Transition to Turbulence Under Low-Pressure Turbine Conditions

TERRENCE W. SIMON[a,b] AND RICHARD W. KASZETA[a]

[a]Heat Transfer Laboratory, Mechanical Engineering Department, University of Minnesota, Minneapolis, Minnesota 55455

Abstract:

Why transition is important to engine low-pressure turbine design:

Design analyses of turbine blade losses and heat transfer often treat the flow through the turbine as a steady, attached, turbulent flow. This may be justified in the high-pressure turbine in lieu of (1) the high turbulence of the flow entering the turbine stage from the upstream components, such as the combustion chamber, and (2) the disturbances inside the turbine passage, such as film cooling, endwall cooling, and surface steps and roughness features. However, in the low-pressure turbine, the pressures are considerably lower while the temperatures remain rather high, making the chord Reynolds numbers relatively low by virtue of property effects. Furthermore, in recent years, market pressures have driven more small aircraft manufacturers to use fan jet engines and military focus has turned to small UAV's, some to fly at high altitude. Additionally, noise regulations have led to offering engines with higher bypass ratios, reduced core flow and, consequently, smaller Reynolds numbers by virtue of geometric effects. Reduced Reynolds number operation demands that turbine designers account more carefully for viscous effects, including rapid boundary layer growth, laminar-to-turbulent transition, and boundary layer separation. Furthermore, in recent years there has been a strong tendency to reduce the number of blades and stages within turbomachinery. Thus, the remaining blades are more highly loaded. A surface static pressure profile associated with increased loading tends to extend the transition region length over a larger fraction of the surface and strengthen separation. As mentioned, the low pressure turbine sees a lower turbulence of the approach flow than experienced by upstream turbine stages. Transitional flows in lower freestream turbulence environments are more sensitive to changes in freestream turbulence. Such enhanced sensitivity, in turn, leads to strong unsteadiness, resulting from a greater influence of wakes convected from upstream airfoils. This unsteadiness is seen as strong temporal and spatial variations in transition length and separation bubble strength, both known to be important to aerodynamic and thermodynamic performance of the engine.

The combination of all these various effects has led to intense interest, recently, in being able to predict boundary layer development, transition, and separation on the low-pressure turbine suction surface, particularly as influenced by wakes from upstream airfoils. The difficulty lies in the prediction of transition, its onset, its length, and its path, whether it be of an attached boundary layer or within a separated flow zone.

This paper will provide a review of the significant findings on the topic of transition as applied to the low-pressure turbine and will discuss in a bit more detail the latest activities on this topic by the authors.

Classical transition research and the low-pressure turbine:

Laminar-to-turbulent transition has been a well-studied topic. However, most of the literature, until very recently, has focused on transition as influenced by infinitesimal disturbances. Transition in the engine environment, with elevated disturbance levels and periodic unsteadiness, is less well documented. High levels of freestream turbulence cause earlier transition than with lower turbulence levels and such transition can prevent separation in the adverse pressure gradient region on the trailing portion of the suction surface of a turbine airfoil. Thus, blades in such an environment can be designed for higher loading if the effects of bypass transition are properly included in the design. This concept is just beginning to be exploited. In a seminal paper

[b] Corresponding Author

on this topic, Mayle[1] observed in 1991 that the majority of the experimental work which might be applied to engine analyses focused on laminar-to-turbulent transition under lower turbulence and steady flow conditions. However, the actual flow present in turbine engines has turbulence levels of 2-10% and significant unsteadiness due to wakes. Since that time, a considerable amount of work on the topic has ensued, as noted in the paper. Mayle further suggested that investigations should be conducted to document the effects of wakes on transition over turbine airfoil surfaces. The paper notes that this also has been aggressively addressed in recent years.

Bypass transition:

To separate the description of transition on the low-pressure turbine blade from "natural" transition, as would be seen in the low-disturbance environment of an aircraft wing, the term "bypass" has been applied. Though the instability processes that lead to natural transition, as described by linear stability theory and the Orr-Summerfeld equation, are present in the low-pressure turbine flow, the higher disturbance levels characteristic of bypass transition disturb the boundary layer with a higher strength and excite three-dimensional instabilities that grow much more rapidly than the instabilities associated with natural transition. These disturbances lead to transition so early in the growth of the boundary layer that the natural transition processes are not observed. Hence the name "bypass transition" is used to imply that such 3-D instabilities lead to a bypassing of the "natural" instability modes.

