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APPLICATION OF THE BACKGROUND-ORIENTED SCHLIEREN METHOD FOR THE ANALYSIS OF AN ENGINE'S EXHAUST JET

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ABSTRACT

The regeneration process of jet engines is complex, time-consuming, expensive, and often requires an engine disassembly or boroscopic examination. One of the main challenges for improving the regeneration process is the reduction of engine down time during the inspection. It is intended to develop a method to locate and characterize defects and damages at an early state, without having to disassemble the engine by measuring and analyzing the density distribution of the exhaust jet. For this goal the application of the Background-Oriented Schlieren (BOS) method is proposed. In a tomographic set-up, the BOS method resolves the three-dimensional density distribution of an exhaust jet. By analyzing and comparing the pattern to a design state, conclusions on the condition of the engine's hot gas path components can be drawn. The present paper summarizes a study on measuring the exhaust jet of a helicopter engine with a two-stage axial turbine. A cold air streak is injected into the exhaust jet in order to simulate a defect, which is associated with a change in the temperature distribution. It is confirmed experimentally that even small defects barely mix with the surrounding flow and can therefore be identified with BOS. Thus the hypothesis that tomographic BOS measurements can resolve small density gradients resulting from defects in the hot gas path is strengthened.

INTRODUCTION

The regeneration of jet engines is a costly and time-consuming process. The growing fleet of aircrafts increases the economic importance of the regeneration and maintenance of jet engines. To reduce costs, as many components as possible should be regenerated and the total down time of each engine should be minimized. The conventional way to detect defects and damage of engine components requires either a complete disassembly of the engine or boroscopic examinations, both being time consuming. Therefore, a method which allows the detection of defects at an early state without disassembling the engine may significantly improve the regeneration process.

Defects within the hot gas path influence the local density and temperature distribution of the flow and can therefore influence the density distribution in the exhaust jet. Adamczuk and Seume [2] performed Computational Fluid Dynamics (CFD) simulations of the flow in a five-stage low-pressure-turbine (LPT) with large-scale temperature non-uniformities. Their results show that these local temperature variations barely mix out with the surrounding flow. They varied the temperature magnitude at the inlet of the LPT in order to model malfunctions of individual burners. The worst-case defect was a complete shutdown of one burner, which has a great influence on the temperature distribution at the outlet. Their investigations have also shown that even small temperature differences have an impact on exhaust jet patterns of density and temperature.

In further work, Adamczuk et al. [3] investigated the influence of different hot gas path defects on the density patterns at the outlet plane of a jet engine. The simulated defects included the complete shutdown of a burner, the loss of trailing edge material in the second rotor and stator of a two-stage high-pressure-turbine (HPT), and the increase of the clearance gap between the blade tip and the casing of the second stage rotor of the HPT. The results demonstrated that different defects lead to different density patterns at the outlet. The hypothesis that the comparison of the exhaust jet density and temperature patterns with an undisturbed reference case yields useful information about the condition of the engine was thus confirmed for a CFD-based analysis.

