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EXPLORING INFLUENCE OF STATIC ENGINE COMPONENT DESIGN VARIABLES ON SYSTEM LEVEL PERFORMANCE

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Abstract

To reach even better operating efficiency and reduced fuel burn, aero engine manufacturers adopt various innovative design methods. Many of the design methods rely on more integrated component and engine design. This makes it necessary for component suppliers such as GKN to be involved more tightly in the design process with the engine integrator. It also necessitates the need for the component developer to predict the effects that its components produce at the engine level so that the designs can be better prepared for future engine architectures. In this paper, an integrated design method is used to make preliminary exploration of the effect of aero-engine static structure design variations on engine performance. Studies were performed on a turbine rear structure (TRS) which is a part of the low pressure (LPT) turbine module. Pressure losses from an aerodynamically well designed TRS (with good LPT outflow match) and a poor LPT outflow matched TRS were coupled to an engine performance model to simulate the effect on engine SFC. The effect on engine SFC due to poor LPT outflow matched TRS coupling is more pronounced than that for aerodynamically well designed TRS. Also pressure drops for an aerodynamically well designed TRS are themselves dependant on structural design variations such as changes in geometrical variables. In this case, the influence of component design variation on SFC is substantial and the relevance of an integrated engine-component design is apparent. Judging from the preliminary findings it can be concluded that additional studies with more variables coupled can reveal further dependencies between engine and the component which are previously un-explored. This seeks to motivate the development of methods to create a multi-level, multi-physics optimization platform for hot engine structures which is the future aim of the project as a part of which this study was conducted.

Nomenclature

SFC	Specific Fuel Consumption
LPT	Low Pressure Turbine
TRS	Turbine Rear Structure
ATC	Analytical Target Cascading
Δp_{min}	Minimum Pressure drop
Δp_{max}	Maximum Pressure drop
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
FEA	Finite Element Analysis
OEM	Original Equipment Manufacturer
KBS	Knowledge Based Systems
KBE	Knowledge Based Engineering
F_D	Force of Drag
s	Vane pitch
T_{46}	Total temperature at LPT inlet
T_5	Total temperature at LPT outlet
p_{46}	Total pressure at LPT inlet
p_5	Total pressure at LPT outlet
$\eta_{\infty t}$	Turbine polytropic efficiency
γ	Specific heat ratio

Introduction

Aero engine manufacturers are constantly looking to offer reduced fuel burn through improved engine efficiencies. One way of achieving reduced fuel burn is to reduce component weights. Efforts of companies that design and manufacture aero-engine components are directed towards producing as light components as possible. This has led to the adoption of advanced materials and advanced design solutions under constantly increasing tolerance requirements. Establishing designs under such conditions tend to increase cost of acquisition and maintenance, as well as the development cost to ensure the desired functionality, performance and manufacturability.

As designs mature, the number of criteria considered while establishing optimal designs continue to increase. As one example, the functional requirements of static components have traditionally been driven by their ability to ensure structural integrity and transfer power from the engine to the aircraft. Their impact on engine propulsive performance has been limited to minimized pressure loss where in contact with the core flow and minimizing their weight contribution. In next generation engines it is expected that the requirements on static components will advance in their functional contribution to the overall engine performance, i.e. that aero performance requirements will entail pressure loss and aerodynamic loading capability and that these capabilities will be defined through balancing other conflicting constraints. The cost of realizing the ever increasing expectations on higher fidelity and tighter tolerances combined with a lowest weight expectation drive the realization of manufactured components.

The design of components is becoming more multidisciplinary in nature, requiring frequent sharing of information both between different design teams (for example aerothermodynamics- and structural-teams) within a supplier as well as between the supplier and the OEM. At the same time, it is important to be able to carry out a design within each discipline simultaneously in order to minimize development time and cost. This creates a dilemma, as communication between different design teams is easiest when the analyses are performed serially whereas simultaneous design within different disciplines in isolation lead to a risk of late and expensive design changes. Moreover, excessive communication can lead to prolonged development times. Therefore, it is important to have a structured method that can identify the functional dependencies, i.e., what needs to be shared between different disciplines, enabling trade-off studies at an early stage in the development process.

Developing a component requires close coordination with the customers which leads to an integrated engine and component development. Facilitating an integral engine and engine-component design require exchange of dependent information among the disciplinary design systems. For whole engine performance analysis, 0D or 1D thermodynamic based design and simulation methods and tools are used, whereas component design makes extensive use of 2D and 3D tools such as CAD, CFD and FEA. Enabling disciplinary design and optimization requires a strict formulation of inter disciplinary dependencies, as well as means to ensure exchange of the same information in a consistent manner.

This paper describes the first steps in a process to develop methods to create a multi-level, multi-physics optimization platform for hot engine structures. An aero engine performance and cycle analysis tool (Grönstedt, 2000) is linked to a conceptual engine design tool (Grönstedt et al., 2009), which establishes boundary conditions for a refined subsystem model. This subsystem model will include a low pressure turbine conceptual design capability and a detailed design implementation (CFD, FEM) for adjacent static structures (MTF and

TRS). The three-dimensional FEM and CFD models, including intermediate design tools for 1D & 2D are a mix of in-house and commercial codes.

