EXPERIMENTAL AND NUMERICAL RESULTS OBTAINED AT LABM AND TSAGI ON AERODYNAMICS OF HELICOPTER ROTOR BLADES IN HOVER

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Abstract

The motivation of the present work is based on a research collaboration between the Helicopter Department of TSAGI at Moscow and the LABM (Aerodynamics and Biomechanics of Motion Laboratory) at Marseilles.

The primary objective was to check the prediction efficiency of numerical codes for helicopter rotor blades performances in hovering flight configuration. The paper aims at the presentation of experimental and numerical methods used in both laboratories and at the analysis of results based on crossed experiments/calculations comparisons.

The paper describes the experimental methodologies used to investigate the rotor blades aerodynamics: airloads, circulation, tip vortex path, velocity fields. From a numerical point of view, the assumptions and calculation procedures based in both cases on a blade modelled as a straight or broken lifting line and on a free wake analysis, needing a short time consuming process, are also addressed. Results on experiments/calculations comparisons concerning thrust and power coefficients, blade circulation, tip vortex path and velocity fields are presented in this paper.

Introduction

The motivation of the present experimental and numerical work was based on the collaboration between two laboratories involved in helicopter aerodynamics: the Helicopter Department of TSAGI and the laboratory of Aérodynamique Subsonique Instationnaire (ASI) at Marseille, renamed LABM (Laboratoire d'Aérodynamique et de Biomécanique du Mouvement) since January 2000.

The collaboration was supported by the DGA (French Department of Defense) on a large program relative to helicopter rotor blades in hover, vertical and descent flights, as well as to oscillating airfoils under and through stall conditions.
The main objective was to quantify the efficiency of aerodynamics prediction codes for helicopter rotors equipped with different blade tips and operating in hovering flight configurations. The paper aims at the presentation of experimental and numerical tools used in both laboratories and at the analysis of crossed comparisons realized between LABM calculations and TSAGI experiments and TSAGI calculations and LABM experiments.

The model-scale of rotors used by TSAGI and LABM and presented in section 2, have nearly the same radius and solidity and are operating at the same tip velocity. The section 3 describes in details the experimental methods used to investigate globally and locally the rotors aerodynamics: loads, blade circulation, tip vortex path, velocity fields. The assumptions and calculation procedures based in both cases on a free wake analysis are presented at the end of the chapter. Results and comparisons concerning thrust and power coefficients, blade circulation, tip vortex path and velocity fields are then discussed in section 4.

Experimental set-up

TSAGI rotor

The rotor model experimented at TSAGI is a four bladed rotor, 1.6m in diameter and 0.138 in solidity. The blades have a NACA 23010 airfoil with linear twist of -5.5 deg and a rectangular plan form.

This basic set of blades has been referenced in the following sections as "rotor TSAGI 217". A second rotor, differing from the preceding only by the leading edge swept angle of 30° at the tip, is referred as "217A". These rotors, described in detail in (Ref 1), are shown in Fig.1.

LABM rotor

The rotor model (Ref 2) experimented at LABM is four bladed, 1.5m in diameter and 0.084 in solidity. The blades (OA209 airfoil) have a linear twist of –8.3 deg. Rotor with basic blades of rectangular plan form ("rotor 7"), and the one equipped with swept tip angle of 30 deg ("rotor 4"), is presented in Fig.1.

Calculations realized by TSAGI on rotors 217 and 217A have shown a very weak influence of the tip on circulation and tip vortex paths. Comparisons between calculations and experiments have then concerned only 3 rotors: LABM rotor 4 and 7 and TSAGI rotor 217. During the experiments (TSAGI and LABM), the tip velocity V_T has been fixed at $V_T \approx 100ms^{-1}$.

Experimental investigations

TSAGI experimental methods

Thrust and Torque. Moments and aerodynamic forces are measured by means of a 6 components balance (Ref 1). The characteristics of the balance are as follows:

-Thrust: ≤300N,
-Longitudinal load H: ≤ 80 N,
-Lateral load S: ≤ 50 N,
-Longitudinal moment Mz: ≤ 10 N.m,
-Lateral moment Mx: ≤ 8 N.m,
-Torque Q: ≤ 30 N.m,
Maximum rotational frequency: 1500 rpm
Rotor maximum weight: 4.5kg.

Thrust and Torque coefficients are defined as:
$C_T = T/q_r\pi R^2$; $C_Q = Q/q_r\pi R^3$, with $q_r = (\rho_H(\Omega R)^2)/2$.

Velocity survey of the wake. The averaged flow characteristics are measured by a Pitot-static tube which is moved in the rotor wake by a traversing device to successive preset locations. In these points the static pressure on the nose part of the Pitot-static tube is measured. Using the values of the measured pressures, with the help of preliminary calibrated dependencies, the magnitude and direction of the velocity vector with respect to the coordinate system of the Pitot-static tube are calculated. Then the induced velocity components, axial (v_z), radial (v_r) and tangential (v_t) are determined in the rotor wake.

Tip vortices trajectories. Visualization of the vortex system is performed using a smoke jet produced by an oil generator. Video camera is used to record tip vortex position as a function of the blade azimuth. The video signal delivered by the camera is conducted to a videotape recorder through a video monitor. An impulse lamp illuminates the visualized vortex and allows the synchronization of the acquisition system based on the determination of the azimuth of one of the blades. Image processing is performed by means of the "PERICOLOR" system. Definition of coordinates of the vortex core was performed in interactive mode using filtration and contrasting.

LABM experimental methods

Thrust and Torque. Measurements of thrust and torque are performed by means of a 6 components rotating balance mounted on the rotor hub. Signals delivered by strain gauges are radio-recorded and allow to obtain thrust and torque coefficients. Measurements are averaged over 300 rotations of the rotor. The full-scale values of forces and moments delivered by the balance in radial and tangential directions are respectively 800 N and 150 Nm, and in the axial z direction 2000 N and 300 Nm. The global measurement error, including non-linearity and hysteresis effects of the sensors, is about 2%.

Velocity field measurements. Measurement of the velocities around a blade section at a fixed azimuth and in the wake are performed using a backscattered Laser Doppler Velocimeter (Ref 3) operating with a long focal length (2m). The seeding of the flow is obtained from an oil and water mixture, and data from the measuring volume ($0.2x0.5x0.3mm^3$) are acquired through burst spectrum analyzers. The velocity components are phase averaged over 300 rotations of the rotor with an accuracy comprised between 4% and 6%. The initiation and synchronization of the data are realized by means of a photocell and an encoder with a precision of ± 0.36deg.

