Aerospace Science and Technology 58 (2016) 467–479

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Using wavelets to study spike-type compressor rotating stall inception

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ARTICLE INFO

Article history:
Received 27 February 2016
Received in revised form 7 September 2016
Accepted 8 September 2016
Available online 14 September 2016

Keywords:
Rotating stall inception
Wavelet
Vanishing moment
Frequency-space resolution
Coherence

ABSTRACT

This paper demonstrates that the derivative of Gaussian wavelet with one vanishing moment can detect the final stable stall cell of the spike-type compressor rotating stall inception. The appearance of the final stable stall cell is estimated to lead the Lipschitz regularity of the transient casing wall pressure signal to be around 0.5. At the initial stage of spike-type stall inception, the detection of the weak rotating disturbances needs wavelets of high vanishing moments because the transient casing wall pressure signal is slightly disturbed. With wavelet of six vanishing moments, the appearance of the initial weak rotating disturbances is estimated to lead the Lipschitz regularity of transient casing wall pressure signal to be around 2. Wavelets that are well localized in frequency space can decompose the spike-type stall inception rotating disturbances into separated harmonics. Based on Morlet wavelet, the principle to select the suitable wavelet resolution in frequency space to distinguish the concerned fluctuation harmonics is established. The validity of this principle is verified and discussed in detail. According to this principle, the wavelet transform can also be used to identify the influential harmonics where most of the fluctuation power is concentrated. With wavelet coherence, the features of the main rotating disturbances, and details of their variance as the stall approaches can be tracked. Consequently, the detection of spike-type stall inception can be significantly brought forward through identifying the crucial pre-stall rotating disturbances for the onset of stall inception. The locations of the sensors are influential to the appropriate use of wavelet coherence. Compared with the wavelet transform results, the detection of rotating stall inception has been brought forward by wavelet coherence for more than 200 hundred revolutions.

1. Introduction

Rotating stall is one instability flow phenomenon that commonly happens in axial compressors and cannot be tolerated at normal operating conditions [25,28]. In general, rotating stall is preceded by a circumferentially propagating wave disturbance. For these circumferentially propagating waves, two stall-inception types are generally recognized. The first type is referred to as modal-type inception and the second type is referred to as spike-type inception. The characteristics of the modal-type stall inception can be well predicted by linearized stability analysis methods [25] and these theories have been experimentally tested already [10, 23]. An alternative more advanced approach to model the modal-type stall inception consists of using 2D Computational Fluid Dynamics (CFD) methodologies together with low-order blade row models e.g. actuator disks or blade force distributions [9]. Different from the modal-type inception, spike-type inception has the features of three-dimensionality, nonlinearity and short time duration [4,7,25], which are detrimental to pre-stall warning signal detection [28]. Nevertheless, numerous efforts have been spared to devise techniques for sensing the spike-type inception, and reviews of the existing techniques have been performed by Tan, Day, Morris and Wadia [28] as well as Cameron and Morris [3].

With the pressure or velocity traces, which were first used by Day [6], visual inspection on these signals can show the developments of rotating disturbances directly; this method remains essential to the study of stall inceptions. Spatial Fourier analysis was first used by McDougall, Cumpsty and Hynes [23] to study the modal-type stall inception. However, high spatial resolution is needed to capture the spike-type stall inceptions with this technique. Later, Tryfonidis, Etchevers, Paduano, Epstein and Hendricks [30] applied the traveling energy method to investigate the pre-stall behavior of high-speed compressors. This traveling energy method is an extension of spatial Fourier analysis and is useful in providing early warning of spike-type stall inception in high-speed compressors [7]. Other correlation analysis methods, including cor-

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http://dx.doi.org/10.1016/j.ast.2016.09.006
1270-9638/

relation measurements [8], and windowed space-time correlation [2] et al. are also very efficient in detecting early warnings of spike-type stall inception onsets. However, the mechanisms behind spike-type stall inception procedures still remain unclear.

As mentioned, stall inceptions are actually rotating disturbances, which have various characteristics, such as rotating speed, length, and time scales. In compressors, spike-type stall inceptions can be regarded as localized abrupt rotating disturbances to the flow field. Within the compressor transient experimental data, the abrupt rotating disturbances are shown as localized signal singularities. In time-frequency analysis, wavelet transform is commonly used for analyzing localized variations of power within a time series. By decomposing signals into elementary building blocks that are well localized both in space and frequency, the wavelet transform can characterize the local regularity of signals. This is the main advantage of wavelet transform over Fourier transform, which is global and provides a description of the overall regularity of signals [5,21]. Consequently, the application of Fourier transform is limited in compressor stall inception studies; thus, it is beneficial to study the variance of rotating disturbances with wavelet transform during the stall inception procedure.

