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A COMPUTATIONAL STUDY OF A NOVEL TURBINE ROTOR PARTIAL SHROUD

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ABSTRACT

The over tip leakage (OTL) flow that exists between the stationary casing and the rotor tip of a shroudless HP turbine remains a major source of loss of performance for modern aero gas turbines.

To-date the principal approaches to reducing OTL loss have been to minimise the clearance gap and/ or apply a rotating shroud to the rotor. Tip clearance control systems continue to improve, but a practical limit on tip gap remains. A rotating shroud is highly effective but increases the rotor weight forcing it to run more slowly, thus increasing other aerodynamic losses. Additional means of reducing OTL loss are still needed. Partial shrouds (winglets) have been tried but none have entered commercial service to-date.

This paper presents a novel design of partial shroud derived from a review of past research. The (arbitrary) objectives were to halve the OTL loss of a shroudless rotor, at less than half the size of a full shroud. This design has been analysed using a steady flow RANS CFD code to qualitatively determine its benefits. Attention has been paid to its validation and a realistic determination of its capabilities.

The winglet is predicted to significantly improve the efficiency of a highly loaded HP turbine, by 1.2 - 1.8% at 2% tip gap/ span. A detailed understanding of the flow field shows this to be credible.

NOMENCLATURE

c	Chord
Cd	Discharge Coefficient, Ratio of Actual to Ideal Mass Flow
c_p	Specific Heat Capacity (constant pressure)
CFD	Computational Fluid Dynamics
$\Delta H/U^2$	Stage Loading
g	Tip Clearance Gap
h	Blade Span
HP	High Pressure
Mn	Mach Number
NGV	Nozzle Guide Vane
OTL	Over Tip Leakage
p	Pressure (static unless subscript denotes otherwise)
RANS	Reynolds Averaged Navier-Stokes
Re	Reynolds Number ($=\rho Vc/\mu$)
s	Pitch
V	Velocity
V_τ	Skin Friction Velocity
y	Distance Normal to the Surface in a Boundary Layer
y^+	Non-dimensional Distance from the Surface $= yV_\tau\rho/\mu$
z	Chordwise distance
β	Relative Angle
η	Stage Efficiency
μ	Viscosity
ρ	Density
ζ	Row Kinetic Energy Loss Coefficient

Subscripts

ax	Axial
in	Stage Inlet
p	Pressure Side
rel	Relative
s	Suction Side
0	Total/ Stagnation
1	Inlet
2	Exit

INTRODUCTION

Over tip leakage in axial flow turbomachinery has been the subject of extensive research since the advent of the gas turbine. An analysis of OTL loss is given in Denton (1993), while VKI (1997) provides a thorough review of OTL flow in shroudless turbines.

The basic form of over tip leakage in a shroudless axial flow turbine is illustrated in figure 1. The pressure difference between the two surfaces of the aerofoil drives a leakage flow through the rotor tip/ casing clearance gap. Typically this flow is ejected as a strong jet which mixes with the main stream on the suction side, usually rolling up to form a vortex. This interacts in some way with the "classical" outer passage secondary flow vortex, described in Sieverding (1985).

Detailed measurements of OTL flow have been made by Bindon (1988), Moore & Tilton (1988), Heyes & Hodson (1992) and Yaras et al. (1991a & b). All of them studied rotor profiles, with a tip gap, in large scale, low speed, linear cascade. Yaras et al. modelled the relative motion between the casing and rotor with a moving end wall.

A summary of this research is given in the next sections.

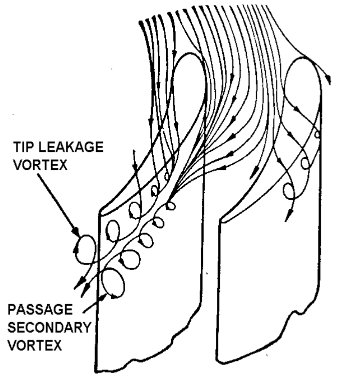

Figure 1. Illustration of OTL and Outer Passage Secondary Flows for a Shroudless Turbine Rotor.

Tip Gap Flow Field

Figure 2 (taken from Denton 1993) illustrates the two typical regimes for flow through the tip gap, depending on the thickness of the aerofoil locally. These are sections through the blade, roughly normal to the camberline. The flow entering the gap from the pressure side of the blade separates from the blade tip and contracts to a jet, which is largely lossless up to the minimum flow area. Figure 2 shows the flow for a sharp corner between the pressure surface and rotor tip.

If the blade thickness is large enough (figure 2a) the jet mixes out above the blade tip, increasing the loss and static pressure. Denton (1993) states this occurs for a gap height/ local blade thickness of 4, while Heyes & Hodson (1992) give a ratio of 6.The static pressure after this mixing is depressed by the blockage of the tip leakage vortex - see Morphis & Bindon (1988) and Yaras & Sjolander (1991a & b).

If the blade tip is thin enough, the jet will not reattach within the gap (figure 2b). This means that there is no pressure recovery in the gap and so the discharge coefficient (*Cd*) will be lower, Heyes et al. (1991). [This is for sharp corners, radiused ones will generally have higher values of *Cd*]. For a typical, cooled, turbine rotor this will only occur near the trailing edge. Denton (1993) gives a maximum gap/ thickness ratio for this of 2.5, Heyes & Hodson (1992) give 1.5.

Effects of Secondary Flows and Relative Casing Motion

The interaction between the OTL and outer passage secondary flows, and the effects of the relative motion between the rotor tip and the casing, have been observed to vary considerably:

1. The two vortices reinforce each other. Yamamoto (1989) found that in the outer half of the passage the OTL and outer passage vortices are in close proximity and counter rotate. By the trailing edge, the outer passage vortex has moved to below the OTL vortex and near the aerofoil suction surface. Govardan et al. (1993) obtained a similar result, describing the interaction as intense.

2. With relative motion between the casing and the rotor the outer passage vortex is enhanced. Morphis and Bindon (1988) and Yaras & Sjolander (1991a & b) found that this reduced the driving pressure difference and "throttled" the OTL flow. They also concluded that pressure forces dominated the flow, rather than viscous ones.

3. Graham (1985) obtained the opposite result - relative motion between the casing and rotor reduced the flow in the gap directly. This may have been related to the low values of *Re* in his experiment.

4. Chan et al. (1994), using the same facilities as Yaras & Sjolander, found that with a tip clearance of 5.5% of span the OTL vortex occupied almost the whole of the passage width by the trailing edge plane with only a small passage vortex.

5. Bindon & Morphis (1990) found uniquely that even by the trailing edge plane most of the OTL leakage flow remained in a flat high energy wall jet rather than rolling into a vortex. The cross passage secondary flow on the casing was weak and there seemed to be no indication of a passage vortex. The presence of the OTL jet, as opposed to the vortex, was confirmed in their testing of a full one and a half stage low speed annular rig, Morphis & Bindon (1994a & b).

6. Yamamoto et al. (1994a & b) found in a 1½ stage turbine that the rotor hub passage vortex confined the outer secondary flow and OTL vortices to near the casing. These two vortices were never present at the same time. The outer passage one was weak at a tip clearance of 0.5% span and disappeared at a clearance of 1.9% span.