In order to measure the velocities around a section, the blade is "electronically" fixed at a given azimuth and the averaged measurements of the velocity components over 300 periods is performed for different positions of the measuring volume surrounding the blade section.
Concerning the wake survey, the measuring volume is placed at a given plane z in the wake and the data delivered at every azimuth along the rotation are stored during 300 rotations, phase averaged from Ψ= 0 to Ψ = 90deg by step of 0.36deg. Fig.2 gives an example of a velocity recorded in the wake.

Circulation distribution along the blade. A rectangular contour surrounding the blade section has been determined as close as possible to the blade (Ref 4). The tangential velocity component to the contour are then integrated to obtain the circulation $\Gamma(r/R) = \oint_{contour} \vec{V}\,\vec{dl}$ at the given section r/R.

Tip vortices trajectories. When a vortex encounters an x hot-wires, it results a typical pick voltage signal that can be visualized on an oscilloscope screen. Such x hot-wires are displaced in the wake of the hovering rotor by means of a 3D traversing device. When a tip vortex shed in the wake encounters the probe, the output signal of the probe is recorded by the oscilloscope. This signal is synchronized on a known azimuth of the blade and the time at which the pick occurs gives the age of the vortex. So, when a vortex is detected on the oscilloscope, its position in space (r/R, z/R) is known from the traversing device as well as its age. Displacing the probe in the wake and tracking the tip vortices allow to determine the full tip vortex path. A tip vortex position is determined using these techniques with an accuracy of about 1mm in r and 0.2mm in z, resulting in $\Delta r/R \leq 1/750$ and $\Delta z/R \leq 1/3750$.

Flow visualization. Very close to the blade, the vortex trajectory is measured by smoke visualizations. The blade is fixed at a given phase Ψ by the use of a stroboscope light and pictures of flow patterns are acquired using a CDD camera. Moreover, the visualizations reveal the radius evolution of the vortex with its age.

Calculation

TSAGI numerical method

The calculation method is basically presented in References 1 and 5. The blade is modeled by a lifting vortex line, having core of small finite radii. The finite core radii provide the finite values of induced velocities at all calculation points. The vortex axis corresponds to a straight line for blade of rectangular plan form and to a broken line for a swept tip blade. The free vortex wake of each blade is represented by a finite number of discrete vortices. Each vortex is replaced by the vortex segments Δl which axis is a straight line. In this case, the induced velocity vector Δv is calculated by means of the Biot and Savart law. In this case, the velocity Δv is determined as the following approach for a diffusible vortex:

$$\Delta v = \frac{\Gamma[\Delta l x l]}{4\pi[\Delta l x l]^2 + \varepsilon^2 \Delta l^2}\left[\frac{\Delta l x l}{\sqrt{l^2+\varepsilon^2}} - \frac{\Delta l x l_1}{\sqrt{l_1{}^2+\varepsilon^2}}\right]$$

Where $\varepsilon=\delta/2$ and δ is the vortex sheet thickness, l and l_1 are vectors directed from calculation point to starting point and end point of the vector Δl.

If the distance between the axes of two neighbor vortices is smaller than the sum of their radii, then they are united in one single vortex (Ref. 6). As a result of such process rolled up tip vortices are formed.

In order to reduce the calculation time:

- The quasi-linear main rotor theory (Ref. 1) is used at the first step of the iterative procedure,
- The vortex form is calculated at one free vortex wake pitch ($\Psi \leq 2\pi$).
- The deformed wake vortices are discrete ones with the constant free vortex radii only applied on some (m) vortex spiral pitches.
- The vortex core radii are zero for far enough vortices and in this case the induced velocity (Δv) is determined by means of usual Biot and Savart law.
- The calculations of the velocities induced by the far vortices (when the number of spiral pitches is higher than m and accordingly $|l| >> |\Delta l|$) is realized along the rotor axis at the constant free vortex radius r/R. Along each far spiral pitch the discrete vortex of constant circulation Γ is replaced by the correspondent constant continues vorticity of the same total circulation and the correspondent integral is considered from end point of the past discrete vortex up to infinity.

The 2D aerodynamic coefficients tables are used to calculate the blade distribution of aerodynamic loads and moments. The Kutta-Joukowsky formula is applied for a blade section to introduce the correlation between C_L, velocity and Γ.

The code can be used in 3 cases, when input data include one of the following:

- Pitch angle $\theta_{0,75}$,
- Rotor thrust coefficient C_T,
- Circulation distribution $\Gamma(r/R)$.

LABM numerical method

The code used is described in detail in (Ref. 2). The blade is considered as a straight or broken lifting line spanning the sections at the quarter chord. The wake is represented by a finite number of discrete vortex lines shed from each blade. This wake is divided in a strong rolled-up filament as a result of grouping some tip vortices, and in several weaker trailing vortices lines representing the inboard vortex sheet. The far path is helicoidally defined with a constant pitch for $5\pi/b \leq \Psi \leq 10\pi/b$ and a radius $r=r(5\pi/b)$. For $\Psi \geq 10\pi/b$, a semi-infinite cylinder model with constant vorticity distribution is used. The code is based on an iterative procedure, with at its initialization step a prescribed wake (Ref. 2). Two optional procedures: one at fixed thrust, the other at fixed blade circulation distribution are proposed. Induced velocities are calculated from the Biot and Savart law, as the 2D aerodynamic tables for airloads and moments coefficient of the blade section are used when calculating the circulation. The diagram of the codes called " SMEROT C_T" and "SMEROT Γ" are presented in Fig.3.

Results and comparisons

Thrust/Torque

Rotor performances (C_T/C_Q) obtained on rotors 4, 7, and 217 are presented in Fig. 4. On the top of the figure which concerns rotors LABM 4 and 7, TSAGI calculations are compared to LABM calculations and experiments. Comparisons concern three values of the pitch angle θ = 6, 8, 10deg. The LABM code has been run at prescribed θ. It can be said that the results of the comparisons are generally good, with a better and unexpected agreement on the tip swept rotor (rotor 4).

On the bottom of the figure, LABM calculations are compared to TSAGI experiments and calculations. Calculations concern 2 values of θ =9.7 and 13.5 deg for TSAGI, and 6 values of θ = 1.2, 4.8, 7.5, 9.7, 11.7, and 13.5deg for LABM. Despite a shift to lower pitching angle observed between experiment and calculations, it can be noted that comparisons are very good for 5deg≤θ ≤13.5 deg.

Circulation distribution along the blade

The Figure 5 shows the results obtained on circulation along the blade. LABM experiments have concerned the integration of the tangential velocities around different section of the blade from r/R=0.2 to r/R=1. Concerning LABM rotors 4 and 7 presented at the top of the figure, TSAGI calculation looks like to be a good compromise between the calculation and experiments given by LABM. Experiments and calculation are in less good agreement on LABM rotor 4, certainly due to the swept tip influence. A shift between the two picks obtained by LABM from experiments to calculation is observed, as TSAGI calculation seems to smooth the results in only one pick of less intensity but well located in span. LABM calculation gives greater intensity of the tip picks as well as TSAGI calculation shows lesser picks intensity than experimental results.

