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Some Unresolved Physical Problems in Turbomachinery Flows

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Abstract

Even for the ostensibly two-dimensional (2D) flow through cascades of blades, much of the basic flow physics is not well understood or predicted. A principal research focus in turbomachinery flows is presently on the computation of three dimensional (3D) flows. This paper is a reminder that 2D flows are also important and their problems are also not resolved. In cascade tests on a turbine nozzle vane many flow features have been identified in the 2D flow through the blade passage that require further attention. Of the issues identified, the focus of this paper is on three of these. The chosen topics are boundary layer transition, wake interaction effects including the calmed region, and shock-boundary layer interactions. The emphasis is on continuing to understand and represent the flow physics.

Introduction

Early Developments

The development of axial flow turbomachines initially assumed free vortex designs with cylindrical sheets of potential flow. These designs relied on 2D wind tunnel cascade testing of blading. Two data sets were widely used. British data were correlated to give incidence and deviation rules [1]. The more extensive American data sets were reconciled by Mellor and reproduced by Horlock [8]. Theoretical blade flow solutions were not widely used until numerical solutions were developed and tested against exact solutions [2].

Subsequent Computational Work

A major area for research and design use was developed by Smith [11]. This was associated with the computation of three dimensional steady rotational flows in compressors and turbines (including radial velocities). This so-called streamline curvature method was developed mainly within industrial groups at General Electric, Pratt and Whitney and Rolls-Royce. It was based on the solution of the full radial equilibrium equation and was suited to computer solution. It was widely used in industry, and indeed is still in use by General Electric today.

Subsequently the time marching method was developed – a successive approximation approach. The full equations of motion are solved at a given time and the solution then advanced by a time step; the equations are then solved again at the new time. This proved remarkably resilient and effective step. This method offers an alternative to streamline curvature.

Inclusion of viscous terms in the equations is obtained by Reynolds averaging and simple approximations for those stresses (e.g. mixing length). Reynolds-averaged Navier-Stokes (RANS) methods are useful workhorses. It has subsequently proved possible to solve the full turbulent flow equations numerically by Direct Numerical Simulation (DNS). This requires low Reynolds numbers and an enormous computing resource. An alternative is to use RANS over the major part of the domain and DNS over a limited smaller part. This is called Large Eddy Simulation (LES); it is really a coarse-grid DNS, with the addition of a subgrid-scale model to account for the scales of motion that are smaller than the grid resolution. A substantial problem within these developments is that of providing the grid structures to match the blading shapes.

Other Areas

Despite these major computational developments, complete understanding of turbomachinery flows cannot be achieved without the experimental data to validate the calculations. It is important to retain an emphasis on representing the flow physics. This is needed even to predict laminar and transitional boundary layers, heat transfer and stall behaviour, as this paper indicates.

Another major area of research involves *unsteady flow*. Initially this followed from the requirement to deal with the effects of maldistribution at entry to the axial compressor resulting in a distortion in the entry duct flow often due to separations from the walls. Subsequently it became clear that the effects of blade wakes from one row on the performance of the next row can be important; pressure distributions and boundary layer development have to be considered. The flow through the whole compressor or turbine is essentially unsteady.

Yet another thread running through turbomachinery research is the general solution of rotational flows – sometimes called *secondary flows*. Shed vorticity from the tip of an aircraft wing was well known and understood, but the concept of vorticity within turbomachinery blade passages (and the associated secondary flow) had not been encountered. In a cascade, the transfer of inlet vorticity into passage vorticity was studied by Hawthorne [7], in parallel with other work [12] on these secondary flows.

More detailed attention is now being devoted to modelling these additional 3D flows including boundary layers and separation. Secondary flows, clearance, sweep effects, cross-flow instabilities etc. need to be incorporated. In a cascade, inlet vorticity is transferred from wall boundary layers on entry ducts into passage vorticity. This is complicated but the real flow is even more complex because of the interaction of secondary vorticity with tip vorticity, the development of secondary vorticity, and the transfer of secondary and tip vortices from one blade row to another.