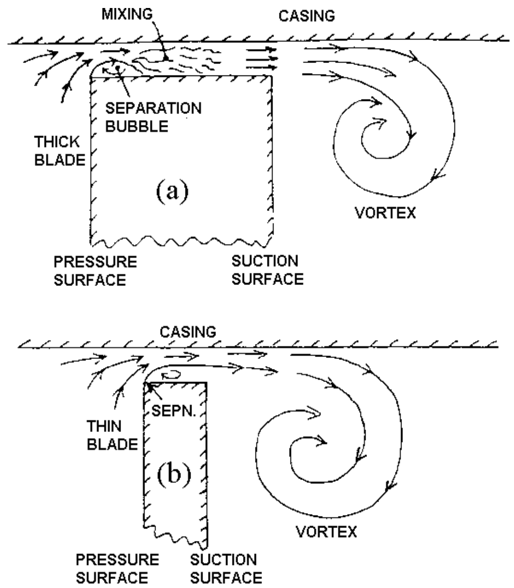

Figure 2. Tip Gap Flow for an Unshrouded Blade (Denton, 1993).

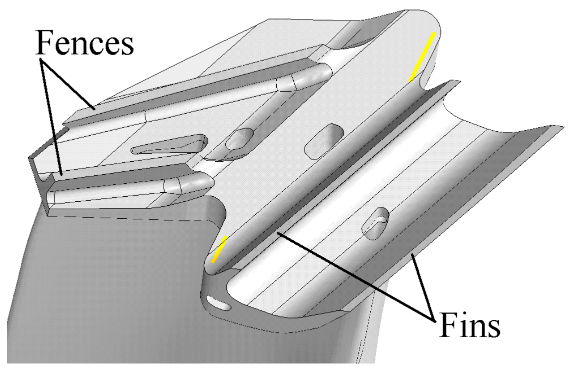

Figure 3. Perspective View of a typical Shroud Top Geometry for a Rolls-Royce Civil HP Turbine Rotor.

Loss Generation

The tip clearance in a typical aero engine varies around its operating cycle and increases during the engine life due to wear and tear, see Stakolich & Stromberg (1983). The sensitivity of the turbine efficiency to changes in tip clearance is very important to the designer. It is usually expressed as an exchange rate: change of efficiency with change in clearance-to-span ratio, $\Delta\eta/\Delta g/h$. Hourmouziadis & Albrecht (1987) investigated a number of shroudless turbine rig and engine tests at MTU as well as other published studies, and found the OTL exchange rate is in the range 1.5 to 3.0, with a mean of about 2.0.

For shrouded turbines, Hartley (1996) shows that for a geometry with two fins and two fences (see figure 3) the exchange rate is reduced by a factor of 4 relative to a shroudless turbine, and by a factor of 2 with just two fins present.

An explanation of the generality of the 2.0 $\Delta\eta/\Delta g/h$ exchange rate for shroudless rotors may be found by considering the control volume analysis of Denton (1993) for the mixing of the gap flow with the passage flow. Denton presents an (incompressible flow) equation for the row kinetic energy loss coefficient ζ due to OTL:

$$\varsigma = \frac{2Cd}{\cos\beta_2}\left(\frac{g}{h}\right)\left(\frac{c}{s}\right)\int_0^1\left(\frac{V_s}{V_2}\right)^3\left(1-\frac{V_p}{V_s}\right)\left[1-\left(\frac{V_p}{V_s}\right)\right]^{1/2}\frac{dz}{c} \qquad (1)$$

Making some further simplifying assumptions (constant lift along the rotor chord, linear variation of $\tan\beta$ through the rotor passage and small blade thickness) Denton produced contours of rotor ζ at 1% g/h with varying inlet and exit angles. Most of the turbines considered by Hourmouziadis & Albrecht (1987) have tip exit angles of 60° or above. For these Denton calculated values of ζ of 4% or more for 1% g/h. The % change in stage efficiency is typically half that in the row loss (depending on reaction), giving a $\Delta\eta/\Delta g/h$ value of 2.0 or above.

Other researchers have further simplified the calculation of OTL loss by effectively assuming that the kinetic energy of the OTL flow *normal* to the blade surface at exit is lost in the subsequent mixing with the main stream. It is supported by Dishart & Moore (1989), Yaras & Sjolander (1990) and Peters & Moore (1996).

Conclusions from OTL Research

a) Apart from Morphis & Bindon, researchers agree that the OTL and passage secondary flows (when present) roll up into vortices soon after the blade trailing edge. There is then little scope for recovering the energy subsequently and it will be dissipated as loss.

b) The effects of relative motion between the casing and the rotor are significant and must be included in any analysis.

c) The loss is largely due to the mixing of the OTL flow with the suction side free stream; a smaller amount is from mixing in the gap.

OVER TIP LEAKAGE LOSS REDUCTION

The objective of the work presented here was to define an alternative means of controlling the OTL loss of a shroudless HP turbine rotor, other than applying a full shroud. Examination of equation (1) revealed a number of possible means of reducing the OTL loss at a given relative gap height g/h.

1. Reduce the discharge coefficient Cd.
2. Increase the pressure side velocity V_p or reduce the suction side velocity V_s - possible using a partial shroud.
3. Modify the rotor aerodynamics to reduce β_2 or increase V_2.
4. Modify the pitch/ chord ratio s/c.

These options are considered in the following sections, together with the additional possibility of casing trenching.

Reduced Discharge Coefficient

This is the option most often pursued by researchers. Booth et al. (1981) carried out an extensive investigation into rotor tip geometries aimed at reducing Cd. They found that a knife edge tip squealer had a Cd 25% lower than that for a plain tip, although the results were strongly dependent on tip gap Re and the details of the configurations. Heyes et al. (1991) showed that a single suction side squealer gave the best reduction in Cd. Morphis & Bindon (1988) gained a similar result with a contoured tip, which approximated to a suction side squealer. While these results offer the possibility of reducing loss by directly reducing the OTL flow, there are a number of problems:

a) Heyes et al. showed that for any geometry to achieve a low Cd, the entry corner radius had to be kept below 0.5% chord. For a typical chord of 30 mm. the radius must be less than 0.15 mm. This dimension could not be maintained for an in-service engine.

b) The vena contracta in the tip gap is a loss source. The lower the Cd, the larger the contraction and thus the mixing loss after it. In addition, if the exit Mn is high enough, shocks will form over the contraction possibly adding to the loss, see Moore & Elward (1992).

c) The presence of the vena contracta significantly increases the local heat transfer rates, especially at the reattachment point, as shown by Moore et al. (1989) and Metzger et al. (1989).

Rather than try to reduce the Cd, it is suggested the tip pressure surface geometry should be sufficiently radiused to remove the vena contracta thereby reducing potential in-service problems - in particular burnout at the blade tip pressure side, see Bindon (1987).

Partial Shrouds (Winglets)

Partial shrouds offer the possibility of modifying the local surface velocities at the rotor tip, in particular increasing V_p .

