UNDERSTANDING FAN BLADE TIP AERODYNAMICS

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ABSTRACT
Tip leakage flow has a significant impact on fan blade performance. It is therefore critical to
understand the effect of both the uniform and non-uniform tip clearance variations that
occur in engines. Firstly, a detailed understanding of the flow physics present in the tip
region of a modern axial flow fan blade is developed using RANS CFD. Analysis is under-
taken of the tip leakage flow structure, tip vortex characteristics and tip leakage massflow
distribution. It is shown how flow acceleration upstream of the pressure surface passage
shock causes an unusual chordwise tip leakage distribution with 'reverse' tip leakage near
the leading edge. The importance of the leakage distribution on the tip flow behaviour is
explained. The sensitivities of blade efficiency to both uniform and non-uniform tip clear-
ances are studied, and it is shown how increasing tip clearances towards the leading edge
has the greatest impact on efficiency.

KEYWORDS
Fan, Tip, Aerodynamics, Clearance, Vortex

NOMENCLATURE
ADP Aerodynamic Design Point
C Chord
LE Leading Edge
OTL Over Tip Leakage
TE Trailing Edge
X1 Datum clearance
X2 Twice datum clearance
X3 Thrice datum clearance

INTRODUCTION
In a jet engine fan, the tip clearance varies significantly throughout each engine cycle and
over its lifetime. There are several mechanisms that lead to this: differing expansion rates of
components as the engine heats up, the non-axisymmetric shape of the casing during flight, and
gusts, which cause the core and nacelle to move relative to one another. These changes cause
the fan tip and casing to vary position and make contact each cycle, leading to rubbing and
cutting of the casing. To reduce damage to the blade tip, an abradable liner is applied to the
casing above the blade, this becomes worn with time. As a result, the tip clearance becomes
non-uniform in both the axial direction and around the annulus.

The effect of tip clearance effects for fans and compressors has been investigated by a num-
ber of researchers. Adamczyk et al. (1991) showed how an increase in tip clearance causes a
reduction in pressure ratio, efficiency and stall margin. The interaction of the clearance vortex
with the blade shock was also shown to have a significant effect on the fan stall margin. Denton
(1993) developed a model to predict turbomachinery tip clearance loss based on the passage
and leakage flow properties. It was shown that entropy generation due to the leakage vortex is
proportional to the difference between the streamwise velocities of the two flows. Sakulkaew
(2013) carried out a study of compressor efficiency variation from large to vanishing clearances. The loss variation with tip gap was found to be linear between tip clearances of 1 and 3%. A linear variation in axial compressor blade efficiency with tip clearance was also shown by Beheshti (2004) and Seshadri et al. (2014). Seshadri et al. (2014) and Sakulkaew (2013) however found that close to zero clearance the relationship becomes non-linear, resulting in an optimum, non-zero clearance. This is because shear loss increases at the casing as the tip clearance becomes very small. All of the described studies focused solely on uniform tip clearances however, ignoring the possibility of chordwise variations.

This paper aims to understand in detail the tip leakage flow physics of a modern fan blade and develop a new insight into the key features that determine blade performance. The chordwise tip leakage massflow distribution, tip vortex trajectory and losses are analysed for a datum tip clearance. The importance of the passage shock positioning on the tip leakage is described, and the effects of this on the tip vortex initiation point. The variation in fan efficiency due to varying tip clearance is assessed and explained. The importance of non-uniform tip clearances is also shown, with the dependence of efficiency to chordwise changes in tip clearance found.

SIMULATION SET UP

CFD simulation

The fan blade analysed for this work is a modern, high-bypass ratio Rolls-Royce fan blade (rig scale). The in-house CFD code Hydra (Lapworth, 2004) is used to carry out RANS CFD simulations of the blade. Hydra is a coupled, unstructured solver where the flow data is stored at the cell vertices. Space discretisation is carried out using a MUSCL-based flux differencing algorithm. It is an explicit solver and multi grid is used to accelerate convergence to steady state. The blade is simulated with periodic boundaries, and in rotor only format, with a downstream splitter geometry and separate exit boundaries for the core and bypass flows. The set up of the simulation can be seen schematically in Figure 1. The hub, blade, casing and splitter are set as viscous walls. The rotational speed of the rotating components is set to match the engine cruise condition. At the inlet a radial distribution of total pressure and temperature (based on experimental data) is specified and at the exit boundaries radially averaged mass-meaned non-dimentionalised flow rates (capacity) are specified (calibrated to match the core and bypass working lines). The Spalart-Allmaras turbulence model (Spalart and Allmaras, 1992) is used for all of the simulations presented here.