The bottom of the figure concerns TSAGI and LABM calculation comparisons performed for 2 values of θ = 9.7 deg, and 13.5 deg, on TSAGI rotor 217. It can be seen that the calculations give a good agreement on the location of the pick and the distribution of the circulation, except on the amplitude of the maximum of circulation. In both cases TSAGI calculation seems to smooth the circulation pick, but it is difficult to conclude on the best-suited code to use for lack of experimental data on rotor 217.

Tip vortex paths

Tip vortex paths are presented as the variation of the space location (r/R, z/R) of a tip vortex with the blade position ψ during the rotation (at ψ =0 the vortex is shed from the blade, at ψ =ψ (t) the wake coordinates of the vortex are: r/R and z/R).
LABM experiments and calculation, and TSAGI calculation of tip vortex paths are given in Fig.6 for LABM rotor 7 at θ = 10deg. The agreement is very good with an excellent prediction on the axial position (z/R) of TSAGI code.
The agreement is not so good when LABM rotor 4 is concerned (see Fig.7). In this case TSAGI calculation is not well suited for radial prediction of vortex path, as LABM calculation fails in the axial prediction.
Tip vortex paths obtained on TSAGI rotor 217 for 2 values of θ = 9.7, and 13.5deg show a generally good agreement between experiments and calculations (see Fig.8). The sparse experimental data obtained in the far wake are well bounded by LABM and TSAGI calculations.

Wake velocity profiles.

Averaged velocities: calculations and experiments have mainly concerned LABM rotor 4 and TSAGI rotor 217. Results obtained on rotor 4 as mentioned in page 2 (LDV measurements) are presented in Figure 9 for θ = 10deg and in 2 rotating planes: z/R= 0, and –0.0641. These comparisons concerning the axial component $V_Z/\Omega R$ attest an underestimation of experimental results by both calculations with a not corresponding localization of the maximum velocity close to the tip, particularly at z/R=0. LABM calculations remain for these cases in better agreement than TSAGI ones.

Figures 10 and 11 present the comparisons between TSAGI experiments and calculations, at 2 values of θ = 9.7, and 13.5deg and in different rotating planes z/R. TSAGI experiments have been realized by use of a multi holes Pitot tube as described in page 2. TSAGI and LABM Calculations are in very good agreement, although the maximum average velocity close to the tip was measured by means of the Pitot tube.

Instantaneous velocities: the radial distribution of the axial velocity component $V_Z/\Omega R$ is presented in Fig.12 for 5 values of the rotating blade phase ψ= 0, 15, 45, 60, and 75deg, in the rotating plane z/R=0. These results, concerning the ASI rotor 4, show that the two calculations provide a good prediction of the velocity distribution generally underestimated when compared to experimental results.

Conclusions

A wide experimental and numerical investigation concerning aerodynamics of helicopter rotor blades in hover have been performed. The crossed comparisons between the experiments and calculations realized at LABM and TSAGI using their own techniques have shown that:

1. Calculations based on a lifting line theory and a free wake analysis have a very good efficiency for determining loads, mean and instantaneous velocities and vortices trajectories in the near wake of rotor blades in hover. This good efficiency has been observed on rectangular blades as well as blades with swept tip.
2. Discrepancies between experiments and calculations have nevertheless appeared concerning the blade circulation distribution, the vortices path and instantaneous velocities in the far wake, particularly for swept tip. Both codes require in this case further development and refinement.

Acknowledgement

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References

1.Baskin, V.A., Vozhdayev, E.S., Vildgruber, L.S., Maikapar, G.I., “Theory of the Lifting Airscrew”, Prof. Dr. A.K. Martynov (Editor-in-chief), Moscow, “machinostroenie”, 1973. Prepared under contract No. NAS-2-8081 by BOEING VERTOL COMPANY. Translated from Russian by W. Z. Stepnievski, transcribed by Wanda L. Metz. 1975.

2.Favier, D., Nsi Mba, M., Barbi, C., Maresca, C., “A Free Wake Analysis for Hovering Rotors and Advancing Propellers”, Vertica vol. 11, No. 3, pp. 493-511, 1987.

3.Berton, E., Favier, D., Maresca, C., “LDA Measurements and Flow visualizations around helicopter Rptpr Blades”, in Fluid Control Measurement”, P. Hebrard Editor, pp. 1021-1028, 1994.

4.Nsi Mba, M., Meylan, C., Maresca, C., Favier, D., “Radial distribution Circulation of a Rotor in hover measured by Laser velocimeter”, ERF, Proceedings of the 10th European Rotorcraft forum, Paper No 12, pp 1-14, The Hague, August 1984.

5.Baskin, V.A., K.K., “To Nonlinear Vortex theory of Helicopter Rotor in Horizontal Flight”, BNI TSAGI, Moscow, TSAGI Works, issue 1013, 1966, (in Russian).

6.Betz, A., “Behavior of Vortex System”, TR, NACA TM-713, June 1933.

FIG.1

ROTORS TESTED IN THE EXPERIMENT AND CALCULATION

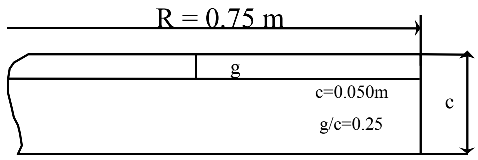
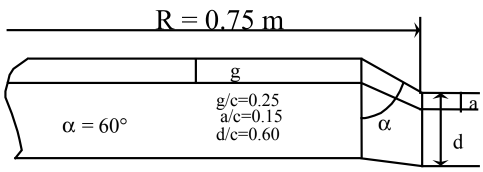
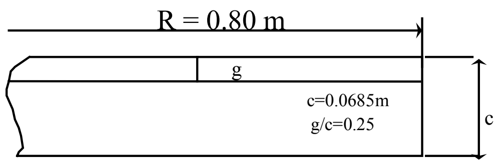
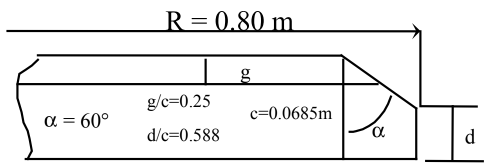
ROTOR NAME	LINEAR TWIST	PLANFORM	AIRFOIL TYPE
LABM 7	-8.3°		OA209
LABM 4	-8.3°		OA209
TSAGI 217	-5.5°		NACA 23010
TSAGI 217A	-5.5°		NACA 23010

Fig. 1. Rotors tested in the experiment and calculation.

