Investigation of Vortex-Induced Vibration for a Flexible Compressor Blade using Time-Resolved Stereo PIV

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ABSTRACT

Stereoscopic particle imaging velocimetry (Stereo PIV) was utilized to investigate the velocity field and flow structure of a single flexible compressor blade around the wing tip as the angle of attack increased from AOA=0° to AOA=12°. Vortex-induced vibration of blade relieves the deviation of wake central line and reduces the velocity loss of mean streamwise velocity at AOA=10° & 12° in the section of H=145mm. Moreover, the blade vibration greatly strengthens the turbulence intensity of velocity field in the near wake. The transformation of vortex structure due to the self-excited vibration of blade leads to these changes of velocity characteristic. In the results of flow visualization and $\Lambda$, a single vortex street with clockwise sense emerges at AOA=4° & 6° and breaks down at AOA≈8°. When vortex-induced vibration of blade model occurs at AOA=10°, many of tiny coherent vortexes form inside the wing tip vortex. At the same time, a new dual vortex street composed by opposite-sign vortex pair replaces the single vortex street in the near weak.

1. Introduction

Vortex-induced vibration in compressors and turbines could lead to the high cycle fatigue structural failure of blades. Investigation of this phenomenon always accompanies the development of the aircraft gas turbine engine (Shannon J F, 1945, Pearson H, 1953 & Bendiksen O, Kiellb R E, Hall K C, 2010). Three aeroelastic problems have been summarized as below: flutter, forced response, and non-synchronous vibrations. For stator blades, upstream flow distortions lead to vibrate or self-vortexes induce the vibration (flutter). As a result, these sources are more difficult to model and their effects are not as well understood.

In order to duplicate the blades interaction in a compressor, some simplified cascades have been built up in experiments. A flutter lab module with four blades rigidly fixed at the two extremities and eleven central blades elastically suspended around a predefined torsion axis has been developed by Lucio M, Bergmans J, Vogt D et al (2015). The stiffness and damping of the blades
can be varied by the free-length of the flat springs. For a certain flow condition, the blades have an adjustable damping and thus be easy to flutter. Except simplified cascades, Mikrut P L (2012) investigated the unsteady fluid-structure interactions an isolated compressor blade cantilevered with an end-wall in transonic flow. Although a single vibrating blade has much simpler boundary conditions than those for a vibrating cascade, Mikrut P L claimed that simple setup could provide a direct interpretation of the fundamental physics.

In our experiment, we are interested in vortex-induced vibration of blade and its effect on the velocity field in the near wake. So a single flexible blade made by PMMA is applied in Stereo PIV measurements. Mean velocity and turbulence intensity have been discussed in the article. The results of vortex structure reveal transformation of vortex structure due to the vortex-induced vibration of blade leading to the changes of velocity characteristics in the near wake.

2. Experimental setup and method

In order to investigate the flow structure of self-excited vibrating blade, time-resolved velocity field in the near wake of a flexible compressor blade was obtained by Stereoscopic Particle Image Velocimetry (Stereo-PIV) in different sections along the span-wise direction in a low speed wind tunnel. The working section of the wind tunnel is 0.2m wide, 0.2m deep and 0.5m long. The free stream velocity can be adjusted in the range of 0~30.0 m/s automatically. The turbulence intensity of the free stream velocity is less than 1.0%. The positions of experimental model and Stereo-PIV system are presented in Fig. 1.

Flow fields in the near wake were measured in the spanwise sections of 125mm≤H≤155mm (span length L=150mm) and at the angles of attach of 0°≤AOA≤12° with the Reynold number of Re=3×10^4 based on the chord length (CC=40mm). For the thin blade model with a thickness of θ/CC=6%, the phenomenon of vortex-induced vibration appears at AOA=10° and 12°. In the
experiments, the origin point of rectangular coordinate system is set in the middle of blade profile when the free stream velocity is $U_\infty=0$ without blade deformation. X axis points to the same direction as the uniform flow and Y axis is vertical to the flow as shown in Fig. 2.

![Fig. 2 Rectangular coordinate system (top view)](image)

In order to eliminate the disturbance of shear layer vorticity on vortex structure analysis, $\Lambda_\omega$ defined as eq. 1 (Zhou J, Adrian R J, Balachandar S et al, 1999) is applied in vortex identification. Here, $\hat{\omega}_i$ is the imaginary portion of the complex eigenvalue of the local velocity gradient tensor, and $|\nabla \omega|$ shows that $\Lambda_\omega$ has the same sign as the local vorticity $\omega$. The method of vortex identification based on $\Lambda_\omega$ is frame independent, so that the problem to correctly select a reference frame is avoided. Moreover, some regions could be removed automatically which contain vorticity but do not have any local swirling motion such as shear layer(Pan C, Wang J J, He G S, 2012).

