PIV Test Investigation of Hovering Rotor Tip Vortex and Free Vortex Wake Simulation

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Abstract: The measurements of hovering blade tip vortex and rotor wake were conducted to investigate the blade tip vortex formation and evolution, and its relationship with the rotor test states. Φ2m rotor model test rig, single-bladed rotor model (airfoil NACA 0015) and 2-D PIV measurement system were applied in the investigation. Detailed flow field measurements were conducted for tip vortex around tip and within near wake local region under various combinations of rotating speed and collective pitch angle. The particle flow images of cross sections in azimuth stations from tip leading edge to near field downstream of trailing edge were obtained by PIV, delivering reasonable and effective results through post-processing. Free vortex wake simulation was adopted to calculate position variation of tip vortex, and the comparison with test result showed a good agreement.

Key words: hovering rotor; blade tip vortex; flow field measurement; PIV; free vortex wake

1 Introduction

Research on the rotor wake has lasted for about one century despite the complexity of rotor wake, and still to be investigated and developed. Key problem which need to be solved in the helicopter aerodynamics is rotor wake analysis which is fundamental basis for the research of rotor loading, flight characteristics, structure vibration, aerodynamic noise, maneuverability and stability. Also the rotor wake analysis is the important means to investigate the aerodynamic interference problems of helicopter. In order to enhance the accuracy of assessment on aerodynamic loading and performance thereby to improve performance and flight characteristics and reduce the vibration loading and noise, detailed investigation on rotor wake is greatly needed.

Lot of researches on visualization and measurement of rotor tip vortex have been performed abroad, initiated form probe and hot-wire until LDV and PIV to do the detailed measurement. Along with the development of non-intruding measurement techniques, possibility of detailed investigation on the forming and evolution of tip vortex came into more and more practical. And understandings on the rotor wake were getting deep and thorough. Typical efforts includes: Mahalingam etc. [1,2] used LDV to measure structure and evolution of rotor under small advancing ratio; Heineck etc. [3] used PIV to measure 3-D wake velocity vectors of rotor under hovering; Martin etc. [4,5] used LDV to measure high resolved 3-D velocity field around the rotor tip to reveal the forming and initial structure of trailing vortex and evolution of vortex core.

Domestic efforts includes: Yang Yong-dong [6] from CARDC used smoke and hot-wire to visualize and measure wake field of a rotor under hovering and forward flight; Tang Zheng-fei [7] from NUAA used LDV to measure wake field of a coaxial-rotor, revealed the interference phenomenon between rotors. Presently, laser based velocity measurement technique has been popularized and became an important method in investigation of complex flow.
This made it possible to measure rotor wake flow field in detail using PIV technique to get instantaneous flow structure. PIV has been an important tool to investigate process of vortex formation and evolution.

This study used PIV to measure rotor’s transient flow field near the blade tip region at different chord-wise sections and different azimuth stations. Various influencing factors, such as the blade chord length, rotation speed and collective pitch angle etc., were studied for single bladed tip vortex characteristics. The measurement results are reasonable, and the measurement results reflect the formation and evolution process of rotor tip vortex, which provides experimental data for further analysis model development and the calculation method verification.

2 Introduction of PIV measure test on tip vortex

2.1 Test facilities and model

The test was conducted in the Key Laboratory of Rotor Dynamics of NUAA, hub and blade model were designed and manufactured by the Laboratory. Φ2m rotor model test rig was used in the test (0). The experiment adopted two sets of blades model, blade number: 1; hub radius: 136mm; rotor radius: 1057mm/936mm; chord length: 120mm/60mm; blade airfoil: NACA 0015; pre-cone angle: 2.5 °; blade twist angle: 0 ° (1.0R to the centre of rotation); shape: rectangle. Because only one blade was used, the corresponding dynamic counterweight was installed. The principle of dynamic counterweight device is to arrange weight balance on opposite direction, its mass is variable and radial position can be fine adjusted in order to balance the centrifugal force imposed on the hub by rotating blade. Dynamic counterweight device is seen in 0.

PIV measurement system is mainly composed of four parts: light source, CCD camera, synchronous control system, image capture and velocity vector calculation system. 0 and 0 are the schematic diagram of the PIV measurement system, the resolution of CCD is 1600 × 1200, the maximum sampling frequency is 15Hz; laser sheet is composed of double pulse Nd:YAG laser, light guide arm and light head. The test used the stage smoke generator as a particle source, and smoke medium was oil.