Physical Features

In this paper some physical features of flows over compressor and turbine blades that are not understood are identified. Even for the ostensibly two-dimensional flow through cascades of blades, much of the basic physics of the flow details is still obscure. Figure 1 gives the layout of a turbine nozzle passage indicating many issues where there are gaps in our knowledge.

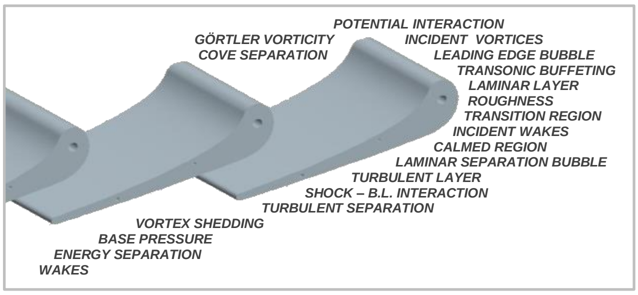

Figure 1. Some Physical Features in Turbine Nozzle Blading Flows.

These cover the entire nozzle vane surfaces from leading edge to trailing edge and beyond. Many of these physical features can also be found on compressor and fan blades. In this paper we try to identify some areas where substantial research is still needed. Predictive capability for boundary layer transition *onset* is still poor despite advances in predicting the subsequent transition in the *region*. Adverse pressure gradient effects occur in triggered spots, wake-disturbed boundary layers, and on blading. Similarities in behaviour are observed between strong adverse pressure gradient tests on triggered spots, wake-disturbed flat plate boundary layers, and on blading. A calmed region follows each wake-induced turbulent strip. A calming effect remains at work even when its domain coincides with that of the following turbulent patch. This has the effect of reducing the mixing effect of the turbulence and therefore continuing to stabilize the flow. This would have a beneficial effect on engine efficiency.

Failure to model the shock-boundary layer interaction correctly results in poor predictions in the region of impinging shock waves and further downstream. There is a need to investigate and improve the modelling of shock-boundary layer interactions, and their influence on the downstream flow, particularly when a laminar separation bubble is triggered or predicted or when the shock is oscillating under the influence of vortex shedding.

Work on base pressure losses and wake energy separation is ongoing. Organized streamwise vortex structures have been detected on the convex surfaces of turbine blades and circular cylinders although this work is not strictly 2D. Both streamwise and cross flow vorticity can be established and are scaled by surface curvature rather than boundary layer thickness [9]. This forms an excellent reference point for subsequent investigations of blade sweep [3].

There are more such features but available space precludes a discussion of all of these. The discussion is therefore limited to three of the issues which emphasise the need for detailed investigation of the two dimensional physical flow phenomena. The features selected for discussion are: *The Transition Region*, *Incident Wakes and the Calmed Region*, and *Shock–Boundary Layer Interaction.*

The Transition Region

The development of streamwise vorticity is an essential step in the process of boundary layer transition from laminar to fully turbulent flow, exhibiting all possible components of vorticity. In "natural" transition of two dimensional laminar flow, streamwise vorticity is first introduced by a three dimensional instability causing periodic distortions in the spanwise vortex lines, arising from an earlier 2D (Tollmien-Schlichting) instability. These distortions are lengthened by a rapid nonlinear process to produce "vortex loops", "lambda vortices" or "hairpin eddies" with substantially streamwise legs. High frequency disturbances appear near the heads of the vortex loops to cause turbulent breakdown or turbulent spot formation. There are several mechanisms by which this rather lengthy process may be bypassed. Of most relevance in turbomachinery are Taylor-Görtler instability of a shear layer, subjected to concave curvature, and distributed (k-type) blade surface roughness. Isolated roughness elements exhibit streamwise trailing "scarf" vortices. In all cases, streamwise vortices may promote earlier transition through superposed high frequency disturbances or by inducing more unstable velocity profiles in adjacent shear layer regions. Aero-engine blades may be roughened in service through erosion or accretion (of dust, soot, sand or volcanic ash particles) or through leading edge icing on inlet guide vanes.