$$\Lambda_\omega = \hat{\omega}_i \frac{\omega_i}{|\nabla \omega|}. \quad (1)$$

3. Characteristic of velocity field

3.1 Mean streamwise velocity

In preliminary data processing, statistical characteristic of the velocity field was calculated. Fig.3 shows mean streamwise velocity profiles at different spanwise sections. When the laser layer illuminates the section of $H=125\text{mm}$, large velocity loss is apparent in the area of $x/CC<2$ close to the blade as shown in Fig. 3(a) which increases quickly with the angle of attack. The valley position moves to the side of negative Y along the streamwise direction. If a line is applied to connect these valley positions, there is an obvious deviation angle between the connecting line and horizontal line. For a two-dimensional rigid airfoil, when the angle of attack increases, the stream flows over the airfoil and deviates from the horizontal line. So the wake central line inclines to the side of negative Y. And the deviation angle increases with the angle of attack before flow separation. When the laser layer moves to the section of $H=135\text{mm}$, Fig 3(b) exhibits...
that velocity loss is reduced greatly compared with that in the section of H=125mm, but the deviation angle is still large.

![Graphs showing mean streamwise velocity profiles for different sections](image)

**Fig.3** Mean streamwise velocity profile

In the section of H=145mm, velocity loss is quite small in the area near the blade model (x/CC<2) in Fig. 3(c) especially compared with that in the section of H=125mm in Fig. 3(a). While, the large velocity loss emerges in 3≤x/CC≤4.5. As the angle of attack increases, the flexible blade model has larger deformation toward to the suction side in the section of H=145mm where it is close to the wing tip. So all valley positions in velocity profiles move towards to the positive Y direction. The deviation angle of the wake central line decreases...
extremely compared with those in the sections of H=125mm & H=135mm. Moreover, the deviation angle and valley value increase gradually with the angle of attack in the range of 0°≤AOA≤8° when the blade haven’t vibrated obviously. While, at AOA=10° and 12°, vortex-induced vibration of the blade model occurs and reduces the deviation angle. Fig. 3(c) shows that the valley positions in the profiles of AOA=10° and 12° are much closer to the position of y/CC=0 than that at AOA=8°. Meanwhile, it is most important that blade vibration reduces the valley value rapidly and largely. These phenomenons indicate the transformation of vortex structure in the near wake due to the self-induced vibration of blade which will be discussed later.

It is obvious in Fig. 3(d) that the valley values in the velocity profiles without vortex-induced vibration (0°≤AOA≤8°) are larger than the values with self-induced vibration (10°≤AOA≤12°) in the section of the wing tip (H=150mm). While velocity loss is not evident in the area of x/CC≥4. In the section out of the blade model (H=155mm), the mean streamwise velocity at each angle of attack is almost equal to free stream velocity as shown in Fig. 3(e).

3.2 Mean vertical velocity
Fig. 4 displays that the deviation angle of peak/valley position exists but is not very large in the profiles of mean vertical velocity. All peaks or valleys are almost near the position of y/CC=0. At the section of H=125mm, the valley value is very small and increases with the angle of attack. All shapes of these profiles are short and fat. At H=135mm, the valley width decreases along the streamwise direction. The laser layer across the blade span of 125mm≤H≤135mm (0.83≤H/L≤0.90) cuts the inner side of wing tip vortex of the blade model which is a region of downwash flow. So valley appears in each profile of mean vertical velocity as shown in Figs. 4(a)-(b).

When laser layer approaches the axis of wing tip vortex (H=145mm), downwash flow concentrates and strengthens more greatly. So the valley shape becomes taller and thinner in Fig. 4(c). It is interesting that, at AOA=8°, the vertical velocity changes from downwash to upwash in the streamwise direction. It means that the laser layer crosses the axis of wing tip vortex. In x/CC≤3, the laser layer cuts the inner side of wing tip vortex. But in x/CC≥4.5, the laser layer cuts the outer side. And there is another question, why the vertical velocity is still downwash at 10°≤AOA≤12°? It is the reason that, at AOA=10° & 12°, blade vibration changes the angle of wing tip vortex. It is estimated that the vortex axis moves toward to the wing tip.
In the section of 150mm ≤ H ≤ 155mm, laser layer crosses the outer side of wing tip vortex. So Figs. 4(d) & (e) display that these peaks in the profiles of mean vertical velocity are shorter and fatter as the laser layer moves away from the vortex axis gradually.

3.3 Mean axial velocity

Fig. 5 exhibits the profiles of mean axial velocity in the spanwise section of H=125mm, 145mm and 155mm. When the laser layer cuts the section far from the wing tip (H=125mm), the valleys in the profiles of x/CC≤1.5 are corresponding to the axis velocity of vortex shedding from the blade which points from wing tip to wing root. As laser layer approaches the wing tip (H=145mm), profiles appear a peak and valley in each streamwise position and the peak and
valley values increase with the angle of attack. Meanwhile, the central points in the velocity profiles move to the position of positive $Y$ at $4^\circ \leq \text{AOA} \leq 8^\circ$ but turn back to $y/CC=0$ at $8^\circ \leq \text{AOA} \leq 12^\circ$ when blade starts to vibrate. This phenomenon is similar to deviation angle of mean streamwise velocity. But in the section outside of the wing tip ($H=155\text{mm}$), the influences of blade deformation and vibration reduce obviously. The central point of each velocity profile almost fixes at the position of $y/CC=0$ as shown in Fig. 5(c).

