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Comparison of Different Stall Conditions in Axial Flow Compressor Using Analytic Wavelet Transform

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Abstract **– The rotating stall inception data analysis using Analytic Wavelet Transform (AWT) in a low-speed axial compressor was presented in the authors' previous studies [1], [2]. These studies focused on the detection of instability inception in an axial flow compressor when it enters into the instability regime due to the modal type of stall perturbation. In this paper, the effectiveness of AWT is further studied by applying it under different testing conditions. In order to examine the results of AWT on highly sampled data, at first, the stall data were acquired at a high sampling frequency and the results were compared with the conventional filtered signals. Secondly, the AWT analysis of stall data was carried out for the condition when compressor experienced a spike type rotating stall disturbance. The stall inception information obtained from the AWT analysis was then compared with the commonly used stall detection techniques. The results show that AWT is equally beneficial for the diagnostic of compressor instability regardless of the data sampling rate and represents an outstanding ability to detect stall disturbance irrespective of the type of stall precursor, i.e. the modal wave or spike.**

Keywords **– Analytic Wavelet Transform (AWT), axial compressor, compressor instability, rotating stall, stall data.**

I. INTRODUCTION

Aerodynamic instability in compressors commonly known as a rotating stall is a well-known instability phenomenon in aero engines caused by flow separation in the compressor blade passage and circumferential rotation, which is referred to as a stall cell. In the past few decades, several studies were dedicated to compressor stall inception and its control methods [3]–[7]. Experimental diagnostic of rotating stall characteristics has always relied on signals acquired from the compressor flow field [8]–[10]. There is no standard for compressor stall data processing and nearly all classical and modern signal processing techniques possess limitations and drawbacks. On the other hand, experimental methods are quite standardized and conventionally include an array of circumferentially distributed pressure or velocity transducers through the casing at different axial locations in the flow passage as described by Day [7], McDougal [11] and Spakovszky [12].

Stall disturbances are embedded with rotor rotating frequencies, blade pass frequencies, and noise; it is, however, difficult to recognize them. Although several signal processing techniques have been introduced; however, low-pass filtering of time series signals is still the most common and fundamental method and was presented in the earlier studies of Day [7], Garnier [13] as well as in the modern studies [14]–[17]. Additionally, there is no standard for the selection of filter range; therefore, different low-pass filters may alter the stall event up to a number of revolutions as well as short time disturbances may also be filtered in selecting filter size. Lin [18] used continuous wavelet transform and gave useful information to explain the stall inception process; however, the description of rotating speeds was still challenging. Several studies [19]–[21] used wavelet filtering to further understand the physical mechanisms leading to rotating stall, but data filtering or denoising turned out to be an essential limitation of those studies as well.

In this study, different rotating stall conditions are studied by the application of AWT (Analytic Wavelet Transform). At first, a review of the previous results of [1] is presented. There the stall was caused by a modal type stall disturbance, which is the natural stall characteristics of the test compressor. Later, AWT was applied on the unfiltered raw signals, which manifested an outstanding comparison with the results of the filtered signals.

In the next step, two case studies are presented. At first, stall signals were sampled at a higher frequency (70 kHz), but no clear information of the stall precursor was experienced; however, the results of the AWT and filtered signals are identical. In the second case study, in order to get a clear picture, AWT was applied to the inlet distortion case of [2], where the compressor stall was caused by a spike type precursor. AWT successfully validated the results obtained from other filtering based techniques used for spike detection. The results demonstrate that AWT possesses a wide range of compressor instability diagnostic capabilities and can be used as a tool for flow related instability detection applications.

II. Experimental Test Facility and Instrumentation

Experiments were performed on the single stage low-speed axial compressor test facility of Beihang University, Beijing, China (BUAA). The schematic layout of the test facility and the detail of the components and measurement sections are given in Fig. 1. Unsteady pressure measurements were acquired by means of pressure transducers and a layout of the location of the transducers is illustrated in Fig. 2. The specifications of the compressor test facility and the details of the steady and unsteady instrumentations are demonstrated in [1]. Sampling frequency was set at 2 kHz for the experiments.

