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# Technical Notes

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## Experimental Investigation of End-Wall Flow in Turbine Rotor

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### Introduction

THE flowfield in the end-wall region of turbine rotors is complex because of the annulus wall boundary layer, blade surface boundary layer, secondary flow, tip leakage flow, and the interaction among these flows. Less work output and higher losses in the turbine stage are results of the complex flows and their interaction. One of these flows, the tip leakage flow and its vortex, could account for up to nearly 30% of total losses in a turbine rotor. The trend in turbine design toward higher loading and lower aspect ratio intensifies the importance of tip clearance effects to turbomachinery designers.

The flowfield in the end-wall region is however one of the least understood phenomena due to difficulty in investigation. Most of the basic research in this area has been confined to cascades. A comprehensive literature review is provided by Sjolander.[1] A few investigations in downstream of turbine rotors have been reported. A recent report[2] reveals a comprehensive investigation of the end-wall flow using a five-hole pitot probe in rotating frame. Because the tip leakage vortex is very small in its early development stage, the measurement from a non-intrusive instrument is a more appropriate choice to provide better accuracy. This Note presents a comprehensive investigation of the flow phenomenon in the endwall region inside a turbine rotor using a non-intrusive instrument.

The objective of the research reported in this Note is to investigate experimentally the flow near the end-wall region, including the tip leakage flow and its effects on the flowfield. A three-dimensional Laser Doppler Velocimetry (LDV) system is used for velocity data acquisition. Secondary velocity and axial vorticity are derived from the velocity data. The circulation of the tip leakage vortex is then integrated from the vorticity distribution.

### Facility, Measurement Technique, and Data Accuracy

A low-speed single-stage axial flow turbine research facility is used in this study. The details of the facility have been reported by Lakshminarayana et al.[3] The test section of the facility incorporates features of a current high-pressure turbine stage. Figure 1 schematically shows the test section and measurement positions. All experimental measurements are performed at design condition. The mean tip clearance is 0.98 mm, or 0.78% of span.

The measurements are carried out within the outer 20% blade height near the end wall. Eight measurement stations are exponentially distributed to cover the 20% blade height. Finer stations are clustered near the end-wall region to improve the resolution of the complex end-wall flow. The eight measurement stations are respectively at $H = 0.800$, 0.846, 0.883, 0.913, 0.936, 0.955, 0.970, and 0.983, where $H$ is relative blade height (0 at hub and 1 at tip). Beyond $H = 0.983$, the accuracy of the LDV data deteriorates as a result of seeding difficulty inside the end-wall boundary layer. In the axial direction nine stations are uniformly distributed from 20% chord to 1% downstream, covering almost the entire end-wall flow region (Fig. 1). These stations are respectively at $X/C_x = 0.20$, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90, and 1.01. In this Note $X$ is the absolute coordinate in axial direction, and $C_x$ is the axial chord at blade tip.

The data acquisition and reduction are accomplished by an ensemble-averaging technique using recorded rotor orientation from a shaft encoder. Ristic et al.[4] provided a detailed description of the technique. A complete data error analysis is given by Zaccaria.[5] Based on this error analysis, the uncertainty of the velocity data for a 95% confidence level is 0.4% in main stream, and 4.0% in flow regions with strong viscous effects. The position accuracy is 0.5 mm, or 0.57% based on rotor axial chord.

### Vorticity Field near End Wall

The measured data show that the velocity field from $X/C_x = 0.2$ to 0.7 is mostly inviscid. The mean velocity varies almost linearly from blade to blade. The leakage flow and its vortex development are not obviously observed until nearly 80% axial chord. Considering the simplicity of the flowfield in this region, the flow velocity data from $X/C_x = 0.2$ to 0.7 are not included in this Note.

From $X/C_x = 0.80$ to downstream, the most important flow features are the passage and the tip leakage vortices as shown in normalized axial vorticity distribution (Fig. 2). The axial vorticitiy $\omega_x$ is calculated from the measured LDV data using the velocity gradients

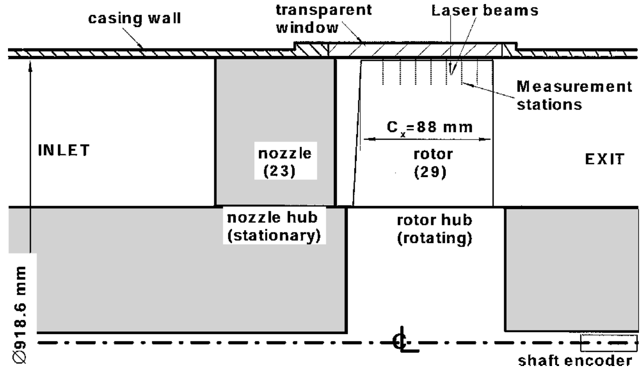


**Fig. 1 Schematic diagram of experimental facility and measurement locations.**

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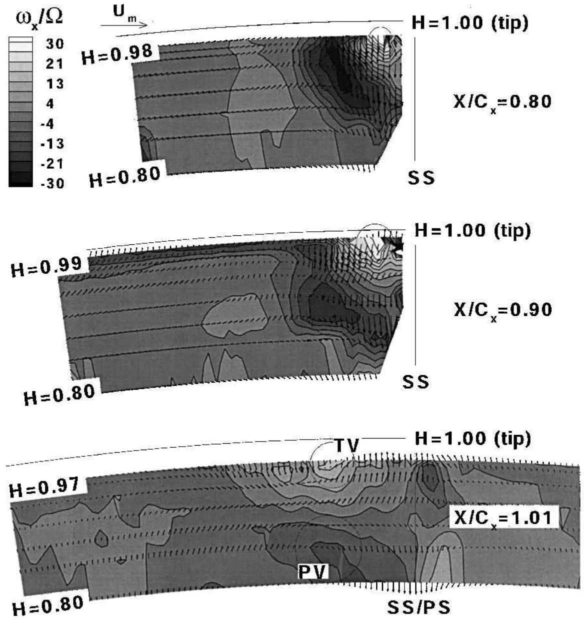


