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Study on Coherence of Composite Unsteady Aerodynamic Excitations and Response Imposed on Rotor Blade

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Abstract: In order to investigate the influences of unsteady aerodynamic excitations imposed on the blade, we focused on analyzing three atypical coherence functions between unsteady aerodynamic excitations and responses. By using the data obtained from single-stage low-speed axial compressor test rig and with coherence and partial coherence methods, we investigated the characteristics of three kinds of excitations and analyzed the coherence between excitation component and response signal. Our results indicated that coherence method could extract the response characteristics of the unsteady aerodynamic excitations and distinguish different influences on the blade. And with this method, we could conduct the quantitative analysis and ordering of each excitation component; rail excitation's influence on the blade concentrates in the higher frequencies, rotating stall' aerodynamic excitation concentrates in the low frequencies and the inlet distortion exists in both high and low frequencies. At the same time, we could use the partial coherence analysis to compare the characteristics of individual aerodynamic excitation and extract various factors existing in the mixed excitations, additionally, we could conduct quantitative analysis of each excitation's influence on the response when a variety of unsteady aerodynamic excitations coexisted.

Key words: Aerodynamic excitation, inlet distortion, rotating stall, trail excitation, coherence method

INTRODUCTION

Modern aircraft engine's structure design turns to be more high-speed and more lightweight and engine's fan and compressor's pneumatic pressure were significantly complicated which had an effect on its working reliability and safety, especially when the compressor blade was working, it was often forced to excite by inlet distortion, blade row trail flow field and rotor rotating. Predecessors have carried out several studies (Hsu and Wo, 1998; Durali and Kerrebrock, 1998). Due to the complexity of the research content, relevant research mostly focused on the form of excitation, such as pneumatic excitation force and there was also study considering the excitation force caused by air flow parameters along the circular blades of the non-uniform flow field (Weatherrill and Hassan, 1994; Caruthers and Dalton, 1993). Lecht and Weyer (1979) successfully converted pneumatic pressure into the unsteady periodic excitation force which simplified the excitation force calculation of the compressor blade (Lecht and Weyer, 1979). Hall and Verdon (1991) studied the trail excitation response of the blade row, setting up the prediction model of the gust response (Hall and Verdon, 1991). Nanjing University of Aeronautics and Astronautics further studied the relations between rotating stall, the distortion and the performance of the compressor (Hu, 2001) and got a lot of achievements; Beijing University of Aeronautics and Astronautics calculated the characteristics of flow field under the condition of the distortion and studied the relation between rotating stall and distortion, obtaining excellent results; Northwestern Polytechnical University studied the distortion excitation's effect on the response (Qiao and Caial, 2001).

Predecessors have achieved considerable results about compressor's various unsteady aerodynamic excitation and response characteristics, but it was necessary to take unsteady aerodynamic excitation and response into consideration at the same time. In terms of excitation response of blades, focusing on coherence problem of various unsteady aerodynamic excitation and response offered a solution for solving the problem.

Based on this consideration, this study took several main unsteady excitations and response into consideration uniformly, exploring the change law of its excitation response characteristics.

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BASIC CONCEPTS OF COHERENCE ANALYSIS

Coherence analysis is a method of studying and describing engineering's random variable in the frequency domain field and coherence function of two zero mean random variable is defined as(Chen and Li, 2007):

$$\gamma^{2xy}(f) = \frac{\left|S_{xy}(f)\right|^2}{S_{xx}(f)S_{yy}(f)} \quad (1)$$

In the equation, $0 \le ?^{2xy}(f) \le 1$, $S_{xx}(f)$ and $S_{yy}(f)$ are the auto-spectra of input and output, $S_{yy}(f)$ is the cross-spectra of input and output.

When there are multiple input and output, the partial coherence function can be defined as:

$$\gamma_{yj(1,2\cdots i)} = \frac{\gamma^{2}_{y(1,2\cdots j)} - \gamma^{2}_{y(1,2\cdots i)}}{1-\gamma^{2}_{y(1,2\cdots i)}} \quad (2)$$

where, ι = 1, 2, 3; j = 1, 2, 1; ι≠j

Cross-spectra (density function) and auto-spectrum (density function) are written as:

$$S_{xy}(f) = \int R_{xy}(t)e^{-j2pft}dt \quad (3)$$

$$S_{xx}(f) = \int R_{xx}(t)e^{-j2pft}dt \quad (4)$$

where, $S_{xx}(f)$ is referred to as auto-spectra density function of auto-spectra.