The best result for a winglet has been that of Patel (1980) who obtained a stage efficiency improvement of 1.2% (at 3% tip clearance). The tip loss exchange rate, however, was surprisingly unchanged from 2.0. Booth et al. (1981) investigated a number of winglet designs in a water rig. Applying one of these (it is not clear which) to a low aspect ratio transonic turbine they achieved a 0.6% improvement in rotor efficiency at a tip clearance of 3% g/h. Yaras & Sjolander (1991) investigated winglets on the suction and pressure sides (individually and together) of a low turning aerofoil in linear cascade at 2.4% g/h. They obtained a reduction of 10% of OTL loss for each design.

Staubach et al. (1996) obtained a negative result with a winglet. They were primarily studying the effect of rotor lean on OTL, but found the winglet reduced stage efficiency by 0.35% at 1.7% g/h.

No partial shroud is known to have entered commercial service.

Modified Turbine Aerodynamics

A standard approach to reducing OTL loss is to reduce the rotor tip reaction (by reducing the exit angle). Farokhi (1988) shows for one turbine that reducing the tip reaction from 89 to 0% halved the tip loss exchange rate. This seems to contradict Denton's equation, since V_2 is reduced which should have increased ζ. However, the lower turning results in lower V_s , and in addition lower local V_2 reduces the contribution of the tip loss to the total rotor row loss.

DeCecco et al. (1995) and Yamamoto et al. (1994a & b) also agree that off-loading the tip should reduce OTL flow. Staubach et al. (1996) achieved this by bowing their rotor thus applying a radial body force towards the casing, moving passage mass flow away from the tip. Their best result is with a tangentially bowed aerofoil only. The tip loss exchange rate was reduced by 40%. This is not yet, however, a mechanically acceptable option for cooled turbine rotors.

Changing Pitch/Chord Ratio

Equation (1) can be used to estimate the effect of changing the pitch/ chord ratio *s/c* on the OTL loss.

The MT2 turbine studied in this paper (see later for details) has a tip *s/c* of 1.14. Loss coefficients have been compared at this *s/c* and at 0.57. For exit angles (β_2) of 60° and above, and inlet angles (β_1) of 0° (axial) and less, the OTL loss reduced by at least 44%. Equation (1) predicts that reducing *s/c* alone should increase ζ. However, reducing the pitch reduces both the velocity of the OTL flow and the free stream velocity V_s - which have the dominant effects on ζ.

Doubling rotor numbers (increasing the cost, weight and cooling air requirement) is not an acceptable design solution. However, there is the possibility of having two "aerofoils" (or aerofoil sections) at the rotor tip, mounted on a reduced size shroud.

Casing Treatments

Offenburg (1987) presents the only detailed investigation into casing "trenching" using a cold flow turbine. The tip loss exchange rate with a smooth casing was found to be the standard value of 2.0. He found that the usefulness of tip trenching was a function of the tip gap. At the nominal clearance level, a smooth casing was best. As the clearance increased, a backward facing step upstream of the rotor leading edge proved beneficial for clearances above 2.4% *g/h* - the initial efficiency was lower, but it had a better OTL loss exchange rate.

Conclusions for OTL Loss Reduction

From this research review it was concluded that the best opportunity for reducing OTL loss was to pursue a design of winglet that effectively doubled the number of rotor tips. This should also be combined with aerodynamically off-loading the rotor tip, but not by tangential lean of the rotor - its mechanical design was not practicable.

Reducing the tip discharge coefficient, by minimising the pressure side corner radius, was rejected because of the risk of exacerbating in-service over heating problems. Reducing tip reaction is an established means of reducing OTL loss - but applying a tip "end bend" to a rotor was also limited by mechanical design considerations. Casing trenching seems only of use at relatively large tip clearances.

DESIGN METHODOLOGY

A numerical investigation of different rotor tip winglet designs was undertaken with a standard turbomachinery CFD code used within Rolls-Royce, Harvey (1997). The exercise was conducted on a single stage HP turbine with highly loaded aerofoils, designated "MT2", the operating conditions for which are given in Table 1. Before presenting the CFD results for the final winglet design the code is described, together with a summary of its validation for turbine rotor OTL flow.

CALCULATION METHOD

The CFD code used in this study is a steady flow solver with a pressure correction method based on the algorithm of Moore (1985). A key feature is the use of upwinded control volumes for the momentum and rothalpy equations, thus allowing the equations to be discretised with second order accuracy without the need to introduce smoothing to achieve numerical stability. The iterative method used is based on the SIMPLER pressure correction scheme. Stability in transonic regions is achieved using an upwinded pressure in the calculation of density. The calculations are based on a structured "letter-box" type of body fitted H-grid, which enables accurate representation of the full blade shape, which is then refined using mesh embedding. Previous work has shown the capability of this method for the prediction of turbomachinery aerodynamics, e.g. Moore and Gregory-Smith (1996) and Robinson and Northall (1989).

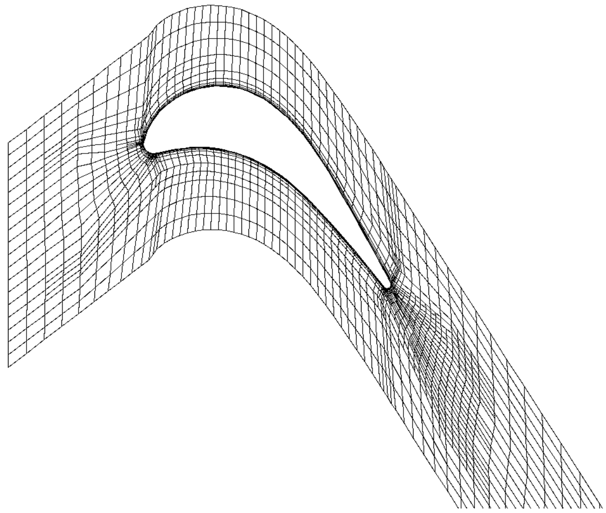

Figure 4. Calculation Grid for MT2. Blade-to-blade View. 50% Span.

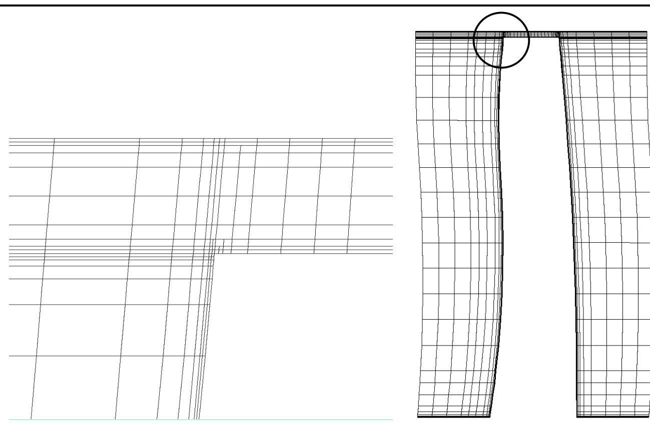

Figure 5. Calculation Grid for MT2. Axial View + Pressure Side Tip Detail, 50% c_{ax}.