Incident Wakes and the Calmed Region

A common situation in turbomachines arises when a wake from upstream blading impinges on a downstream blade, often on a laminar layer. Out of this impingement process, and triggered by it, arises a turbulent *strip*. This turbulent strip is actually a spanwise ensemble of merged and merging turbulent spots. It therefore might be expected to exhibit some of the characteristics of the much studied isolated turbulent spot. One of these characteristics is the calmed region following the spot. The growth of turbulent spots in a laminar layer, with an attendant calmed region, was first studied almost sixty years ago [10].

It had been conjectured that a wake from an upstream blade would behave in a similar fashion. When measurements are made in rotating machines they often show such a calmed region, with an exponential relaxation from the turbulent patch to the laminar state. The calming effect following the impingement of the quasi two-dimensional wake is particularly strong. It will arise if the spacing, or time interval, between the arrival of successive wakes, is sufficiently large to permit this relaxation to a laminar condition. If the interval between wake arrivals is not sufficient then the flow regime will proceed immediately from one turbulent patch to the next. It had earlier been assumed that in this situation the flow regime in the following patch became turbulent and the calmed region effect ceased to exist.

Gutmark and Blackwelder [6] were the first to investigate these interaction effects on triggered turbulent *spots* and their research suggested that when the spacing between the two spots became sufficiently small the fluctuation levels in the following spot were reduced. Experiments on impinging *wakes* were conducted [4] with the spacing between upstream wakes being systematically decreased (figure 2). By examining the passage of a wake over a flat plate it was found that a very strong calmed region followed the wake. It had been assumed that the existence of this strong calmed region would be manifest in improved aerodynamic performance and that it could support higher blade loading. However, the anticipated turbine efficiencies did not materialise and the turbine efficiency typically dropped by around 3%. With the passage of closely spaced wakes, the calmed region appeared to be absorbed by the following wake. However this absorption did not result in a reduced efficiency. Rather the calming effect was still present and had resulted in a significant reduction in the amplitude of local turbulence in the following wake interaction.

With closely spaced upstream blading the favourable calming effect had always existed but had been rather difficult to detect. The sought-after local turbulence reduction from widely spaced impinging wakes and their calmed region had also applied to closely spaced blades. The calming effect remained, even when its domain coincided with that of the following turbulent patch.

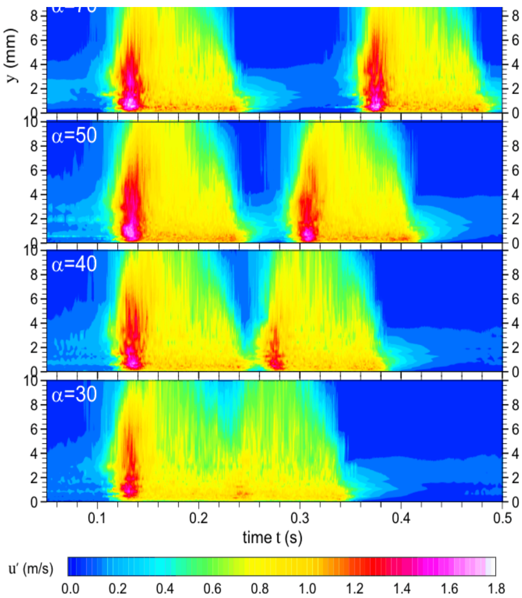

Figure 2. Effect of Close Proximity of Following Wake on Local Turbulence Levels in that Wake.

It therefore turns out that there is no efficiency benefit to be gained by wake interactions from widely spaced blades. The calmed region has the effect of reducing the mixing effect of the turbulence and therefore continuing to stabilise the flow. This would have had a beneficial effect on the efficiency of the machine. This condition of quite close proximity between the wakes and their respective turbulent patches is a usual one for turbomachines, especially towards the blade trailing edges. The effect of calming is therefore expected to be at work in most turbomachines, exerting a beneficial influence at all times.

The impact of this calmed region influence could be to create a desirable reduction in local heat transfer rate. With regard to HP turbine blading, where advanced surface cooling is important, a comprehensive understanding of this suppressive mechanism should lead to improved future cooling strategies.

