Francesco Montomoli *Editor*

Uncertainty Quantification in Computational Fluid Dynamics and Aircraft Engines

Second Edition

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To Arianna

One must still have chaos in oneself to be
able to give birth to a dancing star
F. Nietzsche

Contents

Introduction

The overall goal of this work is to give an overview of the current research on uncertainty quantification applied to aircraft engines. Since the publication of the last book on uncertainty in aircraft engines and CFD, the field has become a very active research area with more researchers from around the globe working on it.

The aim of the book is to summarize the areas where UQ is required and the impact on turbomachinery design. Even if the book is mainly focused on aircraft engines, considerations that are common and relevant to other gas turbines, such as applications in oil, gas and energy, are shown.

Until 10 years ago, the design process of an aircraft engine required 90% of rig tests and 10% of computational fluid dynamics simulations. Today, these numbers are almost inverted with CFD playing a major role in the design and certification of aircraft engines.

However, we have reached a level of detail in the simulations where the length scale that is resolved in CFD is comparable to the microscopic errors due to the manufacturing variability, but these errors are not accounted in many simulations. High-fidelity CFD for gas turbines requires the simulation of these variations; in principle, these effects are stochastic and it is necessary to move from deterministic simulations to probabilistic CFD.

In this work, we will show an analysis of the impact of manufacturing/in-service degradation on the performance of jet engines, as found in the open literature. Afterwards, we will discuss the impact of CFD uncertainty and how different uncertainty quantification techniques have been used to quantify these effects in compressors and turbines. Uncertainty quantification is a general term that encompasses several different methodologies to carry out stochastic analyses: one of the chapters will guide the beginners through the methods that have been currently applied, and it will explain in more detail the mathematical formulation of such methodology.

The idea of the book is to propose a reference text focused on the needs of the turbomachinery community, more than a general text on uncertainty quantification. The book will give an overview of the state of the art and a deeper understanding of current methods.

The structure of the book will allow the reader to tackle what is more appealing to him/her. The main sections on the impact of uncertainties, methods to solve them and mathematical formulations are independent and require different skills.

The learning outcome is the possibility for the reader to identify the major areas where UQ can play a role and the different methods that have been used in the field to solve specific problems.

Besides a lot of tailored solutions, there is a clear trend towards the development of more automatic solutions able to tackle different problems, without the need of a statistical expert. There is a gap of competencies between gas turbine designers, FEM/CFD users and statisticians. UQ ideally requires individuals with a strong background in both areas to use the best possible models (reducing epistemic uncertainty), and accounting manufacturing and in-service variations (aleatoric uncertainty). Modern codes are trying to combine these two aspects, as shown in this work.

Chapter 1
Manufacturing/In-Service Uncertainty and Impact on Life and Performance of Gas Turbines/Aircraft Engines

M. Massini and Francesco Montomoli

Abstract This chapter highlights the impact of manufacturing errors on performances of aircraft engines and gas turbines in general. The reader should use this chapter to identify the regions where uncertainty quantification (UQ) should be used to improve the reliability of a gas turbine design and define where this matters.

Considering the extreme and harsh conditions in gas turbines, very small geometrical variations can have a strong impact on the performance and the life of the components. These variations can be generated by manufacturing errors, assembling inaccuracy or in-service degradation [1].

In this chapter, we have highlighted whether a geometrical uncertainty is a consequence of in-service degradation or manufacturing errors: this poses different challenges to the original equipment manufacturer (OEM).

On one side, it is possible to tackle in-service variation scheduling a more frequent maintenance; on the other side, if it is not possible to improve the manufacturing technology, uncertainty quantification should be introduced in the design system to build parts that are inherently not affected by variations, also known as robust design.

> Why manufacturing errors are important? Gas turbines operate in a very harsh environment, and it is logical to expect, as it is, that a small geometrical variation has a strong impact on life and performance.