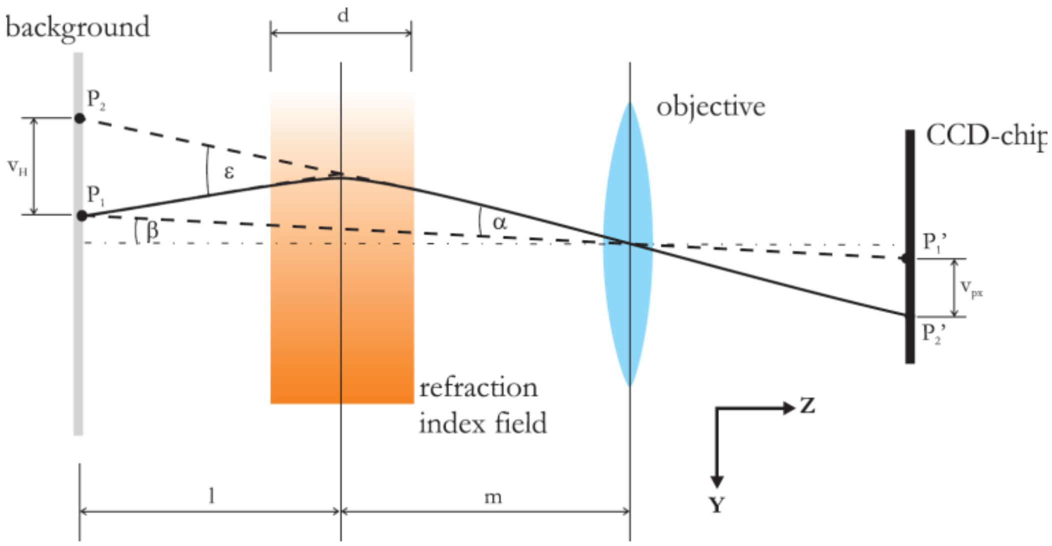

Figure 1. BOS principle (Herbst et al. [7])

In the present study results from Adamczuk et al. [1] are summarized, presenting the non-intrusive Background-Oriented Schlieren (BOS) method as a quick and accurate method to measure and evaluate the three-dimensional density and temperature distribution of an engine's exhaust jet. To perform three-dimensional BOS measurements a tomographic algorithm is required. Adamczuk et al. [1] used the filtered back-projection algorithm, presented and validated by Goldhahn and Seume [4] as well as Goldhahn et al. [5]. Further validation of the algorithm on a linear cascade wind tunnel was provided by Alhaj and Seume [6]. To determine the total pressure loss and the kinetic energy loss coefficient Alhaj and Seume [6] combined the BOS method with the Particle Image Velocimetry (PIV). In order to demonstrate the feasibility of the approach and the possibility of measuring different temperature patterns with BOS, the method is applied in a tomographic set-up to the exhaust jet of a helicopter engine.

NOMENCLATURE

T	Temperature
n	refraction index
ρ	density
K	Gladstone-Dale-Constant
R	specific gas constant
m	distance between density field and objective
l	distance between density field and background
d	thickness of the density field
l_{px}	edge length of a pixel on the CCD chip
v_{px}	pixel shift in the image plane
f	focal length
t	line of sight
β	angle between light ray and optical axis
φ_{th}	angle between light ray and line of sight
ε	deflection angle
s	radial gap height
c	chord length

EXHAUST JET MEASUREMENTS

As described by Adamczuk et al. [1] BOS is part of the Schlieren techniques. It is sensitive to those components of the spatial derivative of the index of refraction n which are perpendicular to the line of sight. For a gas with $n \approx 1$ the integral along the line of sight can be determined by

$$\varepsilon \approx \tan(\varepsilon) = \sin(\varphi_{th}) \int_l \operatorname{grad}(n(x,y,z))dt. \quad (1)$$

The angle φ_{th} between the line of sight and the direction of the refraction index gradient is assumed to be 90°. The Gladstone-Dale relation (Eq. 2) links the density of the gas with the index of refraction:

$$n - 1 = K \cdot \rho. \quad (2)$$

Here ρ represents the density of the fluid and K is the Gladstone-Dale-constant. A change in the temperature or pressure within the exhaust jet can be converted to a deflection of the line of sight with the ideal gas equation

$$p/\rho = R \cdot T. \quad (3)$$

In the exhaust jet a constant ambient air pressure can be assumed and a change in the temperature will therefore lead to a measurable change in the density distribution. For the measurements with BOS the following main components are used:

- A random dot pattern on the background of the flow
- A digital camera to record the measurement images
- A computer to evaluate the measurement images

First a picture of the background is taken without flow as a reference. Then a picture of the background is taken with flow. After a discretization into a grid of squared, overlapping windows, the images are compared using cross-correlation algorithms. A pixel shift resulting from the refraction index gradient is determined for each window. The required geometric dimensions of the BOS set-up are illustrated in Fig. 1.

