Visualisation of Unsteady Flow Field in an Axial Flow Fan

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Abstract

An unsteady flow field with rotating stall cells in an axial flow fan has been investigated experimentally. In order to capture the behaviour of the rotating stall cell, measurements of the flow field at the rotor inlet and velocity field within the rotor blade passage at an 80 % span were carried out with the PIV system. Those data were processed by so-called “phase-locked averaging” technique, which enabled to capture the flow field of the rotating stall cell in the reference co-ordinate system fixed to the rotor. As a result, a sequence of 18 images was composed at the three different flow rates and the behaviour of the rotating stall cell has been analysed.

1. Introduction

In everyday operation the turbo-machinery is not only used in its design point, however, significantly lower flow rates may take place especially when the pressure losses within the system increase. Although small to moderate flow rate reductions do not change the operational characteristic much they may influence the stability of turbomachinery which is demonstrated as a rotating stall, a characteristic flow instability of axial and centrifugal compressors and fans at reduced flow rates [1]. This instability plays a prominent role as a precursory phenomenon of a surge which deteriorates operational characteristics severely and may even damage compressor blades [2, 3]. Day [4] proved by hot wire measurements that rotating stall originates in the instability of a local structure within the compressor’s cascade-flow. This forms one or more rotating stall cells rotating in a circumferential direction at a fraction of the rotor speed [5].

Rotating stall has been investigated over several decades via both analytical and experimental methods. Most of the experimental investigations based on velocity and pressure measurements have used hot-wire [4, 6] or multi-hole pressure probes [2]. Their results verified the periodicity of the rotating stall cell. Hara et al. [2] and Shiomi et al. [6] processed their experimental results with the double phase-locked averaging technique, which allowed for predicting the velocity and pressure fields at the compressor’s inflow and outflow cross-sections, respectively [6] and made the capture of a rotating stall cell and its propagation within the compressor inflow section possible. However, the spatial distribution was low and the averaged results were limited to the non-rotating section of the compressor and the flow structures within the rotor blade rows (passages) remained hidden.

The purpose of this investigation was a visualisation of a flow field within the rotor blade passage of an axial flow fan.
fan operating under rotating stall conditions. Three different operating (OP) points under rotating stall conditions were analysed. A PIV system was used to capture the velocity field at an 80% span of the rotor blade. The Particle Image Velocimetry (PIV) triggering was synchronized with the observed blades’ passing, and obtained PIV images were then phase-locked averaged, and a sequence of 18 images was composed.

2. Experimental set-up

2.1. Fan geometry and instrumentation

Experimental investigations were performed on a test rig. The test rig was built according to ISO 5801:2007 [7] and comprised an inflow section, an axial fan and an outflow section. A transparent duct (\(D_{in} = 290\) mm) formed the fan’s outer casing and extended 1000 mm into the inflow section. Coaxially, an inner cylinder, the diameter of which corresponded to the fan’s hub diameter, was inserted so as to straighten the flow-field ahead of the fan in the axial direction. An axial flow fan was used without a stator and inlet guide vane. The rotor has comprised 10 blades with a NACA 65 profile. The chord length and stagger angle were constant and did not change with the span. The rotor drive was hub-mounted, and the three-phase electromotor rotated the rotor at 1470 rpm. Detailed fan geometry specifications are summarized in Table 1. The outflow section was made of a 2000 mm long duct (\(D_{in} = 290\) mm). It ended with a movable lattice that was used as a flow throttle.

2.1. PIV system

The Dantec low-speed PIV (Particle Image Velocimetry) system was used to capture the flow-field within the blade passage and at the rotor entry (Figure 1). The maximum system operating frequency was 4.5 Hz. A camera and laser were placed on a lightweight traverse system originally used for LDA measurements. A two-cavity Nd: YAG laser was used, operating at high power with 50 mJ pulse energy.