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The so-called forward propagation of uncertainty during the analysis is named uncertainty quantification; the backward propagation of uncertainty in the design system, to achieve solution not affected by uncertainties, is called robust design.

Moreover, some parts are “naturally” almost unaffected by these variations; in such cases, uncertainty quantification will play a minor effect on the design. Identifying these regions gives the designer meaningful information on the value of using expensive optimization processes.

Despite the majority of the work is on manufacturing errors, the authors suggest that this should not be the major/only focus of UQ.

What are the real operating conditions of a turbine? In Oil & Gas, for example, it is not uncommon to have turbines operating continuously at 40% of their design mass flow. Moreover, there are other variations such as parts that have been replaced during the working life of the turbine that were not specifically considered in the original design of the machine. These problems are more common in gas turbine areas other than aviation, but similar examples are found in aviation as well. For example, the pilots have a very strong impact on the engine performance.

Some important data used as input in numerical simulations or for performance evaluation, such as the turbine entry temperature (TET), are not directly measured and are prone to errors that will impact the predictions. Having accurate data and/or a control of data uncertainties is fundamental in the development phase of the design. Nevertheless, it is not always possible to have access to such data, and engineering assumptions are made. Assumptions and lack of data accuracy require a detailed uncertainty analysis to be included in the design phase.

The transient phase is another critical aspect of engine variability, and most of the uncertainties in gas turbine temperatures are observed during transients, not during steady-state operations [2]. When the engine is subjected to full load, emergency trips or fast starts, it has been estimated that a life reduction of about 200 h occurs as a result of each trip. There are several sources of errors in unsteady experiments of real engines such as probe calibration, test vehicle and test facility errors. Even if the measurement apparatus has been perfectly calibrated for time variations and the instrumentation does not show any interaction with the system, an important source of errors is the clock time itself. A typical uncertainty of several tenths of second may be expected in a ground facility. The time uncertainty in aircraft engines is particularly important and can promote an earlier blade failure, for example, if the engine is stressed by fast start-up and shutdown phases. The transient of a real engine has a strong impact on metal gradients, and even if an accurate UQ study is carried out, the system is highly dependent from the tail of the time probability density function.

Even by assuming ideal operating conditions, there are several geometrical deviations that can affect the performance of the real machine in a not negligible way. The main focus of this chapter is then manufacturing errors, in line with what seen in the designer community.

> The core is becoming smaller and smaller and the conditions more extreme. It is clear that variations will have a greater impact in future engines.

Furthermore, the trend for improving fuel efficiency is to increase the TET and to reduce the size of the engine core, which results in a decrement of the overall weight. However, the reduction of the core requires smaller components, and therefore, the impact of manufacturing errors will increase.

The introduction of “new” manufacturing methods in aircraft engines such as additive manufacturing and the introduction of composites are increasing the level of geometrical uncertainty. This is discussed in more details for each component.

> New manufacturing methods such as AM and composites are posing new challenges to designers.

The different aspects that can reduce the turbine life and performance will be analysed in the following paragraphs, focusing on four major components of aircraft engines: fan, axial compressor, combustion chamber, high-pressure and low-pressure turbine.

This introduction to gas turbine variability highlights the reasons why it is important to use uncertainty quantification techniques in the numerical analysis of gas turbines.

1.1 Fan

The fan is driving the engine performance, and the variations in fan performance are mainly due to in-service degradations. Due to the size of the fan blade, manufacturing errors have a smaller impact on the overall performance of the blade, and there are few studies dealing with this problem. Up to few years ago, the engine fan was mainly made of titanium and the geometrical accuracy of a fan has been very good for several years. Considering also that the span increased with the years, the relative errors became smaller and smaller.

> Uncertainty in Fan is mainly driven by in-service degradation. However, the introduction of composites can change this in the long run, with more focus on manufacturing errors.