Modeling

Bypass transition modeling on a fundamental level has seen numerous contributions in the last few years, as discussed in the paper. Some contributions include modeling of the effects of wakes convected from upstream.

Experiments

Steady Flow Experiments

Numerous recent experiments have been conducted in somewhat simplified geometries which represent certain aspects of the low-pressure turbine flows. These are reviewed in the paper.

Unsteadiness due to passing wakes

In the last five years, detailed measurements have included also flows with wakes, Some used wake simulators and others were done within rotating rigs. These, also, are reviewed in the paper.

Analysis and Computation

Numerous contributions to transition modeling by way of CFD analysis have been presented in recent years. Some solved the Reynolds-Averaged Navier-Stokes (RANS) equations, others employed Large Eddy Simulation (LES) and others Direct Numerical Simulation (DNS). Those specific to bypass transition are reviewed in the paper.

Recent work at the University of Minnesota:

The University of Minnesota research was designed to address the need for detailed experimental data which document transition in boundary layers and separated flows over highly-loaded airfoils, including the effects of passing wakes. The program objectives are accomplished with the following steps:

1. The effects of freestream turbulence and varying Reynolds numbers are documented without wakes in a facility which simulates the flow through a modern, highly-loaded, low-pressure turbine. This facility is sufficiently simple that wakes can be added without a major change in geometry.
2. The same flow as in (1.) is documented, but with the influence of simple, rod-generated wakes. By comparing these data with the steady-state data collected on the same facility (1.), one can identify the effects of these simple-geometry wakes on laminar-to-turbulent transition in the boundary layer. These data will be unsteady as a result of the passing wakes so they must be correlated with position within the wake-passing period. These simple-geometry wakes may be more amenable to computer simulation.

Part 1. has been completed[2] and is presented in some detail in the paper. It shows cases with strong separation at low Reynolds numbers and low turbulence levels and cases with much smaller separation bubbles as the Reynolds number or freestream turbulence is raised. It shows also that an algebraic correlation in the literature for the streamwise distance from separation to the start of transition by Davis et al.[3] is quite accurate. This correlation is based upon the effective turbulence intensity at the point of separation. The experimental results show also that a model for the intermittency path by Dhawan and Narasimha[4] is remarkably good, in spite of its derivation from attached boundary layer flow transition data. A need for better prediction of the transition length is indicated by the data, however.

Part 2 is at the stage where the facility is built and qualified, wakes are being generated by sliding a rack of rods through the approach flow tunnel, and profile data are being taken. The wakes are convected into a simulation of a low-pressure turbine passage which is precisely the same as that used in part 1. The airfoil geometry is the Pak B shape offered for research by Pratt and Whitney. On the slider is a photogate which records the rods' positions and allows ensemble averaging on location within the wake passing period.

The measurements taken to-date show the influence of the passing wakes on the state of the boundary layer. One sees the change of shape of the velocity profile as the wakes pass. One also sees a momentary separation of the flow. These data, taken with a Reynolds number based on departure velocity and suction surface length of 25,000 and an approach flow turbulence intensity of 2.5%, are described in detail in the paper.

Projection to the future

The importance to continued engine improvement of raising the low pressure turbine stage loading, removing blades and vanes, while increasing stage efficiency is clear. It will result in continued emphasis on this topic of bypass transition in unsteady flows. Now that experience has been gained in the fundamental experiments, more complex experiments which will allow detailed flow measurements in rotating rigs will be brought on line. With regard to computation, the industry will develop a better feel for the limits of design methodology which use algebraic correlations and simple models for implementation into RANS codes (as well as the direct application of RANS codes) and these will be used with more confidence in design. It is clear that LES and DNS will take a more important role in the prediction of transition behavior in design models. Also, as computer speed grows, DNS will take on increasing importance as a means of generating "data" for the further development of simpler transition models.

References:

1. Mayle, R. 1991. The Role of Laminar-Turbulent Transition in Gas Turbine Engines. J. Turbo. **113**, 509-537.

2. Simon, T., S. Qiu & K. Yuan. 2000. Measurements in a Transitional Boundary Layer under Low-Pressure turbine Airfoil Conditions. NASA-CR 2000-209957.

3. Davis, R., J. Carter & E. Reshotko. 1985. Analysis of Transitional Separation Bubbles on Infinite Swept Wings. AIAA paper # AIAA-85-1685.

4. Dhawan, S. & R. Narasimha. 1958. Some Properties of Boundary Layer Flow During the Transition from Laminar to Turbulent Motion. J. Fluid Mech. **3**. 418-436.