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Turbine overspeed: Characterisation of turbine behaviour for an engine overspeed prediction model

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ABSTRACT

This paper focuses on the characterisation of turbine overspeed behaviour to be integrated into an engine overspeed model capable of predicting the terminal speed of the high pressure turbine (HPT) in the event of a high pressure shaft failure. The engine considered in this study features a single stage HPT with a shrouded contra-rotating rotor with respect to the single stage intermediate pressure turbine (IPT). The HPT performance is characterised in terms of torque and mass flow function for a range of expansion ratios at various non-dimensional rotational speeds (NH), up to 200% of the design value. Additionally, for each HPT expansion ratio and NH, the change in capacity of the downstream IPT, for different IPT non-dimensional rotational speeds (NI), also needs to be characterised due to the extremely positive incidence angle of the flow from the upstream rotor. An automated toolkit is developed to generate these characteristic maps for both the HPT and IPT.

An unlocated high pressure shaft failure will result in rearward movement of the rotor sub-assembly. This causes changes in the rotor tip and rim seal regions, and in the rim seal leakage flow properties. Therefore, in the present work, a high fidelity characterisation of turbine behaviour with the inclusion of tip and rim seals is carried out at three different displacement locations, 0 mm, 10 mm and 15 mm, to improve terminal speed estimation. Furthermore, there is a possibility of damage to the tip seal fins of the HPT rotor due to unbalance in the spool that may result in contact between the rotor aerofoil tip and the casing. Consequently, another set of characteristics are generated with damaged tip fins at each displacement location.

It is observed from the characteristics that the torque of the HPT rotor decreases with increasing NH. The HPT mass flow function initially decreases and then increases with an increase in NH. The IPT mass flow function initially remains similar and then decreases with increase in NH above values of 150%. The HPT rotor torque and IPT mass flow function decrease with rearward movement of the HPT rotor sub-assembly for all values of NH. With worn tip seal fins all parameters mentioned previously are lower than in the nominal undamaged case. The high fidelity characterisation of turbines that follows the sequence of events after a shaft failure, as described in this work, can provide accurate predictions of terminal speed and thus act as a tool for testing design modifications that can result in better management and control of the over-speed event.

1. Introduction

A shaft failure may lead to the decoupling of the compressor and the turbine mounted on the shaft. The decoupling leads to a situation in which the power produced by the turbine is no longer absorbed by the compressor. However, the expansion of the gases through the turbine rotor does not instantaneously cease at the moment of the shaft breakage owing to the flow of gases in the main gas path, causing the rotor assembly to accelerate. Should it not be restrained in some way, it will reach a critical speed at which permanent plastic deformation may occur, followed by disc burst. Should the bearings be arranged in such a way that the turbine is left without axial constraint following the failure, it will move rearward during the event owing to the axial force acting upon it, termed an unlocated shaft failure. The above sequence of events occurring in the engine is typically termed as a shaft overspeed event. Stringent guidelines on the eventuality of shaft failure and its management are specified in the engine certification requirements [1,2]. Engine certification guidelines specify

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Nomenclature

AS	Automation Script
CCL	CFX Command Language
GCI	Grid Convergence Index
HPT	High Pressure Turbine
HPC	High Performance Computing
IPT	Intermediate Pressure Turbine
NH	HP non-d speed function
NI	IP non-d speed function
MFF	Mass Flow Function
PR	Pressure Ratio
RANS	Reynolds Averaged Navier–Stokes
SST	Shear Stress Transport
ref	reference

that the engine can be deemed safe from shaft failure considerations by either a full scale actual engine test or by analyses that provide detailed descriptions of the likely progression of events following a shaft failure, arising from all possible reasons, along with details of design or flow features that will control or limit the possibility of the shaft failure event in becoming a criticality. Therefore, the development of engine models to understand the response of the engine during a shaft breakage event is of paramount importance. During the overspeed event, engine components can exhibit a wide range of behaviour depending upon the architecture of the engine and the type of failure. Typically the compressor behaviour is dominated by reverse flow, surge or stall. The change in compressor behaviour changes the response of the secondary air system. In the case of an unlocated failure, as studied here, the turbine rotor assembly moves axially rearwards because of unbalanced axial forces. This downstream movement of the turbine results in mechanical interaction between the rotor and the downstream components, and damage to the secondary air system elements in the disc region. Therefore, only a transient engine overspeed model that takes into account the behaviour of the compressors, turbines, secondary air system and mechanical interaction of the rotor with other components can accurately predict the evolution of the rotor speed with time after shaft failure [3–6].