Despite that, the flow in the engine fan is inherently transonic and small variations in the shock structures can have a strong variation in performance, due to the nonlinearity of fluid dynamics. Moreover, more integrated solution, reduced axial space and more aggressive core design are exacerbating the impact of the variations.

One of the studies on the variation of fan performances was carried out by Schnell et al. [3]. The author used optical measurements to characterize the geometry of the fan with principal component analysis (PCA) in order to decompose the geometrical errors in their correspondent eigenform. The work of Schnell et al. [3] is important because it shows the application of PCA, which has been extensively used in UQ in different ways. In this book, it will be shown that PCA is the most common methodology to define the modes of manufacturing errors that are used in UQ analysis, for fans, compressors and turbine. Schnell presented the study of a counter-rotating fan; the majority of the variations were in the afterpart of the front stage, due to the unsteady interactions. In a standard fan, without counter-rotation, the authors believe that manufacturing errors should be taken into account near the fan root and near the tip. The flow from the fan root proceeds into the core engine and deviations may affect the downstream low-pressure compressor. Conversely near the tip region, small geometrical variations alter the losses due to the transonic regime of the fan tip. This aspect is going to be even more important in the future considering that composites fan blades are becoming more and more popular with two leading manufacturers, General Electric and Rolls-Royce. This poses new challenges on how to build accurate profile and how to measure them (such as optical measurements and ultrasonic testing).

Other than possible manufacturing errors, the main cause of variation is deterioration due to the impact of fan blades with foreign objects and how they modify the aero-foils geometry.

> Leading edge: Sand ingestion modifies fan profile in particular during take-off. Considering the transonic design of modern fan, small modifications have strong impact on performances.

Among all the possible foreign objects ingestion (such as bird ingestion), one of the most important (and common) phenomena affecting fan aerodynamics is the impact of sand particles [4]. This is particularly critical for aeroplanes flying in Middle East and over deserted areas where aero-engines suffers from erosion caused by sand ingestion as shown by Tabakoff and Balan [5, 6]. The authors of the mentioned papers studied experimentally the impact of sand ingestion in aircraft fan and found that the main effect is erosion of the leading edge and increased roughness on the pressure side. Moreover, the sand ingested by the engine erodes the fan tip. As shown by Ghenaiet, sand erosion can increase the clearances by 65% [7] and can reduce the tip chord by about 10% [7].

In transonic fans, leading edge degradation affects the losses mainly by changing the shock structures at the leading edge [8]. The overall loss of the stage loading found by Klinner et al. was 3.5%. A loss of 4% has been detected for the overall stage efficiency. Other researchers [7] measured a reduction of 7.1% in adiabatic efficiency and 9% in pressure rise coefficient. The results presented in the open literature correlating sand ingestion, and fan degradation are "fan and test specific", and it is difficult to extrapolate these data. Moreover, the variability over the efficiency results is dependent upon the length of the test, fan material, etc., and that should be considered as well when analyses on degradation are carried out.

Sand erosion: clearances up by (up to) 65%, tip chord reduced by (up to) 10%.

Adiabatic efficiency reduction: 4–7%
Pressure rise reduction: ~9%.

The general outcome of these results shows the high impact that in-service degradation can have on the overall performances of the component. Therefore, for a reliable estimate of the machine operation through its life, these changes should be pondered. Modern carbon fibre fans use a metal leading edge to shield this area from foreign objects and from sand erosion; however, the impact of sand erosion still affects the performance. Moreover, the impact of manufacturing uncertainty needs to be accounted for with new composites structure that seems more prone to geometrical errors.

