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ORIGINAL ARTICLE

Using morphological analysis to tackle uncertainty at the design phase for a safety critical application

P.R.N. Childs*, B. Garvey

Imperial College London, South Kensington, SW7 2AZ, UK

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Abstract The gas turbine engine internal air system provides cooling and sealing air to a series of critical subsystems and components such as high pressure gas turbine blades, as well as controlling the thrust load on the turbine and compressor spool assembly. Many potential variations for the internal air system are possible, depending on the requirement, expertise and command of intellectual property. Some subsystems, such as rim seals, pre-swirl systems, and rotating cavities have been the subject of extensive development and analysis leading to robust design solutions. Nevertheless there remains scope for further consideration of the overall system design, and this paper explores the use of a decision analysis tool called morphological analysis applied to the internal air system. Morphological analysis provides an effective means for tackling issues where there is uncertainty, as is the case with many design scenarios, including the internal air system, with some specific parameters and information not available until later in the design phase, after the key geometry has been defined. The problem space comprising seven principal parameters, and a cross consistency matrix which allows identification of compatible and incompatible states are presented.

1. Introduction

The design of many systems requires definition of a wide range of parameters in order to provide an indication of the requirements. This is certainly the case for the internal air system, for example, for gas turbine engines. This system is responsible for cooling and sealing safety critical components and controlling the thrust loads on bearings. A challenge for the engineering design team is that accurate information on some of the key parameters is not known at the start of a design phase, and this information may not be confirmed until many months or even years into the design cycle. A wide range of strategies can be employed to cope

*Corresponding author.

E-mail address: p.childs@imperial.ac.uk (P.R.N. Childs).

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Nomenclature

MA morphological analysis

with this type of uncertainty such as specifying the general layout of the system, but leaving the definition of specific features that can be modified or refined once more accurate information is available. However this approach typically requires selection and commitment to a particular layout, which may not be optimal.

Decision making represents one of the most challenging activities in design. Ideally all parameters would be available, well defined and understood at an early stage in a process to enable commitment on a particular point, or path. As we all know too well, from everyday experience, such definitive information is usually difficult to obtain or comes late in any schedule or even after the project has been completed. Many schemes have been proposed in order to address the issue of decision making in the face of incomplete information and uncertainty. This paper uses the challenging scenario of the design of the internal air system, sometimes known as the secondary air system, of a gas turbine engine, in order to illustrate the application of a tool called generalized morphological analysis which assists in exploring design options where many parameters are uncertain.

An overview of design options for the internal air system for both industrial gas turbine engines, and jet engines and turbo-props is presented in Section 2. The theory underlying the application of morphological analysis to exploring a decision space is presented briefly in Section 3. The application of morphological analysis to the specific challenge of the design of the gas turbine engine internal air system is presented in Section 4.

2. Internal air system design options

Gas turbine engine performance is a function of pressure ratio and temperature ratio, as well as depending on the level of heat recovery. Temperature limitations for metal alloys, suited to the high stress and temperature conditions of modern gas turbine engines, has led to the use of ever higher pressure ratios as well as consideration and use of heat recovery based engine cycles. The high temperature of operation in a gas turbine engine limits the type of material that can be used and the length of time a component can be used. In order to maintain acceptable temperatures, cooling and sealing air can be used to directly cool components or to limit the exposure of a component to a hot gas stream. In addition pressure on a surface is used to reduce imbalance on a bearing system as a result of the differential pressure on turbine and compressor components. A wide range of configurations for the internal air system of gas turbine engines have been developed and implemented over the 80 years of gas turbine engine technology. In the case of a high by-pass ratio aero-engine, the principal areas for consideration for an internal air system design include pressure balancing of the front fan, sealing and cooling of bearings, extraction of air from the compressor, managing windage in the wheelspace formed between compressor discs, transferring air for cooling of turbine components, supply of cooling air to combustor components, supply of cooling air to turbine blade roots and managing the ingress of air through the gaps between rotating and stationary turbine discs.

A typical geometrical feature found in gas turbine engines is the wheelspace cavity formed between co-rotating discs. This may have a shroud at the outer periphery, disc cobs at the inner radius, and a net through flow enabled by means of holes in the outer shroud. Another generic configuration is the stator well formed by a recess in a compressor or turbine drum assembly in order to accommodate a shroud on the inner radius of compressor stator blades or the nozzle guide vanes in a turbine. A further configuration is the rim seal formed at the outer periphery between two coaxial discs, one that is stationary, the other rotating. Many configuration options are available for each of these [1] identified 576 basic options for rim seal configurations alone, just considering hade, relative location of the rim seal to the rotor, seal type, addition of an inner seal, supply of cooling air pressure gradient, inner drive arm and contra-rotation (Figure 1, see also [2,3]). Options for rotating cavities include closed, open with and without throughflow, net radial inflow and outflow, inclusion of a co or contra rotating shaft at the inner radius and multiple cavities, with and without throughflow, with and without an inner co or contra-rotating shaft (Figure 2, e.g. see [4–6]). Further configurations are possible with L and T shaped cavities common in, for example, steam turbines. These examples provide an indication of the scope of variations and options available to the designer at the design stage.

The decision about a particular configuration to adopt or consider is not arbitrary. Instead this is typically determined by the pressure ratio required for the engine and turbine entry temperature. These and the associated stage loading dictate the numbers of rows of blades and their form, which in turn defines the radial dimensions of the discs to support rotor blades and their pitch. These dimensions form the envelope within which the internal air system must operate. The target temperature of operation of the blades represents a key defining parameter for the internal air system, as this provides an indication of the cooling requirement for various components. Prior experience of similar engine