![Velocity Profiles](image)

(a) $H=125\text{mm}(H/L=0.83)$

(b) $H=145\text{mm}(H/L=0.97)$

(c) $H=155\text{mm}(H/L=1.03)$

**Fig.5** Mean axial velocity profile

3.4 Turbulence intensity
For turbulence intensity of velocity field, we compared the standard deviation (Std) of velocity in each spanwise position (1≤x/CC≤4.5). The large Std appears in 3≤x/CC≤4.5 at AOA=10° & 12° in the section of H=145mm as shown in Fig.7. For mean streamwise velocity, the self-excited vibration reduces the valley value which has intensive relationship with aerodynamic drag. Except this part, the valley values of AOA=10° & 12° are higher than those at other angles of attack for mean vertical/axial velocity. Meanwhile, the vibration of blade model exacerbates mightily the turbulence intensity of velocity field. These characteristics prove effectively that vortex-induced vibration of blade transform the vortex structure in the near wake.

![Diagram of turbulence intensity](image)

(a) Std profile of streamwise velocity

(b) Std profile of velocity velocity

(c) Std profile of axial velocity

Fig 6. Turbulence intensity (H=145mm, H/L=0.97)

4. Vortex structure
Based on the results of mean velocity and turbulence intensity, the influence of blade vibration on velocity field is greatly obvious in the section of H=145mm in which Fig. 7 displays the vortex structure at $4^\circ \leq AOA \leq 12^\circ$. Considering the complexity of flow structure, the results of flow visualization and $\Lambda_\alpha$ of vortex structure are both shown.

At a small angle of attack (AOA=4°), Fig. 7(a) displays a clear clockwise vortex street in $y/CC \approx 0.2$ which derives from the shedding vortex at trailing edge of blade. Even in the region of $2.5 \leq x/CC \leq 3.5$, visible secondary vortices with a counter-clockwise sense emerge. Velocity vector around $y/CC=0$ displays a downwash area in the $\Lambda_\alpha$ figure which is the inside region of wing tip vortex. As the angle of attack increases to AOA=6°, the wing tip vortex deviate to wing root and the laser layer is closer to the vortex axis. Meanwhile, the blade sustains more deformation in the direction of positive Y with a larger angle of attack. So the figure of flow visualization in Fig. 7(b) shows a larger downwash area moves to the side of positive Y and its strength grows obviously. But the vortex street becomes indistinct and un-concentrated as that at AOA=4°. Flow separation occurs about at AOA≈8°. In Fig. 7(c), vortex is difficult to identify in the figure of flow visualization but $\Lambda_\alpha$ result exhibits disordered vortex structure where there is single clockwise vortex street at AOA=4° & 6°. In the downwash area, which is the inside region of wing tip vortex, a complicated structure appears in the figure of flow visualization in Fig. 7(c) corresponding to some tiny vortexes in $x/CC \geq 3$ in the $\Lambda_\alpha$ figure.

When blade begins to vibrate owing to the self-vortex induction at AOA=10°, Fig 7(d) exhibits a lot of tiny coherent vortexes with diameter of d≈2mm distribute both sides of wing tip vortex which are obvious clearly in the results of flow visualization and $\Lambda_\alpha$. In addition, new dual vortex street emerges in the position of $y/CC \approx 0.2$ composed by opposite-sign vortex pair. As the angle of attack increases to AOA=12°, Fig 7(e) shows that the size of vortex reduces greatly in figure of flow visualization and vortex strength becomes weaker in $\Lambda_\alpha$ figure.

5. Conclusions
Stereo PIV has been used to measure the velocity field of a flexible compressor blade in the spanwise sections of 125mm≤H≤155mm and at the angles of attach of $0^\circ \leq AOA \leq 12^\circ$. Vortex-induced vibration of blade model relieves the deviation of wake central line and reduces the velocity loss of mean streamwise velocity which has intensive relationship with aerodynamic drag. On the other hand, the blade vibration exacerbates mightly the turbulence intensity of velocity field in the near wake. These phenomena result from transformation of vortex structure due to the self-excited vibration of blade in the near wake, which could be proved by the results of flow visualization and $\Lambda_\alpha$. 
Fig 7. Vortex structure in the section of H=145mm
A single clockwise vortex street is formed by the shedding vortex from the trailing edge at AOA=4° & 6° and breaks down at AOA≈8°. When vortex-induced vibration of blade model occurs at AOA=10°, many of tiny coherent vortices generate around the wing tip vortex. At the same time, a new dual vortex street composed by opposite-sign vortex pair is instead of the single vortex street.

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Reference