Hot-wire measurements behind a propeller model

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Abstract

The modern day regional transport aircrafts are designed for high fuel efficiency. One way to achieve this is by optimized turboprop configurations. A prerequisite for this optimization is the detailed knowledge of the development of the wake flow field behind the propeller. An experimental study was conducted to map the velocity field behind the powered propeller model using hot-wire anemometry in the 1.5m low speed wind tunnel at NAL. The objective is to study the development of the wake behind the propeller and assess the effect of the wake on the wing. Phase-matched velocity survey of the flow field behind the propeller using hot-wire anemometry shows the development of wake with distance and very interesting flow features.

Nomenclature

\[ J \] = propeller advance ratio
\[ r \] = radial distance, mm
\[ R \] = propeller radius, mm
\[ \langle u \rangle \] = ensemble rms of fluctuating component of axial velocity, m/s
\[ U \] = mean axial (streamwise) velocity, m/s
\[ \langle U \rangle \] = ensemble averaged axial velocity, m/s
\[ U_\infty \] = freestream velocity
\[ V \] = mean tangential velocity, m/s
\[ x \] = streamwise distance, mm

I. Introduction

Propeller powered aircrafts, being fuel efficient, are one of the options considered for our national requirement of regional transport. Additionally, low drag configurations are desirable and mandate a multi-disciplinary optimization design on the wing and propeller combination [4]. A prerequisite for this optimization is the detailed knowledge of the development of the wake flow field behind the propeller. Two dimensional velocity field measurements using PIV [5] are unable to capture the three-dimensional and temporal evolution of the propeller wake. In this study, the velocity field behind the powered propeller has been mapped in the wind tunnel at NAL using hot-wire anemometry. The experiments required the fabrication of a high speed composite propeller model, an air turbine powering the propeller and innovative methods for phase-averaging the streaming hot-wire data and data reduction. The results are very revealing and useful for initiating design optimization studies.

II. Literature

Velocity measurements in the wake of a propeller have been conducted by a considerable numbers of investigators [1-3,5]; of these Double/triple sensor hot-wire measurements have been conducted by Hyun & Patel [1] and Lynch et al [2,3]. Hyun & Patel [1] conducted experiments on propeller-body and used phase-averaging techniques to reconstruct the phase-mean velocity and Reynolds-stress fields downstream of the propeller. Their field of interest was in the range of 0.2<r/R<1.0 and made similar measurements but with a triple sensor hot-wire. The basic motivation of Lynch et al [2,3] was to study the aeroacoustic response by varying the oncoming grid turbulence at low advance ratio of different propellers.

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III. Experimental set up

A 1/15th scale six-bladed model propeller of radius R=0.15m was designed for the purpose; matching the propeller advance ratio (J=2.26), and the thrust and power coefficients in cruise of a typical regional transport aircraft. Powered by a suitable air-turbine, the propeller was assembled in the isolated condition inside the 1.5m low speed wind tunnel at NAL as shown in the photograph in Fig.1.

The propeller suitable for the flow conditions specified was designed using combined blade element theory, a rapid prototype of the model propeller was fabricated and used for the making the composite mould. Carbon composite propellers were fabricated from this mould for loading testing and usage. The strength of the propeller blade in the radial direction is most critical and was tested using dead weights.

An air turbine capable of providing the required torque of 1.2N-m at 3500 rpm (model No.LZB 46 AV065-11 from Atlas Copco, USA) was procured. The turbine required air at a pressure of 6-7bar, which was made available from the NTAF compressed air facility. Two pressure regulating valves in series were used to manually control the rpm of the air turbine to within 3500±10.

IV. Instrumentation

Hot-wire anemometry consisted of an X-wire probe, CTA and StreamLine software from Dantec, USA. Instantaneous axial and tangential velocities were measured along the vertical plane containing 18x11 points behind the propeller up to an axial distance of x = 1.7r at intervals of 10mm. Data from the CTA, the freestream velocity data and the tachometer output were acquired on to the computer at 20 kHz for 5s.

A digital strobscopic tachometer was used to set the required rpm of the motor and to provide a time stamp for each rotation. A reflecting tape was fixed on the spinner ahead of the propeller coinciding with one of the blades. The photo sensing diode in the tachometer sensed the light reflected from the tape and its voltage output increased from 5.25 by nearly a volt. This raw output was tapped out and acquired along with the velocity data. The plot of the tachometer output in Fig.2 shows sharp peaks occurring at the position of the reflecting tape and marking each rotation. Peaks from four different cycles of the tachometer data are enlarged and plotted in Fig.3 show high consistency between cycles which can be conveniently used to mark each rotation.