2.2 Test method

Hovering test was conducted in ground laboratory, using rotor model test rig and the PIV system to acquire rotor wake flow field near the tip of the blade under different speed and collective pitch angle. The collective pitch angle: \( \theta = 4°, 8° \). Rotor speed: \( n = 500 \text{rpm}, 700 \text{rpm} \) (corresponding to 565rpm, 790rpm for 60mm chord blade to ensure the same blade tip Mach number as 120mm chord blade). In order to capture the process of formation of tip vortex on the blade, starting from the leading edge the measurement sections were respectively set at 0.0C, 0.25C, 0.5C, 0.75C, 1.0C, 1.5C and 2.0C in the 120mm chord blade. In order to track and capture the tip vortex in the wake, 8 measurement sections (\( \psi = 10°, 30°, 60°, 90°, 120°, 180°, 270°, 360° \)) were set after the 60mm chord blade within 360 degrees azimuth range. Laser light sheet was arranged outboard of and toward to the blade tip, TTL synchronization signal once per revolution was used as trigger method. In order to ensure the distribution uniformity of tracer particles, in the first the test hall was filled with smoke, then during the process of test the smoke was added in need.

2.3 Process of test data

Using specialized PIV image analysis software, the measurement results are analyzed. Correlation analysis was performed for each pair of images to get the velocity distribution in the region. During
the test, more than 50 pairs of images were collected. For each measurement, reasonable results are chosen from repeated acquired data and then be averaged. 0 and 0 shows the relative position of the blade in the measurement region. For the 120mm chord blade, measuring area is rectangular region of 250mm * 180mm; and for the 60mm chord blade, measurement area is rectangular region of 400mm * 300mm. In the image analysis, 48 * 48 pixel window is used in correlation analysis. For the processed results of this paper, the lower left corner of the measuring area is taken as the origin of coordinates to give the velocity vector, vorticity or streamline map.

3 Measurement result and analysis

0 ~ 0 show the flow field vector map measured at chord-wise 0.5c, 1.0c and 1.5c sections around 120mm chord blade tip under the status of rotation speed 700rpm, collective pitch angle 8°. From these figures it can be seen: the maximum vorticity is -300 1/s at the chord-wise 0.5c section, -600 1/s at the chord-wise 1.0c section; -800 1/s at the chord-wise 1.5c section. It shows that the tip vortex increases along the chord-wise sections in the process of vortex formation. It should be noticed that tip vortex main structure has an inboard irregular shape of “tail” which represents the distributing vorticity along the blade. 0 shows the tip vortex vorticity variation with chord-wise sections under various statuses. For the convenience of presentation and comparison, the vorticity in the map has absolute value. It can be seen that the tip vortex increases along the chord-wise range of 0≤z/c≤1, showing that the strength of the vortex reinforces during the formation. In the chord-wise range of 1≤z/c≤2, tip vortex behaves in two distinguish ways. Under the collective pitch angle of 4°, strength of tip vortex maintains constant or slightly decreases; Under the collective pitch angle of 8°, strength of tip vortex firstly follows the trend of increase, and then maintains constant or slightly decreases, specially under the speed of 700rpm the tip vortex carries on increases. Consideration on the phenomenon refers to two physical processes: dissipation of vorticity and rolling-in of distributing vorticity, the former process makes the vortex weaker but the latter process makes the vortex stronger. For the situation of collective pitch angle of relatively small 4°, the strength of initial tip vortex and distributing vorticity are relatively weak, so the dissipation of vorticity gets dominant to make vortex decreased; but for the situation of collective pitch angle of relatively large 8°, the strength of initial tip vortex and distributing vorticity are strong enough to delay the balance point to the range of z/c > 2. 0 shows the variation of circulation of tip vortex along the chord-wise sections, from leading edge to the trailing edge (0≤z/c≤1) the circulation of tip vortex increases along the chord-wise sections, this represents the process of tip formation, while after the trailing edge the circulation of tip vortex maintains constant which is consistent with the theoretical analysis.