Characterisation of the turbine behaviour during the engine overspeed event, for use in an engine overspeed model for HP shaft failure, is discussed in the present paper. The HP and the IP turbine parameters that influence the terminal speed of the HP rotor, at various operating conditions, need to be specified in the engine model as characteristic maps. In the HPT, the rotor aerofoil torque and the mass flow function, at different expansion ratios and NH, influence the terminal speed. Since, during the progression of the over-speed event the NH may attain values in excess of 160% of the design value because of the unloading of the turbine, possibility of surge in the compression system and combustion instabilities that lead to a reduction in the turbine entry temperature, overspeed characterisation should be carried out up to 200% of the design NH value. Therefore, a traditional characteristic map of the HP torque and mass flow function for an extended range of NH is required. In the case of the IPT, the change in the IP turbine mass flow function corresponding to each NH and HPT pressure ratio, needs to be mapped since the IPT throttles the HPT and fixes its operating point. This change in IPT capacity needs to be obtained for different values of NI. Therefore, the IPT characteristic is linked to the HPT characteristic during an overspeed event. A typical overspeed model imposes conditions of equilibrium in the engine to pick up the operating point of each turbine from operating maps and solves for the evolution of rotor speed with time. The only public domain literature available, published outside of Cranfield, regarding the development of engine overspeed model is the work by M. Haake et al. [7]. The model predicts the terminal speed of the overspeeding rotor by the use of main gas path component characteristics. The turbine characteristics are generated using a generic performance synthesis program, and does not explicitly model the events occurring in the turbine after the shaft failure event.

In the present work, a high fidelity characterisation of the turbine behaviour is presented for application in an engine overspeed model for the HP spool of a typical gas turbine engine. The methodology for characterisation includes explicit modelling of the events that occur during an unlocated shaft failure like axial displacement of the HP rotor sub-assembly, damage to the rotor aerofoils, and change in the properties of the leakage flow that interacts with the expanding gases in the turbine flow path. The change in the performance parameters of the turbine for nominal operating conditions at different axial displacements have been studied in detail by the authors using integrated aerodynamic, secondary air system model and structural analyses [8]. Additionally the characterisation is also attempted for the case in which the shroud fins of the rotor tip gets damaged because of an unbalance triggered in the rotor assembly after shaft failure. The effect of the damaged or worn tip fins on the on the turbine performance parameters for nominal operating conditions at different axial displacements have also been explored by the authors using a similar integrated methodology [9]. The need for characterisation of turbines at different axial displacements and for different tip seal configurations results in a large number of operating points for which the flow solution needs to be carried out. Therefore an automation framework is developed to obtain the overspeed maps of the turbine in the present work. This kind of high fidelity characterisation of turbines can greatly improve the accuracy of prediction of the rotor terminal speed. The methodology followed for the characterisation and the discussion of the trends in turbine parameters at different non-dimensional speeds are discussed in this paper.

2. Methodology

The turbine configuration considered in the present study consists of a single stage shrouded HPT that is contra-rotating with respect to a single stage downstream IPT stage. The rearward axial displacement of the HP rotor following an unlocated shaft failure is predicted by the use of a validated thermo-mechanical friction model developed on the basis of non-linear structural dynamic analyses carried out using LS-DYNA [10]. This rearward movement of the HP rotor sub-assembly changes the axial distance between the HP rotor and stator aerofoil, increases the tip clearance and damages portions of the HP rotor aerofoil that comes into contact with the downstream IPT hub platform casing. The HP rotor considered in the present study has a flared shrouded rotor tip that forms a seal with a three step casing that bridges the flare angle. This geometric arrangement of the of the turbine configuration is such that no significant changes in the tip clearance arises until a rearward axial displacement 10 mm from the initial position of the rotor. Further, it is observed that beyond an axial displacement of 15 mm, large portions of the rotor aerofoil sustain damage, and so axial displacement was limited to 15 mm. Therefore, the characteristics of the turbine are generated for the un-displaced rotor, and for the rotor at 10 mm and 15 mm displacements respectively.

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