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FAN BLADE TIP AERODYNAMICS WITH REALISTIC OPERATIONAL CASING GEOMETRIES AND CLEARANCES

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ABSTRACT

During engine operation fan casing abradable liners are worn by the blade tip, resulting in the formation of trenches. This paper investigates the influence of these trenches on the fan blade tip aerodynamics. A detailed understanding of the tip flow features for the fan blade under investigation is developed. A parametric model is then used to model trenches in the casing above the blade tip. It is shown that increasing clearance via a trench reduces performance by less than increasing clearance through cropping the blade tip. A response surface method is then used to generate a model that can predict fan efficiency for a given set of clearance and trench parameters. It is shown that the efficiency sensitivity to clearance is greater for cropped tips than trenches, and is biased towards the leading edge for cropped tips, and the trailing edge for trenches.

NOMENCLATURE

BFS	Backward Facing Step
CFD	Computational Fluid Dynamics
DoE	Design of Experiments
FFS	Forward Facing Step
LE	Leading Edge
PR	Pressure Ratio
RANS	Reynolds Averaged Navier Stokes
RSM	Response Surface Model
TE	Trailing Edge
TR	Temperature Ratio

INTRODUCTION

Background and motivation

Fan blade tip clearances vary significantly throughout each flight cycle and over an engine's lifetime. Several mechanisms lead to this: differing expansion rates of components during start-up, the non-circular shape of the casing during flight, and gusts, which cause the core and nacelle to shift relative to each other. As a result, the fan tip and casing regularly make contact. To maximise the fan blade performance and reduce engine fuel consumption, tip clearances are designed as small as possible. This reduces leakage flow through the gap between the tip of the blade and the stationary casing which, upon entering the blade passage, generates a significant amount of losses and reduces blade performance [1–3]. To allow minimum clearances while also preventing damage to the blade due to contact with the casing, a 'tip rubbing' solution is used, where a sacrificial abradable liner is added to the casing. At certain points during the engine cycle the liner becomes worn by the blade tip. At the extreme points of the blade's movement, steps in the casing liner are created, forming a trench with non-uniform clearance above the blade. The result of these effects is a casing profile with steps just upstream of the leading edge and just downstream of the trailing edge, and clearances larger than initially set by the designer.

It is described by Kammer [4] how the repeated contact of the blades with the fan casing is analogous to the teeth of a milling machine, cutting away at the liner. The mechanical implications of the complex rubbing process (with friction-induced wear, heating and the dynamic coupling of the blade and the elas-

tic casing) are well discussed in the literature from an abrasion and dynamic perspective [5–7]. The effect of this casing rubbing on blade aerodynamic performance is not well discussed however. Realistic casing profiles, with steps up and downstream of the blade, and the implications, are not generally investigated. The trend of increasing overall clearance reducing blade performance and operability is well known [1–3], however work in this area focuses on varying clearance with simple crops of the blade tip. This paper aims to develop a detailed understanding of a modern fan blade’s tip aerodynamics for datum clearance, before investigating the impact that variations to the casing profile caused by rubbing have on its performance.

Firstly, an understanding of the tip flow physics for a modern fan blade is developed using RANS CFD. The tip leakage flow structure, tip leakage massflow distribution and tip vortex properties are analysed. For the datum case, it is shown that an unusual tip leakage distribution exists, which has a large influence on the local aerodynamics. Acceleration upstream of the passage shock sat on the pressure side of the blade causes the tip leakage flow to partially reverse, travelling from suction to pressure surface for part of the chord. The variation in blade performance and tip flow features due to uniform changes in tip clearance are then discussed in detail.

The impact of casing geometries with different tip clearances, trench depths and sharp steps is then investigated using a parametric model. The analysis allows a detailed understanding to be developed of the impact that realistic casing geometries have on the tip region flow. The effect of cuts in the casing profile compared to cropping of the blade tip is investigated at a range of effective clearances. Casing geometries generated using a range of permutations of the model parameters are simulated using high fidelity CFD. Response surface analysis of the results is then able to predict the relationship of each parameter to blade performance. The importance of each parameter is found, allowing an understanding of the effects of trenches and various clearance geometries that is useful for engine designers to be developed.

Previous work

A number of researchers have investigated tip clearance effects for fans and compressors. Adamczyk et al. [8] demonstrated the role of tip clearance in high speed fan stall, showing the reduction in stall margin, pressure ratio and efficiency caused by an increase in clearance. They also described how the interaction of the leakage vortex with the in-passage shock plays a major role in determining the fan flow range. Denton [1] developed a model for predicting the loss generated through turbomachine clearances based on the properties of the leakage and passage flows. He described how the entropy generation by the tip leakage vortex is proportional to the difference in streamwise veloc-

ity of the two flows. A study of compressor efficiency variation from vanishing to large clearance is provided by Sakulkaew [9]. He showed how the loss variation with tip gap is linear for clearances between 1 and 3%. Seshadri et al. [10] and Beheshti [11] also discussed the linear variation of blade efficiency with tip clearance for axial compressors. Both Seshadri et al. [10] and Sakulkaew [9] found however that close to zero clearance the behaviour is non-linear and an ‘optimum’ clearance is found. This is due to increased shear losses at the casing as the clearance becomes small. These studies all focused only on cropping the blade tip uniformly with no changes to the casing streamline.

The main discussion of casing geometry variations in the literature is related to passive casing treatment for improved blade performance. These investigations use several discrete axial or circumferential grooves in the casing above blade tips to ‘trap’ the leakage flow and reduce its impact, improving stall margin or efficiency [12] [13]. Qin [14] demonstrated how casing groove depths and angles can be optimised to provide greater performance benefit. These casing grooves for passive tip treatment are far larger than the blade clearance however (unlike trenches which are of similar magnitude), and the behaviour of these multiple discrete grooves not applicable to this work.

Investigations into the effect of single, circumferential trenches are provided by Robideau [15] and Korting [16]. The first states that a performance benefit can be achieved by allowing the airfoil tips to sit above the full height of the flow path. This is achieved using a trench and allowing the blades to extend further radially. The idea is to move the leakage flow out of contact with the passage flow, and thus reduce losses. The paper by Korting [16] tested the impact of ‘trenched’ clearances above the tip of a compressor blade in more detail. Experimental results describe the impact of various depths of trench and upstream and downstream shapes. It was shown that an important feature was the forward facing step at the trailing edge side of the trench. Increased depth of the trench produced more loss because of the increased forward facing step. The trench only provided an efficiency benefit when the step at the trailing edge was replaced by a sloped geometry. It was concluded that trenches did not alter the sensitivity of the compressor to changes in clearance. While informative, these results are not expected to aid this work as the clearances and trenches described are of far greater spanwise extent compared to those in a modern fan blade. The effects of clearance also differ in a multistage compressor compared to fan blades as tested here.