Meshing

The turbomachinery design and meshing system PADRAM (Shahpar and Lapworth, 2003) is used to create the structured multi-block meshes. A range of mesh sizes was tested until mesh independance was indicated for the overall cell count and the number of tip gap cells in the radial direction. The results of the mesh independance study can be seen in Figure 2. The mesh used in these investigations consists of 4.4M cells with 40 radial cells in the tip gap for datum clearance. As can be seen in Figure 3b the tip gap mesh is well aligned with the leakage flow direction. In this study the number of radial cells in the tip clearance is varied proportionally with the size of the clearance. The \( y^+ \) on the blade surface at mid-span and along the casing at mid-chord is of the order of one. Figure 3 shows a typical PADRAM mesh used.
Figure 1: Schematic of simulation set up (not to scale)

Figure 2: Mesh independence studies

(a) Total mesh size
(b) Radial cells in clearance

Figure 3: CFD mesh used

(a) Blade surface mesh (not to scale)
(b) Mesh across the tip gap
Validation

A comparison of the simulated blade with experimental data can be seen in Figure 4. The data has been normalised by the maximum experimental values. Comparisons of area-meaned total pressure ratio and efficiency (calculated from this pressure ratio and mass-meaned total temperature ratio) are shown. The stall margin was found as the point when the simulation convergence began to significantly worsen. The curves match the experimental data well, although there is a slight delta to the overall characteristic values, and the radial variation in efficiency is under-predicted compared to the experiment. Overall the simulation compares well to the measured experimental data, lying within 1% across the range of flow rates.

![Blade characteristics](image_a)
![PR profile](image_b)
![Efficiency profile](image_c)

**Figure 4: Characteristic and design point radial profile validation**

**TIP FLOW PHYSICS FOR THE DATUM BLADE**

To understand the tip aerodynamics for the datum blade at design tip clearance several features can be analysed. These are discussed here.

**Tip leakage vortex**

The tip leakage vortex is common to all turbomachinery blades with a tip clearance. Flow from the pressure side of the blade is driven through the tip gap to the suction side. This tip leakage flow exits into the suction side passage where it interacts with the passage flow. The difference in the velocities of these flows then causes a vortex to form. Figure 5 shows streamlines that highlight the path of this vortex. The loss and blockage caused by the vortex can be seen in the increase in entropy along its path (highlighted by the entropy contoured slices). Typically the tip leakage vortex begins at the very leading edge of blades, then increases in size and progresses further across the passage due to leakage flow along the chord adding to the vortex. For this case however, as can be seen in Figure 5, the leakage vortex does not begin until around 0.3 chord. This is discussed further in the next section.
Figure 5: Tip leakage vortex highlighted by entropy contours

(a) Clearance streamlines and Mach no. contours
(b) Schematic of vortex formation

Figure 6: Tip leakage vortex visualisation
Unusual tip leakage behaviour

To understand the formation of the tip leakage vortex for this case it is useful to look at streamlines of the flow within the tip gap. Figure 6a shows the flow streamlines on a constant span slice halfway between the tip and casing. The flow is coloured by relative Mach number. As the flow passes from the pressure side over the tip it turns perpendicular to the blade. The leakage flow then exits into the suction side passage and is entrained in the vortex. The path that the leakage vortex takes can clearly be seen, passing from near the blade LE across the passage towards the next blade.

As mentioned previously, it is interesting that the main leakage vortex does not begin at the very LE of the blade. A small vortex can be seen at the LE, but along the chord shortly after this there are no flow streamlines passing across the blade tip. In fact, the streamlines reverse in this location, before (around 0.3c), passing across the tip in the expected direction and forming the main leakage vortex. Figure 6b gives a schematic explaining this vortex formation method.

The cause for this unusual leakage behaviour is the accelerated flow just upstream of the passage shock that impinges on the pressure side of the blade around 0.2c. This low pressure region just upstream of the shock causes a pressure gradient from suction to pressure side, causing the flow to try to pass back across the tip gap in this location. This effect is a critical feature of the tip aerodynamics for this blade and impacts the fan tip behaviour throughout this work.

Chordwise tip leakage distribution

The chordwise tip leakage massflow distribution for datum clearance at design point can be seen in Figure 7a. The influence of the decrease in pressure upstream of the passage shock is felt by the blade loading near the tip, and the result of this can be seen in OTL distribution. The OTL massflow distribution is measured through a radial plane between the tip and casing along the blade camber line. The high velocity upstream of the shock causes the pressure gradient across the tip to reverse, with the blade loading trying to drive flow from suction to pressure side. A small amount of tip leakage occurs near the blade LE but this then drops to almost zero, before returning to more typical behaviour around 0.2c. It is at this point that the main vortex forms.

The importance of the chordwise distribution of tip leakage has not been discussed in detail in the literature. Previous researchers have acknowledged that chordwise variations in leakage flow occur and that it is the tip pressure field that controls this (Storer and Cumpsty, 1991). However the impact that this can have on the tip leakage aerodynamics has not been highlighted. This is discussed in this paper.