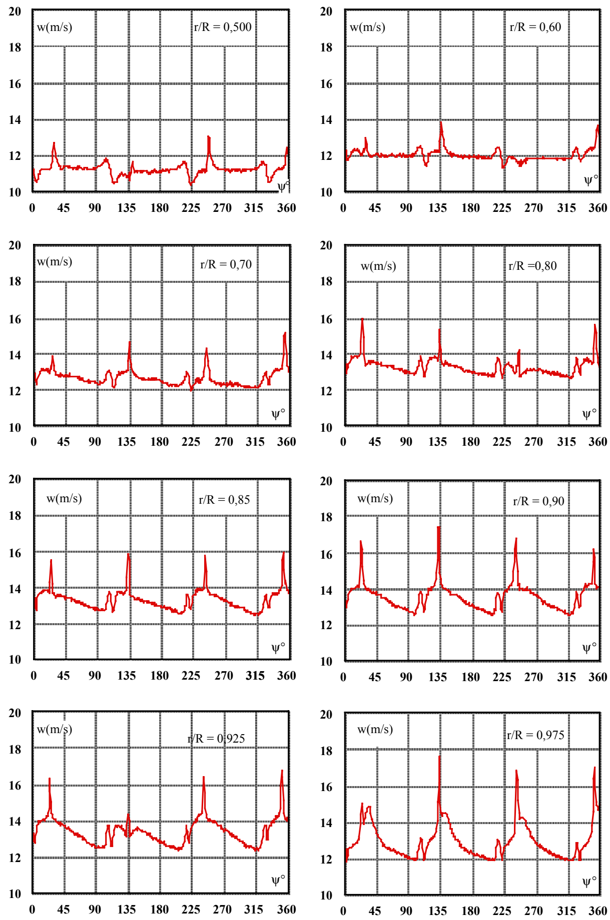


Fig. 2. Instantaneous axial induced velocity at different radial stations in the wake : z/R=0, LABM Rotor 7, θ=10deg