ANALYSIS OF DOMINANT UNSTEADY AERODYNAMIC EXCITATION AND RESPONSE OF ROTOR BLADE

Test data acquisition: The calculated data in this study was obtained from a single-stage low-speed axial compressor test rig. In this test, the compressor's rotor to stator hub ratio was 0.6, the number of front stator of rotor blades was 30 and the rotor speed was 1200 r min^{-1}. By installing dynamic pressure measurement sensor (LQ-125-5A) near the pneumatic interface of the entrance to the compressor (AIP), the dynamic stress condition of trail excitation, inlet distortion and rotating stall was measured and digitally recorded.

Test data analysis: The flow field pressure data acquired above was applied to the blade surface as the force boundary condition. The vibration of the blade was calculated and the characteristics of response were also analyzed. First of all, the unsteady aerodynamic excitation and response of data were analyzed by coherence method.

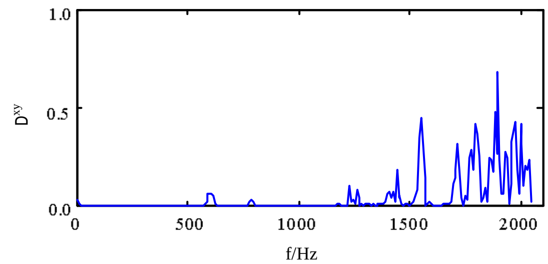

Fig. 1: Causality of coherence between trail excitation and response

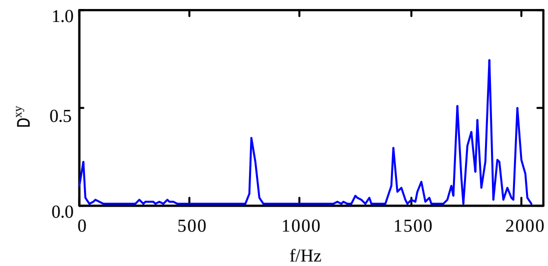

Fig. 2: Causality of coherence between inlet distortion and response

Figure 1 was a causality of coefficient resulted from the analysis of trail excitation and response data. As could be seen from the figure, the maximum coherence coefficient between trail excitation and response was 0.67, showing significant coherence property. And from the frequency of the spectra, the response of blade to trail excitation focused highly focused on the high-frequency portion of the above 1200Hz and there was no significant peak in the intermediate and low frequencies. It indicates that the trail excitation only has a high-frequency response to blade's excitation. According to energy contribution, the descending order were 1900, 1700, 2000, 1550 and 1200 Hz, respectively.

Figure 2 was the causality of coherence between inlet distortion and response. As can be seen from the figure, the maximum coherence between inlet distortion and response was 0.73, also showing significant coherence property. By analyzing the frequencies in the spectra, it can be concluded that the blade's response to inlet distortion not only exists at the high frequency of above 1000 Hz but also exists at 16 Hz of low frequency and 780 Hz of intermediate frequency. This suggests inlet distortion imposed on blade exists at both high frequency and low frequency. According to energy contribution, descending order was 1900, 1700, 2000, 780, 1400 and 16 Hz.

Figure 3 was the causality of coherence between rotating stall and response. As can be seen from the

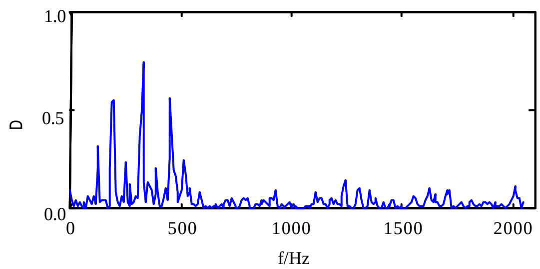

Fig. 3: Causality of coherence between rotating stall and response

figure, the maximum coherence between rotating stall and response was 0.75, indicating significant coherence. By analyzing the frequencies in the spectra, it can be concluded that blade's response to rotating stall merely exists at low frequency below 500 Hz and there was no peak at intermediate and high frequencies which indicates that the rotating stall's excitation at blade only has low-frequency response property. According to energy contribution, descending order was, respectively 330, 440, 190 and 128 Hz, indicating obvious frequency doubling.

