MEASUREMENTS OF THE TIP CLEARANCE FLOW
FOR A HIGH REYNOLDS NUMBER AXIAL-FLOW ROTOR:
PART 2 – DETAILED FLOW MEASUREMENTS

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ABSTRACT
A high Reynolds number pump (HIREP) facility has been used to acquire flow measurements in the rotor blade tip clearance region—with blade chord Reynolds numbers of 3,900,000 and 5,500,000. The initial experiment involved rotor blades with varying tip clearances, while a second experiment involved a more detailed investigation of a rotor blade row with a single tip clearance. This paper focuses on detailed flow measurements of the tip leakage vortex. These detailed measurements show the effects of tip clearance size and downstream distance on the structure of the rotor tip leakage vortex. The character of the velocity profile along the vortex core changes from a jet-like profile to a wake-like profile as the tip clearance becomes smaller. These vortex velocity profiles—as well as the levels of unsteadiness—dominate the rotor wake structure in the endwall region. Also, for small clearances, the presence and proximity of the casing endwall affects the roll-up, shape, dissipation, and unsteadiness of the tip leakage vortex. Measurements also show how much circulation is retained by the blade tip and how much is shed into the vortex—a vortex associated with high losses.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
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<tr>
<td>A</td>
<td>amplitude of oscillation</td>
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<tr>
<td>c_{dp}</td>
<td>blade chord at rotor tip</td>
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<tr>
<td>C_{dP}</td>
<td>total-pressure variation coefficient = \frac{\Delta P_r}{\frac{1}{2} \rho V_{rT}^2}</td>
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<td>h</td>
<td>rotor tip clearance</td>
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<td>N_b</td>
<td>number of blades</td>
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<td>\rho</td>
<td>static pressure</td>
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<tr>
<td>r</td>
<td>radius (relative to tunnel axis)</td>
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<td>r_e</td>
<td>vortex core radius</td>
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<td>Re_{w}</td>
<td>blade tip chord Reynolds number = \frac{W_1 c_{dp}}{\nu}</td>
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<td>W</td>
<td>relative velocity</td>
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<td>\Gamma_r</td>
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Subscripts

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INTRODUCTION

Beginning in the pressure surface boundary layer near the rotor blade tip, a vortex sheet passes through the clearance. Under the influence of the induced velocity field of the vortex sheet, the free edge of the vortex sheet curls over and takes the form of a spiral with a continually increasing number of turns: the roll-up of the tip leakage vortex. As opposed to a wing or a rotor blade tip without an endwall, the higher blade loading produces a larger pressure difference between the pressure and suction sides of the blade, and this pressure difference produces a jet of fluid that carries the vortex sheet through the clearance. Storer and Cumpsty [1991] show that this distinct jet of low-loss fluid occurs downstream of the minimum pressure location on the suction surface. Beside the curling of the free edge of the vortex sheet, the formation of the tip leakage vortex also includes the strong interaction between the leakage jet and the throughflow—further complicating the roll-up of the vortex. Storer and Cumpsty [1991] feel that the interaction of the leakage jet and the throughflow produces an intense shearing that is the principal mechanism of the high loss associated with tip leakage vortices.

Questions still remain concerning the fluid dynamics of the rotor tip leakage vortex—questions that prompted two experiments performed in our high Reynolds number pump (HIRE?), a facility described in the companion paper (Zierke, Farrell, and Straka [1994]). This first paper presented and discussed the experimental results obtained primarily from flow visualization. In this second paper, we will present and discuss results from detailed flow measurements.

EXPERIMENTAL TECHNIQUE

The large-scale HIREP facility can accommodate a variety of instrumentation in both a stationary and a rotating frame of reference. A high-capacity, low-noise slip ring accommodates many measurements in the rotating frame. An incremental, optical shaft encoder provides rotor angular position and speed.