PROBLEM DEFINITION

A demonstration of the variation in the relative blade and casing positions that cause rubbing of the abradable liner can be seen in Figure 1. This shows how the blade’s position can vary in the axial and radial directions and the resulting liner profile that is formed after many cycles. The position of the blade at cruise

and a comparison of these features to the datum liner profile can also be seen.

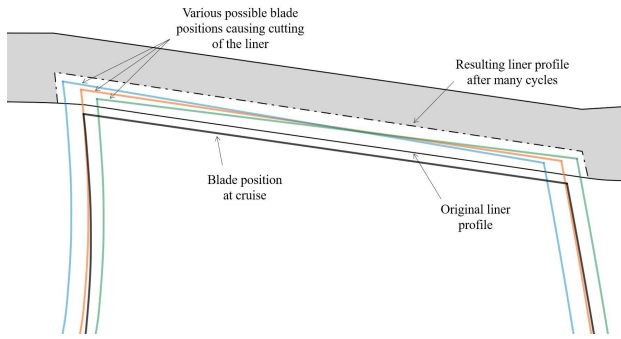


FIGURE 1: CASING LINER TRENCH FORMATION

To understand the realistic size and topology of liner trenches that form in operational engines over their lifetime, an in house tip-rubbing prediction tool was used. The tool input parameters include the blade and casing geometries and the number of engine cycles. The various blade tip and casing positions are predicted and, through calculating when they intersect, the new casing profile is built up cycle by cycle. This tool uses a whole engine model to give the predicted positions of components based on their expansion under varying rotational loads at conditions through each engine cycle. The untwist of the fan blades under load (which causes the leading and trailing edges to move radially different amounts) is included, as is the variation of the axial position of the blade. Together these effects are responsible for producing the steps at either end of the trench. Additionally, a gust prediction model, that can simulate the sudden shift of the core radially within the nacelle, is used. This uses data on the likelihood of gusts occurring each engine flight and adds the resulting displacement into the tip-rubbing prediction tool. Gusts are the most significant contributor to casing liner trenches' depths.

For this study the tip-rubbing prediction tool was used to predict the range, depth and variety of trench geometries and clearances likely to exist in an engine throughout its lifetime. This provides values for the maximum depth of cut and the upstream/downstream positions that the trenches extend to. These are used to define the boundaries for the geometries to be investigated. The exact clearance levels studied are proprietary however, and cannot be included in this paper.

Topologies under investigation

To understand the effects of casing liner trenches three types of tip clearance must be modelled. These are shown in Figure 2. Firstly, a blade with a standard clearance is simulated, and the ef-

fect on the fan aerodynamics of increasing the clearance through cropping the blade tip understood. This is the method usually used to vary blade clearance in simulations, and also represents the result of shortening a blade design to prevent any rubbing occurring should this be a concern. In this study the datum casing streamline is always kept constant (outside of the trench region). This is important as attempting to vary the clearance by adjusting the entire casing streamline would modify the inlet and exit areas of the fan, adding extra variables into the computations that would confuse the results. The second geometry that requires simulating is trenches above the blade tip, with the blade tip remaining outside of the trench and below the datum casing line. This allows an understanding of the impact of a trench appearing above the blade tip for an unchanged blade geometry, as well as a comparison to increasing clearance through cropping the blade. Finally the blade should be allowed to extend inside of the trench, to see whether allowing a blade to extend further radially would provide any benefit, and whether interference from the trench steps has any impact. The clearance will be varied for each of the geometry types.

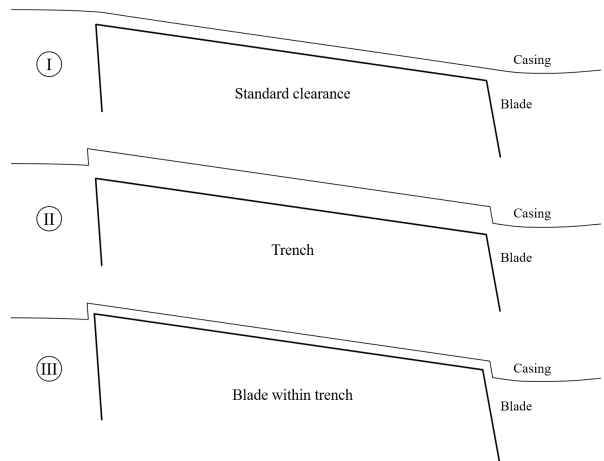


FIGURE 2: REPRESENTATION OF THE TIP TOPOLOGIES UNDER INVESTIGATION

SIMULATION SET UP

The fan blade analysed for this work is a modern Rolls-Royce fan blade (rig scale). RANS CFD simulations of the blade are carried out using the in-house CFD code Hydra [17]. The blade is simulated in rotor only format, with a downstream splitter geometry and separate exit boundaries for the core and bypass flows. An outline of the CFD domain showing the position of the

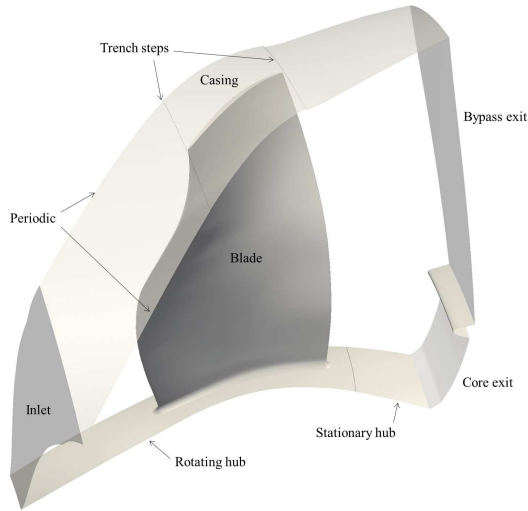


FIGURE 3: LOCATION OF TRENCH WITHIN SIMULATION SET UP

trench steps can be seen in Figure 3. At the inlet a radial distribution of total pressure and temperature is used and at the exit boundaries radially averaged mass-meaned non-dimensionalised flow rate (capacity) is specified. The Spalart-Almaras turbulence model [18] is used for all of the simulations presented here.

The turbomachinery meshing and design system PADRAM [19] is used to create the structured multi-block meshes. A range of mesh sizes was tested until mesh independance was indicated for both the overall mesh count and the number of radial cells in the tip gap. The selected mesh has a total mesh size of 4.4M cells with 40 cells in the tip gap for the datum clearance. An extra mesh block is created above the blade tip when a trench is present to properly model the flow. When tip clearance is varied in this study (through a trench or cropping the blade tip) the number of radial cells in the tip gap is varied proportionally while maintaining those in the remainder of the span. The mesh across the tip gap is well aligned with the leakage flow direction. Figure 4 shows an example of the trench and clearance mesh used at the blade tip. The y^+ measured along the blade surface at mid-span and along the casing above the blade tip at mid-chord is of the order of one.