Grid Details

The calculation grids were first created as a coarse definition on the blade-to-blade plane, stacked in the spanwise direction to produce three-dimensional grids, and then refined using mesh embedding, see Lapworth (1993). The maximum grid size available was about 120,000. The grid for the datum (shroudless) MT2 rotor case with 2% *g*/*h* is shown in figures 4 and 5, while the blade-to-blade grid for the winglet is shown in figure 9. Generally the grid definition in the free stream is coarse, with refinement only in the boundary layer, the wake regions and at the tip. Grid details are given in Table 2. The validation analyses of the two turbine rotors used a finer grid in the flow field than the winglet calculation did (which had grid lines concentrated around the winglet). As a check one calculation was repeated for the plain tip MT2 case with a similar (coarse) grid definition. All the geometries were modelled with sharp corners at the tip.

Boundary Conditions and Convergence Criteria

All the turbine rotor calculations for the validation exercises have used inlet boundary conditions (circumferentially averaged) based on measured NGV exit traverses. The MT2 winglet design studies were carried out using idealised, smoothed boundary conditions and at a slightly different reaction. The inlet relative stagnation conditions and relative angle were fixed together with the exit static pressure profile.

For the calculations for the turbine rig rotors, the boundary layers were set to zero at inlet to the grid. Thus the skewing of the hub end wall boundary layer, as it moves from the NGV exit onto the moving rotor end wall, was not modelled. Bindon (1980) showed this increases rotor hub secondary flow, which as a result is underestimated.

All the boundary layers were set to be adiabatic and turbulent.

Acceptable convergence was achieved when the residuals in all 3 velocity components and the static pressure had fallen by at least two orders of magnitude from their initial values. Usually this should be achieved after 100 iterations. However, the complexity of the grids used here meant that up to 400 were required for some calculations.

The maximum error in mass flow conservation through the passage in any solution was 0.1%, and generally was within ± 0.05%.

Turbulence Model and Wall Functions

An algebraic mixing length model was used based on Prandtl's formulation for the length scale within a shear layer. Wall functions, described in more detail in Harvey et al. (1998), were adopted to represent the near wall variation of the boundary layer based on a generalised expression for the law of the wall, see also White (1991) or Spalding and Patankar (1967). They are valid for values of y^+ up to the edge of the logarithmic region, say 100 to 200 depending on the magnitude of the local pressure gradient. Of particular importance is the ability to apply the wall function model in the buffer layer region, around $y^+ = 20$, and to give good results irrespective of the y^+ value which inevitably varies significantly over the aerofoil surface.

CFD VALIDATION

Despite the extensive use of CFD, users must be realistic in their expectations of it. CFD does not calculate with equal accuracy all features of turbomachinery flow fields. The following ranking for these features is suggested (in order of decreasing calculation accuracy): Static pressure; Mass flow and exit angle distributions; Secondary flows; Overall entropy rise (in subsonic, attached flow); Shocks and separations; Local surface skin friction and/ or heat transfer rates.

The CFD code used here is a general turbomachinery flow solver - validated for the calculation of the bulk flow field and secondary flow deviations, rather than loss. Three test cases are presented which illustrate its capability, with particular emphasis on OTL flow.

Flow Field and Exit Angle Distribution

Moore & Moore (1991) present a very detailed comparison of the measured and calculated flow fields for a rotor in linear cascade with fixed end wall. The rotor was a typical high turning blade with 45° inlet and -66° exit angles. Calculation details are given in Table 2.

The tip leakage and outer passage vortices were well modelled, as can be seen in the whirl angle distributions of figure 6. However, the OTL loss was under estimated by 16%.

Tip Loss Exchange Rate

The single stage research HP turbine, "B22", has been the subject of extensive previous study - see Sheard (1989), Dietz (1990) and Garside (1995). Its operating conditions are given in Table 1. Its stage efficiency has been measured for two tip clearances, 0.82 and 1.7% *g/h*. Calculation details are given in Table 2. They were carried out at 0.82 and 2% *g/h* (referred to as "B22 Fine1" and "B22 Fine2").

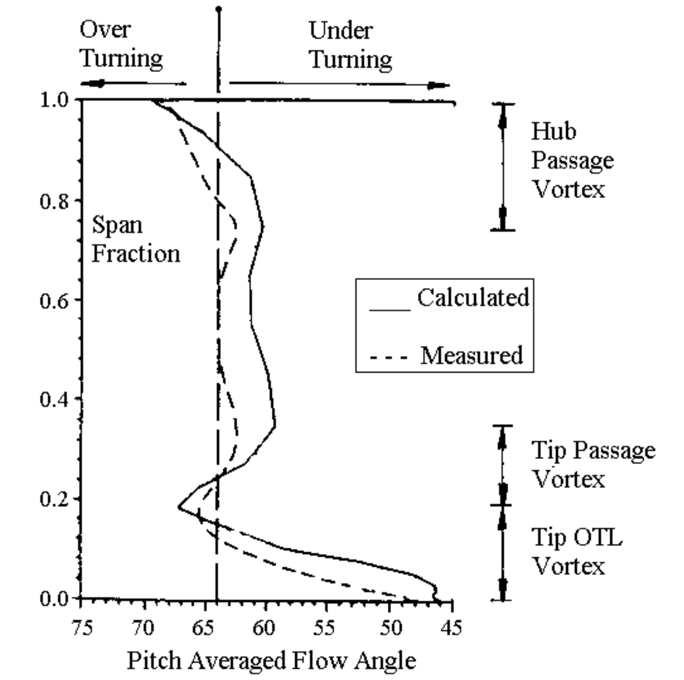

Figure 6. Rotor Cascade Exit Whirl Angle Profiles (40% c_{ax} downstream of Trailing Edge), from Moore & Moore (1991).

Figure 7 plots the measured and calculated changes in mixed-out rotor loss expressed as a loss of stage efficiency. The measured tip loss exchange rate of 2.3, close to the "standard" value of 2.0 identified earlier, is under estimated by 40%, at 1.2 - this is discussed below. At the design tip clearance of 0.82% *g/h*, the code under estimated the measured loss by 32%. This is not surprising, since unsteady effects and the correct inlet boundary layers have not been modelled.

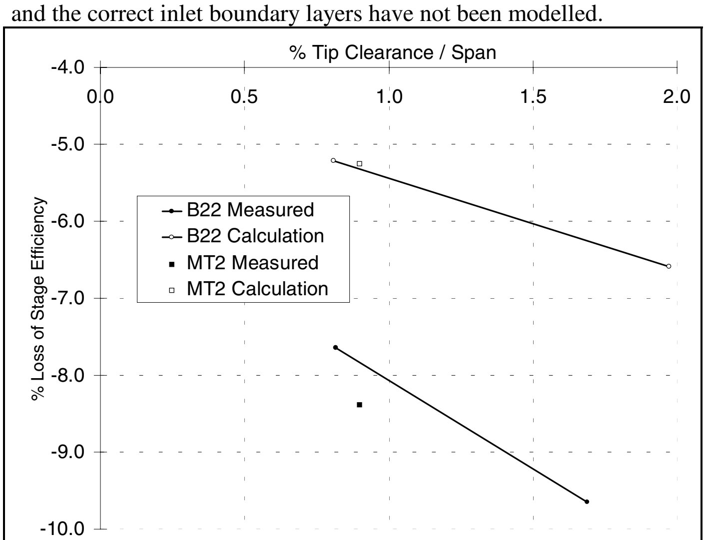

Figure 7. Comparison of Measured and Calculated Rotor Losses (as % Stage Efficiency) for Rolls-Royce Model Rig Turbines.