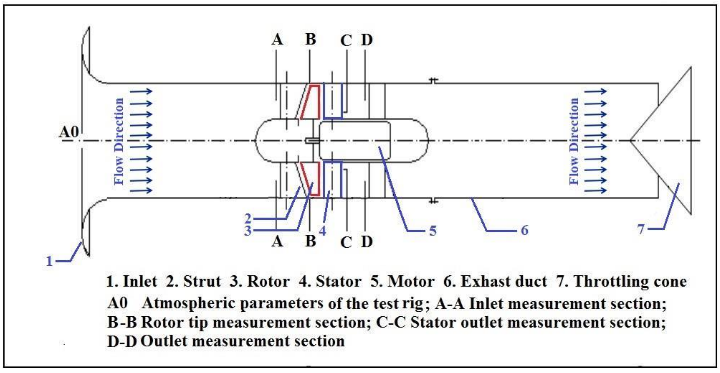

Fig. 1. Schematic of the low-speed compressor test facility.

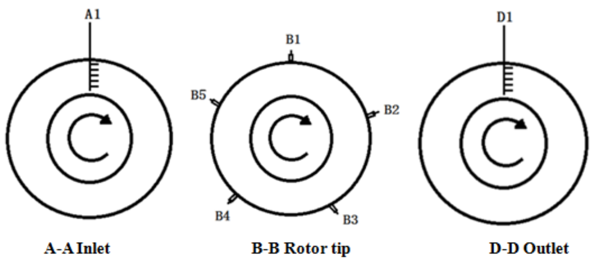

Fig. 2. Schematic cross-section of the instrumentation.

III. Review of the Previous Results

In the previous study [1], an AWT program was developed for the rotating stall inception analysis. Several low-pass FFT frequency filters were applied to the stall data; Fig. 3 indicates the signal filtering method where the stall disturbance frequency can be seen at the 17 Hz spectrum.

Fig. 4 shows the AWT spectrogram, which successfully compares the results of Fig. 3, i.e. without the application of any filters.

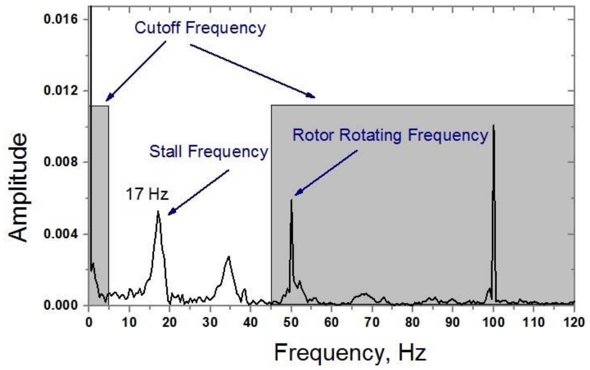

Fig. 3. FFT frequency filtering method (data sensor B1).

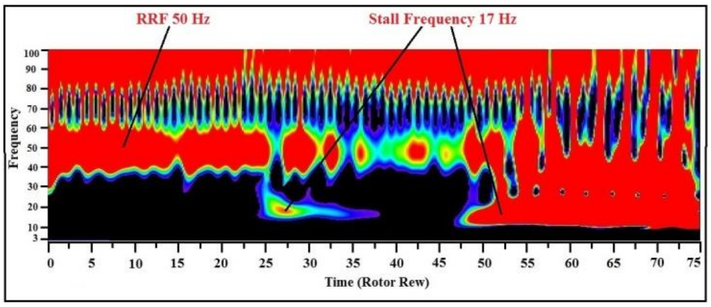

Fig. 4. AWT spectrogram (data sensor B1).

The AWT results were obtained on the unfiltered data of all the transducers. Fig. 5 illustrates the stall analysis results using 1 N low-pass filters while Figure 6 compares the results by the application of AWT and clearly demonstrates that the stall inception and modal wave rotating speeds can be obtained from the AWT spectrogram and results are almost identical to the results observed in the filtered traces. Thus, essential filtering limitations in stall inception studies can be eliminated by using AWT.

In order to increase precision in the stall analysis, it is also suggested that the filtered signal results can also be validated by the AWT analysis. It is necessary that the further applicability of AWT for the rotating stall analysis should be examined under different experimental conditions, especially when the rotating stall is caused by spike type perturbations. For this purpose, two case studies are presented in the next sections.