Validation

A comparison of the simulated blade with experimental data can be seen in Figures 5 and 6. Both the pressure ratio and efficiency curves match the experimental data well, though there is a slight delta to the overall values and stall margin. The radial curves show good comparison to experimental data, although the radial variation in efficiency is under-predicted compared to the experiment. Overall the simulation compares well, lying within 1% across the range of flow rates.

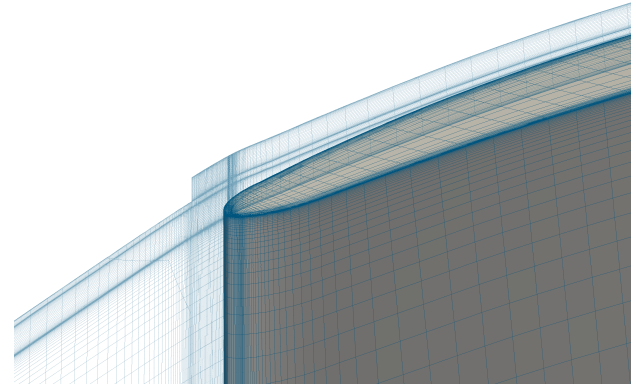


FIGURE 4: A TYPICAL PADRAM MESH ACROSS A CLEARANCE WITH TRENCH

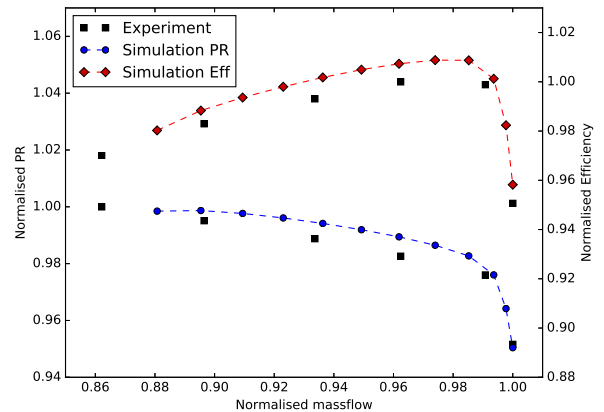


FIGURE 5: COMPARISON OF SIMULATION WITH EXPERIMENT

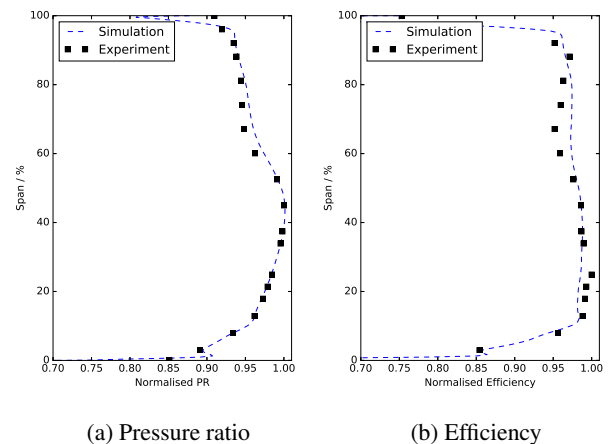


FIGURE 6: RADIAL PROFILES VS EXPERIMENT AT DESIGN POINT

TIP AERODYNAMICS FOR THE DATUM BLADE

The tip leakage vortex is common to all rotating blades with a clearance. The basic mechanism involves flow from the pressure side of the blade being driven through the clearance by the pressure gradient to the suction side. As this leakage flow exits the clearance and interacts with the passage flow, the difference in velocities causes a vortex to form. Figure 7 shows 3D streamlines that highlight the vortex produced for this case. The loss and blockage generating nature of the vortex can be seen in the 2D slices of entropy that highlight the path the vortex takes. The tip leakage vortex would normally be expected to begin at the leading edge of the blade, before increasing in size and progressing further across the passage as leakage flow along the remainder of the chord adds to the vortex. As can be seen however in Figure 7, for this case the tip vortex begins around 0.3 chord. The reason for this is described below.

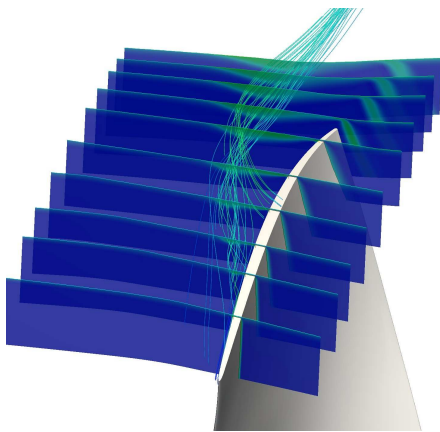


FIGURE 7: TIP LEAKAGE VORTEX HIGHLIGHTED BY 3D STREAMLINES AND SLICES COLOURED BY ENTROPY

A visualisation of the flow streamlines within the tip gap is useful to understand the formation of the tip clearance vortex. A constant span slice taken halfway between the blade tip and the casing can be seen in Figure 9a. The image is coloured by relative Mach number and faint streamlines added to show the flow directions in the plane of the slice. It can be seen how flow from the pressure side turns perpendicularly as it passes over the tip of the blade. It then exits the suction side and becomes entrained in the vortex. The path of the vortex at this height can be clearly seen in the streamlines that pass diagonally from near the LE towards the adjacent blade. Figure 9b gives a schematic of the vortex formation method.

It is interesting to see that the formation of the main vortex does not start at the very LE of the blade. A small vortex can be seen emanating from the LE, but shortly after this there appears to be no flow streamlines passing from the blade gap. In fact, the

streamlines actually reverse in this location, before (at roughly 0.3 chord), reverting to the expected direction and forming the main vortex that continues into the passage.

The cause for this unusual leakage behaviour is the acceleration upstream of the passage shock that impinges on the pressure surface of the blade at around 0.2 chord. The low pressure region just upstream of the shock creates a pressure gradient from suction side to pressure side, which tries to drive the air back across the tip gap around this location. This effect is a critical feature of the tip aerodynamics for this blade, and has an impact on the fan clearance behaviour studied throughout this work.

Figure 8 shows the chordwise tip leakage massflow distribution for the datum case at design point. The data has been normalised by the maximum value at datum clearance. The influence of the sudden change in the flow field around the passage shock is felt by the blade loading near the tip. The high velocity upstream of the shock leads to the pressure difference between upper and lower surface actually reversing, meaning the blade loading is trying to force flow 'backwards' from suction to pressure surface. The resulting tip leakage is measured through sections of a radial plane created along the camber line within the tip clearance and is normalised by the measured area. Some tip leakage occurs at the LE of the blade but then the amount drops to almost zero, before at 0.2 chord returning to more typical behaviour. This is where 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 [2]. However the impact that this can have on the tip leakage aerodynamics has not been highlighted.

