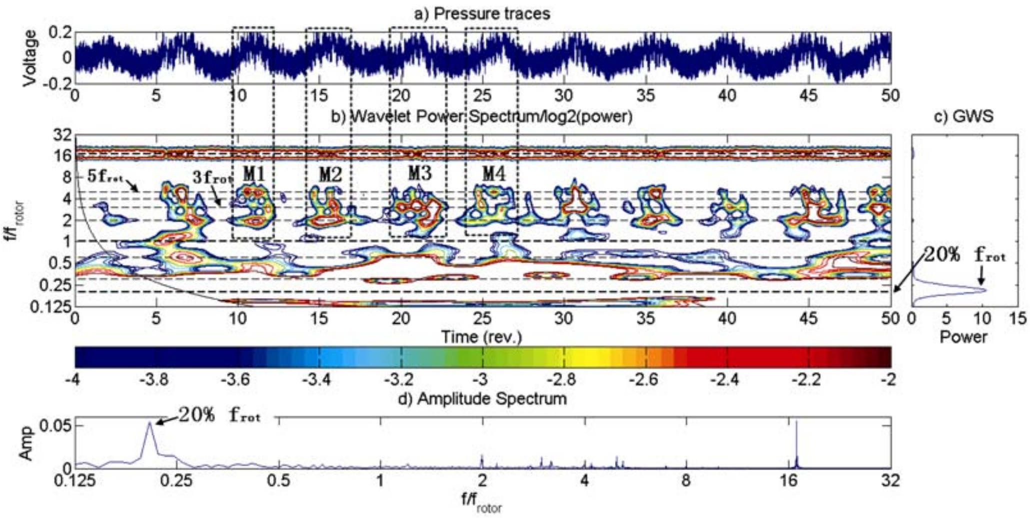

Fig. 6 Wavelet spectrum of the pressure trace at the near-stall condition

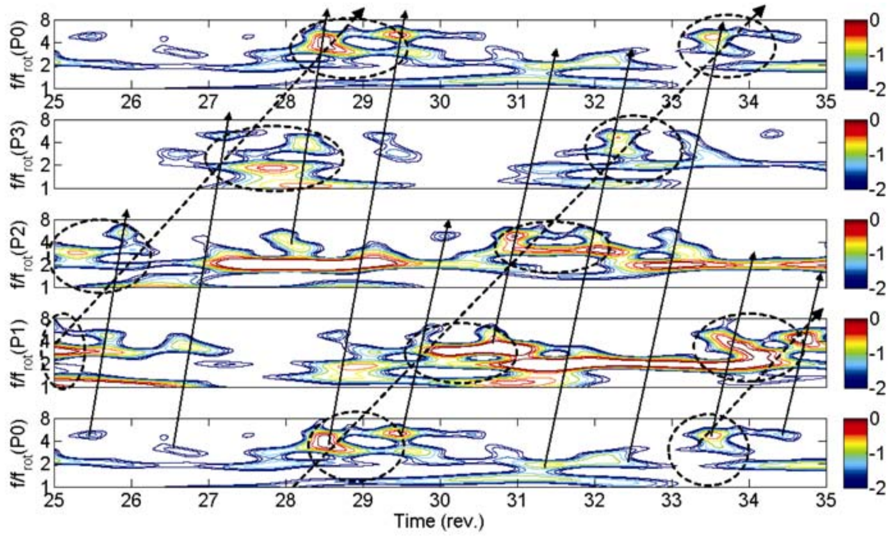

Fig. 7 Propagation of the shaft order perturbations at the near-stall condition (low-pass-filtered at 10frot)