The elements, i.e. the simulation codes, of the multi-level, multi-physics design framework will be integrated using a formulation known as analytical target cascading or ATC (Kim et al., 2003). The benefit of such a formalized coordination of the design problem is that it clarifies the functional dependencies and can be extended to more complex systems. For the components studied, this facilitates the possibility to trade, for example, TRS weight against LPT outlet swirl angle.

This paper takes a first step in this direction by quantifying the impact of design choices in the TRS on the engine SFC.
This is done through comparison of two cases of one-way couplings of TRS pressure drops to engine SFC calculations. In the first case, pressure drop from an aerodynamically well designed TRS is coupled to engine SFC calculations while in the latter, pressure drops from a poorly designed TRS is coupled to engine SFC calculations. In the latter case flow separation occurs on the TRS vanes. This serves to motivate the need for integrating the studied components in a common framework for coupled optimization.

The Turbine Rear Structure

A turbine rear structure is a static structure situated at the rear end of the engine. It is included as a part of the Low Pressure Turbine (LPT) module. GKN Aerospace designs and manufactures TRSs for various engine OEMs. The TRS has the main functions of de-swirling the exit core flow from the LPT on its passage towards the nozzle. It also has mounting points for the engine to the nacelle. A representative figure of the turbine rear structure is shown in Figure 1.

Figure 1 location of a TRS in a Trent 1000 engine (Rolls-Royce plc, 2014)

Survey of current methods to model dependencies

Methods to model dependencies and perform integrated design studies have been extensively used in the area of knowledge based engineering (KBE) and knowledge based systems (KBS). (Dixon, 1995) provides a definition of a knowledge based system and presents early research efforts at creating such a system for a simple product. Larger products and systems will require decomposition of the problem. Different types of decomposition, that relate to products, problems and processes are described in (Kusiak and Larson, 1995). Many of the works done in KBE and KBS also focus on optimisation. Particular focus is often directed to multi-level, multi-objective and multi-disciplinary optimisation techniques. Several methods of decomposing an engineering system optimisation as multi-disciplinary problems exist and (Dépincé et al., 2007) provides an overview of such techniques. (Van Tooren et al., 2005) describe methods to coordinate the design efforts for a freighter aircraft using Knowledge Based Engineering (KBE) principles. The work also describes a software tool that functions as a framework for design of the component making use of multi-disciplinary optimisation and applies it to actual design of a composite aircraft wing component. (Jarrett et al., 2007) proposes an approach to integrated multidisciplinary design of turbo machinery. This work also relies on coordinating efforts from different design teams. To facilitate coordination, (Jarrett et al., 2007)proposes a software tool. Rather than optimisation, minimising the differences between an ideal design and currently achievable design is the focus of the work. Example of application of the methodology is shown on the design of a core compressor.

Common to both (Van Tooren et al., 2005)and (Jarrett et al., 2007) are the creation of a system to coordinate different activities performed within design teams. This is done by coupling different design inputs and outputs with respective systems at appropriate hierarchical levels.

(Reinman et al., 2012) describes 'design for variation (DFV)' that uses various statistical techniques to improve the design of components at Pratt Whitney in addition to performing multidisciplinary analyses. Improving different design requirements on a turbine airfoil is demonstrated in the paper.

(Sandberg et al., 2011) describes a study performed on rotating machinery that uses KBE methods.

It is clear that component design efforts increasingly take into consideration system level influences. Since every firm has its own design practices, methods must be developed and sustained within the firm in cooperation with research establishments which is the aim of this work.

Approach

There are many ways in which the system (engine) interacts with the component (TRS). The system will provide the boundary conditions for the TRS model, in the form of temperatures, Mach number and other such engine operating parameters. The TRS, in turn, will influence the system performance through the pressure drop that is developed in the component, as well as by its weight contribution, for example.

In order to obtain a detailed understanding of the boundary conditions, a good estimate of the inlet flow conditions to the TRS is needed through a thorough LPT model. However, the detailed design of the LPT is only available at the turbine manufacturer and therefore another approach has to be found to be able to model the dependencies between the LPT and TRS. This will be done through the development of a conceptual design tool for the LPT later in the project.

A twofold approach was adopted in this paper. First establish the influence of aerodynamically well designed TRS on the engine SFC followed by establishing the effect of a poorly functioning TRS with no design improvements on the engine SFC.

For establishing the influence of an aerodynamically well designed TRS in the engine, data from a number of design simulations performed on a TRS at GKN was collected. The data includes several inputs such as geometry variations (thicknesses, flange positions), outflow Mach number from LPT and flow path geometry; and outputs such as pressure drop across the TEC flow path. A range of pressure losses are thus available for a number of design variations. From the pressure losses, the maximum and minimum pressure loss was noted and input to the performance calculation code. This gives an estimate of the range of SFC variation corresponding to different design variations for the structure. In other words, how sensitive is engine performance to TRS structural design variations.