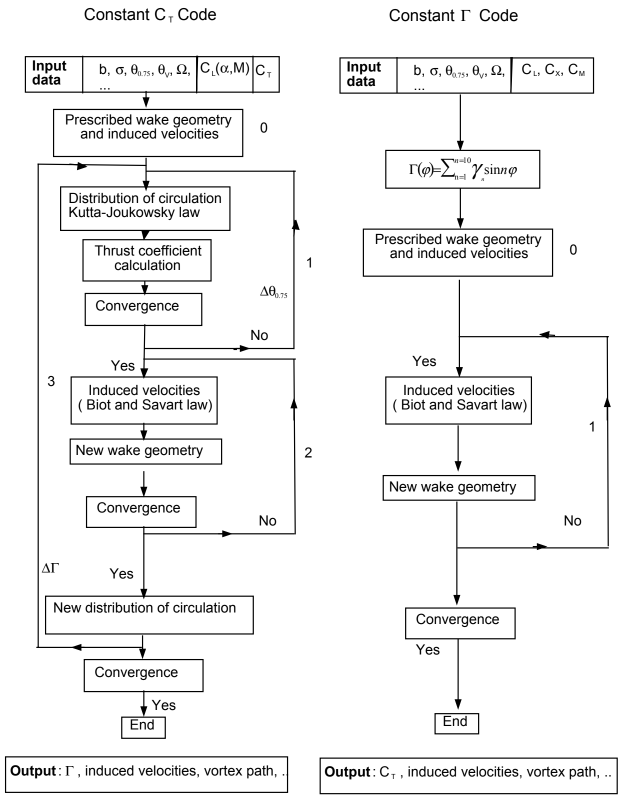


Fig. 3. LABM codes

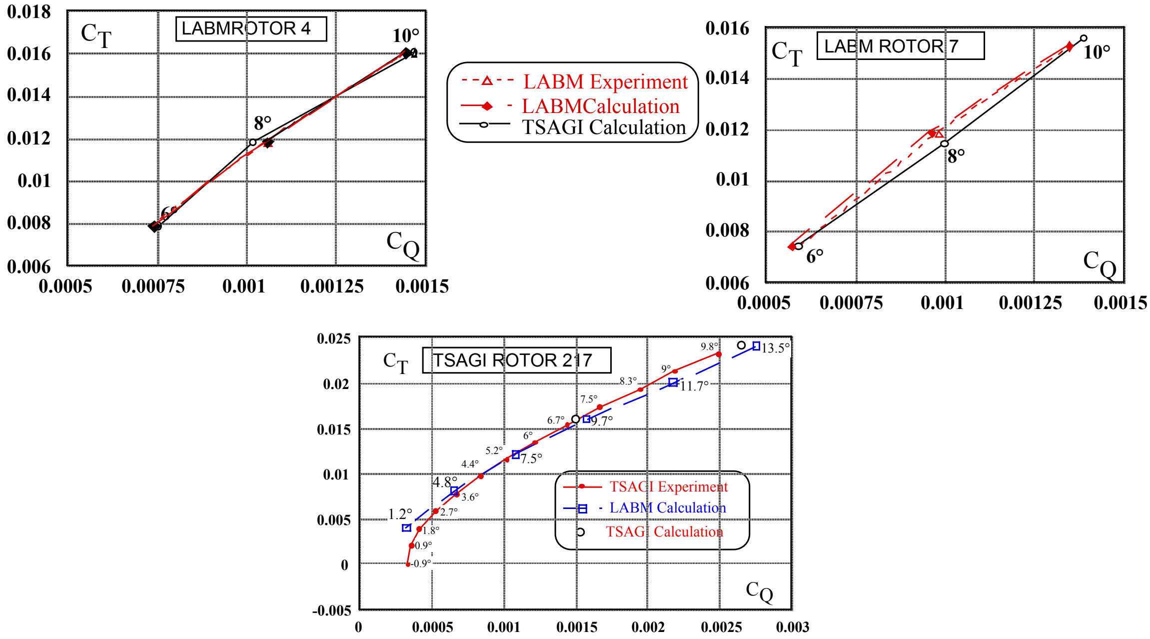


Fig. 4. Experiment and calculation of rotor performances

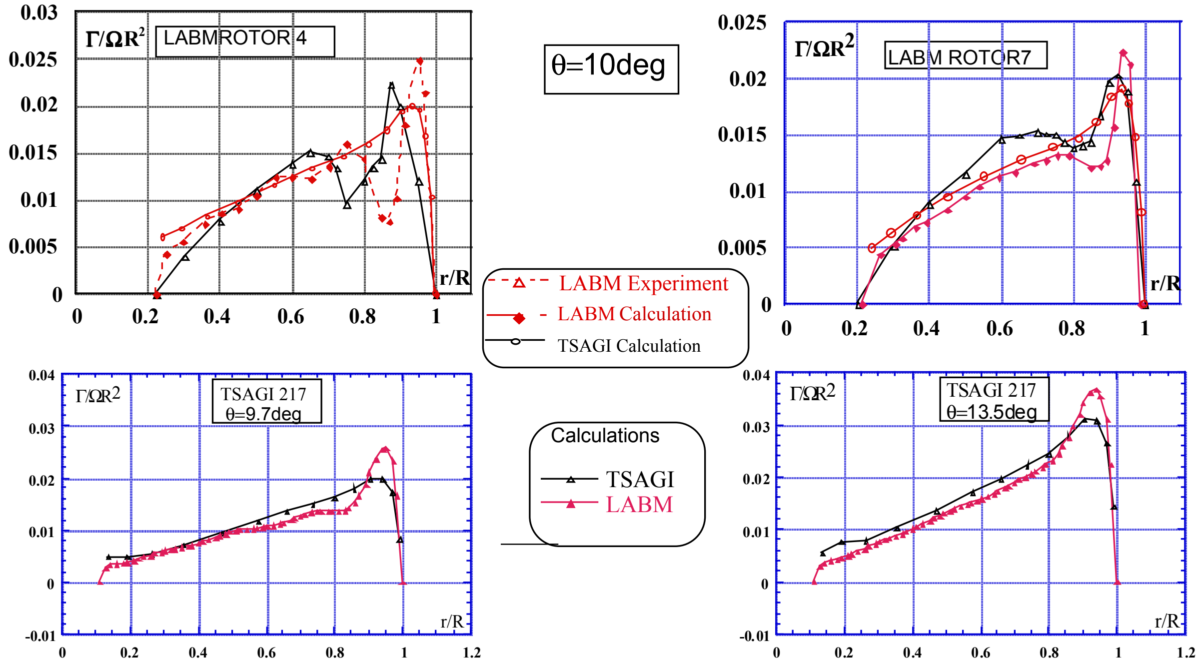