Both the first and second experiments employed many of the same experimental techniques. Calibrated five-hole pressure probes were used to obtain the HIREP inlet flow, as well as the casing endwall boundary layer upstream of the rotor blades. For studying the tip clearance flow, we acquired most of our flow field data with a two-component laser Doppler velocimeter (LDV). The argon-ion laser and associated optics—including Bragg cells for frequency shifting—were mounted on a three-axis traversing table that helped position the location of the measurement volume at the desired flow field location. All of these measurements were made on the test section centerline through a specially designed window. Data were collected using a field point measurement method. In this procedure, the measurement volume remains stationary, and each LDV measurement sample is tagged with the angular position of the rotor—via the optical shaft encoder and a rotating machinery resolver. The water tunnel was seeded with 1.5 \( \mu \text{m} \) silicon carbide particles to increase the data collection rates. Typically, for every position of the LDV measurement volume, a total of 100,000 samples were obtained, of which approximately 50\% were axial velocity measurements and the other 50\% tangential.

A few experimental techniques were unique to the initial HIREP experiment. First, we implemented a dynamic gap measuring system to show that the low angular speed of the rotor did not change the rotor tip clearance from its static value. With this point proven, we did not implement the system in the second experiment. Second, one of the original rotor blades employed a two-component rotor tip force transducer to measure steady-state hydrodynamic loads over the top 10\% of the rotor blade span. This instrumented blade was varied to measure the amount of integrated lift for rotor blades with four different tip clearances. Finally, this initial experiment employed several piezoresistive pressure transducers flush mounted on the rotor blade tip and on the inner diameter of the casing. The three transducers at 99\% span were located at 10\% and 50\% chord on the pressure surface and at 40\% chord on the suction surface. Also, two transducers were located at 50\% chord, one on the tip surface and one on the casing. Farrell [1989] gives further details of the experimental technique used during this first HIREP experiment.

Besides acquiring a larger quantity of data—especially LDV data—we did utilize some additional experimental techniques in the second HIREP experiment. For this experiment, we employed fast-response total-pressure measurements in the same downstream axial plane as some of the LDV measurements, using a probe equipped with a subminiature piezoelectric pressure transducer. Zierke, Straka, and Taylor [1993] give further details of the experimental techniques used during the second HIREP experiment.

EXPERIMENTAL RESULTS

Using the techniques described previously, we performed both experiments within HIREP in order to investigate the tip clearance flow. Since the second experiment involved a larger quantity of detailed data, we shall focus on the results from this experiment. However, results from the first experiment will also be given—especially where they give insight into the effect of a varying tip clearance. Geometrically, the rotor blades from both experiments are quite similar. In the second experiment, the tip chord length is a little larger, giving a tip chord Reynolds number of 5,500,000, compared to 3,900,000 for the first experiment.

Rotor Blade Exit Flow

With all of the LDV data resolved into one degree storage windows, we analyzed the data taken in various axial planes. These measurements included one plane from the first experiment (34.0\% chord downstream of the rotor tip trailing edge) and three planes from the second experiment (4.8\%, 21.4\%, and 32.2\% chord downstream). An analysis showed that no inlet guide vane wake was present in the vicinity of the LDV measurement volume. The presentation here will show only a few significant results from this large quantity of data.

At the furthest downstream axial position in the second experiment, the LDV data provides information on the relative importance between the wakes and the tip leakage vortices in the casing endwall region. Near this endwall and at the furthest downstream measurement plane in the second experiment, Figure 1 presents variations in the axial velocities around the circumference of the machine. At 88.1\% span, Figure 1 shows axial velocity deficits associated with the rotor blade wakes. Also at 88.1\% span, the regions of increased axial velocity between the
wakes result from the three-dimensional influence of the tip leakage vortices. Just closer to the endwall, at 90.5% span, the wakes have a similar deficit, but the tip leakage vortices also have a similar axial velocity deficit—with a broader profile. For the axial velocity distributions at radial locations even closer to the endwall, notice how the flow structures associated with the tip leakage vortices dominate the structures associated with the wakes, having much deeper and broader profiles. With these strong deficits in axial velocity, the tip leakage vortices would have a strong impact on any downstream blades or struts. While many investigators have examined the detrimental effects of blades interacting with wakes created by upstream blades with relative motion, Binder [1985] and Binder, Forster, Mach, and Rogge [1987] have shown that secondary vortices downstream of a row of turbine stator blades will have strong unsteady interaction effects with downstream rotor blades. Not only will the velocity deficits associated with secondary vortices create unsteady interaction effects in the same manner as wakes, Binder [1985] and Binder, Forster, Mach, and Rogge [1987] find that the interaction of blades with vortices can lead to vortex breakdown, which gives rise to a large increase in turbulent fluctuations.