Another impact of the shock on the tip leakage vortex can be seen in Figure 6a. As the vortex passes through the passage shock a sudden change in the Mach number contours can be seen. This shock-vortex interaction causes the vortex to slow suddenly, resulting in an increased vortex size and passage blockage. This is discussed in more detail by Adamczyk (1991), who describes how upon encountering the shock the size of the vortex cross section is increased, and at lower flow rates this contributes to stall inception.
TIP FLOW FEATURES AT VARIOUS OPERATING POINTS

It is important to not only understand the tip flow features at design point but also how they vary across the blade characteristic at various massflow rates. Hence, three flow conditions are assessed; the aerodynamic design point (ADP), a point with lower mass flow (near stall) and a point where the blade is almost choked (near choke). Figure 8 shows the tip leakage streamlines at the various conditions. The main vortex core, passage shocks and shock-vortex interaction have been highlighted. It can be seen that the operating point has a significant effect on the tip flow structure. Near stall the leakage vortex begins right at the LE of the blade because the shock is outside of the passage unlike at design point. The vortex is also at a greater angle to the blade and the streamlines pass over the next blade’s tip, meaning ‘double-leakage’ is present. Near choke the tip leakage flow is similar to the design point but, with the shock further inside the passage and even greater acceleration upstream of it, the features are more enhanced. Near choke reverse leakage flow can be seen from around 0.2-0.3c and the vortex is not initiated until 0.5c.

These differences in the leakage behaviour can be clearly described using the tip leakage massflow distributions shown in Figure 7a. The difference in the leakage flow and the dependence on shock position is obvious. Near stall, the leakage flow is more consistent along the chord. It is maximum for the first 0.3c before the passage shock, as here the pressure difference across the blade is greatest. After this point, the tip leakage flow levels out to a value similar to the other operating points. The reduction in leakage flow near choke around 0.2c is more significant than at the design point, and the net effect from around 0.15-0.3c is ‘negative’ leakage flow across the tip. From these results it is clear that the primary feature controlling the leakage distribution is the positioning of the passage shock.

The overall tip leakage massflow (shown for a range of tip clearances) for each operating point is given in Figure 7b. Near stall, the overall tip leakage flow is significantly greater than at the design point, which again is greater than near choke. While the overall PR and blade loading (which usually has the greatest influence on leakage flow) does vary for each case, it is only small compared to these changes, which are almost entirely due to the unusual leakage distributions, limiting the overall mass flow that can pass across the tip.

Figure 7: Tip leakage at various operating points
UNIFORMLY VARYING TIP CLEARANCE

To understand the effect of variations in tip and casing positions that occur during engine operation, blade geometries with several tip clearances have been simulated. Figure 7b shows how tip leakage massflow increases linearly with tip clearance.

Figure 9 shows the change in tip flow streamlines as the tip clearance is increased from datum to three times datum. It can be seen how with increased tip leakage flow, resulting from increased tip clearances, the vortex forms at a greater angle from the blade and extends further across the passage.

The significance of the tip leakage distribution defined by the shock location is again ap-
parent from Figure 10b. The increase in tip clearance only has a significant effect on the OTL after 0.2c, whereas before this point the lower pressure difference across the tip means that the increase in tip clearance area does not give the same change in massflow. The shock position fixes the lowest leakage point, and dictates the leakage distribution. Towards the TE of the blade a proportional relationship between tip clearance and leakage flow can be seen, but near the LE this is not the case.

![Graph](image1)

(a) Variation in blade efficiency with clearance  
(b) Tip leakage distributions with varying clearance

**Figure 10: Variations in efficiency and leakage with increased clearance**

Figure 10a shows the normalised variation in blade efficiency from zero to three times datum tip clearance. The gradient is linear. To assess whether an optimum, non-zero tip clearance exists, several gaps were simulated between zero and datum clearance. As can be seen in 10a, no evidence of this was found.

**NON-UNIFORM VARIATIONS IN TIP CLEARANCE**

During the operation of a real engine, fan tip clearances are rarely uniform along the chord. As the blade and casing positions vary, the casing liner becomes rubbed. Due to way the blade untwists under varying loads and at different rotational speeds sometimes the LE rubs more than the TE and vice-versa. The result is that in reality the fan will often experience non-uniform tip clearances, with variations from LE to TE. To investigate the impact of this, several geometries have been simulated. Figure 11a gives examples where the LE/TE tip clearances have been changed by +50%. The geometries here are referred by their relative tip clearances to uniform; i.e. 0.5-1.5 has 50% of datum tip clearance at the LE and 150% datum clearance at the TE. Several variations have been tested up to a 75% increase/decrease. The tip clearance of each of these designs was then uniformly increased to understand the impact of a sloped clearance at different average radial gaps between tip and casing. This indicates which regions have the biggest impact, and how critical the variations are compared to the overall average tip clearance.