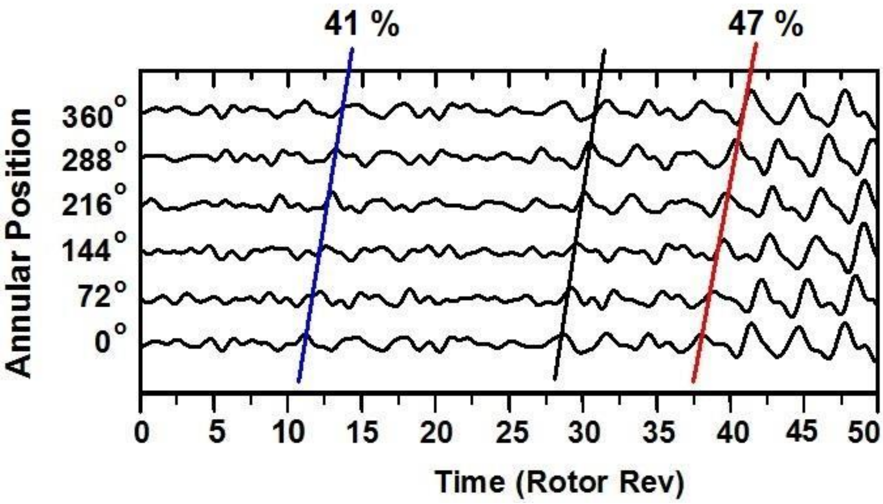

Fig. 5. Rotating speeds of stall disturbance and the stall cell (1N low-pass frequency filter, 50 Hz).

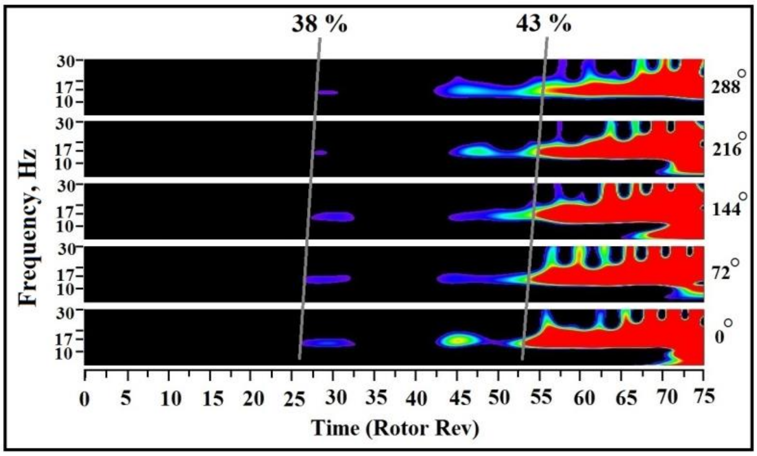

Fig. 6. Rotating speeds of stall disturbance and the stall cell (AWT analysis).

IV. Case Study-1: High Sampling Frequency Data Acquisition

AWT is especially suitable for the analysis of data sampled at higher rates. In high-speed test compressors, a higher sampling frequency is often selected. Due to the unavailability of experimental schedule at the high-speed test facility, experiments on the low-speed compressor facility were performed at higher sampling rate, i.e. 70 kHz.

Pressure signals of all the five transducers filtered at 1 N (50 Hz) are illustrated in terms of time traces in Fig. 7. As the data are acquired at a very high sampling rate, which is not suitable for this low-speed test compressor, no prominent stall disturbance is visible in the traces. Though it seems the compressor went through an abrupt spike disturbance before actually falling into stalled regime but it is unclear from the traces; however, the stall inception speed is clearly visible – approximately 52 % of the rotor speed is in the fully established stalled condition. The unfiltered signals from this experiment were further analyzed by using AWT. Fig. 8 illustrates the AWT spectrogram manifesting the identical results as that of the filtered traces with no visible or recognizable disturbance at 17 Hz of stall frequency before the establishment of the stall cell. The only visible spectrum in the spectrogram is of 50 Hz, which is the RRF (Rotor Rotating Frequency). The stall cell speed in the AWT analysis is calculated as 51 % of the rotor speed, which demonstrates the successful validation of the results from the filtered traces.