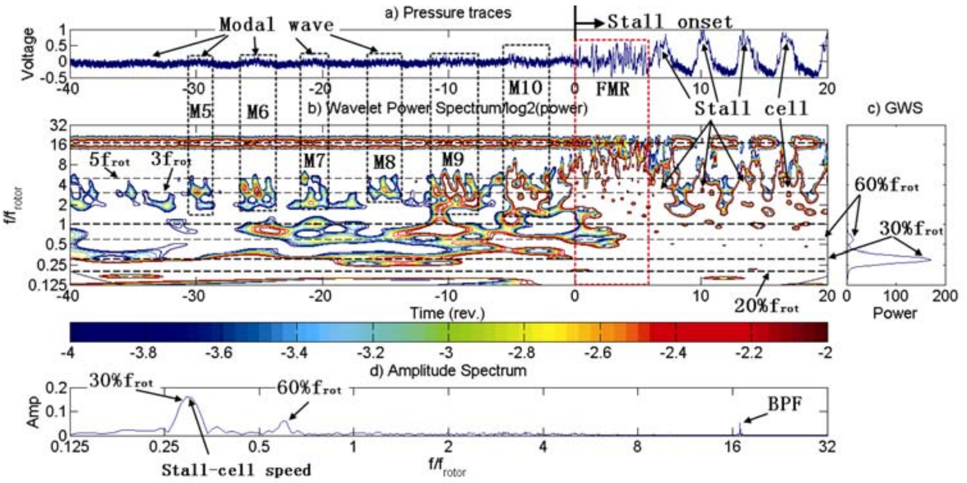

Fig. 8 Wavelet spectrum of the pressure trace throttling from unstall to full stall

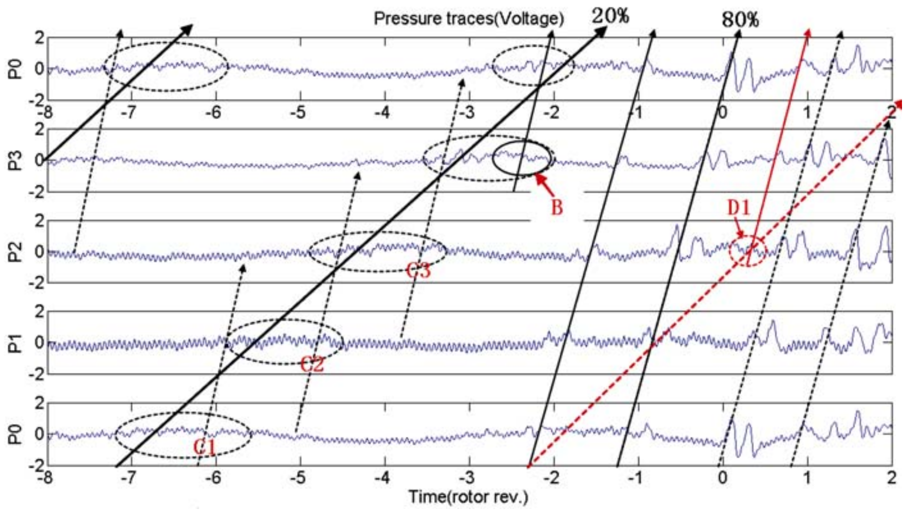

Fig. 9 Stall inceptions in LLAC (low-pass-filtered at 20frot)

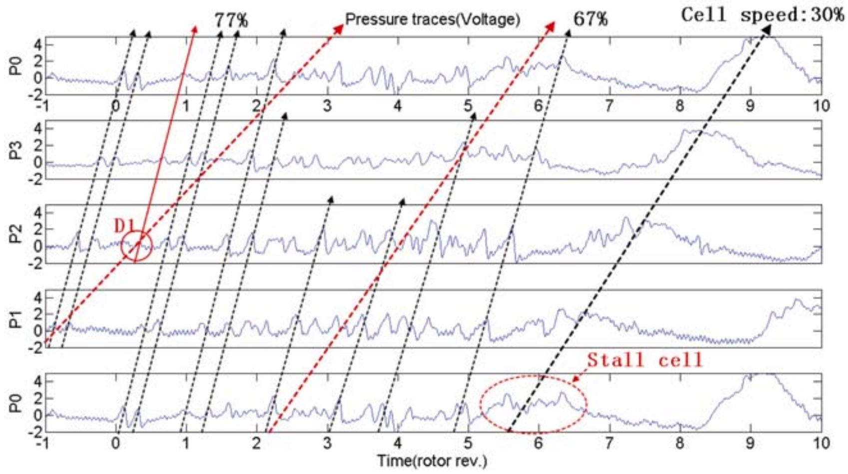

Fig. 10 Process of the stall-cell formation (low-pass-filtered at 20frot)

The propagation speed is about 20% rotating speed. At the peak of the modal wave, the intensity of the shaft-order-perturbation increases obviously, while it decays at the trough of the modal wave.

4. A shaft order perturbation aroused by modal-wave grows into stall inception in the pre-stall period. It propagates at a speed slightly lower than the rotor speed.

5. In the frequency mixing region, many disturbances are produced and increase in size and amplitude. These disturbances are merged into a large-scale stall-cell and the propagation speed is about 30% rotating speed. The modal stall is triggered by the modal wave rather than shaft order perturbation.

Acknowledgement

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