Rotor Pressure Field

The MT2 turbine was tested only at 0.9% *g/h*. In addition to the turbine performance, on-blade surface static pressures were measured.

Static pressures measured on an aerofoil section at 93.7% span are presented in figure 8, normalised by the rig inlet total pressure, and compared with calculation on a grid plane at 96.4% span. There is a very good match between the two. The strong depression in the static pressure at about 70% chord is due to the presence of the OTL vortex. Yamamoto & Nouse (1988) found in their linear cascade experiment that for any "strong" vortex (passage, not just OTL) there is a static pressure minimum which nearly coincides with the vortex centre. This confirms that for MT2, the OTL does roll up into a vortex (whose kinetic energy would probably not be recovered in a downstream row).

Details of the calculation are given in Table 2 (referred to as "MT2 Rig"). The code under estimates the measured rotor loss by 36% - a similar result to that for B22, see figure 7.

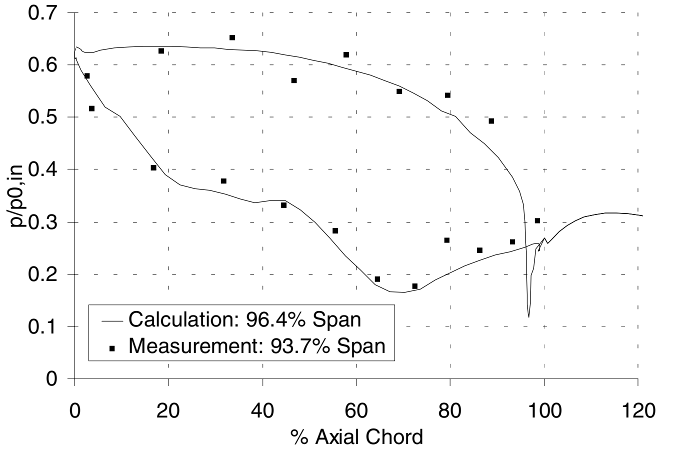

Figure 8. Comparison of Tip Static Pressures for the MT2 Rotor.

Conclusions from Validation

The code can be used to calculate the static pressure field and exit whirl angle distributions in the presence of OTL. At best, it can make qualitative comparisons of the losses of different rotors, but not absolute levels. Rotor loss is under estimated by 32 - 36% and the tip loss exchange rate by 40%. The large error in the tip loss exchange rate is disappointing. As noted before, the CFD code has previously been used for the prediction of passage flow fields, not loss. The code does not appear to resolve the mixing of the OTL jet with the free stream well, in particular the turbulent viscosity appears to be under estimated resulting in low levels of loss. This is clearly an area for future development of the code, although the detailed data required (such as measured Reynolds stresses in the OTL vortex) are in short supply. The validation presented here is limited, and to make any conclusions about the effect of the winglet on the OTL loss it has had to be assumed that the code is at least consistent in under estimating it.

NEW WINGLET DESIGN

From the research review it was judged that the best opportunity for reducing OTL loss was to pursue a design of partial shroud that effectively doubled the number of rotor tips, with the aim of:

a) Reducing velocity of the OTL flow and of the free stream (on the suction side of the tip) that it mixes with.

b) Reducing the OTL mass flow by off loading the aerofoil tip, but not by significantly changing the tip gap *Cd*.

The (arbitrary) targets for the design were to halve the shroudless OTL exchange rate and to be less than half the size of a full shroud.

Figures 13 and 14 show the winglet in perspective views, while figure 9 shows it in plan view with the embedded calculation grid. The basic elements of the geometry are as follows:

1. There are two "aerofoil" shapes at the rotor tip, which form a channel or "gutter", along which there is an *additional*, chordwise leakage flow from the leading edge. They are not equally spaced (pitchwise), and thus are not equally loaded aerodynamically.
2. The pressure and suction side overhangs of the winglet almost halve the passage throat width at the tip.
3. The pressure surface shape is intended to increase blockage, and thus lower the local static pressure driving the OTL flow.

The vehicle used for this study has been the single stage HP turbine MT2. A larger tip gap, 2% *g*/*h*, was chosen to resolve the effects of the winglet better. The turbine parameters are given in table 1, and details of the CFD calculations in table 2. There were three analyses of the plain tip rotor, with smoothed inlet conditions: fine grid at 0.82% *g*/*h* (referred to as "MT2 Fine1" in Table 2), 2.0% *g*/*h* ("MT2 Fine2") and "coarse" grid at 2.0% *g*/*h* ("MT2 Coarse2"). The latter was for comparison with the coarse grid winglet analysis ("Winglet").

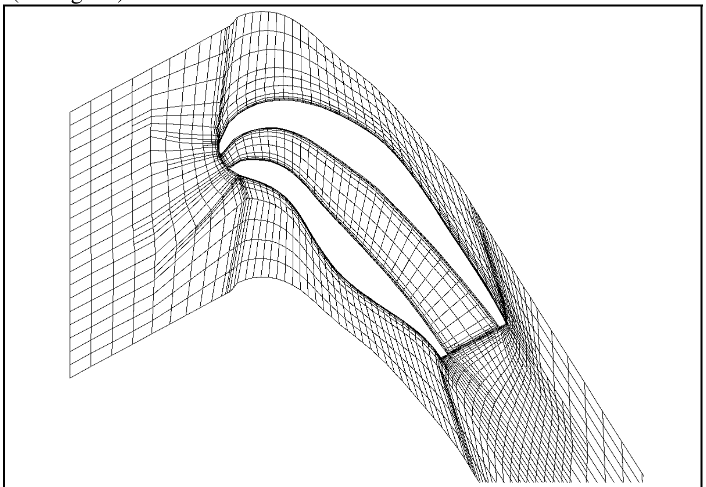

Figure 9. Calculation Grid for MT2 Winglet. Blade-to-blade View.

Loss Results

Although the validation exercise concluded that the CFD code under estimates OTL and total rotor loss, these results are presented first to make some conclusions about the overall effect of the winglet.

Figure 10 shows the calculated OTL loss for the datum MT2 rotor with plain tip and with the winglet. The value of the rotor loss at zero tip clearance value was found by extrapolating from the 0.82% and 2.0% *g*/*h* (fine grid) results. This datum has been *assumed* to be the same for all the results of figure 10 (with and without winglet).

At 2.0% *g*/*h* the rotor loss is the same with coarse and fine grids, reassuringly, even though the average near wall y^+ values of 91 and 25 respectively are opposite sides of the optimum range for the boundary layer wall functions. Although not shown here, the two flow fields are similar, but with some details lost with the coarse grid.

