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Methodology for evaluating hot gas path defects in an exhaust jet

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ABSTRACT

The components of modern jet engines represent state-of-the-art technologies. Their technological complexity results in costly components and thus expensive spare parts. Therefore, one of the main goals during the regeneration of jet engines is to repair, rather than replace, the components. So far, defects are mostly detected after a complete disassembly of the engine and an individual inspection of each component. One approach to reduce the costs of the regeneration process, therefore, is to acquire the information necessary for planning at an early stage and particularly before the disassembly of the jet engine. This approach requires new measurement methods. The present paper shows the Background-Oriented-Schlieren (BOS) method to be a promising contribution towards achieving this goal. Every defect in the hot gas path of a jet engine has a direct influence due to changes in the local temperature on the density of the flow. The BOS method provides a three-dimensional measurement of the density distribution in the exhaust jet. The localization and identification of non-uniformities in this distribution can be used to identify defects within the hot gas path. A three-dimensional unsteady CFD-simulation of the full annulus of a five-stage low-pressure turbine as well as a steady calculation of the exhaust jet is used to identify the signature in the exhaust density distribution of typical defects. As prototypical hot gas path defects, temperature variations at the inlet of the turbine were used to demonstrate that temperature non-uniformities can be detected with BOS. Hence, BOS measurements can be used for the identification of defects modeled a priori by CFD within the hot gas path before the disassembly of a jet engine. A methodology for evaluating the limits of detectability of non-uniformities with BOS is also provided.

1. Introduction

One major goal of the regeneration of jet engines is to restore as many components as possible. Replacement of damaged parts would be too costly. The components of jet engines are near the limit of technical feasibility. Moreover, the economical importance of the maintenance and regeneration of jet engines in comparison to the sale of new apparatus is increasing. In order to reduce the overall time of the regeneration process, it is necessary to get the relevant information as early as possible in order to plan the process in advance and reduce the idle time of the engine. Therefore, a quick and accurate method is presented below for an assessment of the condition of an engine before disassembly.

Defects within the hot gas path always have an influence on the local temperature and thus the density. By quantifying these non-uniformities, defects can be identified. The optical measurement method chosen for this approach is the Background-Oriented-Schlieren (BOS) method. Goldhahn and Seume [6] as well as Goldhahn et al. [7] presented and validated a tomographic algorithm for the three-dimensional reconstruction of the density distribution of a free jet. The algorithm was further applied by Alhaj and Seume [2] in combination with the Particle Image Velocimetry for the measurement of the total pressure loss and the kinetic energy loss coefficient in linear cascades. Further work includes the visualization and measurement of blade tip vortices of helicopters by Richard and Raffel [19] and Kindler et al. [12]. Loose et al. [13] measured the vortex distance and strength of flow around a high speed train with BOS in a wind tunnel. Venkatakrishnan and Suriyanarayanan [20] used BOS to measure the density field of supersonic separated flow past an afterbody nozzle. The reconstruction in this case, however, was performed using only one camera and assuming axis-symmetric flow.

Other measurement methods such as the Raman Spectroscopy (e.g. Hatzl et al. [9]) or the Rayleigh Scattering Diagnostic (e.g. Maisto et al. [14] and Mielke et al. [15]) could also be used for the presented purpose, as they both provide a non-intrusive measurement of exhaust jet temperatures. The BOS-method however allows for the recording of complete three-dimensional exhaust jet patterns rather than point-wise measurements of the flow properties. Tomographic BOS offers therefore much faster measurements

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Nomenclature

TR	temperature ratio
T	temperature
n	refractive index
ε	deflection angle
φ_{th}	angle between line of sight and light ray
t	line of sight
ϱ	density
K	Gladstone–Dale constant
Θ	angle in circumferential direction
R	specific gas constant
m	distance between density field and objective
l	distance between density field and background
l_{px}	edge length of pixel on CCD chip
d	thickness of the density field
υ_{px}	pixel shift in the image plane
f	focal length
β	angle between light ray and optical axis
x, y, z	Cartesian axes

Subscripts

CS	referred to the cold streak
FB	referred to an unaffected burner
CO	referred to the compressor outlet
min	minimal value

and data evaluation in comparison to the other two methods. Speckle methods as presented by e.g. Hirahara and Kawahashi [11] or Erbeck and Merzkirch [5] can also be used to measure density gradients. However, as already described by Raffel et al. [18] BOS measurements offer a significantly less complex experimental setup. Therefore it is possible to achieve a tomographic setup, which allows three-dimensional measurements.