V. Results

The variations of the mean axial velocity in the radial direction at all the measurement stations are shown in Fig. 4. The axial velocities in the mid-radius region (0.3<r/R<0.95) are higher than U∞; expected as the blades are performing optimally in this region; the maximum difference is about 1.5m/s at r/R~0.5. The velocity decreases to U∞ at the propeller tip. The data do not show any major change in the velocity profiles in the axial direction up to a distance of 225mm (x=1.5R) and a random spread of about ±0.5m/s (±1%) is visible.

The variations of the mean tangential velocity in the radial direction at all the measurement stations are shown in Fig. 5. The figures show that the mean tangential velocity attains a maximum value of about 1.6m/s in the mid-radius region at x<125mm and drops to about 1.35m/s at x=0.2m. The tangential velocity changes its direction close to the hub as well as beyond 0.8R. There is not much of a change observed in the velocity profiles within an axial distance of x=150mm, beyond which there is a slight decrease in the mid region.

Selected ensemble averaged axial velocity profiles at each phase angle across three blades (half rotation) are presented for x = 10mm in Fig.5. The figure shows that the wake profile is clearly decipherable with a sharp reduction in velocity, as well as from the location of the minimum velocity, its value and the width of the wake at its base. The details of the profile in the region between blades are also clearly visible. It is also evident that the wake profiles for different blades are not exactly repetitive. The size of the wake is at its minimum in the mid-radius region, it is large in the blade-root / hub junction as well as near the tip. The figures also show that at x=100mm the axial velocity between blades is higher than the freestream values by about 8%; the profile being identical for r<0.51R. The maximum velocity between blades gradually decreases for r>0.51R reaching a minimum for r≥0.91R, still being greater than the freestream velocity. Thus the region between blades contributes to the thrust and the blade wake counteracts that. It is clear that decreasing the wake drag, especially in the hub region, will improve the propeller performance. The corresponding velocity profiles for x = 150mm(Fig.6) shows that with streamwise distance, the wake decreases in size and undergoes a phase shift due to the rotation of the blade.

The axial velocity profiles were compiled to form a contour map at each x. The maps for x=10 and 150mm displayed in Fig. 7 clearly show higher velocities in regions between blades, the wake velocity sharply decreasing at x = 10mm; becoming diffused and changing its shape radially at x = 150mm with the mid-radius wake convecting in the positive angular direction due to the tangential velocity. The presence of the tip vortex is also perceived.

The root-mean-square of the velocity fluctuations, normalised with U∞ was calculated for each phase angle and plotted in Fig.9. The figures show that the fluctuation level in the wake of the blade at x=150mm has a maximum value of about 10% near the hub (at x = 10mm it is about 20%). As we move outward the maximum
value decreases about 5% at r=0.51R, maintains the level up to r=1.04R and at r=1.07R the wake is barely recognizable. For the region between blades, the turbulence level can be better described through enlarged plot (Fig.9b) as that it reaches a base value of about 0.5% which is still very high for any possible laminar flow.

VI. Conclusions

Axial and tangential velocities have been measured in the tunnel in the wake region of a propeller model rotating at an advance ratio corresponding cruise condition of the aircraft. Effectively using the phase information, the ensemble phase averages and the rms of the velocities were calculated in the vertical plane behind the propeller. These velocity profiles proved to be very consistent and the details were well resolved. The mean streamwise velocities in the wake do not show any change in the profile in a streamwise distance of 1.5R while the tangential velocities show some reduction within 1R. The phase averaged velocity profiles show that the blade wake is sharp right behind the blades, and diffuse and distort with distance. The tip vortices are intense right behind the propeller extending to about 0.7R and diffuse with downstream distance. The wake is highly turbulent and the regions between blades have comparatively lower fluctuations, still so high that laminar boundary layer flow on the wing would be difficult.

References

Fig. 1 Powered propeller model in the wind tunnel

Fig. 2 The raw voltage output from the photodetector of the tachometer acquired at 20kHz. The peaks indicate one revolution.

Fig. 3 The enlarged peak of the tachometer output over four cycles.
Fig. 4 Mean axial velocity (U) profiles for all axial distances (x)

Fig. 5 Mean tangential velocity (V) profiles for all axial distances (x)
Fig. 6 Ensemble phase-mean axial velocity plot at $x=10\text{mm}$

Fig. 7 Ensemble phase-mean axial velocity plot at $x=150\text{mm}$

Fig. 8 Ensemble phase-mean axial velocity contour map at (a) $x=10\text{mm}$ & (b) $x=150\text{mm}$
Fig. 9a The variations of the streamwise fluctuations for $x=100mm$

Fig. 9b An enlarged plot of the variations of the streamwise fluctuations for $x=100mm$