The calculated OTL exchange rate for MT2 is 1.85 $\Delta\eta/\Delta g/h$, above that calculated for the B22 turbine rotor, but not unexpected as the MT2 rotor aerofoils are more highly loaded. From the validation the ratio of measured to calculated loss is 1.5 (based on total rotor loss for B22 and MT2) Applying this factor gives an OTL exchange rate of 2.7 $\Delta\eta/\Delta g/h$. This is high, but is plausible for a highly loaded turbine and within the range observed by Hourmouziadis & Albrecht (1987).

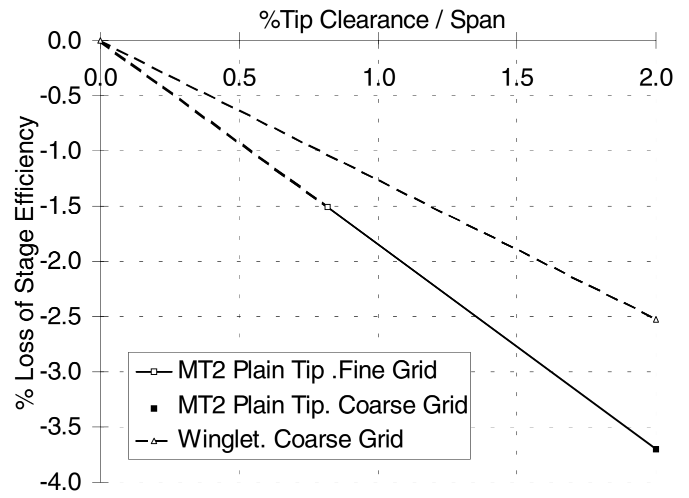

Figure 10. MT2 Rotor. Calculated OTL Loss for Plain Tip & Winglet.

The striking result for the winglet is that it is calculated to improve stage efficiency by between 1.2% (unfactored) and 1.8% (factored). Figure 12 shows contours of relative total pressure ($p_{0,rel}$) in the trailing edge *grid* planes [which are not wholly axial, as can be seen in figures 4 and 9]. The reduction in the depth of the OTL vortex loss core is clear, although there is extra loss in the "gutter". Equally as importantly as this, the region of loss below the OTL vortex has almost completely gone. The flow field in the plain tip case exhibits a strong interaction between the OTL and passage vortices, as seen by Yamamoto (1989). The calculation of its elimination is significant.

The winglet reduces the (unfactored) OTL loss exchange rate $\Delta\eta/\Delta g/h$ from 1.85 to 1.28, a reduction of 31%. This is short of the arbitrary target of 50%. However, it compares favourably with the result of Staubach et al. (1996) who achieved a reduction of 40% with their leant rotor, and the reduction of 44% predicted from equation (1).

The plausibility of these results is discussed in the next sections, but some comment can be made from figure 12 on the quality of the calculations. Total pressure oscillations in the flow field are visible in the figure, in particular there are radial striations in the contours which correlate with grid lines (not shown). This confirms grid dependency in the solutions. This is also indicated by the (unexpected) differences in detail between the $p_{0,rel}$ contours in the inner half of the passage. These concerns should not be over stated, however. The effects of the winglet are still large relative to the effects of grid dependency.

Description of Flow Fields

The tip static pressure distributions give an insight into the operation of the winglet. Figure 11 compares the static pressures (normalised by stage inlet total pressure and plotted against aerofoil c_{ax}) at 97.1% span for the two cases. Most authors take the driving static pressures to be at about 90% height. A comparison plane close to the tip has had to used here to capture the effect of the winglet.

For the plain tip the difference between these pressures drives the OTL flow. In the case of the winglet the situation is more complicated. Figure 11 includes the static pressure along the gutter camberline at 99% span (tip gap mid-height). This is the intermediate pressure between the two halves of the winglet. Figure 11 shows that the pressure difference driving the OTL is largely across the pressure side half. There is little additional acceleration of the OTL flow across the suction side "aerofoil" section of the winglet. The pressure drop across its early part is negligible, and the OTL rolls up into a vortex in the gutter. Towards the trailing edge a pressure drop develops, largest between 65 - 85% c_{ax} - since to satisfy mass flow continuity some OTL flow must exit the tip gap on the suction side of the winglet.

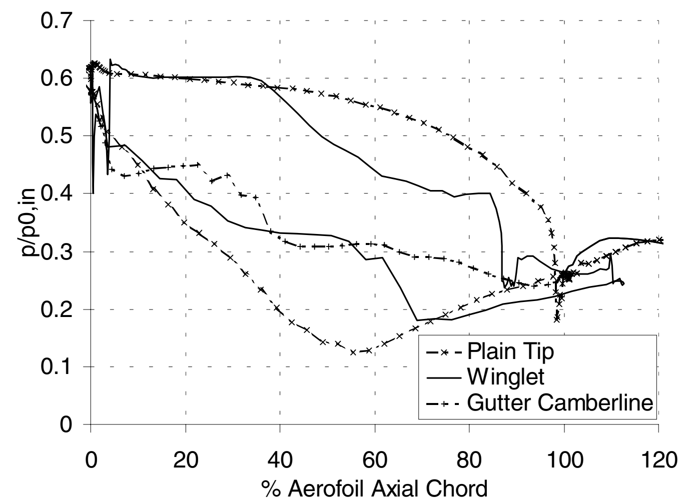

Figure 11. Calculated Static Pressure Distributions for MT2 Rotor at 97.1% Span, + "Gutter" Camberline at Tip Gap Mid-Height.

On the pressure side the blockage of the winglet significantly lowers the driving pressure, reducing the tip leakage velocity and flow. Normally, this blockage would have an effect on the suction side, raising local velocities there also. However, these are reduced for the winglet. This is because the winglet aerofoil section is off-loaded relative to the plain tip - due, as noted previously, to the winglet overhang effectively halving the passage throat width at the tip.

[The pressure distributions with plain tip in figures 8 and 11 are not expected to be the same as they are respectively at rig test and nominal design conditions, and the tip gaps are also slightly different].

The effect of off-loading the tip pressure distribution can be seen in figures 13 and 14 which show the MT2 rotor, with and without winglet, in plan view (onto the tip) and side elevation (onto the suction surface). The OTL flow has been visualised by injecting particles at every grid point in the plane at the entrance to the tip gap. The particle paths are in blocks of the same colour, changed every 20% of chord. The same convention has been used for plain tip and winglet, with additional black particle paths injected at the entry to the "gutter".

For the plain tip, figures 13 and 14 show that the early OTL flow feeds into the outer passage vortex. This would not be expected as the two vortices are of opposite sign. The mechanism appears to be that although there is significant OTL flow over the early suction surface, shear effects due to the relative casing motion are significant. The resulting relative velocity profile increases from near the casing to a maximum almost at the tip, and thus largely has the same vorticity as the passage vortex. After about 50% chord the OTL flow velocities are higher, pressure forces dominate and the shear effect is much less. The OTL flow then rolls up into a vortex with the conventional vorticity - interacting strongly with the passage vortex subsequently.