CROSS CORRELATION ANALYSIS OF EXCITATION AND RESPONSE WHEN VARIOUS UNSTEADY AERODYNAMIC FORMS COEXIST

Firstly, we calculate the response when rotating stall and inlet distortion coexist and according to the definition of partial coherence function and formula (4), we perform the cross-correlation calculation on response signal with previous single rotating stall excitation signal and draw the diagram of cross-correlation and cross-spectra, as shown in Fig. 4.

According to the partial coherence Fig. 4a, when two kinds of unsteady excitation coexist, the blade response is remarkably coherent with the excitation signal of rotating stall (coherence coefficient is 0.73). In the diagram of spectra, the response of blade to rotating stall only exists in the low frequency and doesn't exist at the intermediate and high frequency. According to energy contribution, descending order was, respectively, 192, 330, 447 and 128 Hz. Compared with Fig. 3, two figures are very similar, so are spectra's frequencies. It can be inferred that rotating stall exists in the excitation.

Then, we performed partial coherence calculation on response signal of various excitations and made coherent coefficient diagram, as shown in Fig. 4b.

From Fig. 4b, it can be concluded that blade response has significant coherence (coherence coefficient is 0.67)

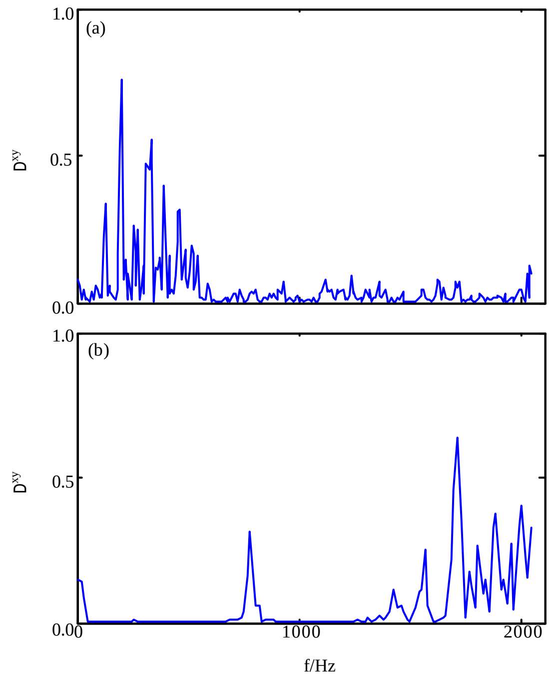

Fig. 4(a-b): Partial Coherence between excitation and response when the distortion and rotating stall coexist, (a) Rotating stall and (b) Inlet distortion

with the excitation signal of inlet distortion when the two kinds of unsteady excitation coexist. From the analysis of the spectra diagram, it can be concluded that peaks exist at both high and low frequencies and the peak of high frequency is lower than that of low frequency. Compared with Fig. 2, the spectra frequency of two figures is consistent with each other. According to energy contribution, descending order was, respectively, 1900, 1700, 2000, 780, 1400 and 16 Hz which is also consistent with the frequency property of Fig. 2. Therefore, inlet distortion exists in the excitations.

It can be found that the response of blade concentrates in the intermediate frequency of 600Hz when calculating blade response under multiple excitations. The reason for that is that 600Hz is inherent frequency of the blade, thus, the response of this frequency is the maximum and there's no significant peak in each causality of coherence. Then we perform partial coherence calculation on this response signal with previous single trail excitation and make the figure of partial coherence coefficient.

As can been seen from Fig. 5, blade response has no coherence with trail excitation because of low coherence coefficient (lower than 0.1). It can be determined that, trail excitation does not exist in the multiple signals.