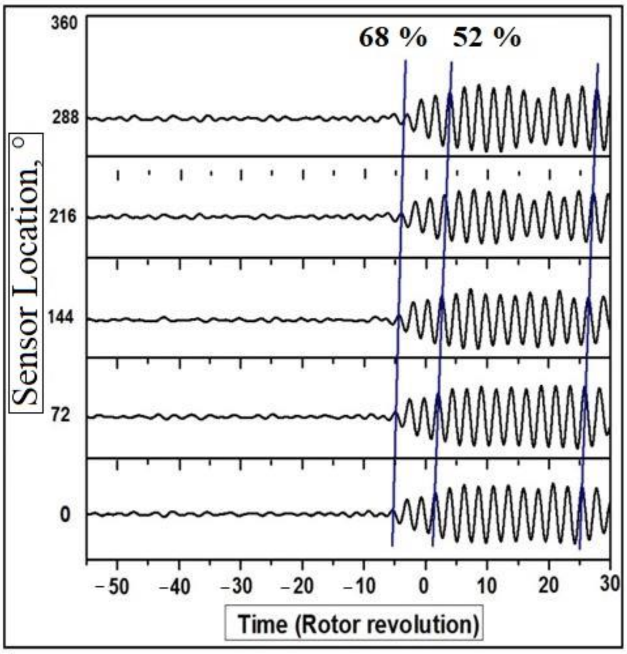

Fig. 7. Rotating stall analysis using 1N (50 Hz) low-pass frequency filter (case study-1).

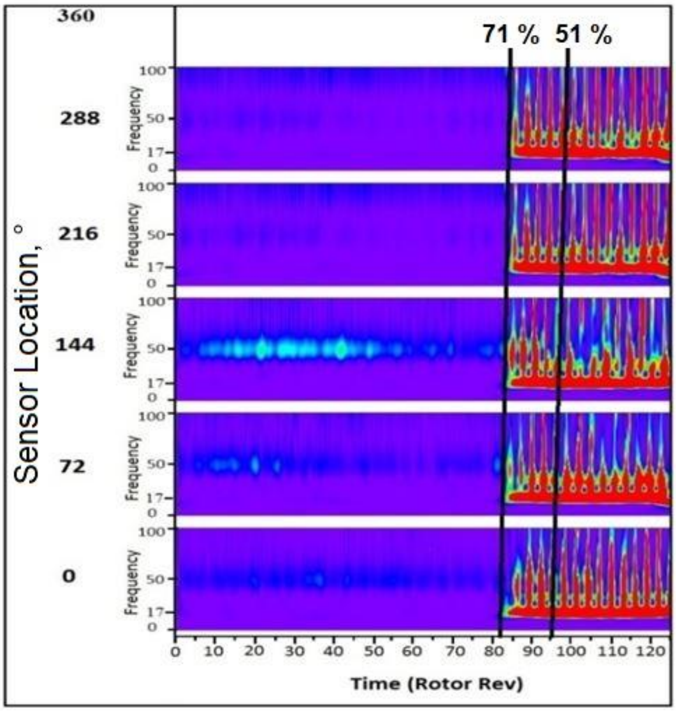

Fig. 8. Rotating stall analysis using AWT (case study-1).

The above results show that the AWT application for the rotating stall analysis is equally beneficial for all types of data sampled at any frequency. This also manifests that the stall analysis of the high-speed compressors can also be carried out by using AWT. AWT can provide a good comparison of the filtered signals. As seen in this case, there might be several reasons for losing the early stall perturbations; one reason can be due to the too high sampling frequency for the low-speed compressor while other probable reasons may involve the mixing of stall precursor with the overall stall cell, which makes it impossible to identify the type of perturbation. So far, AWT analysis is performed in the two cases of stall analysis, i.e. the modal type stall disturbance and high sampling rates. However, it is very important to study the effectiveness of AWT in a case when compressor undergoes the spike type stall precursor, which is studied in the next section.

V. Case Study-2: Spike Type Stall Detection

Authors have conducted several experiments on the test compressor with different inlet loading distributions in [2]. The precursor switching mechanism was observed when the loading distributions were altered and a spike type perturbation due to the higher tip loading was experienced. In all previous studies conducted by the authors, the compressor stall was observed because of the modal type stall disturbance. Hence, it would be a good idea to compare the spike results of [2] by applying AWT on the raw (unfiltered) signals in which spike was experienced. Fig. 9 illustrates the stall inception analysis of [2] by using db-5 Framelet analysis where the spike perturbation was observed at approximately 22nd revolution and at about 31st revolution a stall cell was developed in the system. The rotating speeds of spike and stall cell were determined as approximately 68 % and 34 % of the rotor speed respectively.

The AWT results on spectrogram are shown in Fig. 10. The AWT results are remarkably identical with the results of Fig. 9. The AWT spectrogram also identified the first stall disturbance which is a spike at about 22nd revolution while the stall cell is detected at approximately 31st revolution. Spike and stall cell rotating speeds, i.e. 64 % and 37 % of the rotor speed respectively, are also nearly identical to the results of Fig. 9. Therefore, in this case, the verification of stall analysis results by using filters could also be successfully established by means of AWT analysis without the application of any filters.