The variation in pressure drop data input to the engine performance code can be seen Figure 2.

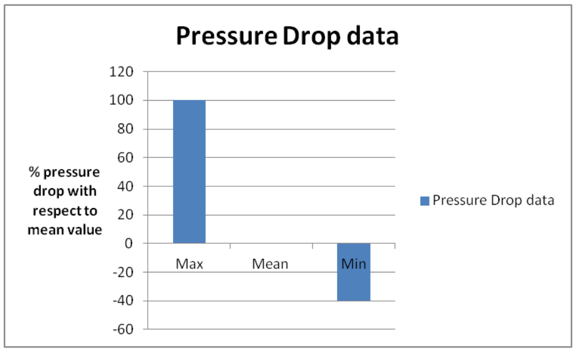

Figure 2 Maximum and minimum % variation in pressure drop corresponding to TRS design variations

The maximum pressure drop observed is 100% more than the mean value. The minimum pressure drop observed is 40% less than the mean value. It is evident that the design variations have significant influence over the pressure drop.

If a light weight TRS is designed with few struts and no consideration to its aerodynamic efficiency (a non-aerodynamically optimised TRS), it can result in a high pressure loss over the structure. To ascertain the impact of such a TRS on the engine SFC, flow separation that occurs on the airfoils was considered.

This was done in a simplified way by comparing the drag coefficient (C_D) of the airfoil at design incidence flow angle with the drag coefficient at an incidence where separation has occurred, slightly higher than the incidence at which maximum lift is obtained on the airfoil. It is assumed that the airfoil geometry is the same as for the TRS with low pressure drop, Δp, and that the vane pitch, s, is the same for both configurations. This means that the pressure loss increase is proportional to the drag force, F_D, increase according to (1) (Cumpsty, 2004):

$$\frac{F_D}{s} = \Delta p \qquad (1)$$

and hence it is also proportional to C_D, since density differences between the two cases are small.

Further, it is assumed that the effects at the end-walls scale in the same way as the losses over the airfoil. The increased pressure drop is then translated into a corresponding drop in the LPT polytropic efficiency through (2) (Saravanamuttoo, 2009):

$$\frac{T_{46}}{T_5} = \left(\frac{p_{46}}{p_5}\right)^{\eta_{\infty t}(\gamma-1)/\gamma} \qquad (2)$$

where $\eta_{\infty t}$ denotes the turbine polytropic efficiency, γ the specific heat ratio, T_{46} and p_{46} the total temperature and pressure at the LPT inlet and T_5 and p_5 represent these values at the outlet.

This reduced LPT efficiency is then input into a performance simulation which gives an SFC that can be compared to the baseline SFC of the engine with the TRS with low pressure drop.

A schematic of the arrangement to predict the system level effects can be seen in Figure 3.

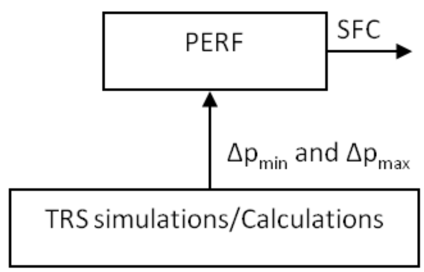

Figure 3 Simulation of system dependency

Results

The variation in pressure drop that corresponds to the aerodynamically well designed TRS produced an SFC variation of about 0.06%. While using the non-optimised TRS, the variation in pressure drop is 7 times the most minimum value of pressure drop for the optimised TRS. This in turn causes the SFC to vary by about 0.9% larger than that found for the aerodynamically optimised TRS. A summary of the results with the least pressure drop value of aerodynamically optimised TRS as baseline is shown in Table 1

Table 1 non optimised TRS data (least pressure drop value) Vs optimised TRS

	Pressure drop	SFC
non optimised TRS with respect to aerodynamically optimised TRS data	7 times more	0.9% more

Concluding discussion

This paper explored the effects of static engine structure design variations on overall engine performance. This was done by means of coupling the pressure drop across the structure to a performance calculation code that gives engine SFC. The coupling for an aerodynamically optimised structure resulted in, at the system level, a change in SFC of about 0.06%. Coupling for a non optimised structure results in an SFC change about 0.9% more than that for the optimised TRS. Thus a measure of the effect of design changes at a lower system on a higher system is obtained.

For further work, more dependencies between the system design and component design will be studied. For instance the weight of the TRS can be coupled in addition to the pressure drop. Compared to the pressure drop, variation in weight is ±15 % from its mean value. When weight as well as pressure drops are coupled together resulting SFC variation is expected to change. It is also possible to construct a model for the pressure drop (and weight) from TRS design simulation data and couple with the performance code. This will enable both performance and TRS detail design models to operate in loops towards an optimum pressure drop. To enable such coupled system studies, systematic methods should exist.

In the demonstrated case, the influence by component design variation onto SFC is substantial and the relevance in co-designing the system and the component is apparent. In the future works, development of such an integrated, engine and component design framework will be developed utilizing optimization formulations such as ATC (Kim et al., 2003).

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