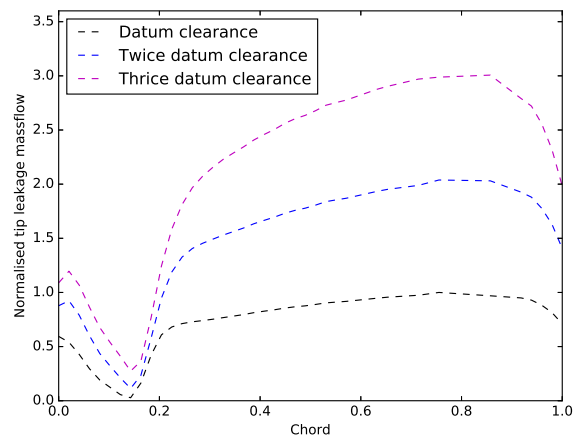
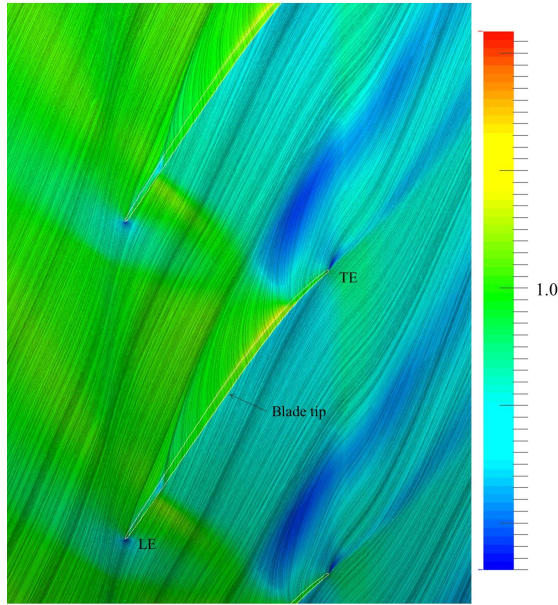
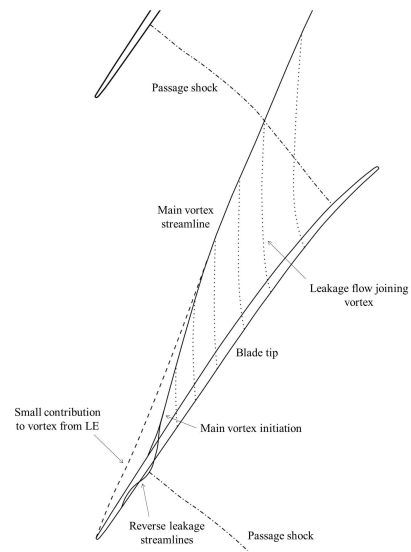


FIGURE 8: TIP LEAKAGE DISTRIBUTIONS FOR VARIOUS CLEARANCES



(a) Clearance streamlines and relative Mach no. contours



(b) Schematic of vortex formation

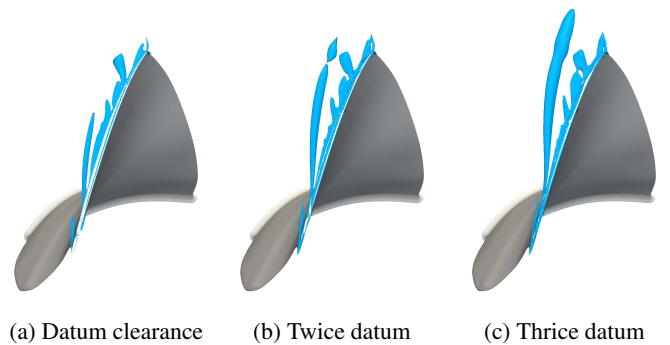
FIGURE 9: CLEARANCE VORTEX FORMATION METHOD

Variation in performance due to cropping blade tip

This section discusses the impact on blade performance of increasing clearance through cropping the blade tip. The significance of the tip leakage distribution defined by the shock location is again apparent from Figure 8. Increasing clearance can be seen to only have a significant effect after 0.2 chord, whereas before this point the lower pressure difference across the tip means that the increase in 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 clearance and leakage flow can be seen, but near the LE this is not the case.

It can be seen in Figure 10 how the strength of the leakage vortex develops as the gap increases. The leakage vortex cores are highlighted by contours of high q-criterion. Q-criterion is a measure of vorticity, and hence these contours surround and reveal the vortex cores. The vortex core is larger and moves further across the passage as the clearance increases. The vortex also forms at a greater angle to the blade as the greater momentum of the increased leakage competes with the passage flow.

Figure 11 shows the increase in tip region loss associated with cropping the blade tip. The values have been normalised by the maximum loss for datum clearance. The increased tip leakage massflow and the resulting larger vortex means there is greater mixing with the passage flow and generation of losses. The increased maximum loss in the tip region and the radial extent of the losses due to leakage can be seen. It is obvious from this figure how significant the loss due to tip leakage flow is, hav-



(a) Datum clearance (b) Twice datum (c) Thrice datum

FIGURE 10: Q-CRITERION ISOCONTOURS (10^8) SHOWING CHANGE IN VORTEX WITH CLEARANCE

ing far greater magnitude than lower down the span.

Figure 12 shows the variation in blade performance from zero clearance as the gap changes. A blade with no clearance (but maintaining correct rotating boundary conditions) was simulated to give the reference point. The gradient is almost linear. This is similar to results found by previous researchers. To assess whether an 'optimum' clearance occurred at a non-zero value, several gap sizes were simulated between zero and datum clearance. As can be seen in Figure 12, no evidence of this was found.

