

Pathway to non-intrusive in-flight flow diagnostics with Filtered Rayleigh Scattering (FRS)

Nicholas J Lawson*, Matteo Migliorini[†], Ulrich Doll[‡], Sergey M
Melnikov[§], Jonas Steinbock^{**}, Michael Dues^{††}, Pavlos K Zachos^{‡‡},
Ingo Röhle^{§§}, David G MacManus^{***}.

Abstract

A pathway to in-flight application of Filtered Rayleigh Scattering (FRS) is herein presented, including a viable concept, based on recently published related work. The proposed pathway considers the key technical, operational and regulatory challenges to enable in-flight measurements using FRS for inlet flow distortion characterisation ahead of the aero-engine. Solutions to these challenges are proposed, in particular methods for light delivery, flow imaging and integration of the measurement system in the in-flight environment. This complements the experimental lab-scale demonstration of a FRS concept for flow distortion measurements and provide a route for further exploitation as a diagnostic tool for the next aircraft generations.

1. Introduction

In the path to net zero for aviation, new approaches for improving propulsion efficiency are being developed, including unconventional architectures such as boundary layer ingestion (BLI) [1]. These configurations generally involve complex geometries, which are highly sensitive to the aerodynamic scaling parameters Reynolds number and Mach number [2,3]. One approach to address these scaling challenges is to consider in-flight characterisation of aerodynamic performance, which was previously successfully applied in certain configurations [4]. Current industrial practice for inlet distortion measurements primarily relies on intrusive pressure rakes and multi-hole probe arrays located at the

* Associate Professor, Aerospace Engineering, University of Sydney, Camperdown NSW 2006, Australia. ORCID ID: 0000-0002-1915-8209.

† Senior Research Fellow, Centre for Propulsion and Thermal Power Engineering, Cranfield University, Bedfordshire, MK43 0AL, UK. ORCID ID: 0000-0002-0745-7578.

Corresponding author.

Email address: matteo.migliorini@cranfield.ac.uk

‡ Assistant Professor, Department of Mechanical and Production Engineering, Aarhus University, Katrinebjergvej 89, Aarhus, 8200, Denmark. ORCID ID: 0000-0002-9876-9509.

§ Researcher, ILA R&D GmbH, Rudolf-Schulten-Straße 3, Jülich, 52428, Germany. ORCID ID: 0000-0001-9664-7156.

** Researcher, ILA R&D GmbH, Rudolf-Schulten-Straße 3, Jülich, 52428, Germany.

†† Managing Director, ILA R&D GmbH, Rudolf-Schulten-Straße 3, Jülich, 52428, Germany.

‡‡ Reader, Centre for Propulsion and Thermal Power Engineering, Cranfield University, Bedfordshire, MK43 0AL, UK. ORCID ID: 0000-0002-3273-7475.

§§ Professor, Berliner Hochschule für Technik, Luxemburger Str. 10, Berlin, 13353, Germany.

*** Professor, Centre for Propulsion and Thermal Power Engineering, Cranfield University, Bedfordshire, MK43 0AL, UK. ORCID ID: 0000-0002-5638-8409.

aerodynamic interface plane (AIP). While such methods are widely used, they suffer from limited spatial coverage and often insufficient temporal resolution, which restricts the ability to capture the unsteady flow phenomena that critically influence engine stability [9]. Previous studies have shown that time-averaged measurements may underestimate instantaneous peak events, leading to incomplete or even misleading interpretations of inlet distortions during engine development programs [9]. These limitations underscore the urgent need for richer, high-resolution data in both space and time, particularly under in-flight conditions where extreme distortion events cannot be replicated in ground or wind-tunnel testing. Advanced optical flow measurement techniques, such as particle image velocity (PIV) are promising candidates to offer a more completed understanding of the flows around complex architectures pertinent to novel, closely coupled- propulsion systems [4]. Work published from a major research program Advanced In-Flight Measurement [4], demonstrated the potential for in-flight PIV applications. The requirement for flow tracers was identified as a major limitation for the in-flight application of PIV. This led to unreliable test conditions for measurement, due to the high variability of the particle sizes [6]. Recent work by Doll et. al. [9] has also considered other measurement techniques as candidates for flow diagnostics for in-flight applications, which included also O₂ LIF, CO₂ LIF, FLEET, and DGV. However, these have been discarded due to technical limitations of their implementations for flow distortion assessments. The main limitations included the requirement complex hardware, signal weakness due to output levels or oxygen quenching, limited interrogation area to investigate flow topology, incapability to capture multiple quantities at once, and seeding requirements [9]. To overcome these restrictions, Filtered Rayleigh Scattering (FRS) is proposed as a seedless optical method for planar synchronous velocity, pressure and temperature measurements, that was previously found able to characterise complex flow fields in ground testing facilities [7]. A pathway to the application of FRS is herein proposed, including both technical and regulatory aspects to enable the application of the method in an in-flight environment.