Vortex Models

Visualization of the rotor tip leakage vortex from the first paper (Zierke, Farrell, and Straka [1994]) provided very important information on the position of the vortex, as well as information on the vortex unsteadiness. However, for a complete analysis, one must also examine details about the velocity profiles and strength of the vortex. In order to examine these details associated with any vortex in a measured velocity field, one can compare the measurements with ideal formulations of a vortex velocity distribution. First, one must transform the data from a cylindrical coordinate system associated with the turbomachine to a cylindrical coordinate system aligned with the axis of the vortex. In the case where no measurements exist of radial velocity in the turbomachine coordinate system, one can attempt to find an angle between the axial direction of the turbomachine and the axial direction of the vortex and, then, transform the velocity components using this angle. Either before or after transforming

\[
\frac{V_x V_y}{U^2_{	ext{ref}}} = 100
\]

**FIGURE 1. CIRCUMFERENTIAL VARIATION OF THE AXIAL VELOCITY MEASURED 32.2% CHORD AXIALLY DOWNSTREAM OF THE ROTOR TIP TRAILING EDGE WITH LDV.**

A more detailed investigation showed that the circumferential variation in tangential velocity and in the axial and tangential nondeterministic unsteadiness (unsteadiness that does not correlate with rotor shaft speed) also show the dominance of the tip leakage vortices. As shown in the first paper (Zierke, Farrell, and Straka [1994]), the nondeterministic unsteadiness associated with tip leakage vortices involves turbulence, as well as a random motion of the vortex structures themselves. Figure 2 presents a contour plot of the axial nondeterministic unsteadiness at the farthest downstream axial position in the second experiment. The locations of the skewed rotor blade wakes and the tip leakage vortices are very clear. In terms of turbulence intensity, the wakes within the casing endwall region reach maximum values of 14.9% for axial turbulence intensity and 12.1% for tangential turbulence intensity. Using the same freestream velocity for normalization, the tip leakage vortices reach values of 21.2% for axial turbulence intensity and 22.6% for tangential turbulence intensity. All of the variations in velocities and unsteadiness have been examined at the two upstream measurement planes. Although similar in shape, these distributions show larger velocity deficits and increased unsteadiness levels—a trend consistent with viscous decay. Also, variations associated with potential flow effects are more evident at the upstream planes.
the velocity components, one should also make sure that the axial and tangential velocities are velocity perturbations caused by the presence of the vortex. One can simulate these velocity perturbations by subtracting the circumferential-average velocities from the locally measured velocities. Finally, one must take the effect of vortex wandering into account.

Zierke, Straka, and Taylor [1993] give details of the ideal formulations for the Rankine vortex and the Burgers vortex, which were used with the LDV data in the analysis of the rotor tip leakage vortex measured in HIREP. For simplicity, the formulation for axial velocity presented by Maxworthy, Hopfinger, and Redekopp [1985] will be included as part of the Burgers vortex.