Previous work on the mixing of non-uniformities within turbines concentrated on the effects of combustor hot streaks and their effects on the first turbine stages as presented in Basol et al. [4], Qingjun et al. [16], and Qureshi et al. [17]. Adamczuk and Seume [1] showed with a CFD-simulation that large scale temperature defects barely mix out with the surrounding flow in a five-stage low-pressure turbine (LPT). The assumed causes of the defects were malfunctions of individual burners. A total of six different non-uniformities in inlet temperature were applied, including the worst case defect being the complete shut-down of one burner. Based on these findings, the present paper evaluates whether the non-uniformities in the exhaust jet lead to density gradients which are high enough to be detected with a tomographic BOS set-up in a jet-engine test cell. For this purpose, it is necessary to distinguish density gradients resulting from the temperature non-uniformities from those which might arise from a pressure difference between hub and casing. Furthermore, they have to be distinguished from effects of the wakes of the exit guide vanes on the exhaust jet.

2. Numerical methods

The numerical methods as well as first results are already described by Adamczuk and Seume [1]. Therefore, in the present paper the approach is described only briefly. The LPT flow computations were performed using the parallel flow solver TRACE (Turbomachinery Research Aerodynamics Computational Environment), which is developed at the Institute of Propulsion Technology of the German Aerospace Center (DLR) in cooperation with MTU Aero Engines. The computations were conducted solving the Reynolds-Averaged Navier Stokes (RANS) equations assuming fully turbulent flow that is without predictions for laminar-to-turbulent transition. A structured mesh (see Fig. 1) with the OCHG-Topology was used. The meshing of the five-stage LPT uses a coarse design grid in order to reduce the number of grid points to 100 million for a full annulus computation. The quality of the mesh was controlled by the comparison of the spanwise distribution of the relative pressure loss coefficient for the first vane between the coarse and the fine grid. It was shown that the distributions agreed well, that is the absolute error in the pressure loss coefficient is around 1.8%. A courser mesh led to an error above 2.1%, however, as shown in Adamczuk and Seume [1] resulting in a significantly different distribution so that the mesh with 100 million nodes was chosen.

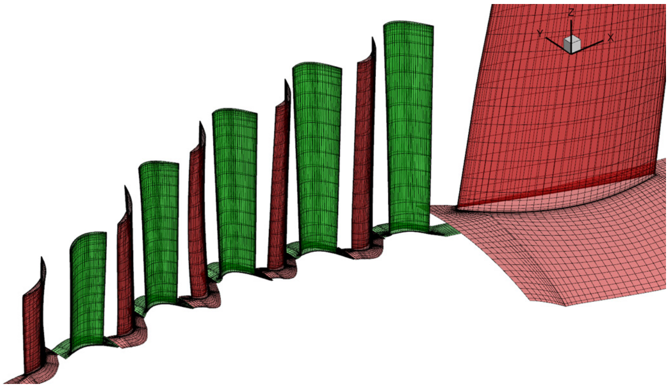

Fig. 1. Meshing of the five-stage low pressure turbine (Adamczuk and Seume [1]).

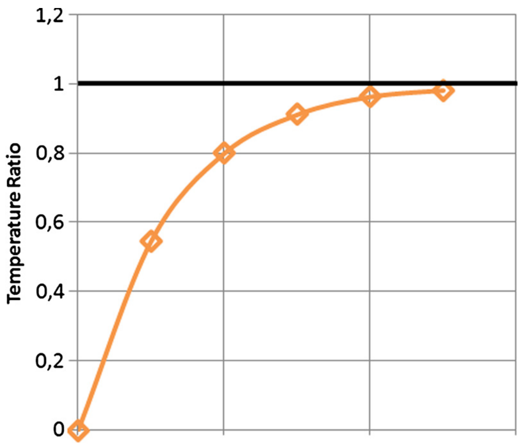

Fig. 2. Graph of the temperature distribution at the inlet of the turbine.

As mentioned before, the goal is to evaluate the detectability of possible large scale defects e.g. burner malfunctions with BOS in the exhaust jet. The engine used for the evaluation has a total number of 20 burners. To simulate the effect of different defects, six temperature non-uniformities of the geometrical scale of one burner were included, so that a complex temperature distribution results. The minimal inlet temperature was defined by the possible worst case defect, which is a complete shut-down of the burner and is represented by streak 1. The other five magnitudes of temperature non-uniformities were distributed logarithmically between the worst case and the design temperature as illustrated in Fig. 2.