A detailed investigation of fan root aerodynamics was carried out by Zamboni and Xu [9]. The authors pointed out the impact of the variations of the fan root flow on the core engine. In particular, they discussed the impact of root aerodynamics on specific fuel consumption growth at increasing bypass ratio, in line with the current design trend. As an example, they found that a variation of 3% of stagnation pressure losses in the root region could modify the specific fuel consumption by 0.3% at a bypass ratio of 3 and 0.6 at a bypass ratio of 10. Roughly, a 1% variation of the pressure losses increases the SFC by 0.2% at a BPR of 10. Even if the overall goal of the paper was oriented to define design rules, the work provided some useful hints on the impact of variations on the engine performance. The authors discussed the impact of the leakage between the stationary and the rotating platforms on the downstream core engine, reducing the capacity of the stator vane. The amount of leakage is a parameter that it is difficult to quantify, but it has a strong impact on the overall engine performance. The authors show that the impact of the leakage blockage on the loss generation was smaller with a reduced hub line curvature [10] (Fig. 1.1).

Fan root aerodynamics: this is a critical area because it affects the core of the engine. Variations in this area have not been investigated with UQ, but it is critical for the engine.

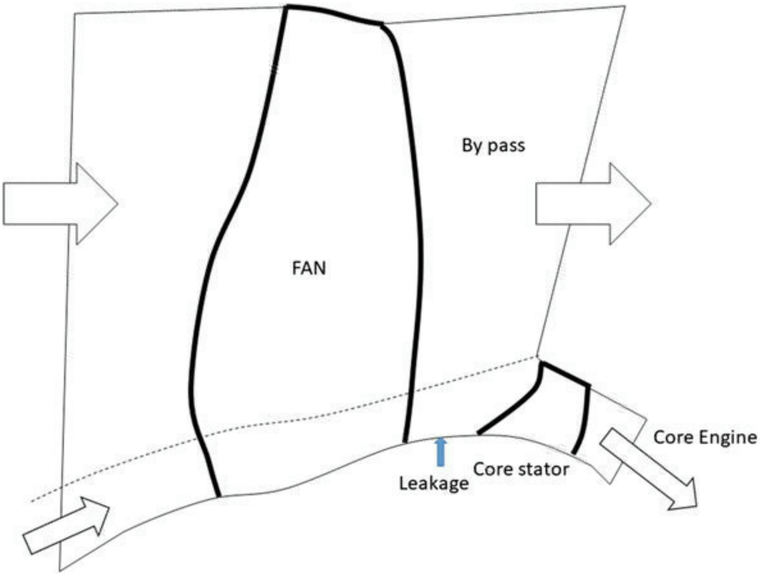

Fig. 1.1 Schematic of the test case used by [8] modified from the original

A particular aspect related to fan random variations and aeroelastic behaviour is the so-called mistuning. Real fan blades, due to manufacturing errors and wear, show variations in mass, geometry and stiffness known as mistuning. The aeroelastic stability is influenced by all these parameters, and there is a great interest in the effect of mistuning on stability [11]. Mistuning can also be intentional in order to suppress flutter. More recently, there is a growing interest towards aeroelastic mistuning in order to predict and minimize the impact of such variations. Franz et al. [12] analysed a probabilistic framework for fan blade off events. After a fan blade off, the unbalancing of the fan due to the missing blade can generate an impact between the blades and the inner casing. The authors used a Bayesian approach to identify the most likely combination of conditions after a fan release. They used expert judgement and in-service data for the Bayesian inference analysis.

Even if this is not a subject tackled by this work, it is important to remember the uncertainty associated with measurements errors. In a recent paper [13], it has been shown the important impact of probes error in the efficiency predictions in fan. The authors suggest a method to correct this with correlation terms.

We believe that uncertainty in CFD and experiments should be analysed with the same propagation framework in order to have a direct comparison of not only the main parameters but also the deviation observed.

1.2 Axial Compressor

In axial compressors, manufacturing errors and in-service degradation alter the compression ratio and stability margin and therefore the overall performance of the engine [14, 15]. A compressor is strongly affected by small variations, and one of the main reasons is the adverse pressure gradient on the airfoils. The impact of small errors in the front stages is propagated and amplified moving downstream. Moreover, the geometrical parameters of a compressor blade, in particular in the high-pressure stages, are of the order of millimetres or less; therefore, the manufacturing accuracy has a higher impact on the relative geometrical deviations.