ε can be calculated based on the geometric dimensions

$$\varepsilon \approx \left(1+\frac{m}{l}\right)\cdot v_{px}\cdot l_{px}\left(\frac{l+m-f}{(l+m)\cdot f}\right)\cdot(\cos\beta)^2. \quad (4)$$

By applying several cameras from different viewing directions at the same time the three-dimensional density distribution in the exhaust jet can be reconstructed. Here the filtered back-projection algorithm of Goldhahn and Seume [4] is used.

MEASUREMENT SET-UP

The BOS-measurements are described in detail in Adamczuk et al. [1]. The measurements are conducted with the exhaust jet of a Turbomeca Artouste II C5 engine. The test cell is shown in Fig. 2. The single-shaft gas turbine consists of one radial impeller followed by a radial and axial diffuser, an annular combustor, a two-stage axial turbine and an exhaust diffuser.

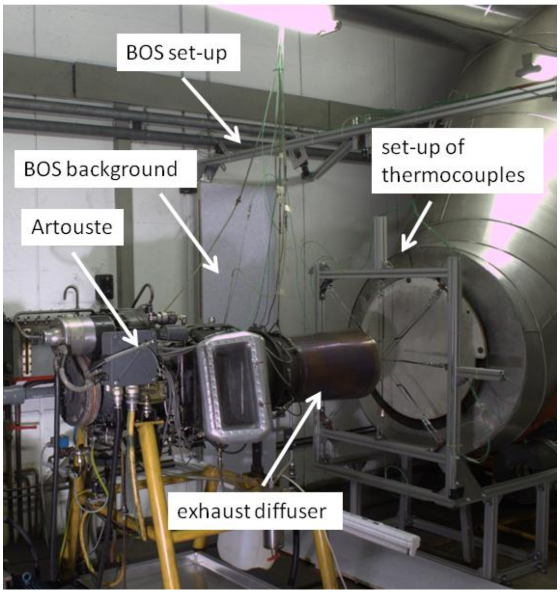

Figure 2. Test cell (Adamczuk et al. [1])

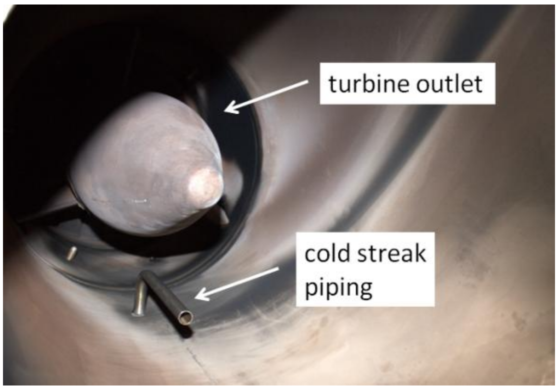

Figure 3. Exhaust of the engine with the cold streak piping (Adamczuk et al. [1])

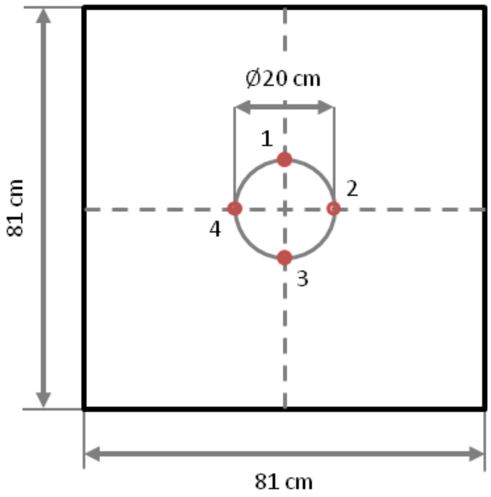

Figure 4. Schematic of thermocouple set-up (Adamczuk et al. [1])