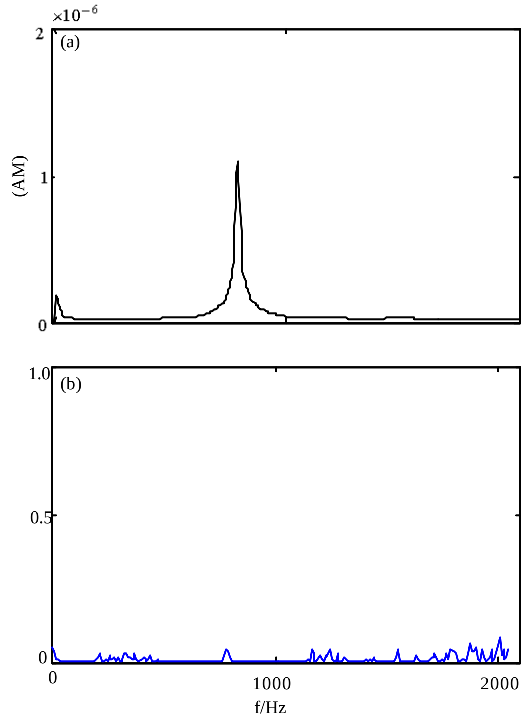

Fig. 5(a-b): Partial Coherence of response when the inlet distortion and rotating stall coexist, (a) Spectra of response and (b) Partial coherence between trail excitation and response

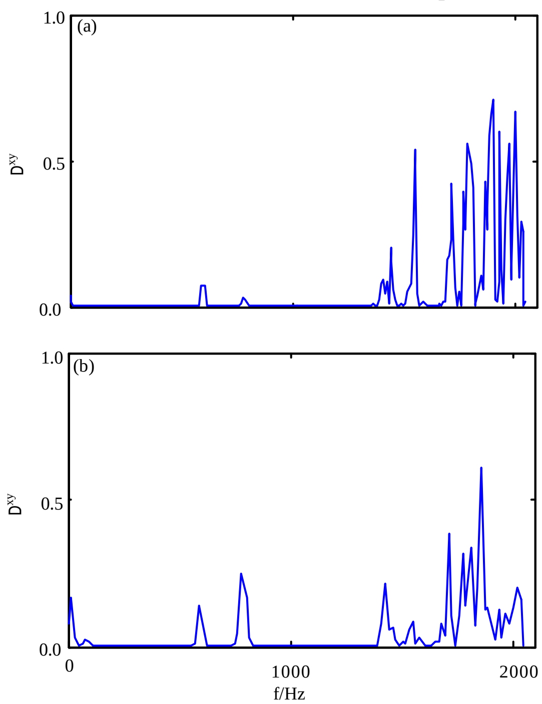

Fig. 6(a-b): Partial Coherence between excitation and response when the inlet distortion and trail excitation coexist, (a) Trail excitation and (b) Inlet distortion

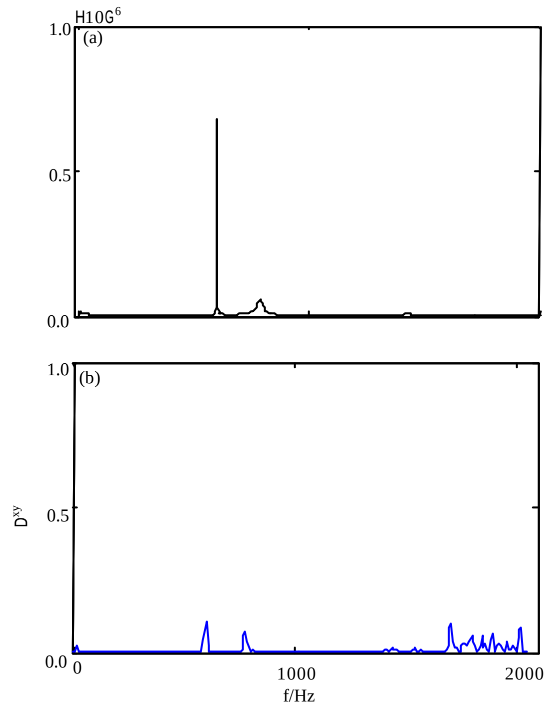

Fig. 7(a-b): Partial Coherence of response when the inlet distortion and trail excitation coexist, (a) Spectra of response and (b) Partial Coherence between rotating stall and response

After using the same method to calculate the blade response when the inlet distortion and trail excitation coexist, we perform partial coherence calculation on this response signal with previous single trail excitation and make the figure of partial coherence coefficient, as shown in Fig. 6.

Based on the analysis above, Fig. 6a shows that trail excitation exists in the composite excitations and Fig. 6b shows that inlet distortion exists in the composite excitation. However, Fig. 7 shows that rotating stall does not exist in the composite excitations.

First of all, we calculate the response when the rotating stall and trail excitation coexist, then we perform partial coherence calculation on this response signal with previous single excitation signal and finally make the figure of partial coherence coefficient, as shown in Fig. 8.