Many researchers have already used wavelets to problems concerned with compressor rotating stall inceptions. Both Liao and Chen [18] and Lin [19,20] used the Morlet wavelet to perform the time-frequency analysis of stall inception in a low-speed axial compressor. Later, Salunkhe, Joseph and Pradeep [26] as well as Salunkhe and Pradeep [27] also applied Morlet wavelet to study the stall inception mechanisms in an axial flow fan. In both the work of Lin, Chen and Li [19] and Salunkhe and Pradeep [27], wavelet transform results of more than six dynamic pressure sensors are analyzed simultaneously in a similar way to the simple visual inspection method developed by Day [6]. According to their results, Morlet wavelet with a center frequency of 6 can detect the spike-type compressor rotating stall inception procedure, but no detailed discussion on selecting the proper wavelet properties is given. Inoue et al. [15–17] have applied the Mexican hat wavelet and one point-symmetrical wavelet to study both short and long length-scale rotating disturbances in a low-speed axial compressor. With the point-symmetrical wavelet, which has high resolution in time space, the moments rotating disturbances appear and the counts of each kind of rotating disturbances can be clearly identified, but time-frequency analysis is not performed with this point-symmetrical wavelet in their publications. Apart from the stall inception studies, Morlet wavelet with center frequency of 6 has also been adopted by [13,14] to study the rotating instability; this unsteady phenomenon has been recently recognized as an important factor that can influence the performance of axial compressors.

Although results of these research have proved the advantage of wavelets in studying compressor unsteady flow phenomena, the main ideas behind these applications of wavelets still come from other research fields, e.g. geophysics, where the physical process is very different from the compressor rotating stall inceptions [29]. In wavelet signal singularity detection studies, both vanishing moments and time-frequency resolution are crucial to obtain precise predictions. However, the influences of these two parameters have not received considerable attention in previous compressor stall inception research studying the rotating disturbances. For the complexity of flow structures inside the compressor, some rotating disturbances may be modulated; moreover, the harmonics of a rotating disturbance can sometimes be very influential to the compressor performance. Therefore, ensuring that the wavelet chosen could not only detect the rotating disturbances but also decompose them in frequency space is important. The characteristics of rotating disturbances are changing in time with the stall approaching; hence, the corresponding singularities aroused by these disturbances will behave as different regularities in the compressor experimental data. With wavelet vanishing moments and Lipschitz exponent, Mallat studied the method and theory to detect different kinds of signal singularities based on wavelet transform [21,22]. According to the theory of Mallat and Hwang [22], to ensure that the vanishing moments of the wavelet is sufficiently large to estimate the Lipschitz regularity of the signal is essential. Taken together, to further extend the application of wavelet transform in compressor stall inception studies, both the influences of wavelet vanishing moments and frequency-space resolution on compressor stall inception studies should be analyzed.

Wavelet coherence is another wavelet application that has received a lot of attention in time-frequency analysis. Although wavelet transform has been used in rotating stall inception studies since two decades ago, few experiments in compressors have applied wavelet coherence to analyze the unsteady flow phenomena in the internal flow field. Recently, Hermle and Lawerenz [13] used wavelet coherence to study the rotating instability in axial compressors. The results of wavelet transform and wavelet coherence are not always in accordance, which means that wavelet coherence can provide extra information on the unsteady flow structures. Previous compressor data analysis studies proved that application of signal correlation analysis is useful in earlier detection of stall inceptions, but few details about stall inception mechanisms can be obtained with the traditional signal correlation analysis. In frequency space, correlation analysis through calculation of the wavelet coherence can be employed at pre-stall phase to identify both the existence and development of rotating disturbances that will directly lead to the onset of stall inception. Applying the wavelet coherence as an implement to track the developments of those rotating disturbances during the stall inception procedure is beneficial for elucidating the mechanisms of spike-type compressor rotating stall inception with wavelets.

In this paper, signal singularity detection theory with wavelets is applied firstly to study the Lipschitz regularities of the transient casing wall pressure during spike-type compressor rotating stall inception procedure in a low-speed, large-scale axial compressor. Based on the experimental data, the Lipschitz regularities of the transient casing wall pressure at different stages of stall inception are estimated with proper wavelet vanishing moments. To further perfect the application of wavelet transform in compressor stall inception studies, the principle to select the suitable wavelet frequency-space resolution to decompose the detected rotating disturbances is then analyzed. At last, wavelet coherence is introduced to better elucidate the mechanisms behind spike-type compressor rotating stall inception and detect the initial pre-stall rotating disturbances. This study enables a wider scope for the application of wavelets in compressor stall inception studies.

2. Spike-type rotating stall inception of a low-speed axial compressor test

2.1. Test facility and measurement setup

The experimental data used in this paper were obtained in a low-speed large-scale axial compressor of Beihang University. The details of this compressor facility have been introduced by Yu and Liu [31] and Yu, Zhang and Liu [32]. The sketch of the low-speed large-scale axial compressor and sensor locations are shown in Fig. 1 and main parameters of the compressor are shown in Table 1. Transient casing wall pressure signal was measured at the leading edge of the rotor blade (plane 2 in Fig. 1). Four dynamic pressure sensors (Kulite XT-190M-5D) with a sampling frequency of 10 kHz were utilized and equally spaced 90° apart in the circumferential direction. All the wavelet transform results with the four sensors are slightly different, and wavelet transform results