Figures 13 and 14 also show that for the winglet the tip gap flow over the first 50% chord remains in the gutter or carries on into the OTL vortex - no appreciable flow enters the passage vortex. The flow angles over the tip are closer to the streamwise direction, reducing the mixing between the two streams.

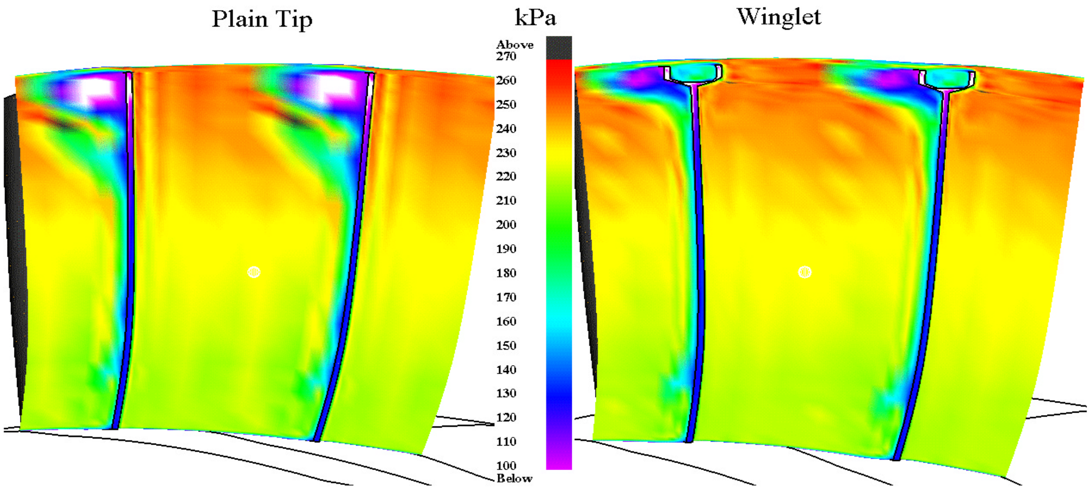

Figure 12. Contours of Calculated Relative Total Pressure at the Trailing Edge Grid Planes for MT2 Plain Tip and Winglet.

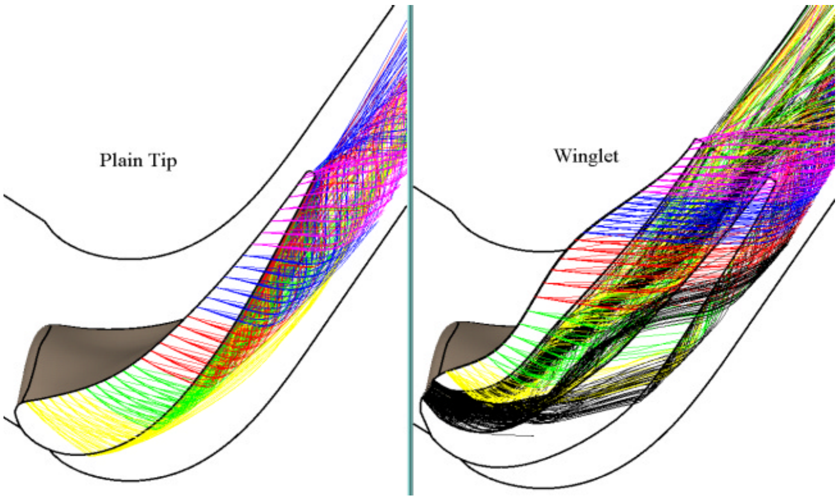

Figure 13. Visualisation of Calculated OTL Flow for MT2 Plain Tip and Winglet. Plan View on Tip.

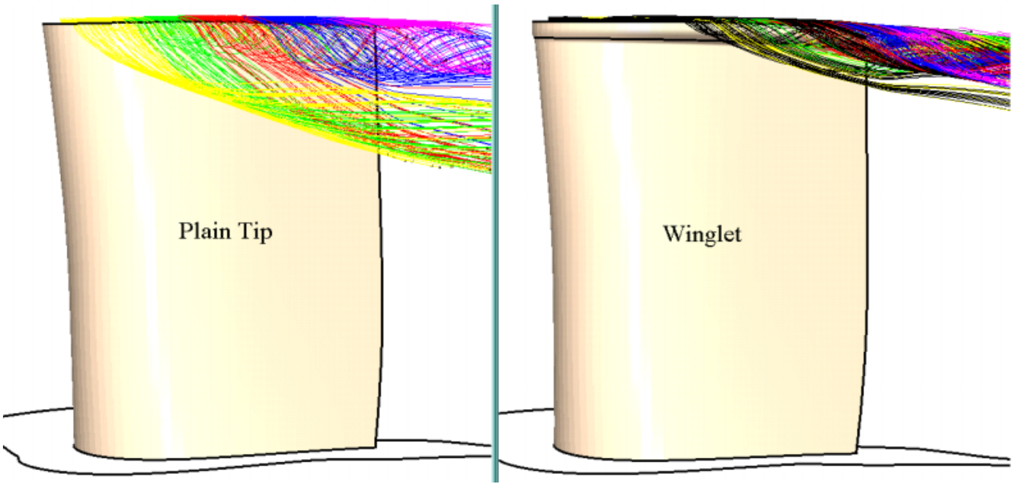

Figure 14. Visualisation of Calculated OTL Flow for MT2 Plain Tip and Winglet. View on Suction Side .

Figure 15. Calculated Exit Whirl Angle Profiles for MT2 Rotor, Plain Tip and Winglet. 60% c_{ax} downstream of Trailing Edge.

The reduction in the strength of the vortices can be seen in figure 15 which compares the circumferentially averaged whirl angle profiles at 60% c_{ax} downstream of the rotor trailing edge. The whirl angles for the plain tip case have a similar form to those seen by Moore & Moore (1991), see figure 6. Both distributions exhibit under turning in the three vortices (OTL and inner and outer passage), with over turning at the hub end wall and between the OTL and outer passage vortices. The winglet substantially reduces these angle deviations in the outer half of the passage. This would be expected to be beneficial for any downstream blade row. In the inner half of the passage the whirl angle profiles, which should be the same, are slightly different. This again highlights the issue of grid dependency. The differences between the calculations give an indication of the minimum uncertainty.

Although the winglet reduces the OTL flow velocities it does not change the flow contraction at the pressure side inlet to the gap. Velocity vectors (not shown here) confirm that this part of the flow behaviour is much like that shown in figure 2, although the calculation grids used do not resolve the reverse flow in the separation bubble of the vena contracta well. The important result is that the winglet does not operate by significantly changing the tip gap *Cd*.

The capacity of the rotor with the winglet is only reduced by 0.3%, despite the off-loading of the winglet section. Examination of the aerofoil lift distributions shows that this has not been achieved by increased profile loading below the tip. It appears that the extra area of the gutter and the reduced loss compensates to maintain the capacity.