Comparing Fig. 1 with 3 and based on Fig. 8a and b, it can be concluded that rotating stall and trail excitation coexist in the composite excitations. Additionally, there is no inlet distortion existing in multiple excitations signal in terms of Fig. 9.

According to the analysis above, when multiple unsteady aerodynamic excitations coexist, using partial

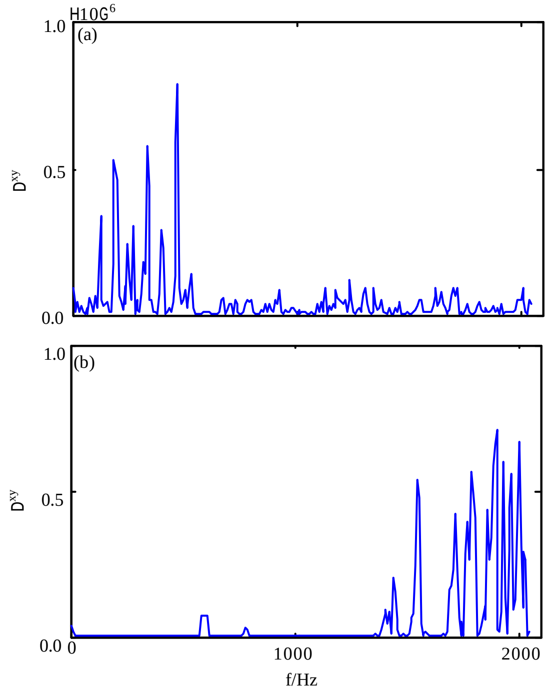

Fig. 8(a-b): Partial Coherence between excitation and response when the rotating stall and trail excitation coexist, (a) Rotating stall and (b) Trail excitation

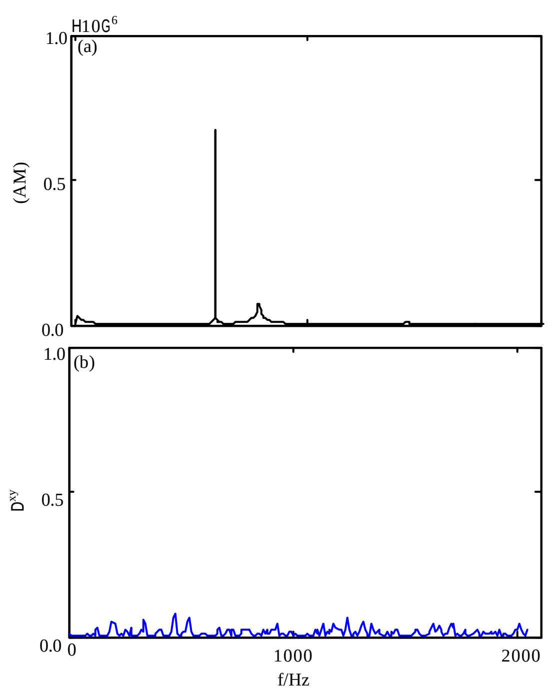

Fig. 9(a-b): Partial Coherence of response when the trail excitation and rotating stall coexist, (a) Spectra of response and (b) Partial Coherence between inlet distortion and response

coherence method, we can reach a favorable result of the existence of different excitation factor and quantitatively analysis and ordering of the frequency of components in the excitations. As a result, since cross-correlation method only can qualitatively analyze the existence of excitations, coherence method has the advantage of quantitative analysis.

CONLUSION

By analyzing the test data obtained from main aerodynamic excitations imposed on compressor blade and calculating blade's response and coherence function when multiple unsteady aerodynamic excitations coexist, conclusions are obtained as follows:

- Coherence method can extract response characteristics of unsteady aerodynamic excitations, distinguish effects of different forms of excitations on the blade and order and quantitatively analyze excitations components according to the energy contribution
- Trail excitation's effect on blade concentrates in the higher frequencies (above 1 KHz) and the amplitude of low frequency is low. While the blade's response to rotating stall concentrates in the low frequencies and inlet distortion excitation imposed on blade exists in both high and low frequency region
- When multiple unsteady aerodynamic excitations coexist, we take advantage of partial coherence between excitations and response signals and compare the characteristics of various signals of unsteady aerodynamic excitations, then extract individual excitation signal existing in multiple excitations and eventually sort the excitation components according to the results of quantitative analysis
- For each aerodynamic excitation, the blade response's characteristics remain constant when multiple unsteady aerodynamic excitations coexist

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