Fig. 5. Circulation distribution along the blades

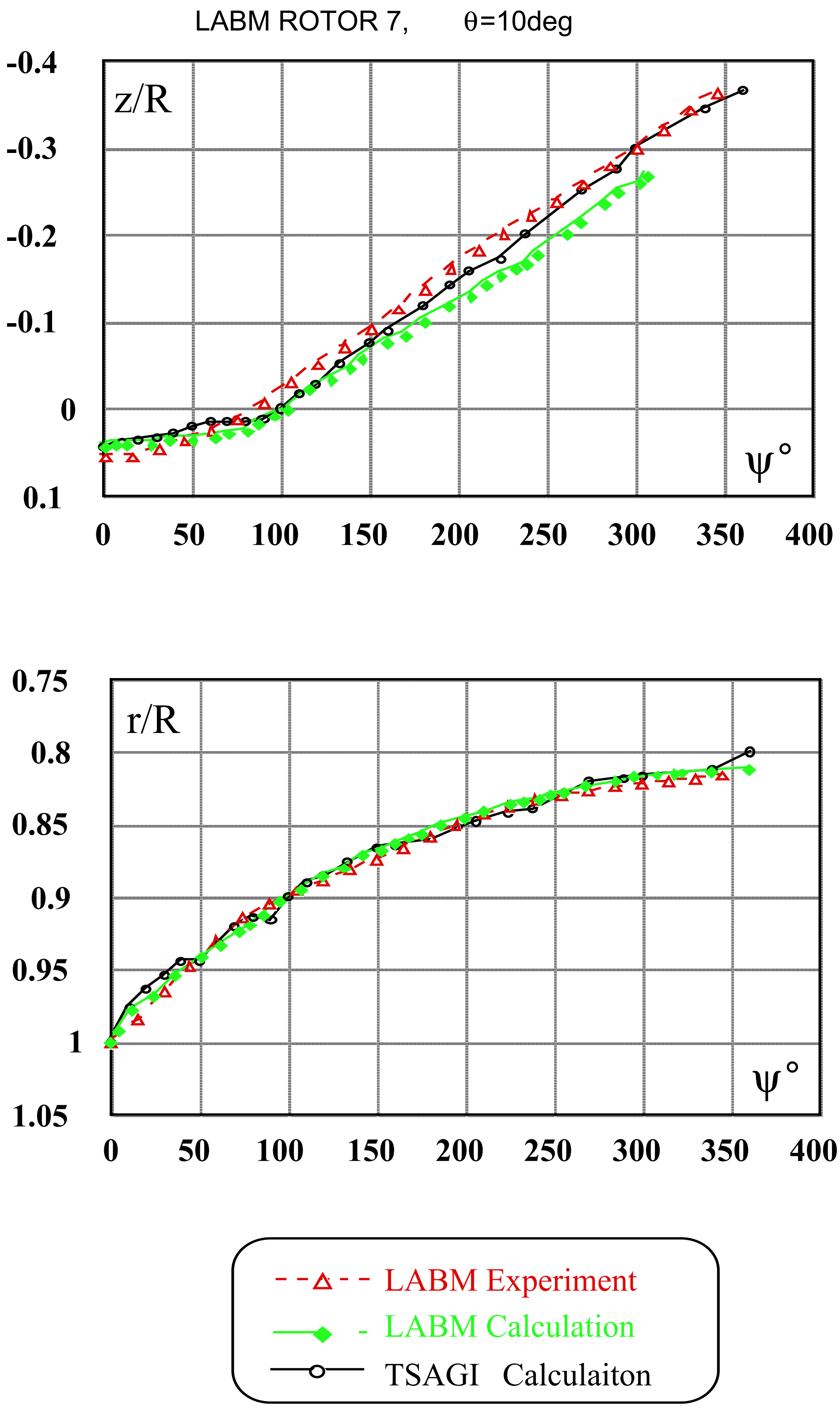


Fig. 6. Tip vortex path

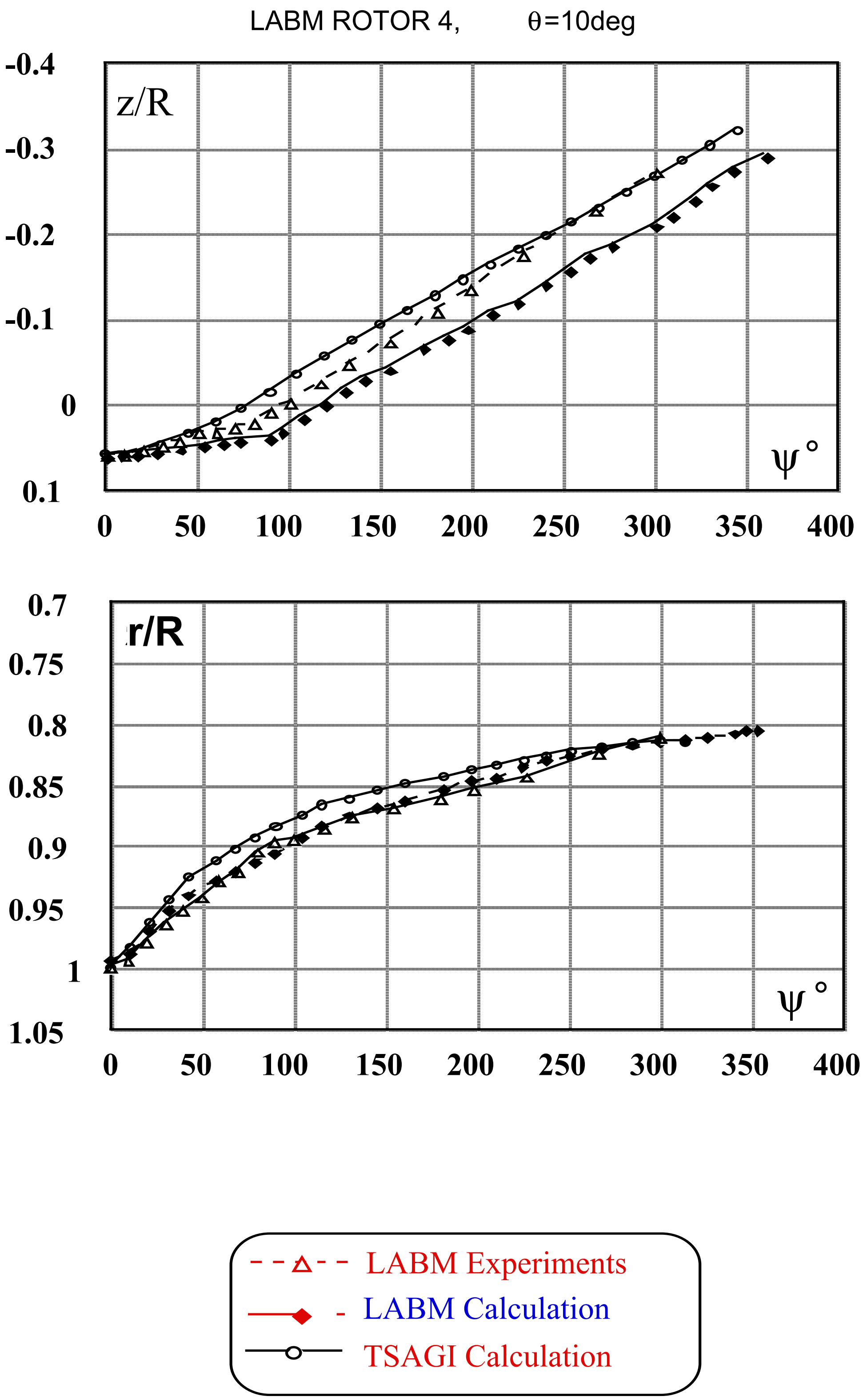


Fig. 7. Tip vortex path

