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On the performance simulation of inter-stage turbine reheat

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HIGHLIGHTS

- An innovative gas turbine performance simulation methodology is proposed.
- It allows to perform DP and OD performance calculations for complex engines layouts.
- It is essential for inter-turbine reheat (ITR) engine performance calculation.
- A detailed description is provided for fast and flexible implementation.
- The methodology is successfully verified against a commercial closed-source software.

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ABSTRACT

Several authors have suggested the implementation of reheat in high By-Pass Ratio (BPR) aero engines, to improve engine performance. In contrast to military afterburning, civil aero engines would aim at reducing Specific Fuel Consumption (SFC) by introducing 'Inter-stage Turbine Reheat' (ITR). To maximise benefits, the second combustor should be placed at an early stage of the expansion process, e.g. between the first and second High-Pressure Turbine (HPT) stages.

The aforementioned cycle design requires the accurate simulation of two or more turbine stages on the same shaft. The Design Point (DP) performance can be easily evaluated by defining a Turbine Work Split (TWS) ratio between the turbine stages. However, the performance simulation of Off-Design (OD) operating points requires the calculation of the TWS parameter for every OD step, by taking into account the thermodynamic behaviour of each turbine stage, represented by their respective maps.

No analytical solution of the aforementioned problem is currently available in the public domain. This paper presents an analytical methodology by which ITR can be simulated at DP and OD. Results show excellent agreement with a commercial, closed-source performance code; discrepancies range from 0% to 3.48%, and are ascribed to the different gas models implemented in the codes.

1. Introduction

Attempts to further increase the efficiency and power output of industrial gas turbines and aero engines resulted in the study of various cycle extensions. Amongst them, reheat consists in a second heat addition in the main gas path, downstream of the main combustor. While this concept is widely used as 'afterburning' for short-period thrust augmentation in military low-bypass turbofans and turbojets, many authors suggest its application in large civil aero engines, for size reduction and efficiency improvement. Sirignano and Liu [1], and El-Maksoud [2] propose a continuous combustion throughout the turbine for simultaneous expansion and heat addition, resulting in near-constant temperature combustion. A concept with more practical relevance considers one or multiple discrete reheats along the expansion section and this has been studied by Vogeler [3], Chen et. al [4] and Bergantzel and Waters [5]. Their results show a potential for significant performance improvements, when introducing a second burner. Apart from performance benefits, Lindvall and Conzelmann [6] discuss further potential advantages of ITR in industrial gas turbines, namely operational flexibility and reduced emissions.

In order to increase thermal efficiency in power generation (typically single-spool) or aerospace propulsion (typically 2-shaft or 3-shaft) applications, the second combustor should be positioned very early in the expansion process [7]. In case of a HP spool with a 2-stage HPT, the reheat must take place between the first and second stage of the HPT to allow for heat addition at high pressure. However, the above-mentioned papers either include only DP

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Nomenclature

BPR	by-pass ratio [–]	TET1	1st burner TET [K]
CPR	compressor pressure ratio [–]	TET2	2nd burner TET [K]
c_p	heat capacity at constant pressure [J/(kg∗K)]	TW	turbine work [W]
DP	design point	TWS	turbine work split [–]
ITR	inter-turbine reheat/inter-stage turbine reheat	W	mass flow [kg/s]
HP	high pressure	γ	heat capacity ratio [–]
HPT	high-pressure turbine	η	efficiency (for other than turbomachinery) [–]
HPT1	1st stage HPT	η	isentropic efficiency (for turbomachinery) [–]
HPT2	2nd stage HPT	η_p	polytropic efficiency [–]
N	shaft physical rotational speed [rad/s]	π_{burn}	pressure losses fraction through the burner [–]
NDMF	non-dimensional mass flow [(kg/s)∗(K^0.5)/(Pa)] or [kg/s]	π_{intake}	total pressure recovery coefficient for the engine intake [–]
NGVs	nozzle guide vanes	in	(subscript) inlet of the component
OD	off-design	out	(subscript) outlet of the component
P	total pressure [Pa]	in1	(subscript) inlet of HPT1
PCN	compressor relative rotational speed [–]	out1	(subscript) outlet of HPT1
PLI	power law index [–]	in2	(subscript) inlet of HPT2
PR	pressure ratio (also called expansion ratio in turbines) [–]	out2	(subscript) outlet of HPT2
SBTR	second burner temperature ratio [–]	1	(subscript) related to HPT1
SFC	specific fuel consumption [(kg/s)/MN]	2	(subscript) related to HPT2
T	total temperature [K]	DP	(subscript) related to DP
TET	turbine entry temperature [K]	OD	(subscript) related to OD