Loss Reduction Mechanisms

The off-loading of the winglet section generally reduces the OTL velocities. The OTL flow partly mixes in the gutter and on the aerofoil suction side. The main flow velocities in these locations are both reduced, relative to the suction side of the plain tip rotor, and thus the mixing losses are reduced. Equation (1) showed that the loss depends on the cube of these velocities, and thus a significant loss reduction would be expected. The reduction in pressure loading of the tip is about 80% of the reduction seen by Staubach et al. (1996) for their leant rotor, and they achieved a reduction in OTL loss of 40%.

The reduced OTL velocities, more streamwise OTL flow angles, and thus reduced mixing losses, are a direct result of the changes to the tip pressure distribution. As discussed in the CFD validation, this should be the most accurate part of the calculated flow field. Thus the calculated reduction in OTL loss is a wholly plausible result of the operation of the winglet. The open entry to the gutter does add to the total leakage area, but this flow continues on in a largely streamwise direction. The total OTL mass flow has not significantly increased - the reduced OTL velocities at the pressure side entry to the gap outweighing the extra leakage area of the "gutter" entry.

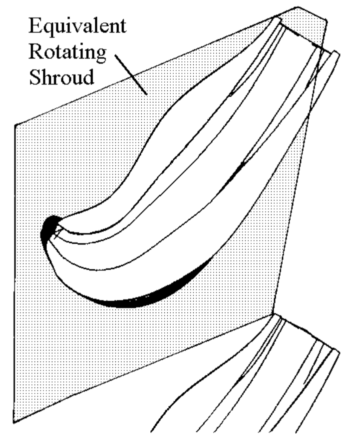

Figure 16. Comparison of Outlines of Winglet and Typical Rolls-Royce HP Turbine (Plain-Sided) Rotor Shroud, scaled to the same c_{ax}.

Cooling and Mechanical Issues

Figure 16 compares the external shape of the winglet with that of a typical rotating shroud (scaled to the same chord), taken from Hartley (1996). The winglet extent is everywhere within that of the shroud, and thus should be mechanically feasible, except at the suction side trailing edge. This additional overhang may not be mechanically acceptable - if so a cut back version should be investigated.

Compared to a full shroud, the much smaller surface area of the winglet should mean that the total heat load would be reduced. The lower tip gap velocities should result in lower net heat transfer rates at the rotor tip relative to a shroudless rotor. However, it is still expected that positive cooling of the winglet would be necessary.

In a typical aero engine there are large radial and circumferential temperature distortions in the flow entering the rotor, with the hottest gas emerging from the upstream NGV near mid-height and mid pitch and the coldest gas near the end walls. The 'hot streak' from the NGV is periodically convected towards the rotor pressure surface and radially outward up it. (Doorney et al. (1990) showed that the hottest gas can still enter the tip gap, near the trailing edge, by this mechanism). Thus cooling of the pressure side "aerofoil" section of the winglet would be crucial to ensure its success in service - possibly using small internal convective cooling passages such as those currently applied in HP turbine rotor shrouds, see Hartley (1996). These might also eject cooling air onto the winglet surface (especially onto the pressure side) to provide an additional external barrier to the hot gas. The tip pressure side corner should be radiused to eliminate the separation bubble and prevent the high heat transfer its reattachment would cause, see Bindon (1987). This would increase the OTL mass flow but minimise the loss in the tip gap.

The open leading edge entry to the winglet should help cool it. The flow into the gutter here will be cooler gas from near the end walls (migration of the hottest gas occurs *within* the rotor passage, not before it), helping to reduce the heat load, see Lee et al. (1994).

For cooled rotors, air is ejected at the tip from "dust holes" at the ends of the main internal cooling passages. The visualisation of figure 13 shows some OTL flow does remain in the gutter to the trailing edge. This could then entrain some of the ejected air which would help cool the winglet further. This might also have an aerodynamic benefit. It is thought that the fences on a full shroud (see figure 3) extract useful work from this ejected air, see Hartley (1996). The trailing edge geometry of the winglet is very similar to these fences and could act in the same way, providing some of this air does stay in the gutter.

CONCLUSIONS

A novel design of winglet (partial shroud) for application to an HP turbine rotor, as an alternative to a full shroud, has been derived from a study of the existing, extensive work on OTL.

The winglet has been analysed using a steady flow CFD code, using mesh embedding to generate the complex grid.

The turbine rotor studied is highly loaded aerodynamically and, with simply a plain tip, exhibits a strong interaction between the OTL and outer passage secondary flow vortices.

The winglet is calculated to significantly reduce OTL flow and loss. A limited validation indicates it would improve the turbine stage efficiency by 1.2 - 1.8%, at a tip clearance of 2% *g/h*, and reduce the tip loss exchange rate by 31% (the original target was 50%).

A detailed examination of the calculated flow fields indicate that the basis for these predicted improvements is plausible.

The winglet is significantly smaller than a full shroud (less than half the size - the original target). It would remove the limitations of a full shroud on rotor pitch, and should require less cooling overall - but cooling the pressure side section will be critical.

Although this is only a theoretical study the winglet shows sufficient potential to warrant further experimental investigation - both to verify the concept and provide further data for CFD validation.

Although there is some grid dependency in the CFD solutions obtained, the predicted effects of the winglet are large compared to the resulting uncertainties in the flow fields. Further development of the code is needed to improve its loss prediction capability.

A patent application has been made for the winglet "gutter" concept conceived during this work, see Harvey (1996).

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Table 1. Summary of Parameters for Validation Turbines

Parameter	B22	MT2
$\Delta H/U^2$	1.79	1.68
$c_p\,\Delta T_0/T_{0,in}$, J/kg K	218.9	223.2
Total Pressure Ratio	2.62	2.72
Hub-to-Tip Ratio	0.83	0.83
Reaction, %	42.8	49.4
Nominal Tip Gap, mm.	0.38	0.44
Tip s/c_{ax}	1.28	1.14
Rotor Mid-height Conditions		
Inlet Angle (degrees)	46	51.5
Exit Angle (degrees)	-62.8	61.8
Exit Reynolds number	980,000	783,000

Table 2. Summary of Calculation Grids

Reference	Grid Nodes				Minimum Spacing	Tip Gap			Near wall y^+			Iterations
	Axial	Tang-ential	Radial	Total* (1000s)	mm.	g . mm.	g/h %	Points in gap	Average	Minimum	Maximum	to Converge
Moore & Moore (1991)	45	28	26	33	(0.001 c_{ax})	5	2.1	6				
B22 Fine1	97	52	48	108	0.032	0.38	0.82	8	14	1	43	200
B22 Fine2	97	52	51	117	0.032	0.92	2.0	11	13	0.4	49	400
MT2 Rig	99	52	41	124	0.032	0.44	0.90	7	19	1.5	61	200
MT2 Fine1	97	52	44	104	0.032	0.40	0.82	8	20	2	93	400
MT2 Fine2	98	54	46	107	0.032	0.98	2.0	9	25	1	75	250
MT2 Coarse2	90	44	44	88	0.125	0.98	2.0	8	91	5	294	350
Winglet	89	65	51	115	0.125	0.98	2.0	8	83	4	281	250

* Solid nodes removed for embedded grids