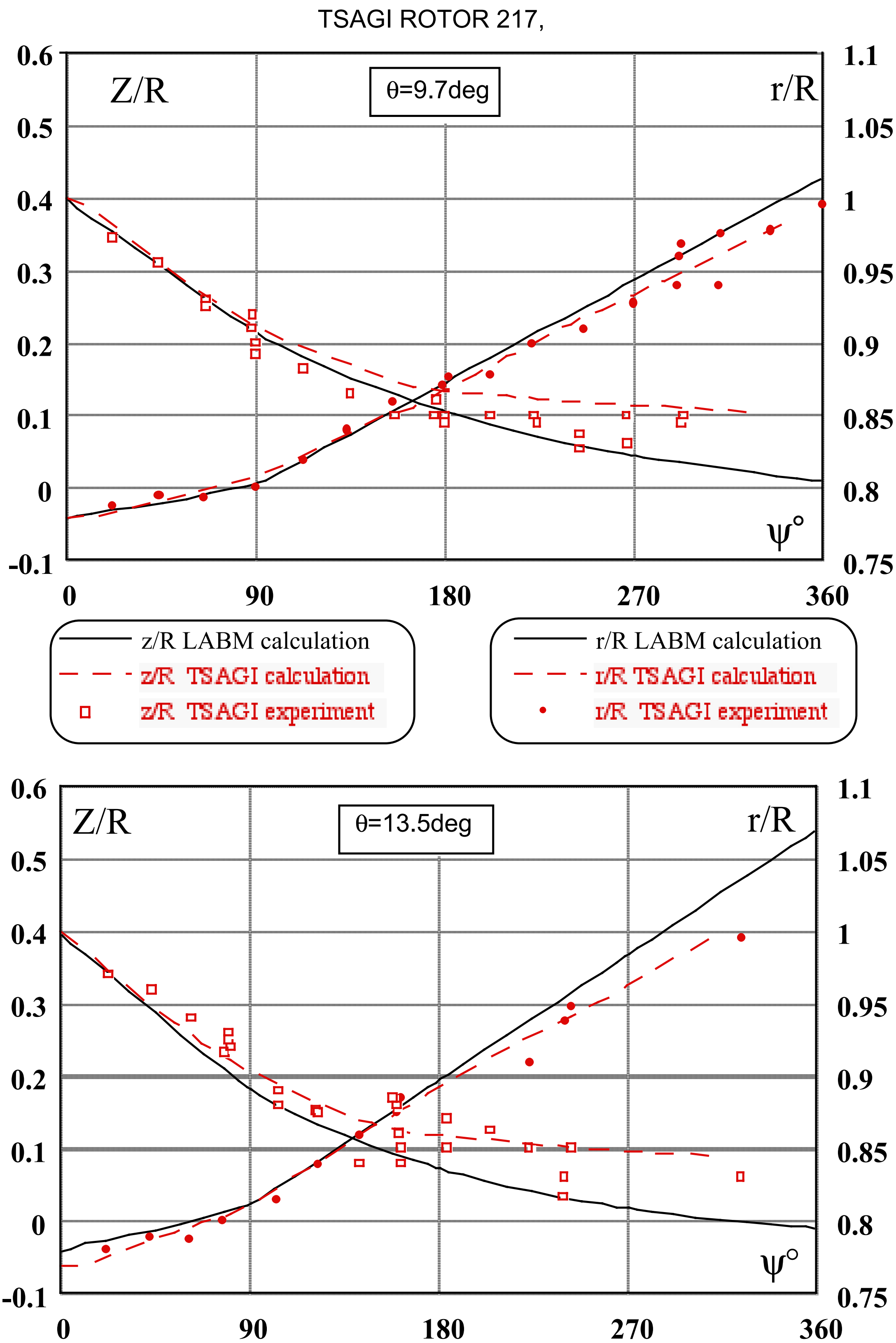


Fig. 8. Tip vortex path

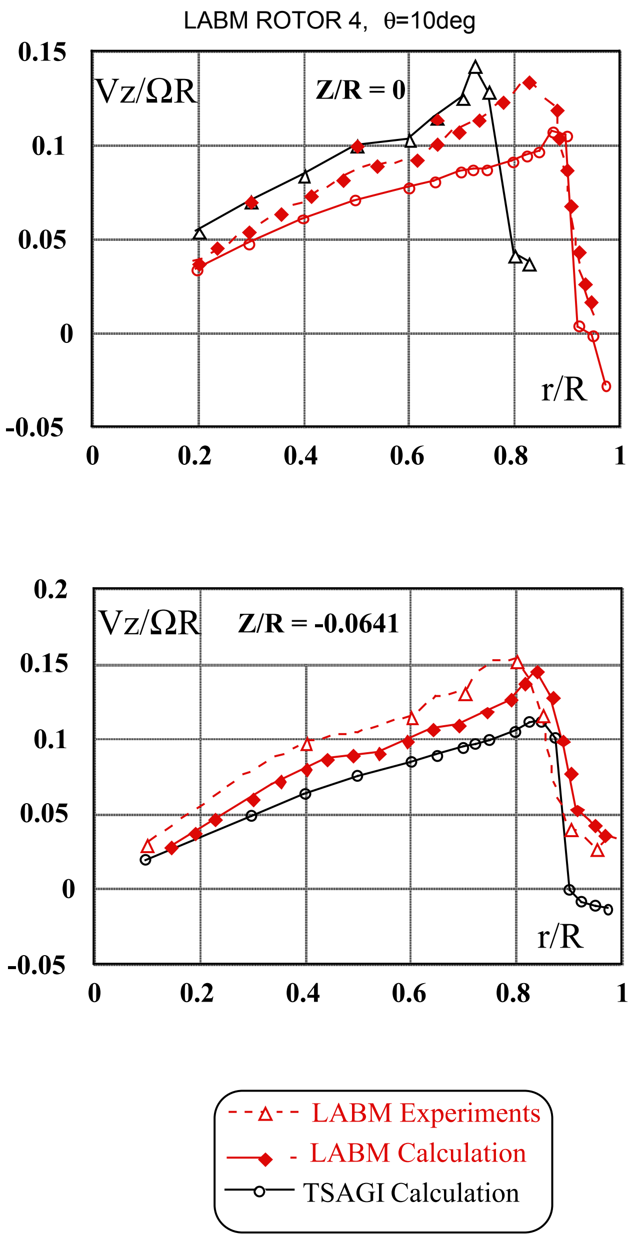


Fig. 9. Mean axial induced velocities

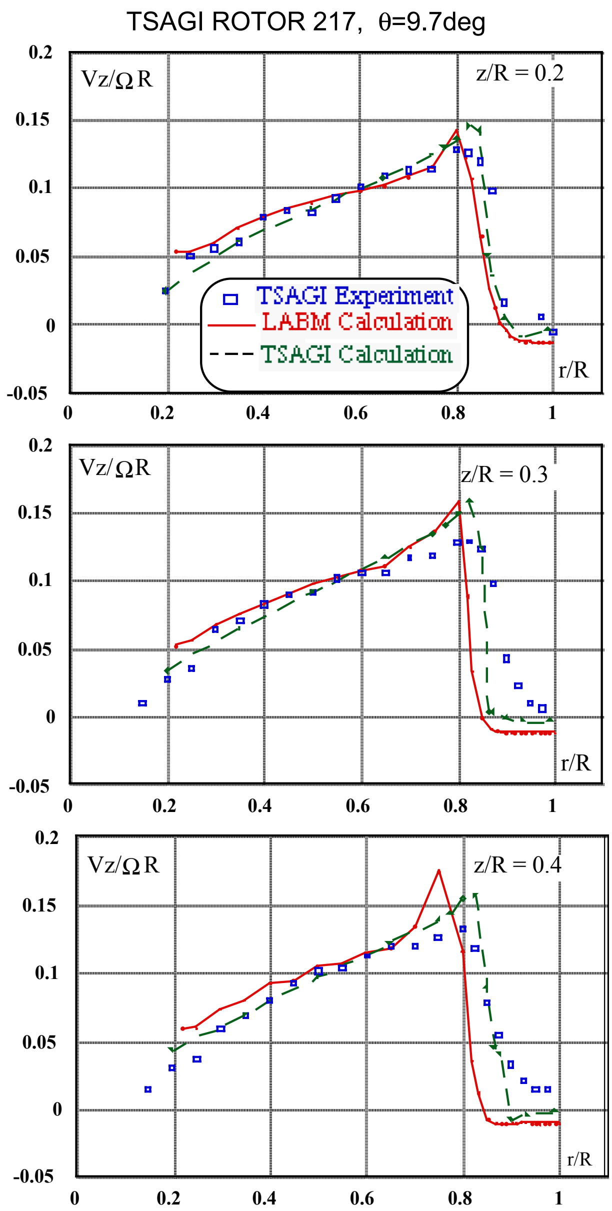