**Axial Velocities within the Tip Leakage Vortex**

A strong coupling exists between the tangential and axial velocities of a vortex. The instabilities in the initial roll-up of a vortex can lead to either an excess or deficit of the axial velocity in the vortex core, relative to the freestream. As the vortex begins to convect downstream within the blade passage, the circulation (and maximum tangential velocity) about the core increases as more vorticity is continuously wound into the core region. From the conservation of momentum across the vortex,

\[
\frac{\partial \rho}{\partial t} + \frac{V_z^2}{r} = 0,
\]

this increase in vorticity and tangential velocity causes a drop in the centerline pressure which, in turn, increases the axial velocity. Batchelor [1964] discusses the theory of axial velocities in tip vortices in more detail.

For tip vortices without the presence of an endwall, several investigators have found this jet-like behavior in axial velocity. For instance, Singh and Uberoi [1976] used a hot-wire probe to measure the tip vortices from a wing at an angle of attack. The tip vortex, which originated near the leading edge, contained an axial jet in the vortex core near the trailing edge. This jet decayed to zero in about 2.4 chord lengths and then further decayed into a wake-like structure, with an expansion in the core size. Two chord lengths downstream of the trailing edge, Orioff [1974] acquired LDV data through the tip vortex at three angles of attack. While he measured axial velocity deficits at the two lowest angles of attack, he measured an axial velocity excess at the highest angle of attack. Measurements showed that the

**Tangential Velocities about the Tip Leakage Vortex**

The roll-up of the tip leakage vortex produces a swirling flow about the centerline of the vortex. Using the procedure outlined in the previous section, we determined the tangential or azimuthal velocity about the vortex axis at the three downstream LDV measurement planes. First, we subtracted the circumferential-average values (using area averaging) from the measured axial and tangential velocities. Then, we found that the angle between the

**FIGURE 3. TANGENTIAL VELOCITY PERTURBATION DISTRIBUTIONS FOR THE ROTOR TIP LEAKAGE VORTICES MEASURED 4.8%, 21.4%, AND 32.2% CHORD AXIALLY DOWNSTREAM OF THE Rotor TIP TRAILING EDGE.**
higher loading at the increased angle of attack gave a tip vortex with larger tangential velocities. Again, the larger tangential velocities reduce the pressure at the centerline of the vortex, which increases the axial velocity. Finally, in a similar wing experiment, Lee and Scheiz [1985] used a five-hole probe to measure the tip vortex six chord lengths downstream of the trailing edge at chord Reynolds numbers ranging from 210,000 to 1,500,000. While changes with downstream distance due to viscous diffusion are slow, they found large changes in the vortex structure with Reynolds number. The tangential velocity—and, thus, the axial velocity—increased with Reynolds number until the largest chord Reynolds number yielded an axial jet, even at a distance six chord lengths downstream of the trailing edge.

For tip leakage vortices, the vortex structure changes because of the presence and proximity to the endwall. From the first HIREP experiment, at a position 34.0% chord axially downstream of the tip of the rotor blade trailing edge, Figure 4 shows how the tangential velocity within the tip leakage vortex changes with tip clearance, while Figure 5 shows how the axial velocity changes. Remember that these measured vortex characteristics result from an experiment with a blade chord Reynolds number of 3,900,000.

For large tip clearances ($h/c_{tip} = 0.547$ and 0.540), large tangential velocities and jet-like profiles of axial velocity exist. As the clearance decreases ($h/c_{tip} = 0.329$), the tangential velocity decreases and the axial velocity vanishes. Finally, for small clearances ($h/c_{tip} = 0.279$ and 0.099), the tangential velocity reduces further, giving wake-like profiles of axial velocity. Also, the lack of axisymmetry in the vortices for smaller clearances results from the close proximity of the endwall. Observations for smaller clearances also showed that the vortices originate closer to the leading edge and that these vortices experience more vortex kinking and oscillation.