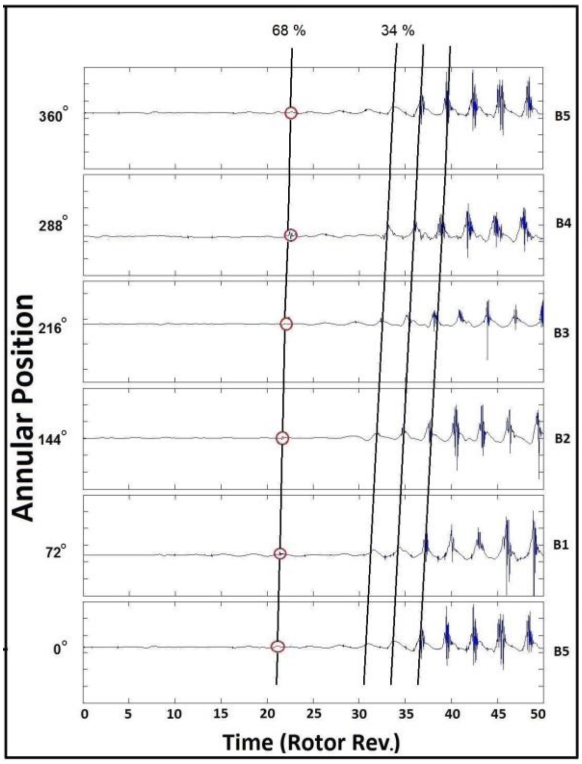

Fig. 9. Rotating stall analysis: spike disturbance (case study-2).

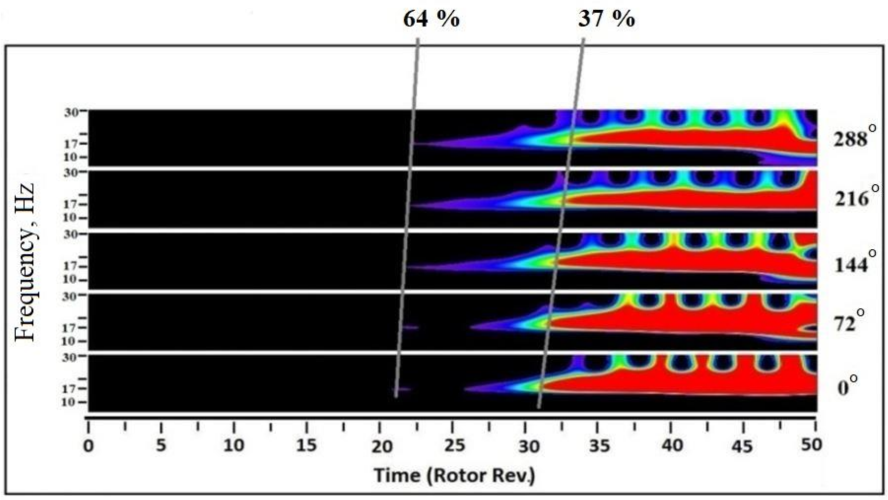

Fig. 10. Rotating stall analysis: AWT spike comparison (case study-2).

VI. Conclusion

After experiencing satisfactory results in the previous studies, the effectiveness of AWT in the rotating stall inception analysis was further explored in this study. The results show that AWT offers a useful tool for the future stall inception studies on low and high-speed compressors. The following conclusions can be drawn from this study:

1. AWT can be used for a wide range of flow instability problems where commonly used techniques have limitations and drawbacks.
2. Even though a direct identification of the type of stall perturbation cannot be drawn from the AWT analysis, but due to its sensitivity to diagnose very small disturbances in the flow, it is not hard to judge of the stall precursor type. As in the previous and current studies, stall inception events, modal and spike perturbations could be easily guessed by looking at the interval between the first stall disturbance and the stall cell where modal waves are seen tens

of revolutions prior to the stall cell (case study-1), while spikes are observed within 5 to 10 revolutions before the fully developed stall cell (case study-2).

3. AWT is valid for the data acquired at any sampling frequency.
4. It is suggested to verify flow instability problems, especially the rotating stall, by using AWT, which does not possess the prerequisition of data filtering.

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