Fig. 10. Mean axial induced velocities

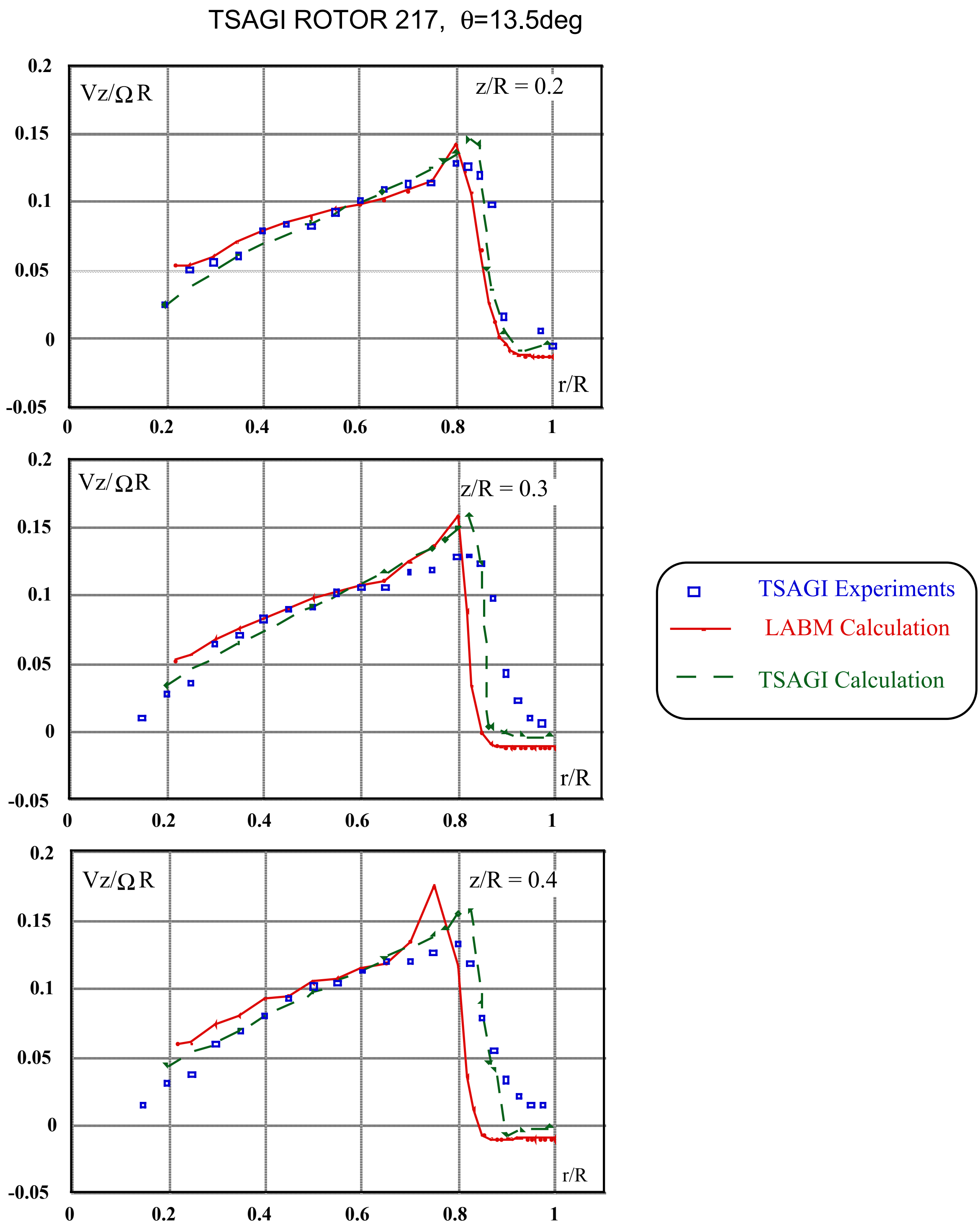


Fig. 11. Mean axial induced velocities

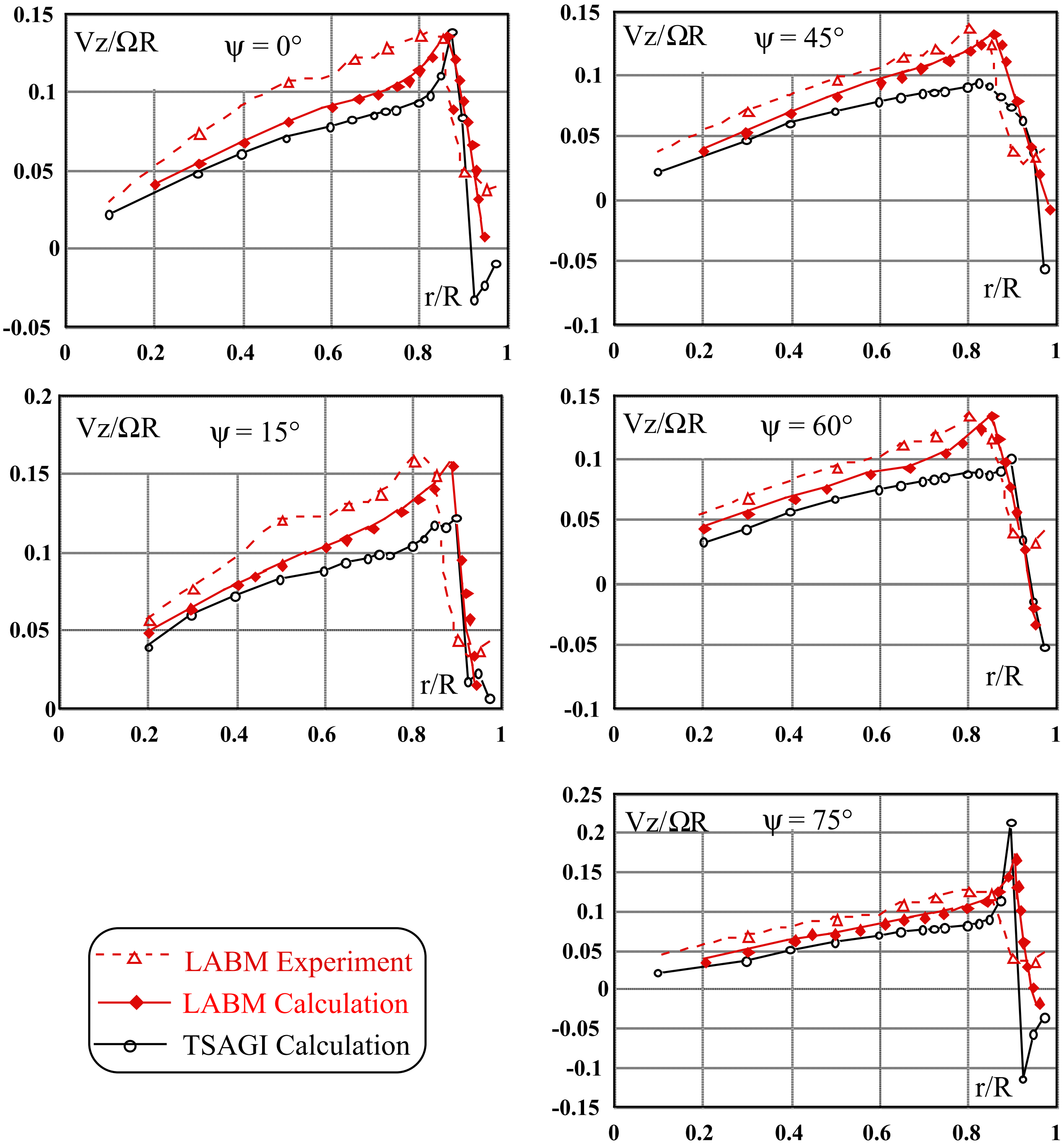


Fig. 12. Instantaneopus axial induced velocities