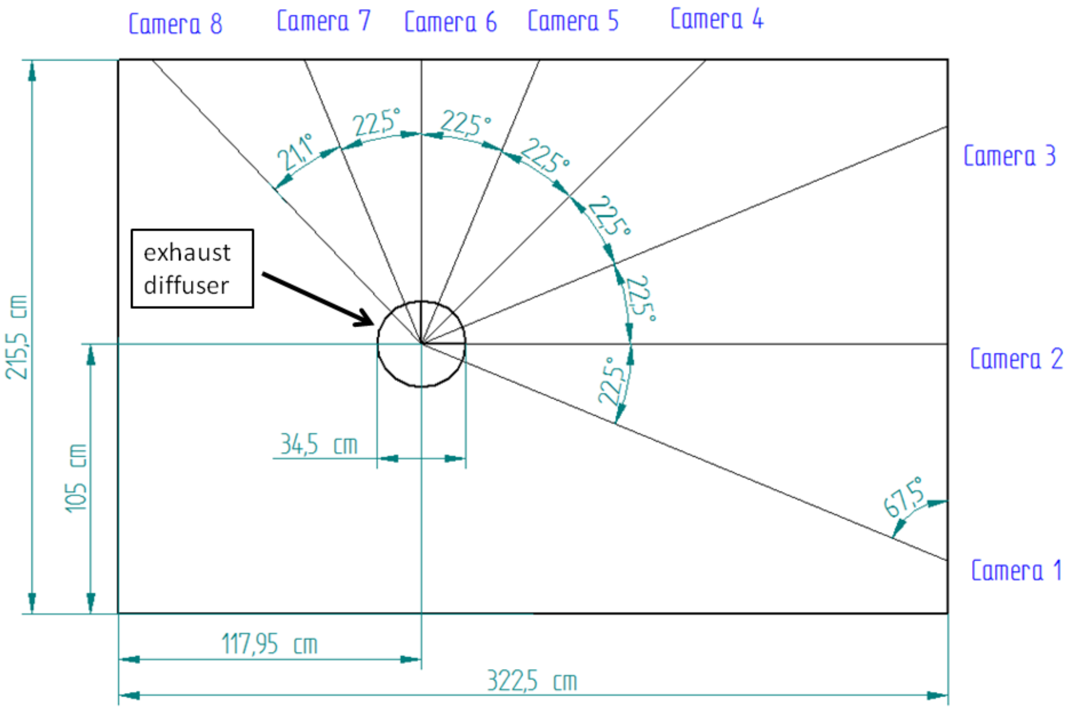

Figure 5. Schematic of the camera set-up (Adamczuk et al. [1])

An eddy current brake is used to dissipate the output power while the exhaust jet is ducted into an exhaust pipe. A non-uniformity within the temperature pattern of the exhaust jet is simulated by mounting a pipe into the exhaust diffuser, which provides a cold mass flow (see Fig. 3). The cold streak corresponds to 1.6% of the total mass flow of the exhaust jet. The temperature of the flow at the outlet of the piping is around 300 K. The distance between the outlet of the cooling air pipe and the first measurement plane is 31 times and the distance to the last reconstruction plane is 39 times the diameter of the cooling pipe. In order to determine the pressure in the exhaust jet, the ambient pressure is measured. On this basis the temperature distribution in the exhaust jet can be calculated. Four thermocouples are mounted in the exhaust jet as illustrated in Fig. 2 and Fig 4. Thermocouple 3 measures the temperature of the cold streak. The eight cameras, which are used for the measurements are equipped with a 1/1.8 inch CCD chip with a resolution of 1628 x 1236 pixels. For data transfer and electric power supply an Ethernet connection is used. A LabView code is used in order to simultaneous trigger the cameras with a frame rate of 12 frames per second during acquisition. For each measurement 100 images are taken per camera. The size of the dots on the background corresponds to four pixels on the CCD chip of the cameras.

An operating point generating 206 kW (+/- 3 kW) of shaft power is maintained for all measurements. Two measurements are conducted, one without cooling flow (case 1) and one with cooling flow (case 2). The displacement vectors between the reference and the measurement images are evaluated using a window size of 16 pixels by 16 pixels. Furthermore a median filter is used. The angles and the focal length of the lenses as well as the distances between the cameras, the measurement object and the background differ for each camera (see Fig. 5). Therefore the displacement vectors are corrected for each camera (see Adamczuk et al. [1] for a more detailed description). Camera 6, whose optical axis is perpendicular to the background, is chosen as the reference camera for this purpose. The displacement vectors of all other cameras are corrected based on the geometrical and optical specification of this camera.