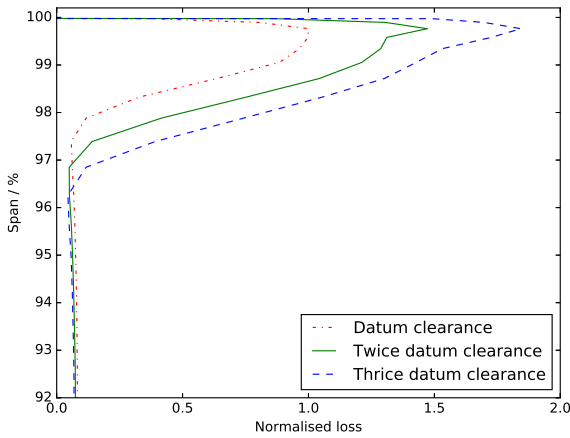


FIGURE 11: TIP REGION LOSS DUE TO CROPPING BLADE

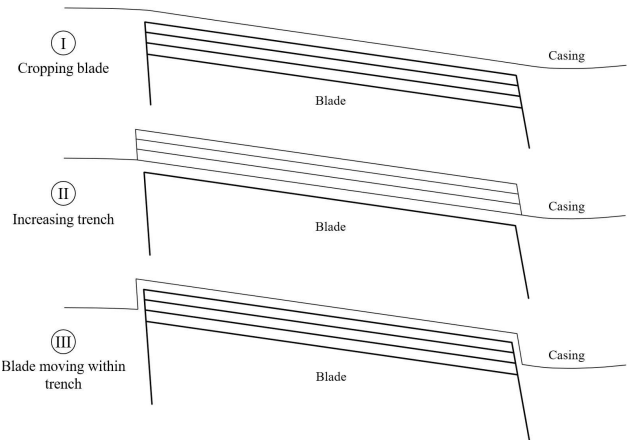


FIGURE 13: REPRESENTATION OF THE GEOMETRY TYPES UNDER INVESTIGATION

Comparison of different trench topologies

The variation in performance due to cropping the blade tip was discussed above and is given in Figure 12. To compare the effect on blade performance of this to varying the clearance with trenches, four clearances were simulated for each geometry type. Representations of the various clearances simulated can be seen in Figure 13. The results are given in Figures 14 and 15. The result have been normalised by the datum clearance value.

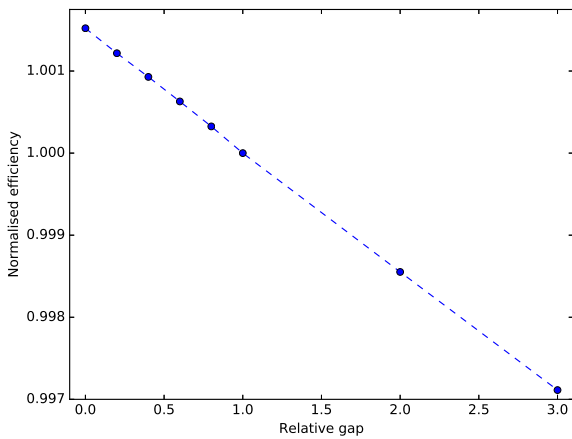
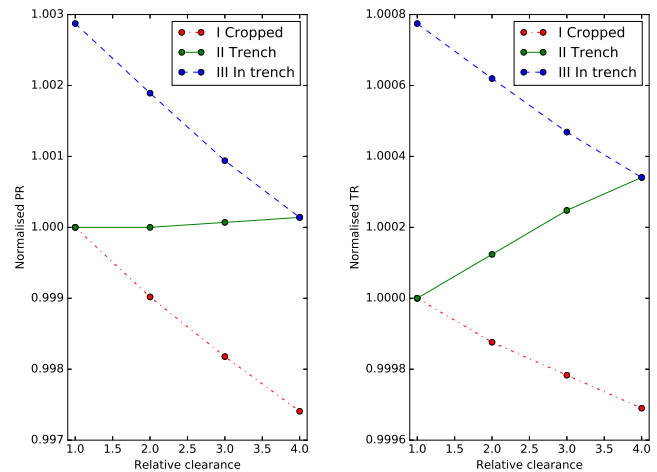


FIGURE 12: VARIATION IN BLADE PERFORMANCE WITH CLEARANCE (DUE TO CROPPING TIP)

MODELLING TRENCHED CASING GEOMETRIES

To understand the impact on the tip aerodynamics of trenches above the blade tip, the three types of geometry shown in Figure 2 were simulated. Each case was simulated with a range of clearances between the blade and casing. This was achieved by either 'cropping' the length of the blade for the case with no trench (type I in Figure 13), raising the depth of the trench above a constant blade (type II), or by increasing the length of the blade inside of a large trench (type III). The clearances are all referred to here by their relative magnitudes to datum clearance.



(a) Pressure ratio

(b) TR

FIGURE 14: PR AND TR VARIATION WITH CLEARANCE

It can be seen in Figure 14a how there is a linear relation-

ship between pressure ratio and clearance for each of the geometry types. As the blade is cropped for type I the PR decreases. However a different behaviour is seen for the trench case. As the trench is introduced above the blade and increased in depth, the overall pressure ratio remains almost constant. For the in-trench case (type III), extending the blade inside of the trench follows the same linear gradient of PR as the case with no trench. The impact of varying the trench depth above the blade tip clearly has a different effect to cropping/uncropping the blade.

Figure 14b shows the variation of temperature ratio with clearance. It can be seen that the gradient of TR with clearance does not follow that of PR from 14a. This is due to the increased losses associated with increased clearance, caused by extra tip leakage massflow and mixing of the tip leakage vortex. These viscous effects result in additional non-isentropic temperature generation which increases the temperature ratio, despite little variation in pressure ratio. For the cropped and in-trench cases the variation in TR is caused by a combination of the PR variation and the increase in viscous heating. The overall TR decreases with clearance for these cases, because the variation in PR (and therefore isentropic TR) is greater than the TR change due to extra tip leakage effects.

To understand the impact of the three different cases on performance, the variation in blade efficiency can be analysed. This is given in Figure 15. It can be seen that the gradient of efficiency with clearance is steeper for the cropped (I) and the in-trench (III) cases than for the trench case. The geometries where the blade is being cropped are most sensitive to clearance, and very similar to one another, suggesting the performance gradient is not sensitive to whether the blade tip is sat in or out-side of the trench. It is the difference between cropping the blade or varying the clearance through a trench that is most significant.

To understand the performance differences between the three cases, geometries with the same clearance for each case can be directly compared. Figure 15 shows a delta in efficiency for geometries with twice datum clearance from each case. The radial profiles of loss for these are given in Figure 16. These were taken at 0.9 chord ('within' the trench in the axial direction), to ensure the effect of tip region features could be clearly seen. It can be seen that the extent of tip region loss is lower for the blade within the trench compared to the other two. The trench case also has less tip region loss than the cropped blade. This shows that lower tip region loss is produced when the clearance is moved further radially via a trench. It can also be seen how the region of the span affected by the tip loss has been shifted radially, moving the leakage out of the main passage flow. The effects seen match the explanation by Robideau [15], who described how moving the clearance outside of the main flow path is beneficial.

