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Introduction

The main aim of this book is to help practising engineers and researchers understand, apply and advance methods for estimating flow and heat transfer in rotating disc systems. While this subject has much in common with other areas of fluid mechanics, rotating flows exhibit some unique, and sometimes counter-intuitive, features. Combined with their practical significance, this has attracted considerable interest from researchers for more than a century.

The content is particularly relevant to turbomachinery internal air systems, reflecting the motivation for much research in recent decades. Cavities between rotating discs and between rotating discs and stationary discs are an important element of such systems. Examples are shown in Figures 1.1 and 1.2. Both figures relate to Rolls-Royce three-shaft (or three-spool) turbofan aeroengines. HP, IP and LP denote high-pressure, intermediate-pressure and low-pressure compressors (C) or turbines (T). The first figure highlights the rotating blades, stationary vanes, rotating discs and rotating shafts (connecting the compressors and turbines), with contours of temperature at a particular operating condition. The blade and vanes reflect the positive axial temperature gradient of the air as it is compressed and a negative axial gradient in the turbine as the hot combustion gases expand. Cooling of the discs and shafts balances heat transfer from the mainstream gas and gives generally positive radial temperature gradients. This figure is from a finite element ‘whole-engine thermo-mechanical model’, as described by Dixon *et al.* (2004). Such finite element analyses (FEA) often assume axisymmetry with approximate treatment of 3D features. Transient analyses are conducted to obtain component temperatures, movements and stresses through a flight cycle. These models may contain around 1000 ‘boundaries’ for which aerothermal boundary conditions are required throughout the flight cycle.

Figure 1.2 shows a central section of an engine core containing part of the HPC, the burner (or combustor), the HPT and the IPT. The white areas correspond to engine components, including discs, blades and shafts, and the main gas path through the compressor, burner and turbines. The colours or shades in this picture show the source of the air for the internal air system. For example, the highest pressure cooling air is fed from the HPC outlet, bypasses the burner and supplies cooling for the HPT disc front face and blades. Areas in other colours or shades are supplied with lower-pressure air from further upstream in the compressors. The bearing chamber will contain a mixture of oil and air.

The internal air system plays a vital role in modern gas turbines, serving to dissipate heat generated by shaft work (known as windage) and heat conducted to the discs, deliver air for turbine blade cooling, maintain the required axial pressure loading on the bearings, prevent hot gas ingestion from the main annulus overheating the turbine discs and isolate the oil system. Running clearances between rotating and stationary components, and the variation of clearances through a flight or operating cycle, are also affected or controlled by the air system. These depend on a combination

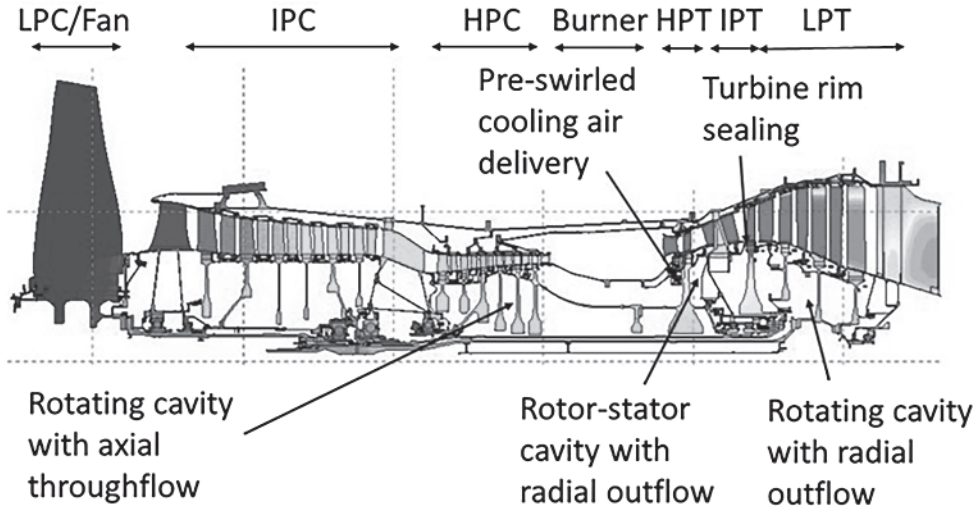


Figure 1.1 Whole-engine thermomechanical model. *Source:* Following Dixon *et al.* (2004).