As a possible explanation for the change in vortex structure with changing clearance, consider the pressure field in the flow external to the vortex. Within the blade passage—especially near the suction surface, closer to the vortex—the vortex convects through a region with an adverse pressure gradient. The static pressure within the core of the vortex increases as the vortex convects through this external adverse pressure gradient and reduces the axial velocity. As Erickson [1981] points out, the pressure increase within the core will be larger than that of the external flow. This result occurs because the external adverse pressure gradient also reduces the tangential velocity of the vortex (see Figure 4) which, in turn, increases the static pressure in the core and reduces the axial velocity. Downstream of the blade passage, the external pressure gradient diminishes and the vortex changes form only in response to viscous effects, requiring hundreds of vortex core diameters for significant structural changes. As the clearance increases, the loading of the tip section decreases and less of the circulation is retained at the blade tip. Instead, more circulation is shed into the vortex. This reduction in blade loading also decreases the streamwise adverse pressure gradient—resulting in larger axial velocities in the tip leakage vortices corresponding to larger clearances.

![FIGURE 4. TANGENTIAL VELOCITY PERTURBATION DISTRIBUTIONS WITHIN THE TIP LEAKAGE VORTICES FROM VARIOUS CLEARANCES MEASURED 34.0% CHORD AXIALLY DOWNSTREAM OF THE ROTOR TIP TRAILING EDGE.](image1)

In a different, but related explanation, consider the leakage flow as the clearance increases and more circulation is shed into the tip leakage vortex. Recall that the oil-paint patterns from the first HIREP experiment showed that the angle between the relative skin-friction lines and the chord line decreased with increasing clearance (as shown in the first paper by Zierke, Farrell, and Straka [1994]). Erickson [1981] considered the familiar spiral sheet model of the vortex, where the inclination of the spiralling vortex lines to the vortex axis is such as to make them all induce a downstream component of velocity along the axis. If the streamlines move in a circular motion along the vortex sheet and the orthogonal vortex lines move parallel to the vortex axis, one
has a circular vortex with no axial velocity. Relative to the axis, larger inclinations of the vortex lines induce larger velocities along the axis. This result corresponds to a decreasing angle between the streamlines and the vortex axis. Therefore, from the relative skin-friction lines observed in the first HIREP experiment, increases in clearance should give a larger component of velocity along the vortex axis.

At 32.2% chord downstream of the tip of the rotor blade trailing edge, viscous dissipation appears to reduce the defect in axial velocity. From Figure 3, note that the tangential velocities also decrease; the usual coupling between that tangential and axial velocities does not hold. Also, from both the tangential and axial velocity profiles, note that the structure of the asymmetric vortex appears to be changing faster than one might expect from viscous dissipation alone. Again, the presence and proximity of the casing endwall seems to be having a strong influence on the tip leakage vortex. Phillips and Head [1980] suggest that large-scale motions within the turbulent endwall boundary layer will obscure and absorb the tip leakage vortex. Barker and Crow [1977] studied the interaction of a vortex pair with a wall. In the vicinity of the wall, the vortex showed a strong eccentricity, with the normally circular vortex core becoming elliptical. The deformed vortex core then became unsteady. Further complications occur in the formation of the tip leakage vortices within HIREP; namely, the casing endwall affected the vortices before they were fully rolled-up. If one measured these vortices even farther downstream, they might exhibit the "rebounding" or "bouncing" effect that airplane wing tip vortices experience when interacting with the ground.
profiles for the tip leakage vortices at all three axial measurement planes, compared to the Rankine and Burgers vortices. The measured vortices at all three axial positions are similar, with the strong asymmetry giving a larger peak in tangential velocity at the edge of the core nearest to the endwall. The vortex furthest upstream compares better with the Burgers vortex than the downstream vortices. Next, using the minimum axial velocity with the Maxworthy, Hopfinger, and Redekopp [1985] empirical fit for the Burgers vortex, Figure 8 presents the nondimensional axial velocity profiles for all three tip leakage vortices. These asymmetric vortices all have minimum values of axial velocity that vary slightly from the vortex centers as found from the tangential velocity profiles. Also, the measured axial velocity gradients appear larger than those indicated by the Burgers vortex.