The typical measurement results of wake can be seen in 0 ~ 0, which give the 30 °, 60 ° and 90 ° azimuth measurement results of 60mm chord blade under speed of 790rpm and collective pitch of 8°. The results reflect the evolution characteristics of tip vortex behind the blade in different azimuth positions. Notice that maximum vorticity in the tip vortex center is obviously
too small to be shown at 30°, 60° and 90° azimuths, this may be due to the blade tip vortex structure has just generated from the blade tip and is highly concentrated to the center while large measurement area has insufficient resolution for recognition, the fine vortex structure cannot be distinguished clearly. After the development of one revolution, blade tip vortex core expands and vorticity diffuses, so the maximum vorticity of blade tip vortex center at 390°, 420° and 450° azimuths can be correctly recognized. For 60mm chord rectangular tip blade, 0 gives the variation relationship between the blade tip vortex radial position and azimuth, it can be seen that the tip vortex radial position shrinks inwards with the azimuth increases, but after azimuth of 360° the contraction trend gets disordered which may be caused by the influence from the new generation of the vortex at blade tip. 0 gives the variation relationship between the blade tip vortex axial positions and azimuth; obvious downwash effect can be seen in the figure, the greater collective pitch the stronger downwash under the same rotation speed. Notably, the slope of the curve relatively increases after 360° azimuth which also may be caused by the influence from the new vortex generation at blade tip to make its down move speeding up.

4 Calculation on tip vortex trajectory

The engineering calculation method of numerical simulation of rotor wake is used to calculate the blade tip vortex trajectory. In the calculation the blade is modeled as a rigid blade, and lifting line theory and the blade element theory are used in the blade aerodynamic model, and the rotor wake uses free wake model in which the wake is described by constant contours line method. The comparison of calculation results and test results in typical state (speed 790 rpm, the collective pitch 8°) of 60mm chord blade are shown in 0 and ∙, the calculated blade tip vortex trajectory trend are consistent with the test results, and the speeding up phenomenon of down move of tip vortex after 360° azimuth is well predicted.

5 Conclusions

Through this study, the formation of blade tip vortex and the wake were measured and studied, the measurement results are reasonable, reflects the characteristics of the formation and evolution of the blade tip vortex. Through the analysis, we can draw the following conclusions:

1. Through the test, the "vorticity dissipation + vortex rolling-in" and "circulation conservation" phenomenon were captured. Along the blade chord the blade tip vortex vorticity and circulation gradually increases from the leading edge to the trailing edge, and after trailing edge the circulation maintains constant, but vorticity’s variation depends on the confrontation between the two processes of vorticity rolling-in and vorticity dissipation.

2. The radial position of blade tip vortex contracts to the axis of rotation with azimuth angle increased.

3. The axial position of tip vortex goes down with the azimuth angle increased, and affected by the new generation of blade tip vortex, the down-move speeds up after 180° azimuth.

4. Calculation and experimental measurement of the trend of blade tip vortex trajectory are of good consistent, and the motion characteristics from the interference are predicted well.
Fig. 2  Φ2m rotor model test rig

Fig. 3  Schematic diagram of the PIV measurement system

Fig. 4  Schematic diagram of the PIV components

Fig. 5  Relative position of the blade in the measurement region (120mm chord blade)

Fig. 6  Relative position of the blade in the measurement region (60mm chord blade)
Fig. 7  Measurement result of flow field of 120mm chord blade tip at position of z/c=0.5 (n=700 rpm, 0.7°=8°)

Fig. 8  Measurement result of flow field of 120mm chord blade tip at position of z/c=1.0 (n=700 rpm, 0.7°=8°)

Fig. 9  Measurement result of flow field of 120mm chord blade tip at position of z/c=1.5 (n=700 rpm, 0.7°=8°)

Fig. 10 Variation of vorticity of tip vortex along the chord-wise sections for 120mm chord blade tip

Fig. 11 Variation of circulation of tip vortex along the chord-wise sections for 120mm chord blade tip
Fig. 12  Measurement result of flow field of 60mm chord blade tip at position of azimuth 30° (n=790 rpm, θ0.7=8°)

Fig. 13  Measurement result of flow field of 60mm chord blade tip at position of azimuth 60° (n=790 rpm, θ0.7=8°)

Fig. 14  Measurement result of flow field of 60mm chord blade tip at position of azimuth 90° (n=790 rpm, θ0.7=8°)

Fig. 15  Variation of the blade tip vortex radial position with azimuth for 60mm chord blade tip wake

Fig. 16  Variation of the blade tip vortex axial position with azimuth for 60mm chord blade tip wake
The 2nd Asian/Australian Rotorcraft Forum and The 4th International Basic Research Conference on Rotorcraft Technology
Tianjin, China, September 08-11, 2013

Fig.17 Radial position comparison between calculation results and test results of 60mm chord blade tip vortex (n=790 rpm, $\theta_{0.7}=8^\circ$)

Fig.18 Axial position comparison between calculation results and test results of 60mm chord blade tip vortex (n=790 rpm, $\theta_{0.7}=8^\circ$)

Reference