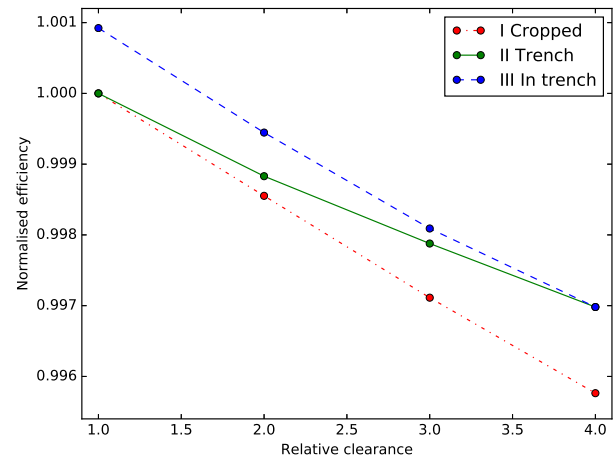


FIGURE 15: EFFICIENCY VARIATION WITH CLEARANCE

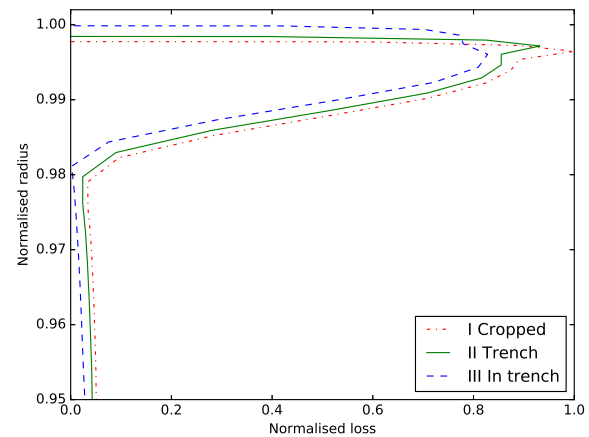


FIGURE 16: TIP REGION LOSS FOR THE DIFFERENT CASES AT TWICE DATUM CLEARANCE, MEASURED AT 0.9 CHORD

Flow visualisation

To further understand the differences between the tip region flow and losses for the three cases as described above, visualisation of the tip flow features are given in Figures 17 and 18. These confirm that seen in Figure 16. Figure 17 demonstrates how raising the clearance through a trench shifts the leakage vortex radially. The spanwise slices shown are at a constant height just below the casing streamline, and show how the vortex size and intensity at this height is reduced by raising the clearance via a trench.

Figure 18 shows zoomed slices of entropy just downstream

of the trailing edge step, looking upstream. These highlight the vortex size and intensity for each case. It can be seen how lower vortex intensity and entropy is present where the clearance has been raised radially via a trench. This shows the impact of the trench on the main passage flow outside of the trench region, indicating that shifting the leakage flow radially reduces the losses generated.

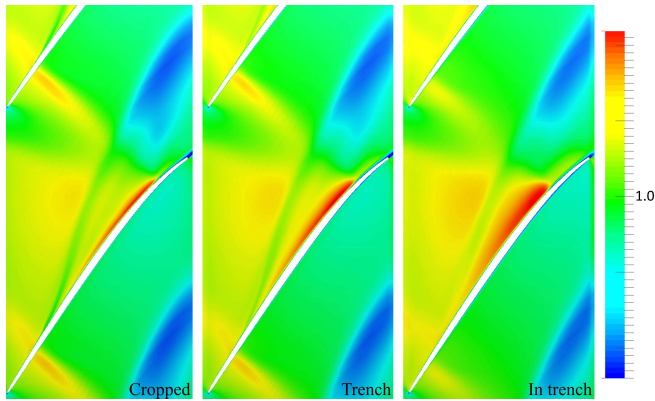


FIGURE 17: REL. MACH NO. CONTOURS SHOWING THE VARIATION IN VORTEX SIZE AT A CONSTANT RADIUS FOR TWICE DATUM CLEARANCE

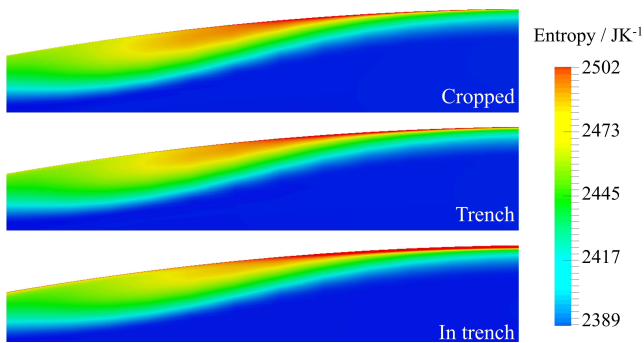


FIGURE 18: VARIATION IN BLOCKAGE INTENSITY DOWNSTREAM OF TRAILING EDGE STEP FOR EACH CASE AT TWICE DATUM CLEARANCE

The influence of trench steps

An additional objective was to understand the importance of the trench steps themselves and whether they have any direct influence on the tip flow behaviour. Figure 19 shows contours of separated flow in the LE and TE tip regions. The separation

caused by the LE BFS and the TE FFS can be seen, as well as the tip leakage flow. It can be seen that the LE trench step separation does not directly interact with the tip leakage flow. The extent of the separation is not great enough for this to happen and also the tip leakage vortex is initiated away from the blade LE, as discussed previously. The TE trench step appears more significant. The leakage flow can be seen to directly interact with the TE step, and separation at the step is reduced on the suction side, where the leakage vortex passes over it. The separation at the TE step enters the main passage flow, and is therefore likely to have greater impact than separation from the leading edge step. The increase in entropy due to the TE FFS can be seen as the dark red contour along the top right of the in trench image in Figure 18.

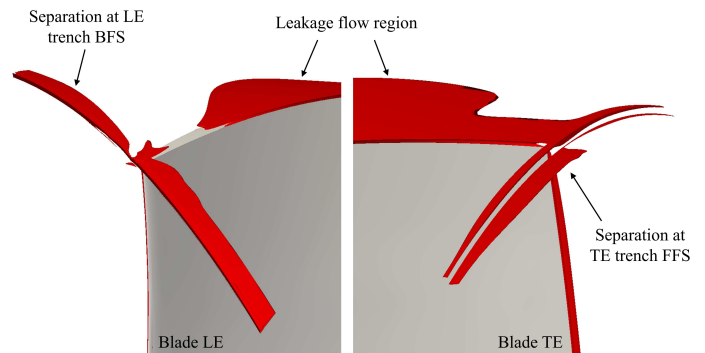


FIGURE 19: THE INFLUENCE OF TRENCH STEPS (ZERO AXIAL FLOW CONTOURS SHOW SEPARATION)

Radial profiles

Aside from the differences in the tip region behaviour between the three cases, the gradients of performance with clearance are also shown to vary. Figure 14a showed how for the trench case the PR appeared to stay almost constant while when cropping the blade tip a drop in PR was seen. Figure 20 shows the delta in radial PR profiles from twice datum clearance to datum clearance for each of the three cases.

It can be seen that there are differences in the tip region between the three topologies, reflecting the differences described above. What can also be seen is the difference slightly further down the span. The PR delta for the trench case is different to the cases where the blade is cropped. The effect of this is that the PR deficit in the tip region caused by increasing clearance is almost cancelled out by the changes lower down the span, which is the reason the PR gradient appears nearly constant in Figure 14a. This suggests that the overall blade length has an influence on the blade performance, and also shows how the differences between these cases are not isolated to the tip region.