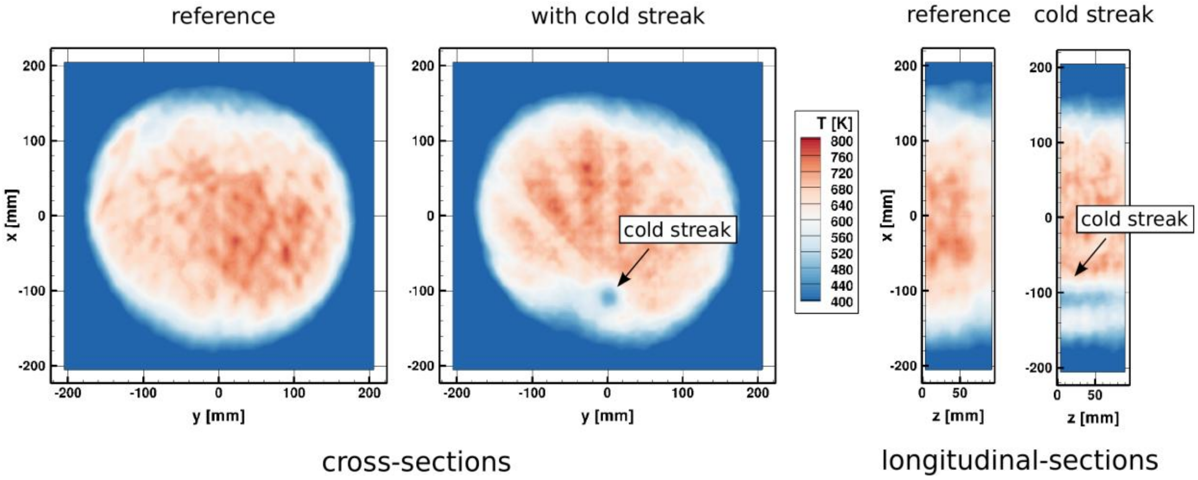

Figure 6. Comparison of the temperature distribution in the plane perpendicular to the axis of the exhaust jet and a longitudinal plane in flow direction without (left) and with (right) cold streak (Adamczuk et al. [1])

RESULTS AND DISCUSSION

Fig. 6 shows the temperature distribution obtained by Adamczuk et al. [1] without (left) and with (right) a cold streak. The temperature distribution is illustrated for a plane perpendicular to the jet axis on the left side of Fig. 6. The distance between the measurement plane and the outlet of the cooling air pipe is 31 times the diameter of the pipe. The temperature of the exhaust jet without cold streak is around 700-750 K. The shape of the exhaust diffuser causes the oval shape of the temperature distribution. The temperature distribution for case 2 shows a similar shape. However, the cold streak clearly influences the temperature distribution and can therefore be identified. The temperature of the cold streak is determined to be around 450 K. The magnitude of the temperature of the surrounding flow agrees well with case 1. Furthermore, Fig. 6 shows on the right side the progress of the exhaust jet over an axial length of 90 mm. The cold streak is also clearly visible in this illustrated longitudinal section of the flow. The results show that even temperature non-uniformities, which affect only a small part of the total mass flow, barely mix out with the surrounding flow. The mass flow of the cold streak is only 1.6% of the total mass flow of the helicopter engine. Despite this small mass flow ratio the cold streak stays concentrated on a small area of the