In principle, it is possible to measure deviations related to manufacturing errors in a compressor blade using optical techniques. However, the measure itself is not "perfect", and laser techniques have an accuracy of about 15 μm [16]: a "standard" leading edge has a radius of 0.1 mm, and the measurement error is about 10% of the quantity that is important to estimate. Optical techniques are indeed very accurate for the surface reconstruction far from the leading edge. However, as shown below, it is the leading edge that affects the engine performance.

The evaluation of geometrical errors is even more complex when it is important to quantify the variations in the assembled engine. The engine moves and deforms subject to thermal stresses; and the assembled compressor is different from the cold measured one, even when the metal expansion is accounted for. This aspect is not considered in nowadays studies, but it can be important to estimate the engine core movement during operations in order to predict accurately the engine efficiency and stall margin.

In the open literature, four areas have been identified as the most important for the compressor performance related to manufacturing errors:

1. The leading edge shape
2. The rotor tip gap
3. The aero-foils roughness
4. Real geometry features such as fillets, leakages, inter-platform gaps.

In the next paragraphs, these uncertainties will be presented as separated effects. However, as pointed out by Goodhand and Miller [17], the interaction of all the possible errors does not follow the superposition law and should be analysed together.

1.2.1 Compressor Leading Edge Shape

The leading edge radius of a modern axial compressor is of the order of 0.1 mm [18], and despite the very small dimension, geometrical variations of the compressor leading edge have a strong impact on the single stage and on the whole compressor performance. In general, the response of a compressor to geometrical variations is non-linear, with few exceptions. Goodhand and Miller [16] pointed out that for the leading edge the incidence range of an aerofoil responds approximately linearly to small geometry variations.

> Compressor leading edge shape is maybe the most significative small geometrical variation that can impact the overall engine performance.

In order to define the impact of the errors in absolute terms, all the figures below use 0.1 mm as reference value for the leading edge radius. Small variations in the leading edge region can thicken the boundary layer on the early suction side and promote/increase the size of three-dimensional separations. This effect was shown by Wheeler et al. [19], comparing two geometries: a circular arc and an elliptic shape. With the elliptic shape, the flow was attached and laminar; with the circular arc, which is the common geometry in the majority of the engines, the flow was separated at the leading edge and reattached turbulent with an increment in profile losses by 30%. Figure 1.2 shows the leading edge shape adapted from the study in [19]. The radius of a leading edge in a transonic compressor is of the order of 0.1 mm, and the radius in the experiments of [19] was 4.72 mm; this explains why the impact of microscopic variations is important. This microscopic variation of leading edge shape modified the suction surface losses by 38%, being the elliptic shape more efficient. The overall goal of the work was to define which configuration was better for modern engines. However, Fig. 1.2 shows that the overall max difference between the two geometries was small, (~0.02 mm estimated by the authors of this book) but nevertheless responsible for strong variations in the transition mechanism and in the losses.

Following studies have shown that the key mechanism relating LE errors and losses is associated to the generation of spikes and subsequent decelerations in the early suction side. Theoretically, it is possible to produce spike-free profiles [17] in order to reduce the losses. However, the leading edge region is characterized by particularly small dimensions and therefore highly affected by manufacturing errors. By using measured data, Lamb [20] has shown that the mean total pressure

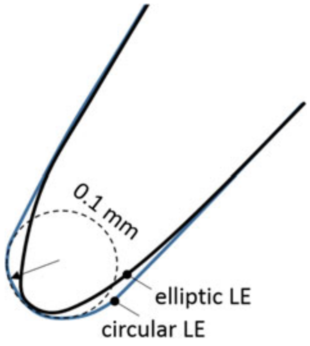

Fig. 1.2 Elliptic versus circular leading edge, reproduced after the work of Wheeler et al. [19]

losses of a given set of compressor blades are higher than the expected losses of the baseline profile, with only few blades over-performing the baseline. At the same time, Lamb [20] proved that the criteria to assess a profile based on geometrical variations, such as the requirement for a leading edge shape to be between a minimum and a maximum design radius, are not directly correlated to the performance. It is commonly assumed that if the leading edge is within a specific bound, the performance will be inside the acceptable range, but this is not true. In particular, it has been shown the weakness of the minimum criterion to discard blades, due to the fact that some airfoils below the minimum acceptable criterion outperformed the baseline.