Figure 12 shows the differences in efficiency and tip leakage massflow between a design with no tip clearance and the maximum varying clearance tested, +75%. A delta in both efficiency and massflow is clearly seen between the geometries. This stays quite consistent as the average tip clearance is increased. Increasing the LE tip clearance (shown in blue) is interestingly shown to decrease both efficiency and tip leakage massflow.
(a) Example clearances with variation LE to TE
(b) OTL distributions for varying clearances

Figure 11: Non-uniform clearance schematic and leakage distribution

(a) Efficiency variation
(b) Tip leakage variation

Figure 12: Deltas in efficiency and OTL variation for +75 % sloped gaps and datum
Figure 13 highlights how across the range of sloped tip clearances analysed a decrease in LE clearance increases efficiency. A consistent correlation is seen across all levels of tip clearance bias, and the greater the variation between LE and TE clearances the greater the effect. This is reflected with decreased TE tip clearance having the opposite effect. It is interesting that the impact of the varied tip clearance is the same for both tip leakage massflow and efficiency. This is counter-intuitive, as typically an increase in tip leakage massflow leads to a reduction in blade efficiency and vice versa. There is normally a negative correlation between tip leakage mass flow and blade efficiency. The opposite is observed here for chordwise tip clearance variations.

Figure 13: Sloped gaps delta efficiency and leakage to uniform clearance

Figure 11b shows the impact that a sloped tip clearance has on the chordwise tip leakage flow distribution. Once again the impact of the unusual leakage distribution is shown to be important. The low pressure gradient near 0.2c fixes the minimum leakage near this point and at a low value. The change in the leakage flow caused by the varying tip clearances can be seen. In the TE half of the chord the variation in tip clearance size results in a large change in the leakage flow, whereas towards the LE the same variation in tip clearance has a lesser effect. The result is an overall increase in leakage when the tip clearance is biased towards the TE, and vice-versa. The reduced pressure gradient across the tip towards the LE means that an increase in tip clearance has very little effect on the leakage flow there.

To understand why an increase in LE leakage has a negative impact on efficiency despite a reduction in leakage flow, it is useful to look at the vortex cores for each geometry. Figure 14 shows the difference in leakage vortices formed for increased LE tip clearance, uniform and increased TE clearance cases. The most prominent vortex and the one that passes furthest into the passage and at the greatest angle is that in Figure 14a. For the increased TE tip clearance case, despite the overall leakage massflow increasing, the vortex does not have as great an angle to the flow, and the main vortex core sits nearer to the suction surface of the blade.

Leakage flow towards the leading edge can be seen to have the greatest impact on the main vortex trajectory and size. Increased leading edge region flow leads to the vortex having a greater angle to the passage flow, and this is responsible for generating increased losses. Beyond the leading edge part of the chord, whilst increasing tip clearance increases the leakage flow, this does not have the same influence on the main vortex. Denton (1993) explained how, beside
the overall leakage flow, the difference in velocities of the leakage and passage flows is critical in determining the losses generated. Increased LE tip clearance means increased leakage in the vortex initiation region, resulting in a greater angle of the vortex to the passage flow. Leakage in the LE half of the blade is therefore shown to have the greatest impact on blade efficiency.

CONCLUSIONS

This work presents further understanding of the tip leakage aerodynamics of a modern jet-engine fan blade. The tip vortex features have been presented and discussed for a range of flow rates and tip clearances. Two important effects have been found. Firstly, the dependence of the leakage distribution on the passage shock location was demonstrated. The impingement of the shock on the pressure surface dictates the minimum leakage position along the chord. The tip leakage distribution is a critical feature of the tip aerodynamics as it determines the vortex initiation location along the chord. This leads to large flow changes in the tip region as the shock position varies at different operating points.

Non-uniform tip clearances were studied to understand the impact of chordwise clearance variations. Biasing the tip clearance towards the TE was shown to increase the overall tip leakage flow, while biasing it towards the LE reduces leakage. This is due to the chordwise leakage distribution and minimum pressure gradient location limiting the leakage due to tip clearance near the LE. Despite biasing the tip clearance towards the LE reducing the overall leakage massflow, it was shown to cause an increase in losses. This is due to leakage flow towards the LE having a greater influence on the tip vortex trajectory and size, which is key to the generation of losses. This shows that the distribution of leakage and resulting vortex trajectory can be more critical for fan tip losses than the overall leakage massflow.

For an understanding of fan tip aerodynamics (especially when a passage shock is present), it has been shown that an assessment of the chordwise leakage distribution is critical. It has also been shown that a slight efficiency advantage is achievable by allowing a bias of tip clearance towards the TE (away from the vortex initiation region), as this reduces the losses generated for the same average clearance.
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