Shock-Boundary Layer Interaction

High loading requirements in modern axial flow machines often call for transonic and supersonic flows. The fan blades of high by-pass engines operate with supersonic inlet velocities and these result in a shock-boundary layer interaction in the leading edge region of an adjacent blade. This interaction involves a thin boundary layer, such that the interaction effects are relatively benign. This cannot be said for turbine nozzle vanes where high loadings may call for supersonic discharge flows. A representative highly loaded nozzle vane is shown in figure 3. In turbine blading the shock wave emanating from the trailing edge of one vane may impinge on the adjacent vane at around 45% of true chord (70% axial chord). There is the potential for 55% of the suction surface to be wrongly predicted if the physical representation of flows in the interaction region and further downstream are not correctly modelled.

Failure to model the shock-boundary layer interaction correctly results in poor prediction in the region of impinging shock waves and further downstream. There is a need to investigate and improve the modelling of such interactions, and their influence on the downstream flow, particularly when a laminar separation bubble is triggered or predicted or when the shock is oscillating under the influence of vortex shedding. This test case has been used for validating a number of codes. The most recent two-dimensional time-accurate numerical simulations of the mid-span flow are quoted in figure 3 and were performed by Mahallati over

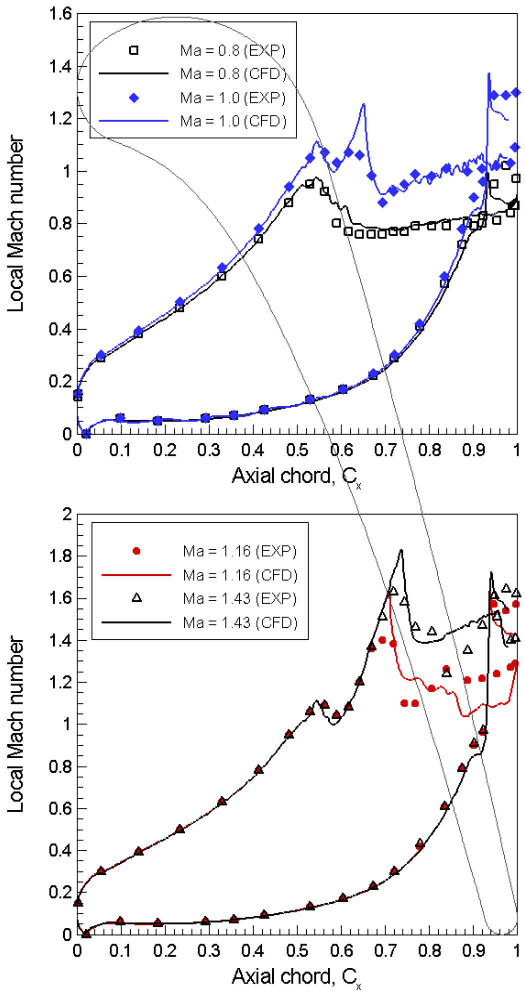

Figure 3. Agreement between Experiment and Computation at Four Different Discharge Mach Numbers**.**

the speed range to Ma = 1.43 [5]. The spatial derivatives were discretised with a second-order accurate upwind Roe flux difference-splitting scheme. The temporal terms were treated with a second-order implicit method. The k-*ω* turbulence model was used for closure. Convergence was accelerated using multi-grid techniques. The mesh was refined such that the minimum value of y^+ was less than unity. No wall functions were used and the turbulence model was integrated all the way to the wall.

At a discharge Mach number of 0.8 the agreement between computational prediction and experimental measurements of local Mach number is good. At a Mach number of unity it is not clear that the shock impingement is accurately predicted. At discharge Mach numbers of 1.16 and 1.43 the agreement on both surfaces is excellent apart from the region downstream of the shock. Shock impingement here results in a significant discrepancy between computation and experiment. The flow is clearly adversely affected but the computation under-predicts the strength of the expansion followed by the strength of recovery.