Garzon [21] has shown an overall reduction of 1.2% in efficiency when geometrical variations are applied to a six-stage compressor using a numerical simulation with experimentally measured blades. The geometrical error was decomposed using a principal component analysis, which is a method frequently found in literature.

Goodhand et al. [16] have studied the impact of in-service degradation versus manufacturing errors for a real compressor in order to understand which one is the most important in different areas of an engine. The variation due to in-service degradation was estimated using an ex-service set from an engine with about 4000 cycles (= ~ 3–4 years of operation on a medium range aircraft). Figure 1.3 shows the envelope of the manufacturing errors found by Goodhand et al. [16].

They found that for the majority of the high-pressure compressor the manufacturing variations seem to dominate and that the main region affected by in-service degradation is concentrated near the tip region. This suggests that erosion is not having a significant effect in most areas over the first 4000 cycles of operation and that uncertainties in the performances of high-pressure compressors are mainly dominated by manufacturing errors.

Another cause for the leading edge to be "out of shape" is the coating, as shown by Elmstrom et al. [18]. The different profiles studied by Elstrom et al. have been reproduced in Fig. 1.4, with uniform and non-uniform coating distribution. While there is evidence that coated compressors can outperform uncoated ones in certain applications, there are situations where this may not be the case. For example, coating the base metal airfoil can result in a change in shape of the leading edge that can create an adverse aerodynamic impact.

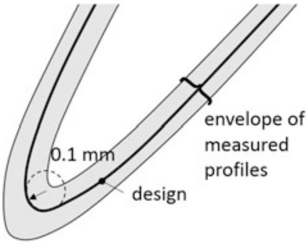

Fig. 1.3 Envelope of measured profiles by Goodhand et al. [16]; 0.1 mm is the radius of a realistic transonic compressor leading edge, added as reference

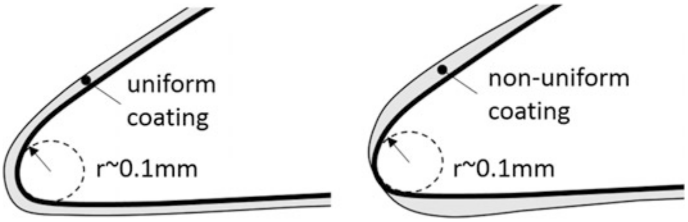

Fig. 1.4 Coating on compressor leading edge, reproduced after the work of Elmstrom et al. [18]

In a recent test, a compressor in a naval application after the coating was no longer able to meet the minimum specifications, as reported by Caguiat [22]. Specifically, the compressor showed a loss in the maximum power output, an increase in specific fuel consumption SFC and an increase in starting time beyond the acceptable level. In "mission critical" applications, involving commercial aircraft safety or military operations, this diminished capacity at start-up or to restart the engine can be critical.

Transonic or supersonic compressor blades typically have leading edge radii between 0.08 and 0.13 mm, and even uniform coating can change the radius by 20% (Elmstrom et al. [18]). While the coating thickness over most of the blade is very uniform, it is unlikely that airfoils will have uniform coatings near the leading edges. The coatings are generally applied as liquid, and from the moment of application until the coating is sensibly dry, various physical forces, surface tension being an important example, cause the coating to flow away from sharp convex corners and "bunch up" a short distance away before it dries. This can introduce a leading edge spike that can alter an optimized LE shape.