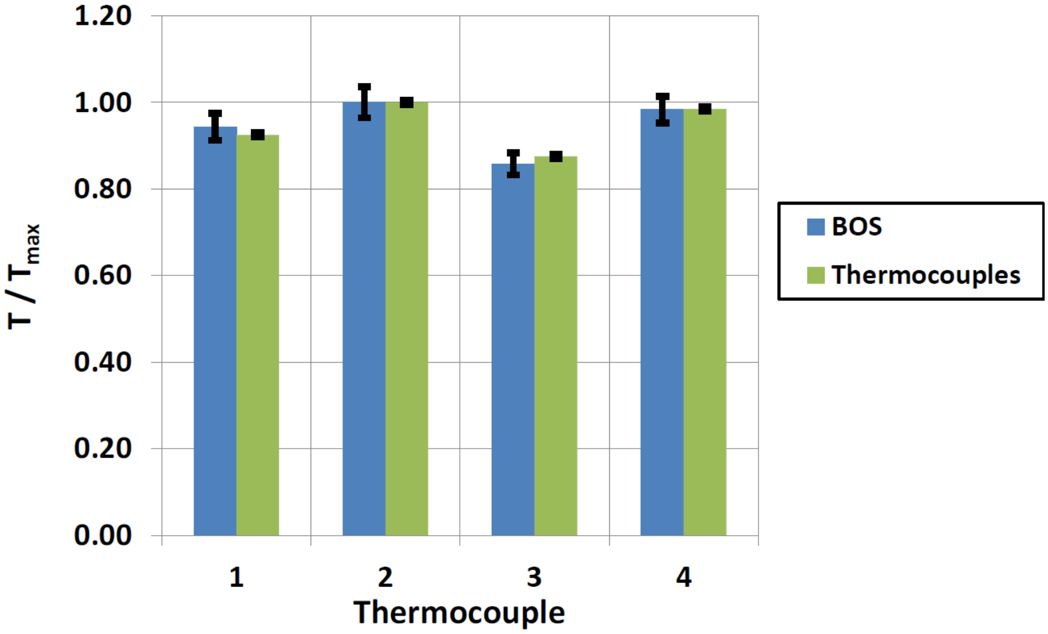

Figure 7. Temperature comparison of the values obtained with BOS and values obtained with thermocouples (Adamczuk et al. [1])

whole exhaust jet. Furthermore, the results clearly demonstrate that the tomographic BOS-approach can be applied for the measurement and identification of temperature non-uniformities in the temperature distribution of an engine's exhaust jet.

The temperature in the exhaust jet is measured with four thermocouples in addition to the BOS measurements. The thermocouples are placed in a distance of four times the diameter of the pipe behind the last reconstructed BOS measurement plane, in order to ensure that the thermocouples do not affect the flow in the measurement volume. Due to vibrations of the thermocouples during the measurements, the exact position of the tip of the thermocouples cannot be determined. Therefore, the temperature values obtained with the BOS method are averaged over a square with an edge length of 10 mm in the region where the thermocouples are placed. The tip of the thermocouples is assumed to be in the center of the square.

Fig. 7 shows a comparison of the normalized temperatures obtained with BOS to those obtained with the thermocouples. The measured temperature differs for both measurement techniques for reasons yet to be resolved. Therefore the temperature values are normalized with respect to the highest temperature obtained with the corresponding measurement method. The values obtained with BOS agree well with the values obtained with thermocouples. The deviation lies within the measurement uncertainty. Thermocouple 3 is placed in the cold streak and hence shows a lower temperature value than thermocouples 1, 2, and 4. Figure 7 thus shows that the BOS method correctly captures the exhaust gas temperature distribution.

CONCLUSION AND OUTLOOK

The present study summarizes the results of Adamczuk et al. [1] and demonstrates the feasibility of measuring the three-dimensional density and temperature patterns of a gas turbine's exhaust jet with the non-intrusive measurement technique Background-Oriented Schlieren (BOS). Three-dimensional density and temperature distributions are reconstructed using a tomographic algorithm and the images of eight cameras. The feasibility of BOS detecting density and temperature non-uniformities in the exhaust jet is demonstrated by inducing a cold streak with a mass flow of 1.6% of the total mass flow of the exhaust jet in the diffuser. The results show that the temperature non-uniformity does not mix out with the surrounding flow, despite the small mass flow-ratio. Hence, a clear identification of the non-uniformity is possible. Within the uncertainties of the measurement techniques the temperature distribution obtained with BOS agrees with the values obtained with thermocouples. Future work can include, measurements with real defects in the hot gas path of an engine to investigate their effect on the reconstructed exhaust jet pattern.

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