HP Axial Flow Turbine Aerodynamic Design

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Introduction

The following is intended to provide a basic introduction to the aerodynamic design of axial flow turbines, and will focus on understanding the fundamentals of turbine aerodynamic design, i.e., velocity triangle, mean line methods, 2-D profile design, etc. Although it would be undesirable to undertake the aerodynamic design of a blade row without utilising the benefits of computational methods, the author intends to show that a large part of the design can be undertaken utilising basic understanding, simple methods and design rules.

Figure 1 is a general arrangement for a modern high bypass ratio 3-shaft turbofan engine. The figure highlights the different types of turbine, i.e., HP single stage subsonic, LP multi-stage, etc., and their corresponding expansion ratios.

Figure 2 highlights the variety of different flow regimes within HP, IP and LP turbines. Due to proximity of the blade rows all aerofoils experience unsteady interaction resulting from upstream potential and vortical flows (wake, tip leakage and secondary). The relative strength of these upstream disturbances being dependant on the cycle requirement and particular aerodynamic design, i.e., single stage HP turbines influenced primarily by potential interaction, multi-stage LP's by wake interaction.

In addition, the requirement to utilise film cooling and the large range of Reynolds number within the HP, IP and LP turbines results in a significant variation in the aerofoil boundary layer state, i.e., HP nozzle guide vanes primarily turbulent flow from leading edge due to film cooling, LP unsteady transition - separation bubbles with becalmed regions.

Before considering the details of the aerodynamic design of a turbine, it is worthwhile familiarising ourselves with some interesting facts about modern turbine designs

It is clear from the data presented in figure 3, that modern gas turbine engines have a significantly higher power to volume (and weight) ratio than internal combustion engines (10 to 20 times), which were in the 1940's and 1950's at similar levels of technical maturity. Apart from the fundamental limitation regarding the maximum speed of propeller driven aircraft (propulsion efficiency), it is clear that the gas turbine offered a step change in technology.

However, in order to achieve the high levels of efficiency demanded by airlines, the cycle pressure ratio and turbine inlet temperatures have steadily increased over the years. This has resulted in the requirement to develop efficient cooling systems to protect the aerofoils from the primary gas flow, which can be in excess of 700 degrees hotter than the melting point of the aerofoil material. Although thermodynamically it is advantageous to increase the pressure (and temperature) ratio of a gas turbine engine, modern gas turbines are already approaching a point where these cycle efficiency improvements are being outweighed by the thermodynamic inefficiencies resulting from high cooling loads (the cooling load of the HP turbine will boil a domestic kettle in 0.05sec).

The requirement to minimise size (and weight) whilst maintaining high blade speed to improve efficiency, has also led to significant mechanical loads being placed on turbine rotor blades and disks (HP blade 60,000g at take-off).

Overall the design of the HP turbine is one of the most difficult engineering tasks in the gas turbine engine.

Figure 4 is an overview of the aerodynamic design process undertaken within Rolls-Royce turbines. The process is broken down into 5 main activities, 1) whole engine design studies - usually undertaken by the advanced project group, 2) preliminary annulus design utilising simple design rules and understanding, 3) preliminary annulus and vortex design utilising a detailed throughflow model, 4) detailed 2-D and 3-D design of blade rows including steady and unsteady CFD analysis, 5) rig/engine testing to verify results and understand new technologies.

Although not normally regarded as part of the main design process, rig/engine testing is one of the most valuable tools at the disposal of the aerodynamic designer. As the correlations used to optimise a new design of turbine will be based on existing experimental data, each test undertaken adds to the accuracy and range of these correlations. In addition, these tests provide the detailed steady and unsteady flow field data used to further validate the 2-D and 3-D CFD design methods.

As it would be unwise to incorporate a new design concept directly into an engine design, turbine rig testing (low and high speed) provides a cost effective means by which to validate new aerodynamic design concepts. If successful, these new concepts can then be incorporated into an engine turbine design at a reduced risk to the overall engine project.

There are three main types of turbine design currently being utilise in civil and military engines, i.e., conventional rotation - HP and IP (or LP) turbines rotate in the same direction (figure 5a), reverse rotation - HP and IP (or LP) turbines rotate in opposite directions resulting in reduced turning in the IP (or 1st stage LP) vane (figure 5b), and contra-rotating statorless - HP and IP (or LP) turbines rotate in opposite direction with the deletion of the IP (or 1st stage LP) vane (figure 5c).