Variations are due to manufacturing, including coating, and in-service degradation.

There is a 2% penalty in relative total pressure loss due to the addition of a uniform coating. At low incidence, the non-uniform coating shows total pressure losses that are nearly 5% greater than the uniform coating and 8% greater than the uncoated airfoil. Elmstrom et al. [18] suggest a criterion to predict the impact of non-uniform coating on the separation bubble. However, the basic idea is that non-uniform coating can have a detrimental impact on compressor performance, even without accounting for in-service degradation.

1.2.2 Compressor Rotor Tip

Sakulkaew [23] analysed in detail the impact of tip geometrical errors on efficiency. Sakulkaew studied compressor rotors with tip clearance ranging from 0.04 to 5% span. In large industrial gas turbines, the rotor tip and stator hub clearance can be less than 0.5% span in the front stages and more than 5% span in the rear stages.

The authors identified three distinct mechanisms of losses. From 0.5 to 0.8% span, the change in efficiency is driven by two competing mechanisms: decreasing tip leakage mixing losses and increasing viscous shear losses when decreasing the tip gap. For medium tip gaps, 0.8–3.4% span, the efficiency decreases linearly with increasing the tip clearance in accord with Denton's tip leakage mixing model. The main effect is due to the tip leakage mixing. They found that for the specific compressor, there was one point efficiency benefit for every 1% span decrease in tip gap size. The numbers agree with what was found by Freeman et al., as shown in Fig. 1.5. Freeman [24] found a 1.4% drop in efficiency for a 1% (of span) increase in tip clearance.

However, for tip gap beyond a threshold value (3.4% span for this rotor), the efficiency becomes less sensitive to tip gap as the blade tip becomes more aft-loaded, thus reducing tip flow mixing loss in the rotor passage. The threshold value is set by two competing effects: increasing tip leakage flow and decreasing induced mixing loss due to increasing tip gap.

1.2.3 Compressor Aero-Foils Roughness

Only a few experimental tests are available in the literature on the effect of roughness on the performances of a compressor. An experimental assessment on the degradation of rotor performances for a high-speed axial compressor due to fouling was performed in the past by Suder et al. [25], who investigated the effect of adding thickness and roughness to the airfoils surface; they identified the leading edge and the front half of the suction side as the regions with the greatest effect on the rotor performances.

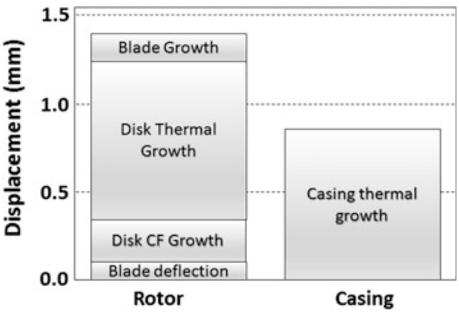

Fig. 1.5 Freeman [24] Tip clearance effects in axial turbomachines

Other experimental results are presented by Gbadebo et al. [26], where the effects of a distributed surface roughness on 3D flow separation are investigated. More recently, Syverud et al. [27] described a salt ingestion test campaign performed on a GE J85-13 jet engine. The front stages were found to have the greatest amount of deposit, with a non-uniform distribution of the surface roughness that was higher on the pressure side of the vanes. Another work by Syverud et al. [7] compares the experimental data with stage losses correlations; it shows that nowadays models match the mass flow variation but underestimates the efficiency reduction due to the increased roughness.

A significant amount of work has been recently done by Morini et al. [28] on stage-by-stage models based on a stage-stacking procedure that predicts the actual modification of compressor and turbine maps due to blade fouling and mechanical damage. Using this approach, each single stage performance map was scaled in order to take into account the stage deterioration. The authors used a computational approach to quantify the impact of these variations, considering also the local geometrical variations due to the fouling.