A fog-generator was used for seeding in order to produce seeding particles with average diameters of 1 \(\mu\)m. The laser was placed upstream at ca. 1000 mm from the rotor. A CCD camera with 1280×1024 pixels resolution was used, and the area covered was ca. 81×65 mm. The time-interval between the laser pulses was 20 \(\mu\)s, and 32×32 pixel-size interrogation areas were used for velocity calculation. Cross-correlation and adaptive correlation were used, both with 25% overlaps.

The blade passage velocity fields were measured within the axial-circumferential plane at 80% of the rotor blade span (Figure 2).

The captured area covered the whole blade passage and extended approximately 20 mm into the fan entry. A signal relating to the stall cell propagation was needed in order to utilise the phase-locked averaging technique. A signal from the pressure transducer measuring the dynamic pressure 10 mm upstream of the rotor’s leading edge (Figure 2) was used for this purpose. The output of the photo-encoder mounted on the rotor shaft was used to trigger the PIV system, and the 2-D

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Table 1: Design parameters of the test fan

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of blade</td>
<td>10</td>
</tr>
<tr>
<td>Casing radius</td>
<td>145 mm</td>
</tr>
<tr>
<td>Hub radius</td>
<td>92.5 mm</td>
</tr>
<tr>
<td>Chord length</td>
<td>80 mm</td>
</tr>
<tr>
<td>Tip clearance</td>
<td>2.5 mm (constant)</td>
</tr>
<tr>
<td>Blade profile</td>
<td>NACA 6508</td>
</tr>
<tr>
<td>Stager angle</td>
<td>45°</td>
</tr>
<tr>
<td>Hub/Tip ratio</td>
<td>0.65</td>
</tr>
<tr>
<td>Rotation speed</td>
<td>1470 rpm</td>
</tr>
</tbody>
</table>

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Figure 1: Schematic view of the PIV
3. Results and discussion

3.1. Overall characteristic of the test fan

The overall fan performance was measured and is presented in Figure 3. It was obtained by moving the exit lattice from fully opened to almost closed, and measuring the pressure rise and fan flow rate. The fan design point DP was located in the middle of the stable region at flow coefficient $\phi = 0.32$ and pressure rise coefficient $\psi = 0.325$. When the flow was reduced below the design point, the pressure rise coefficient $\psi$ increased until reaching the stall point E. Below this point, a discontinuity occurs, and the operating point is suddenly moved to point G. Further flow reduction is accompanied by continuous pressure rise decrease towards points G, H and I, where the fan surge starts. With the increase of the exit lattice opening, the flow and pressure rise increased, and the fan’s performance characteristic started moving back, crossed points H and G and reached point F, where the second discontinuity occurred, and the operating point moved suddenly into a stable region (point C). Characteristic hysteresis was formed in this way, as reported by [8]. The region between the operating points F and H formed the rotating stall region, which was experimentally investigated.

3.2. Simple averaging

PIV measurements were performed at operating points A, B, D, F, G, H and I. Around one hundred and sixty PIV images of the same blade passage were made for each operational point. The results were averaged without phase-locking during the first step. The results obtained at six characteristic operating points are presented in Figure 4. No flow separation from the suction side of the rotor blade took place at operating point A and D. At operating points F, G and H, the conditions seemed similar, although the rotating stall was presented; however, any unsteadiness was smoothed by the averaging process and the rotating stall remained hidden. Due to the surge, the blade passage was severely blocked at operating point I most of the time, and averaging intensified these conditions even more. At this point, we can conclude that simple averaging does not ensure any realistic results when flow unsteadiness, such as rotating stall, is presented. The smoothing effect erases any low amplitude flow fluctuation.

Figure 5 presents relative velocity’s standard deviation fields within the blade passage at 80 % span. The standard deviation of velocity is within the range between 0 and 1 m/s under normal-flow conditions (operating points A and D). At the operating points, where the rotating stall was detected, the standard deviation increases significantly. It reaches its maximum of 9.5 m/s at the operating point G, where the oscillations in relative velocity between normal flow and rotating stall cell were the greatest. At the operating point I, where surge occurs, the relative velocity’s standard deviation in comparison to the rotating stall is reduced to around 4 m/s.