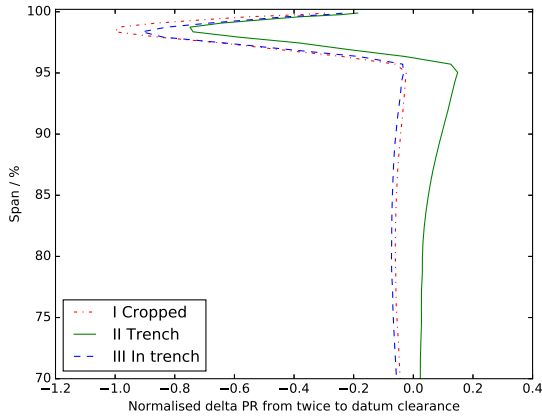


FIGURE 20: DELTA PR RADIAL PROFILE FROM TWICE TO DATUM CLEARANCE FOR EACH CASE

The above results demonstrate the differences between cropping the blade tip and varying clearance through a trench, and the mechanisms that lead to differences between the tip region flows and overall performance values. To gain a more complete understanding and investigate which regions of the clearance and trench are most critical to control performance, a more complete parameterisation is needed.

FULL PARAMETRIC STUDY

To fully understand the effect of casing liner grooves and the impact of the large variety of possible casing shapes, a detailed parametric model has been developed. The parametric model is able to generate casing liner profiles and varying tip clearances to be used within the PADRAM meshing system. The parametric model consists of eight parameters allowing varying blade clearances and trench depths from LE to TE, with different up and downstream trench step heights and axial positions. Figure 21 shows the parameters controlled in the model:

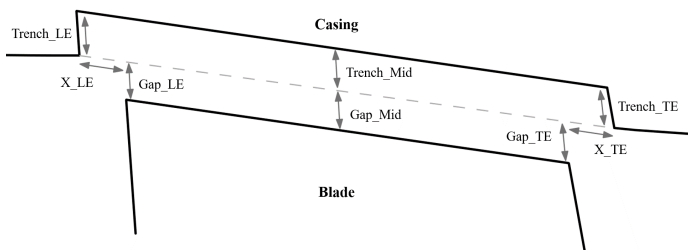


FIGURE 21: REPRESENTATION OF THE PARAMETRIC DEFINITION OF THE GEOMETRY

The parametric model allows chord-wise variation of both the casing and blade geometries. The blade tip and casing profiles are generated through a linear interpolation of the specified parameters. It is necessary to model chord-wise variation of the trench depth as this occurs in an engine as the blade cuts differently at the leading and trailing edges. Uneven blade tip clearances from LE to TE can also occur in an engine due to varying untwist of the blade during expansion.

Design of experiment

To understand the influence of each parameter on the blade performance, simulations of various combinations of the parameters were carried out. To plan the set of design points to simulate a design of experiments approach was used. Through the Rolls-Royce optimisation toolbox SOFT [20] a latin hypercube [21] design of experiments was set up. Latin hypercube sampling is a method for generating a near-random distribution of parameter values for a multidimensional system. Unlike truly random sampling, where there is no guarantee of the distribution of sample points, latin hypercube sampling attempts to ensure a good representation of the real variability by ensuring the design space is evenly covered. This was used to maximise the relevance of the results obtained through the surrogate modelling approach to be used.

The trench and gap parameters could vary up to three times datum clearance, while the axial step positions could vary up to five times. Fifty sample points from the design space were selected to be simulated through the latin hypercube sampling. The objective function extracted from each simulation and to be used in further analysis is efficiency.

Surrogate model

To find the dependence of blade performance to each parameter, a polynomial response surface analysis method was used [22]. This is a surrogate modelling method that allows an empirical model to be built from the results of the simulations carried out, allowing the response (blade performance) to be predicted given the input variables (geometric parameters). A first order polynomial response surface was fitted to the data. This allows a coefficient for each parameter to be found, allowing an equation to be formed that relates the blade performance to each of the input parameters.

Figure 22 shows a comparison of the first order RSM versus the data to which it was fitted for each point run in the DoE. It can be seen that the model fits the data well, accurately reflecting the variation in efficiency of each design. This gives confidence that the model is reflecting the physics captured by the CFD and that the linear trends predicted are a good representation of the real effects of each parameter.

The form of the generated first order polynomial is given in Equation 1 where f is the blade performance, X represents a pa-

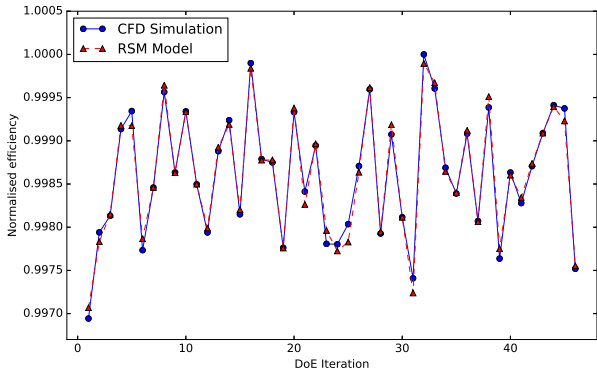


FIGURE 22: COMPARISON OF RSM FIT TO CFD DATA

parameter and C a coefficient. The calculated coefficients (C) for each parameter found via the response surface method are given in Table 1. A negative coefficient means blade efficiency reduces with increased magnitude of that parameter. The constant in the equation is the efficiency value that a geometry with zero clearance or trench has, equivalent to setting all gap and trench parameters to zero.

$$f = X_1 \times C_1 + X_2 \times C_2 + \dots + X_n \times C_n + const \quad (1)$$

Figure 23 shows a comparison of previously obtained simulated results versus predictions from the response surface model. This can be used to assess the ability of the polynomial response surface to represent the real effect of each parameter. The points shown here were not sampled during the response surface analysis. It can be seen that the polynomial equation obtained does a good job of predicting the gradient of efficiency to clearance for the two cases.

It can be seen in Table 1 that the axial position of the trench steps is of far less importance than the clearance magnitudes. The axial position of the trench steps does not seem that important. While the separation at the steps may have an influence, the position of the steps relative to the blade LE/TE is not that critical. The relationships also indicate the mid-trench and mid-blade clearance parameters are most important. However, to understand which region has the most influence on the blade performance, the relationship of the clearance area to the parameters in the model must also be considered. If every parameter in the geometric model were kept at zero, then the LE and mid-trench values increased in turn, it would be obvious that increasing the mid value increases the clearance area by twice as much as the LE parameter. Hence, the mid values (of both blade and trench) geometrically have twice the influence on tip leakage as the LE/TE values in this model.