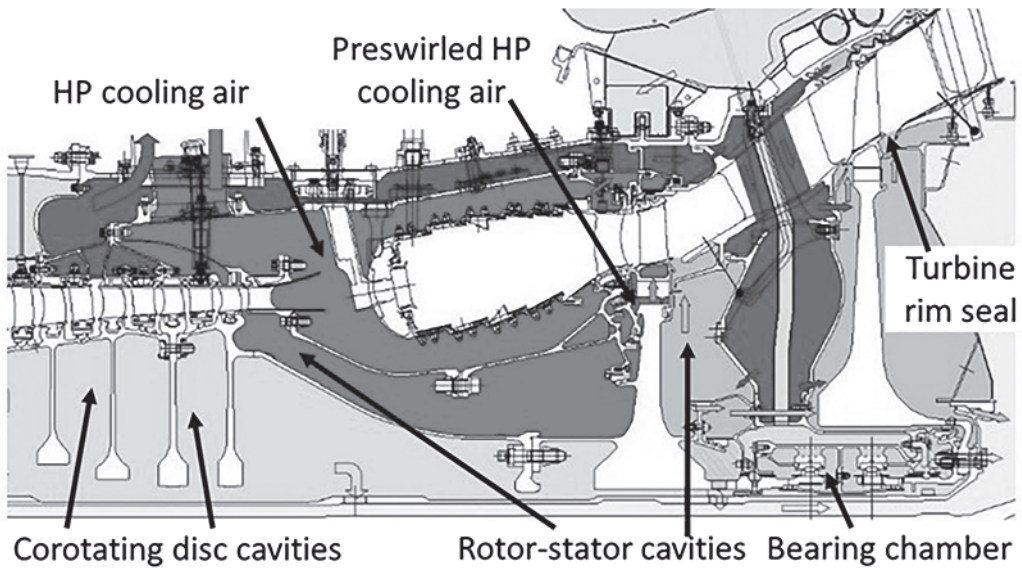


Figure 1.2 Section of the internal air system, showing the HP and IP sections for a three-shaft engine. *Source:* courtesy Rolls-Royce plc.

of thermal and centrifugal expansion of components and pressure loads. With clearances affecting compressor and turbine efficiencies, and up to 25% of compressor air being used for cooling and sealing, the air system has a significant impact on engine efficiency. Considerable attention must be given to the internal air system and its interaction with the main annulus flow.

Some rotating disc cavities are indicated in Figures 1.1 and 1.2. In multistage axial compressors and turbines, such as the HPC and LPT in Figure 1.1, cavities are formed between co-rotating discs. In the compressors shown, these are vented by air flowing axially through the gap between the disc

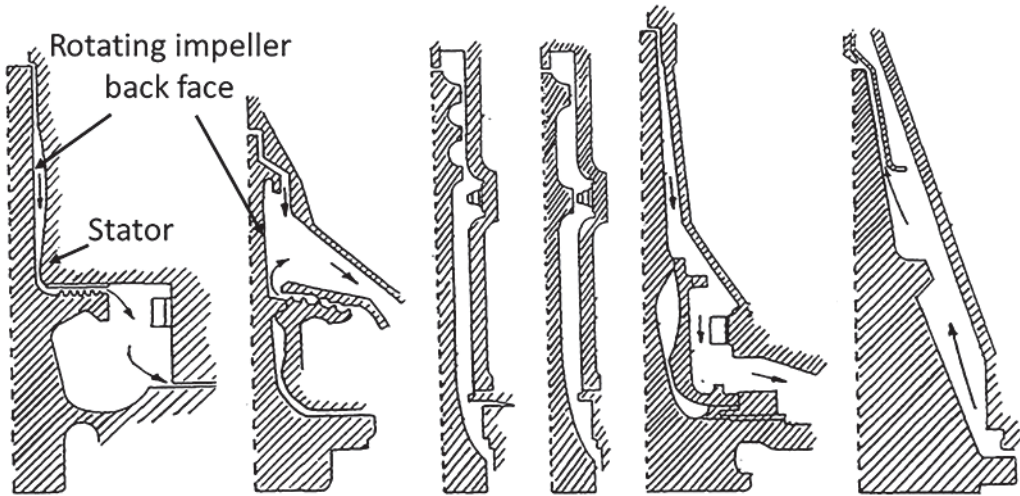


Figure 1.3 Typical impeller rear face rotor-stator cavities for centrifugal compressors. *Source:* Hart and Turner (1994) / with permission of American Society of Mechanical Engineers (ASME).