3.3. Phase–locked averaging

When rotating stall occurs, the flow pattern within a blade passage alternates between a through flow and a backflow. If only one rotating stall cell exists, two domains can be observed: normal-flow and rotating stall cell. Whilst in the normal-flow domain the through flow...
Figure 4: Averaged relative velocity fields within the observed blade passage at 80% span (every tenth vector is shown) – operating points (OP) A, D, F, G, H and I

d) $\varphi = 0.18$ – OP G
e) $\varphi = 0.14$ – OP H
f) $\varphi = 0.09$ – OP I

Figure 5: Relative velocity’s standard deviation fields within the blade passage at 80% span – operating points A, D, F, G, H and I

g) $\varphi = 0.28$ – OP A
h) $\varphi = 0.24$ – OP D
i) $\varphi = 0.19$ – OP F
j) $\varphi = 0.18$ – OP G
k) $\varphi = 0.14$ – OP H
l) $\varphi = 0.09$ – OP I
Table 2: The frequency of the rotating stall reference signal

<table>
<thead>
<tr>
<th>Operating point</th>
<th>Flow coefficient $\varphi$</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>0.19</td>
<td>15.8</td>
</tr>
<tr>
<td>G</td>
<td>0.15</td>
<td>14.8</td>
</tr>
<tr>
<td>H</td>
<td>0.14</td>
<td>14.8</td>
</tr>
</tbody>
</table>

Figure 6: Raw rotating stall reference signal, generated sine-wave signal, and the PIV system trigger signal – operating point F

Figure 7: The sequence of averaged velocities along the averaging line before and after sorting – operating point F

prevails, the back flow is locally present in a domain of the rotating stall cell. This alternation between the through flow and back flow may simply be observed as a dynamic pressure variation ahead of the rotor which can be used as a rotating stall reference signal when performing phase-locked averaging.

It was obvious from our previous research that the rotating stall cell formed at the tip of the rotor; therefore, a small twin-tube probe with a total pressure tap in front and a static pressure tap at the back was inserted 10 mm from the fan tip and 20 mm deep from the outer casing (Figure 2). Figure 6 shows the dynamic pressure signal from the twin-tube probe. Its periodic shape allowed for the assumption that the rotating cell propagates at a constant speed. For different operating points the FFT procedure was applied to obtain the characteristic reference signal frequency. The results are presented in Table 2. The stall cell frequency depended on the flow coefficient. At the operating point H and G, the frequency of the rotating stall cell was 14.8, which is 60% of the rotor rotational frequency. With increasing flow-rate, the rotating stall cell speed increased by up to 65% of the rotor speed (operating point F) and with further-flow increase the rotating stall cell decayed (operating point C), whilst the reference signal frequency equaled the rotor frequency. Below operating point H no characteristic frequency was detected. It indicated the rotating stall transformed into surge (operating point I).

The phase-locked averaging was applied for the fan’s operating points, where the rotating stall cell frequency was obtained. A special focus was on the operating point F, where the shape of the raw rotating reference signal was the most periodic among all operating points with the rotating stall. At that operating point F additional PIV images were obtained, and the final number of processed images was 1020. Acquired raw rotating stall signal was not appropriated for the averaging process, therefore a simple sine-wave signal was used instead. A sine-wave signal with amplitude of 0.5 V was generated using the characteristic frequency $f_{\text{ref}}$ of the raw rotating stall reference signal. It can be represented by a simple time–dependent function as:

$$f_{\text{sw}}(t) = 0.5 \cdot \sin(2\pi f_{\text{ref}} t + 1)$$  \hspace{1cm} (1)

The quality of describing raw rotating stall reference signal with generated sine-wave signal depended on the operating point. The generated sine-wave signal for operating point F is presented in Figure 6.