TABLE 1: MODEL COEFFICIENTS FOR EACH GEOMETRIC PARAMETER - EFFICIENCY VARIATION WITH CLEARANCE

Parameter	Performance sensitivity %/mm		
	LE	Mid	TE
Trench	-0.008	-0.150	-0.117
Gap	-0.103	-0.307	-0.028
Step position	0.004	-	-0.009

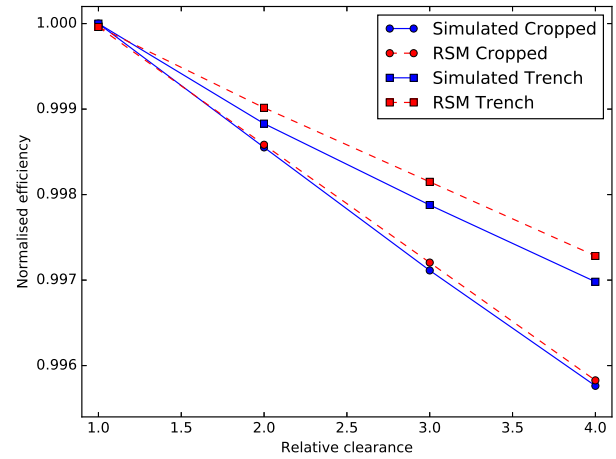


FIGURE 23: COMPARISON OF SIMULATED AND PREDICTED PERFORMANCE VARIATIONS WITH CLEARANCE

To understand the effect of equivalent variations in clearance at the LE, mid and TE, the RSM coefficients must be normalised by the clearance area that they influence. The result of this can be seen in Table 2.

Explanation of the coefficients

Table 2 gives a comparison of the influence on blade performance of different regions of the tip/trench clearance. It can be seen that overall the sensitivity of performance is greater due to cropping the blade tip than increasing the depth of trench, reflecting results found earlier. The chordwise distribution of this sensitivity varies however between the gap and trench.

The sensitivity to gap clearance is biased towards the LE half of the blade, between the LE and mid-chord. This can be explained by understanding the method of tip leakage vortex for-

TABLE 2: TRENCH AND GAP COEFFICIENTS ADJUSTED BY THEIR INFLUENCE ON CLEARANCE AREA AND NORMALISED

Parameter	Adjusted performance sensitivity		
	LE	Mid	TE
Trench	-0.05	-0.49	-0.76
Gap	-0.67	-1.00	-0.18

mation for this case. Due to the nature of the passage shock position controlling the tip leakage distribution, the tip leakage vortex is initiated around thirty percent of chord. It is therefore around this point that the leakage massflow will have the greatest impact on vortex formation, and therefore changes to clearance in this area will have the greatest impact on blade performance.

The sensitivity of performance to the trench clearance magnitudes is reduced compared to the gap sensitivities due to the partially positive effect that adding a trench and raising the clearance has. This can be seen in the individual sensitivities. The LE trench clearance is far less critical than the LE gap clearance, due to the benefit that it provides by moving the critical region of vortex formation radially out of the passage flow. The TE trench parameter is significant however, and the impact of the trench is biased towards the TE. This demonstrates the difference between the impact of the LE and TE trench steps. The TE trench step acts as a FFS, and the separation due to this generates losses and enters the passage flow. The LE BFS separation does not have the same impact, any separation is confined to the corner of the LE trench step, remaining out of the flow path, and does not have any influence on the downstream flow.

Additional impact of clearance variations

Aside from variations in the tip region, an additional effect of varying clearances and trench geometries that must be noted is the influence of the tip flow behaviour on flow in the remainder of the span. Changes in blockage and local velocities at the tip can slightly influence the radial distribution of massflow and velocities for the rest of the blade. An impact of this can be seen in Figure 24.

This shows that separation at the blade TE is affected by different clearance geometries and sizes. The effect of this can also be seen in Figure 20 where localised changes at the tip cause an additional effect from 95% span and below. This will result in a secondary impact on the blade performance, aside from changes localised to the tip region, and the performance variations with clearance discovered for each trench parameter also include these effects.

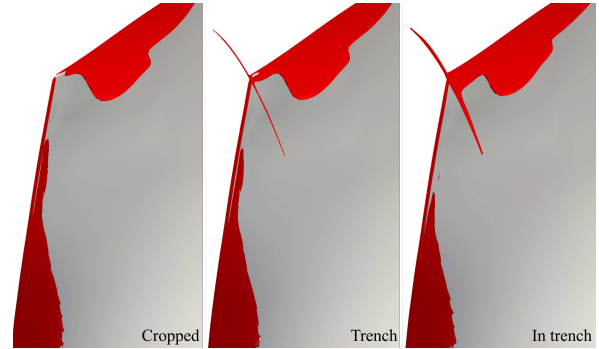


FIGURE 24: VARIATION OF TRAILING EDGE SEPARATION DUE TO DIFFERENT CLEARANCE TYPES

The upshot of this is that the performance trends given are influenced by the overall blade design and aerodynamic behaviour away from the tip region. This behaviour is specific to this fan blade design, and therefore the relationships found may not be directly applicable to blades with different designs. This must be considered when trying to translate tip performance trends found for one blade to another, or develop generic relationships.

CONCLUSION

This paper has investigated the tip region aerodynamics of a modern fan blade. The tip flow features, tip leakage distribution, clearance vortex size and tip loss have been studied for the datum design, as well as the effect of increasing clearance through cropping the blade tip. It was shown how an unusual tip leakage distribution exists due to the acceleration near the passage shock controlling the chord-wise vortex initiation location.

A parametric model was used to compare the effect of increasing clearance through cropping the blade tip, creating a trench above the blade tip and modifying the blade length inside of a trench. It was shown that a benefit is achieved by increasing the clearance via a trench compared to cropping the blade tip. This is due to lower tip region loss being generated when the clearance is raised radially out of the main passage flow.

A response surface method was used to fit a polynomial equation to a set of sample points selected by latin hypercube DoE. The polynomial equation was shown to accurately capture the dependence of blade efficiency to each parameter. It was confirmed that blade performance is more sensitive to cropping the blade tip than increasing clearance through a trench. For the blade clearance the key region is between the LE and mid-chord (where the tip leakage vortex is initiated). It was shown that the axial position of the trench steps is generally of less importance than the clearance magnitudes. The TE of the trench is of greater importance than the LE, due to the extra loss caused by the FFS.

This work has discovered performance relationships for tip geometries and clearances that can be used to influence fan blade design and understand engine performance degradation in-service. It is also apparent from this work that these relationships depend on the specific tip aerodynamics of the blade under investigation. The presence of a passage shock, the tip leakage distribution, shock-vortex interaction and overall blade design influence the tip flow behaviour and associated performance variation with clearance.

FUTURE WORK

It would be interesting to apply this methodology to other fan/compressor blades to understand how specific the trends shown here are to this blade design, and whether generic relationships could be discovered.

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