Figure 4 presents an experimental schlieren image of the flow and figure 5 shows the numerical schlieren of the flow. The experimental image shows the shock directly impinging the blade surface whereas the numerical schlieren indicates impingement on a separated region or bubble. The experimental flow then appears more capable of recovery than the computed flow. The impingement and the flow on the downstream surface are not correctly predicted. This discrepancy when strong shocks are present appears to be a failure to model the shock-boundary layer interaction correctly. There is a need to investigate and improve

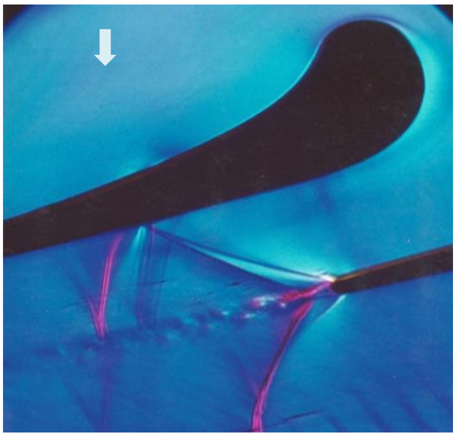

Figure 4. Schlieren image of flow at M_e. $=1.16$.

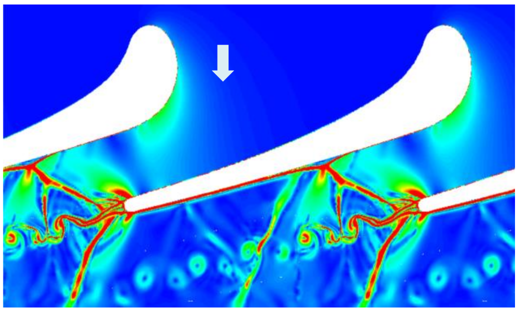

Figure 5. Instantaneous Computational Schlieren View of Shock Wave Interaction at $M_e = 1.16$.

the modelling of shock-boundary layer interactions, and their influence on the downstream flow, particularly when a laminar separation bubble is triggered or predicted or when the shock is oscillating under the influence of vortex shedding.

An early approach to transition modelling, using RANS procedures, was to backward extrapolate from the turbulent region, and assume that conventional turbulence modelling could also describe transitional flow. This produces transition-like behaviour, initiated by diffusion of turbulent energy from the free-stream to the boundary layer; unfortunately, however, it does not model the actual flow physics. In this case a non-physical separation region has been predicted for the interaction.

Conclusions

Even for the ostensibly two-dimensional flow through cascades, much of the basic physics of the flow details is not well understood or predicted; many features in the two dimensional flow over a turbine blade that need further work were identified. Despite major computational developments, complete understanding of turbomachinery flows cannot be achieved without experimental data to validate the calculations. It is important to retain an emphasis on representing the flow physics. This is needed even to predict laminar and transitional boundary layers, heat transfer and stall behaviour properly. This paper contains some original results but is also an attempt to identify some areas where substantial research is still needed.

Predictive capability for boundary layer *transition onset* is still erratic despite advances in predicting the subsequent transition *region*. Adverse pressure gradient effects occur in triggered spots, wake-disturbed flat plate boundary layers, and on blading. A *calmed region* follows each wake-induced turbulent strip. A calming effect remains at work even when its domain coincides with that of the following turbulent patch. This has the effect of reducing the strength of the turbulence and therefore continuing to stabilize the flow. This would almost certainly have had a beneficial effect on the efficiency of the machine.

The *shock-boundary layer interaction* is not modelled correctly. These interactions, and their influence on the downstream flow, are not well predicted, particularly when laminar separation is triggered, or when the shock is oscillating due to vortex shedding. Since turbomachinery flows are inherently unsteady a major area of research involves unsteady flows.

Despite major computing developments, complete understanding of turbomachinery fluid mechanics cannot be achieved without experimental data to validate the calculations. It is important to retain an emphasis on representing the flow physics. This is needed even to predict laminar and transitional boundary layers, heat transfer and separation properly.

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