**Fig. 2 Normalized axial vorticity ($\omega_x/\Omega$) and secondary flow.**

in radial and tangential directions as follows:

$$\frac{\omega_x}{\Omega} = \frac{r_m}{r}\left[\frac{\partial(rW_\theta/U_m)}{\partial r} - \frac{\partial W_r/U_m}{\partial\theta}\right]$$

where $\Omega$ is the rotating speed of turbine rotor, $W$ is the relative velocity, $r$ and $\theta$ are respectively the radial and tangential coordinates, $r_m$ is the radius at midspan, and $U_m$ is the blade speed at midspan. Secondary velocity is calculated from the measured velocity by subtracting its corresponding design value.

The upper vortex rotating in counterclockwise direction and marked TV (Fig. 2) is the tip leakage vortex, and the lower vortex rotating in clockwise direction and marked PV is the passage vortex. The tip leakage vortex rolls up near the suction corner in the current turbine rotor as observed in turbine cascades. The axial vorticity distribution (Fig. 2) provides the strongest evidence that a tip leakage vortex does exist near the suction corner. The passage vortex is well organized and its center changes considerably as the flow progresses downstream. At $X/C_x = 0.80$ the center of the vortex is at about 6% blade height from the blade tip. At $X/C_x = 0.90$ the center moves further away from blade tip to about 10% blade height. The center of the passage vortex also progresses in the tangential direction as the flow goes downstream. Figure 2 shows that a strong interaction exists between the two vortices, resulting in an elongation and distortion of their shapes.

## Development of Tip Leakage Vortex: Size and Strength

The size and the circulation of the tip leakage vortex are shown in Fig. 3. Because the shape of the vortex is irregular as a result of the interaction between the passage vortex and wall, equivalent (hydraulic) diameter is employed to represent the size of the vortex. An investigation of the pressure distribution on the blade suction surface indicates that the tip leakage vortex starts near midchord ($X/C_x = 0.50$). The vortex size at the midchord is therefore set to zero. The size of the tip leakage vortex gradually grows until $X/C_x = 0.80$, then starts to rapidly grow until about $X/C_x = 0.90$ (Fig. 3). After its rapid growth the diffusion dominates the tip vortex development and its size growth slows down.

The circulation associated with the tip leakage vortex is integrated from the axial vorticity distribution (Fig. 2) and normalized by the ideal circulation ($\Gamma_{\mathrm{2Dtip}}$) around the turbine blade profile. The shed circulation ($\Gamma_{\mathrm{shed}}$) is given by

$$\Gamma_{\mathrm{shed}} = \Gamma_{\mathrm{2Dtip}} - \Gamma = \iint_A \omega_s \, \mathrm{d}A_s = \iint_A \omega_x \, \mathrm{d}A_x$$

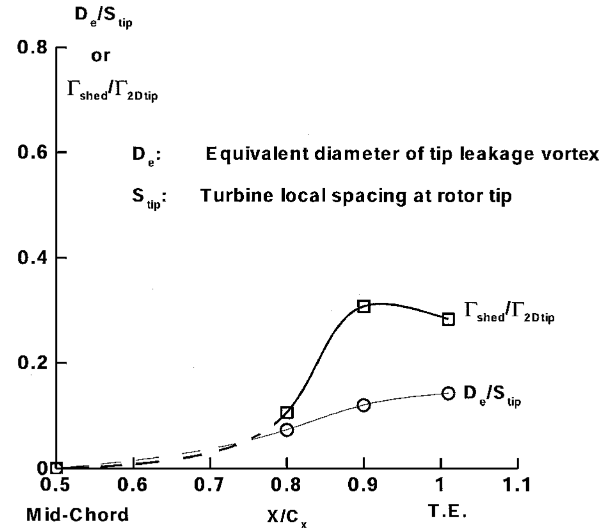


**Fig. 3 Development of tip leakage vortex size and strength.**

where $\Gamma$ is the circulation remained at blade tip; $\omega_s$, $\omega_x$ are the vorticity components along streamwise and axial directions, respectively; $A$ is the area near the end wall region where axial vorticity is positive (due to the tip leakage vortex); and $A_s$, $A_x$ are the areas normal to $\omega_s$ and $\omega_x$, respectively.

The development of the vortex size shows a similar trend to the development of the vortex ciculation (Fig. 2). Rapid development occurs from about 80% chord to about 90% chord, at which vortex diffusion starts to dominate the developing process. Some vorticity might even disperse to an area beyond the measurement region (20% blade height). At the trailing edge about 30% of bound vorticity is shed into the blade passage as the tip leakage vortex.

## Conclusions

A detailed flowfield measurement is carried out near the end-wall region in a turbine rotor using the three-dimensional Laser Doppler Velocimetry technique. A complex flowfield is observed inside this turbine rotor from about 80% chord to downstream. A tip leakage vortex is identified. The most rapid development of the vortex occurs from about 80% chord to about 90% chord. Approximately 30% of bound vorticity is shed into the blade passage as the tip leakage vortex at trailing edge.

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