performance studies or refer solely to engine configurations with one burner installed between turbines on different shafts. The current research work extends the known practices to OD simulation of engines with inter-stage reheat.

For detailed performance assessments of ITR and cycle optimisation studies, the required methodology should be able to model engines with multiple turbine sections on the same shaft. Moreover, to investigate operability issues and potential part-load benefits, it also needs to be capable of OD calculations, where the work split between the separate stages changes according to the thermodynamics and component characteristics. GasTurb [8], which is a commercial gas turbine simulation program, features ITR, but its application is limited to single-spool industrial gas turbines with a pre-built setup of bleeds and cooling flows. Therefore, it is not applicable to studies of aero applications or gas turbines with sophisticated secondary cooling flows and several spools.

This paper describes a methodology to simulate multiple turbine stages on the same shaft. The methodology was developed with regard to its application in ITR engine studies, however, the detailed modelling of separate turbine stages also provides advantages in the accurate representation of turbine cooling flows, which is of particular importance to industrial gas turbines with multiple turbine stages on a single spool.

The aforementioned methodology is implemented into TURBOMATCH (the Cranfield University in-house 0-D performance simulation code, already featuring OD and transient calculations). TURBOMATCH [9,10] is a gas turbine performance simulation tool, where the user defines the engine's architecture through the declaration of the sequence of turbomachinery components ("bricks") and the specification of their respective properties. This modularity allows for high flexibility and for a theoretically unlimited number of bleeds and cooling flows (i.e. it allows for the sophisticated modelling of both the main gas path and secondary air system). Therefore, it is particularly useful for research purposes, e.g. the study of complex flow arrangements and accurate representation of real engines that have multiple compressor bleeds for turbines' nozzle guide vanes (NGVs) and blade cooling. The code has been successfully validated against experimental, test and simulated data [11–13].

2. Theory/calculations

2.1. DP turbine thermodynamics

This section explains the use of concatenated, simplified turbine characteristics for the determination of the DP operating point. The expansion section of a simple turbojet engine with ITR is considered, consisting of two consecutive turbine stages, followed by a convergent exhaust nozzle. This setup is shown in Fig. 1.

First, by looking at Fig. 1 it can be observed that a crucial parameter in the design of the expansion section is the TWS. This parameter determines the ratio by which the interconnected turbine stages share the overall work (i.e. the work required by the compressor, plus any auxiliary/output work) between themselves.

$$TWS = \frac{Stage\ 1\ turbine\ work}{Overall\ turbine\ work} \tag{1}$$

Eq. (1) is sufficient to determine the work split in a setup with two turbine sections on one shaft. In configurations with more than two turbine sections, an individual TWS can be defined for each stage as follows:

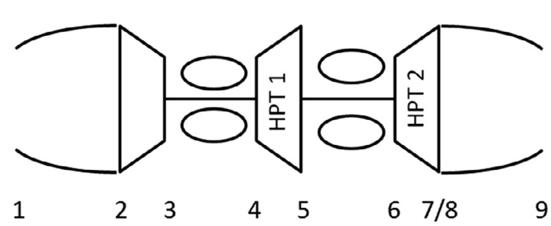

Fig. 1. Turbojet engine with ITR.