hubs and the IP shaft. This air subsequently flows radially outwards through co-rotating LPT disc cavities and re-joins the main annulus flow through turbine rim seals. These seals (or gaps) are formed between the rotating blade platforms and stator vane platforms that define the inner annulus line (or radial boundary) for the main gas path. In the HP and IP turbines in both figures, rotor-stator disc cavities are formed between the rotating discs and static components. Such co-rotating and rotor-stator cavities are common in turbomachinery and may vary considerably in geometry and in the nature of the throughflow. Cavities between differentially co-rotating or counter-rotating discs occur in some engines at the interface between compressors and turbines rotating at different speeds.

Rotor-stator disc cavities are also common and of considerable interest in other rotating machines, including centrifugal pumps, compressors and turbines. Variations in geometry that can occur are illustrated in Figure 1.3. This shows typical impeller rear face rotor-stator cavities for centrifugal compressors, as considered by Hart and Turner (1994), and was based on a survey of small gas turbine engines powering helicopters, business jets and light aircraft. Hart and Turner state that imposed radial inflows or outflows are typically in the range of 0–1% of the compressor main flow. Geometries vary to accommodate labyrinth seals, stiffening rings and balancing features, and the air flow must provide adequate cooling and acceptable axial pressure loads for the structure.

It is common industrial practice to model internal air systems with a 1D flow network comprised of multiple elements relating pressure changes and mass flow rates through the various components. For example, discharge coefficient correlations may be used for seals, and frictional pressure loss coefficients may be specified for duct flows with further allowance for pressure drops through bends and expansions or contractions. The network equations are solved numerically to provide pressure and mass flow data throughout the system. In some cases, the flow network model may be coupled to a thermal model, such as that illustrated in Figure 1.1, so that better estimates of seal clearances and temperature-dependent fluid properties are obtained. This may also improve thermal modelling through an engine acceleration or deceleration as seal clearances and the air system flow rates change. The book by Sultanian (2018) gives a good account of network modelling for internal air systems with guidance and illustration of how rotating disc cavity flow

characteristics may be estimated and incorporated into the network. Such treatments inevitably involve some simplification and engineering judgement, so adjustments are often required to match engine test data.

Many experimental and theoretical research studies have provided correlations or formulae that may be used in flow network and thermal modelling. An early example is von Kármán's (1921) analysis of the flow due to a disc rotating in a quiescent environment. As will be discussed in Chapter 5, this solution continues to provide a benchmark and basis for engineering estimates. Further examples are given in books by Dorfman (1963), Owen and Rogers (1989, 1995), Shevchuk (2009), Childs (2011) and Sultanian (2018).

Interest and research in rotating flows is not confined to engineering applications. On earth and other planets, large-scale motions in the atmosphere and oceans are affected by rotation. Early research in geophysical fluid dynamics, often treating the flow as a small perturbation in a rotating frame of reference, has relevance to engineering flows. Ekman's (1905) laminar flow boundary layer solution is shown later to apply directly in some engine conditions and has inspired consideration of turbulent Ekman layers. Simple co-rotating disc cavities have often been used in research to give insights into geophysical flows, and flow features similar to those encountered in engineering have been identified. Examples and descriptions of the linear mathematical theory are given in Greenspan's (1968) book.

Chapters 2–6 of this book describe analysis, computational methods and solutions available for the prediction of rotating disc flow and heat transfer. Examples are given to illustrate the underlying flow mechanisms that are relevant in a wide range of applications and to show the strengths and weaknesses of the methods. Comparisons with experimental data indicate the degree to which methods have been validated and the uncertainty in their use for engineering estimates. Chapters 7 and 8 then focus on more specific applications to rotor-stator cavities and co-rotating disc cavities and include relatively complex examples. Chapter 9 considers the interaction of a rotor-stator cavity flow with the surrounding flow when the gap between the rotor and stator allows the external flow to be ingested. This relates to the turbine rim seals shown in Figures 1.1 and 1.2. Chapters 6–9 include results from relatively recent research using advanced computation and experimental methods to provide insights into the more complex flow phenomena.

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