It fits the general periodic form of the reference rotating signal well. When the flow was reduced below the operating point F, towards points G and H, the periodicity of raw reference signal with sin-wave signal dropped. Consequently, the quality of phase-locked averaging procedure was reduced. The PIV trigger signal is also presented in Figure 6. The PIV system operated at a 2.7 Hz frequency, thus approximately every sixth
passing of the rotating stall cell was captured; however, the captures were not synchronized with the rotating stall position. In order to obtain phase-locked averaging, every single PIV image had to be correctly sorted according to the rotating stall cell position. This sorting was performed by a simple procedure. The time-delay ($\Delta t_r$) between the trigger point and the nearest point, in a positive time direction, where the increasing sine-wave crosses value of 0.5 was first found for each PIV image. Then the angular position of the PIV image in respect to the rotating stall cell position was assigned, and finally the images were sorted in respect of their angular positions from the minimum to maximum values.

To test the effectiveness of the sorting procedure, an averaging line in the measurement plane perpendicular to the blade chord (Figure 2) was drawn. For each PIV image the average velocity along this line was calculated. Figure 7 presents the sequence of averaged velocities before and after sorting at the operating point F, proving that the images were successfully sorted.

The next step of phase-locked averaging was the averaging of previously averaged velocities along line. It was performed within constant 20° angular steps and resulted in 18 consecutively averaged velocities. The averaging minimized the velocity fluctuations, which can be seen in Figures 7b and 8, respectively.

The domains of normal-flow and rotating stall cell (RSC) are clearly distinctive. The rotating stall cell at the operating point F occupied approximately 40% of the rotor circumference. Figure 9 presents that at operating point G and H approximately 70% and 90% have been occupied by rotating stall cell, respectively. The averaged velocities dropped significantly within this region. Their fluctuations were extremely high at the operating point F. With the flow reduction towards operating point G and H, the fluctuation became lower.

The last step of phase-locked averaging was the averaging of sorted PIV images. It was performed within constant 20° angular steps, and resulted in 18 consecutively averaged PIV images. Only two characteristic relative velocity fields (images at 0° and 200°) within the blade passage at 80% span for all three operating points with the rotating stall cell are presented in Figure 9. Each velocity vector represents relative velocity, i.e. absolute measured velocity reduces by a circumferential one. In this way, the representation of the flow around the rotating fan’s blade is much more adequate. Images with angular position 0° represent the blade passage flow under normal-flow conditions. The flow entirely follows the contour of the suction side of the rotor blade and no swirls are shown in the flow fields. Images with angular position 200° represent the rotating stall cell passing the observed blade passage. At the operating point F the swirl is due to the averaging process small and it exists only at the trailing edge. When the flow is reduced towards the operating point G and H, the averaged swirl increases, the flow separation point is moved to 40% and 50% of a chord length, respectively. The whole intake domain is blocked (axial velocity component is 0).

4. Conclusions

This paper has presented the visualization of flow in an axial flow fan under the unstable aerodynamic condition. The PIV measurement system was used to capture velocity flow fields within rotor blade passage. A FPGA chip was used to trigger the PIV measurement system corresponding to the blade passing reference signal. This enabled the same blade passage to be captured at a desired instant. The measured velocity fields were simply averaged first, which gave a totally unrealistic impression of the flow structure within the blade passage. The influence of the presence of rotating stall was only noticed with a slight velocity reduction and only a highly unstable surge flow operation regime was detected. Analysis of relative velocity’s standard deviation fields within blade passage showed the possibility of detecting significant fluid flow changes.
when influenced by rotating stall cell. The intensity graphs showed that the standard deviation increases significantly under rotating stall conditions. Although the relative velocity’s standard deviation improved the understanding of flow patterns within the blade passage, it could not be used for flow animation of the rotating stall cell. With the dynamic pressure measurements at the rotor tip the rotating stall cell frequencies were detected. This made possible the phase-locked averaging of PIV measured velocity fields. Sequences of averaged velocities along chosen line were composed, presenting a flow field changing over 20° steps. The domains of normal-flow and rotating stall cell were clearly distinctive. With the flow reduction, the domain of rotating stall cell became larger. Sequences of images were also composed. Two characteristic images (0° and 200°) presents the blade passage flow under normal-flow and rotating stall cell conditions, respectively.

References