1.2.4 Compressor Real Geometries Effects

Real geometry effects is a broad term to identify all the effects related to accurate description of the real geometry such as gaps, fillets that are usually not considered during the design phase; nevertheless, they can have an impact on the real machine. For example, it was proven in the literature that the blade fillet can also affect the size of the three-dimensional separations. Curlett [29] showed that by varying fillet radius, the separation size and thus the blade loss were altered. He found that the lowest loss occurred with no fillet, while the highest loss occurred with the largest fillet tested.

Figure 1.6 shows some flow visualization carried out at the University of Cambridge, Whittle Laboratory, on the low-speed axial compressor known as Deverson test rig. Figure 1.6 shows the impact of the fillet at near stall conditions in a low-speed rig. Introducing a fillet near the casing stator (radius of the fillet 2.5 mm, radius of the leading edge 1 mm), it is possible to have a more stable condition. In particular, Fig. 1.6 shows that the incipient separation bubble is reduced. The same effect was observed also numerically.

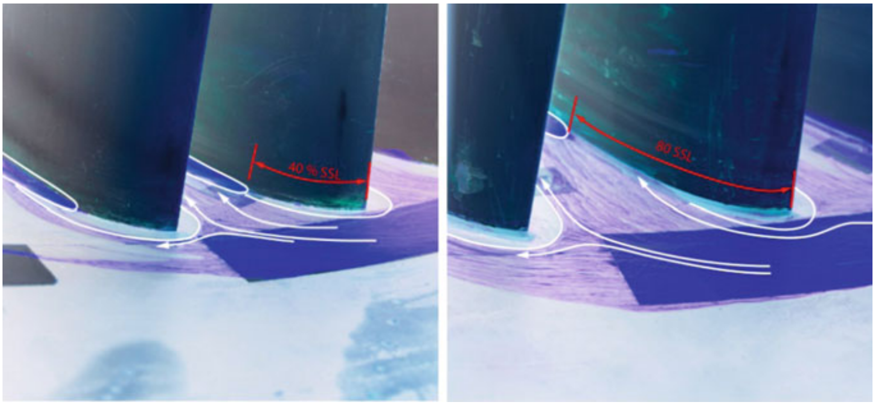

Fig. 1.6 Flow visualization, Deverson rig, Univ of Cambridge, Whittle Laboratory. Authors Montomoli F, Naylor E, Goodhand M

1.3 Combustion Chamber

1.3.1 Fuel Variability and Aviation

There is a growing request of renewable-synthetic fuels in gas turbine applications, for power generation and aeronautical propulsion [30–34]. Figure 1.7 shows the roadmap of the reduction of the emissions before 2050 and the expected contribution from fuel.

Synthetic fuels can be obtained from coal, natural gas and biomass [34] and have been extensively tested to evaluate the variations on gas turbine performance [35].

Figure 1.8 can be used as a reference to show the variation of syngas composition that has been used for gas turbine.

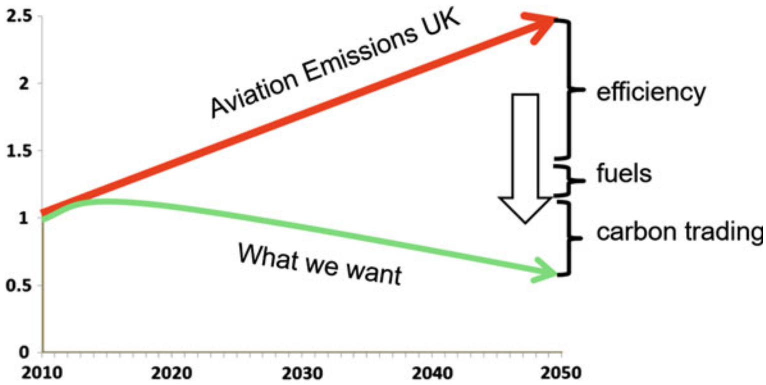

Fig. 1.7 Aviation emissions prevision before 2050