![Figure 8. Nondimensional Axial Velocity Distributions for the Rotor Tip Leakage Vortices—Measurements and Ideal Formulations.](image)

The measured values of \( r_e \) and \( (V_e)_{\text{max}} \) allow us to compute the total circulation of the tip leakage vortex, \( \Gamma_e = 2\pi r_e (V_e)_{\text{max}} \). Using the oscillating vortex model of Straka and Farrell [1992] and the amplitude of oscillation determined from the cavitation visualization in the first paper (Zierke, Farrell, and Straka [1994]), \( A/r_e = 2.1 \), we approximated how the vortex parameters change from the averaging effect of vortex wandering. Table 1 presents these vortex parameters at all three measurement planes. As also seen in Figure 7, Table 1 shows that the size of the vortex initially grows and then remains constant, while the values of \( (V_e)_{\text{max}} \) decrease as the vortex convects downstream. Also, Table 1 shows a decrease in \( \Gamma_e \) with increasing axial distance. Actually, one might expect the vortex circulation to increase as it leaves the blade passage since streamwise vortices within the trailing vortex sheet should be wound into the tip leakage vortex. However, viscous dissipation can reduce \( (V_e)_{\text{max}} \) and, thus, reduce the circulation—with the casing endwall seemingly increasing this dissipation. Two other points must be considered. First, a further examination of Figure 7 will show that the density of LDV data near the edge of the vortex core farthest from the casing endwall may not be sufficient—increasing the uncertainty of the vortex core parameters. Second, the values of \( (V_e)_{\text{max}} \) taken at this edge of the vortex core may not be representative of the actual values of \( (V_e)_{\text{max}} \) within this asymmetric, elliptical vortex core—resulting in smaller estimates of the circulation.

**TABLE 1. MEASURED AND CORRECTED PARAMETERS FOR THE ROTOR TIP LEAKAGE VORTICES.**

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<th>( z/z_0 )</th>
<th>0.048</th>
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<td>16.8</td>
<td>16.8</td>
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<tr>
<td>( (V_e)_{\text{max}} ) (m/sec)</td>
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<td>( \Gamma_e ) (m/sec)</td>
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<tr>
<td>( (V_e)_{\text{max}} ) (m/sec)</td>
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<td>2.02</td>
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<tr>
<td>( \Gamma_e ) (m/sec)</td>
<td>0.119</td>
<td>0.103</td>
<td>0.066</td>
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**Retained Lift**

As mentioned previously, not all of the bound circulation in the blade is shed downstream into the rotor tip leakage vortex—unlike the case of a tip vortex without the presence of an endwall. Lakshminarayana and Horlock [1962] first suggested changing their lifting line model to account for the circulation retained at the blade tip, and this modification formed the basis for the improved model of Lakshminarayana [1970]. Later, using the leakage jet model of Rains [1954], Lewis and Yeung [1977] developed another model for the retained lift. These models imply that the fluid between the tip and the endwall will effectively experience a lift force that is related to the circulation shed into the tip leakage vortex.

For the second HIRep experiment, we can determine the circulation at all spanwise locations by computing

\[
\Gamma = \frac{2\pi}{N_b} \left( r_2 \overline{V_y} - r_1 \overline{V_y} \right)
\]

along a streamsurface around the entire circumference of the machine, where \( N_b \) is the number of blades. Assuming cylindrical streamsurfaces, we used measured values of tangential velocity to compute the spanwise variation of circulation on the
rotor blades. These results showed that the value of circulation at the rotor blade tip is roughly 0.325 m\(^2\)/sec, and that the circulation decreases across the clearance, where the circulation should vanish at the casing. Referring back to Table 1, we can estimate the shed circulation as \( \Gamma_c = 0.119 \) m\(^2\)/sec in the tip leakage vortex near the trailing edge—after correcting for the effects of wandering. Thus, 73.2% of the total circulation is retained at the blade tip. For the rotor clearance within HIREP, the model of Lakshminarayana [1970] predicts that 71.9% of the circulation will be retained at the blade tip, while the model of Lewis and Yeung [1977] predicts 84.1%.

Using the results from the first HIREP experiment, we used two alternate methods to determine how the amount of retained lift varies with tip clearance. First, the two-component rotor tip force transducer provided direct measurements of the retained lift—albeit, an average value integrated over the top 10% of the blade. The normalized value of retained lift was obtained by extrapolation to zero clearance. Second, the pressure transducers flush mounted at 50% chord on the pressure surface and at 40% chord on the suction surface provide useful data. Since the position of maximum lift on the rotor tip section should occur near midchord for this design, the static-pressure data from these two transducers allowed us to estimate the variation of retained lift with clearance. Figure 9 shows these results, along with the results from the second experiment and the models of Lakshminarayana [1970] and Lewis and Yeung [1977]. Both of these models resulted from experimental data, and these data—along with the data of Inoue, Kuroumaru, and Fukuhara [1986] and Yaras and Sjolander [1990]—show a large scatter in retained lift (or circulation). One problem occurs in the various methods of estimating the retained lift from different types of data. And even though a broadly applicable model does not exist, these correlations do allow a designer to perform trade-off studies at normal operating clearances (\( h/c_{up} = 0.01 \) to 0.03).

**Total-Pressure Measurements**

At the farthest downstream measurement plane used to acquire LDV data in the second HIREP experiment, we also performed a radial survey with a fast-response total-pressure probe. This probe continuously measured data with a response time fast enough to resolve the total pressures for instantaneous angular positions of the rotor—positions measured via the optical encoder. Even though piezoelectric transducers cannot measure the mean value of total pressure, they do provide excellent measurements of the total-pressure variation about the mean, \( \Delta P_T \). For different circumferential positions of the rotor, Figure 10 shows how the total pressure varies from the mean in terms of a pressure coefficient,

\[
C_{\Delta P_T} = \frac{\Delta P_T}{\frac{1}{2} \rho V_r^2}
\]

As with the LDV measurements of axial and tangential velocity, the total pressure variations of Figure 10 clearly show the structure of the rotor tip clearance vorticies and the skewed rotor blade wakes. The low total pressures in these regions—especially in the tip clearance vorticies—indicate that these are regions of large total-pressure losses. In other experimental investigations, Inoue, Kuroumaru, and Fukuhara [1986], Yaras and Sjolander [1990], and Storer and Cumpsty [1991] have also shown that tip clearance flows lead to high losses.

**SUMMARY**

Two experiments have been performed to acquire flow measurements in the rotor blade tip clearance region of a high
Reynolds number pump. The initial experiment involved rotor blades with varying tip clearances, while a second experiment involved a more detailed investigation of a rotor blade row with a single tip clearance. This paper primarily focuses on detailed flow measurements of the tip leakage vortex. Both experiments included two-component laser Doppler velocimetry (LDV) measurements. The first experiment also provided measurements of rotor tip static pressures and integrated lift. Besides containing more LDV measurements, the second experiment included some downstream measurements with a fast-response total-pressure probe.

The detailed measurements show the effects of tip clearance size and downstream distance on the structure of the rotor tip leakage vortex. The character of the velocity profile along the vortex core changes from a jet-like profile to a wake-like profile as the tip clearance becomes smaller. This change in character is related to the adverse pressure gradient in the region of the tip leakage vortex and the angle at which the vortex lines are wound into the vortex core. Also, for small clearances, the presence and proximity of the casing endwall affects the roll-up, shape, dissipation, and unsteadiness of the tip leakage vortex. This vortex unsteadiness must be taken into account when analyzing the LDV data, since it leads to averaging errors in time-average measurements. The leakage vortices would also strongly influence periodic unsteady interactions with any downstream blades, since the structure of the vortices dominate the structure of the rotor blade wakes. Several types of measurements show how much circulation is retained by the blade tip and how much is shed into the vortex. Finally, fast-response measurements show that this vortex structure includes low total pressures associated with high losses.

ACKNOWLEDGEMENTS
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REFERENCES