2. Proposed FRS concept

The principle of FRS is outlined in more detail in this recent paper [7]. In-flight measurement is suited to closely integrated aero-engine configurations with limited access to the engine fan face (Figure 1). Several observation probes must be installed in the ambient conditions of the engine bay, to record the light signal, with an image fibre bundle (Figure 1a). Similarly, the laser light illumination can be provided using beam forming optics and optical access ports at the measurement plane (Figure 1a). The FRS signal is processed into 3D velocity components, static pressure and temperature and is collected from at least 3 observation probes (5 for unsteady measurement with pulsed laser sources). The probes can be flush mounted into the intake walls (Figure 1b). Recent work has demonstrated that the steep viewing angles are feasible for this concept, provided that the probe mounts satisfy the Scheimpflug criterion for full-plane focusing [8]. The more sensitive components of the system such as the laser, cameras and iodine cells can be installed inside the aircraft, in a controlled environment, as the fibre imaging and light delivery system enable the data transmission between the two locations (Figure 1a). The introduction of a processing hardware and machine learning algorithms will also provide rapid data evaluation in the route to real-time data processing of inlet distortion conditions of the propulsion system [9]. The proposed FRS concept builds upon validated concepts and findings from prior studies. Among others, this includes a review of the suitability of non-intrusive experimental techniques to characterize distorted flow fields [9], the demonstration of time-resolved multi-property measurements with FRS [8], and the experimental implementation of FRS to a laboratory-scale complex intake facility to demonstrate applicability for flow distortion measurements in aero-engine intakes [7].

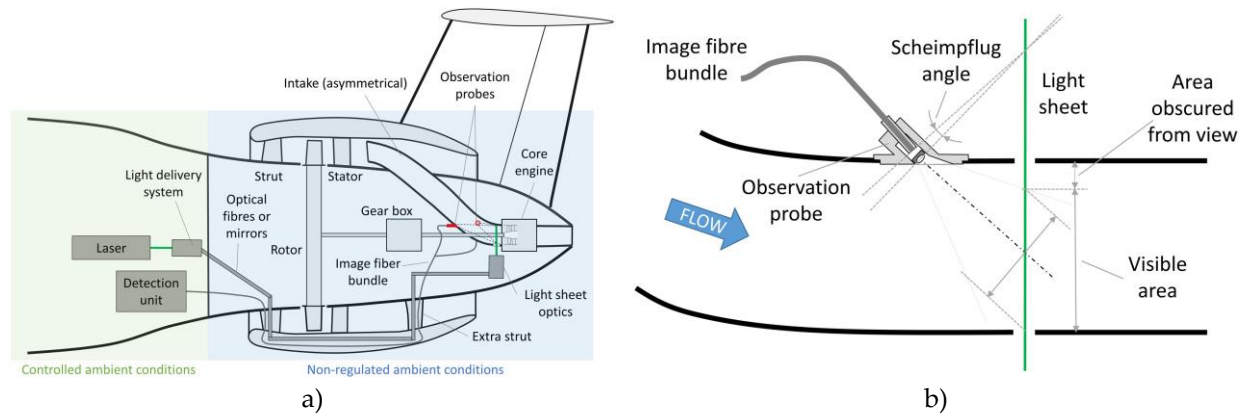


Figure 1: Proposal for in-flight FRS system inspired by the Bauhaus Luftfahrt “propulsive fuselage” concept. Data taken from [9][10].

3. Pathway to In-Flight Measurements

The following section considers the major challenges, technical, operational and regulatory, based on the design in the previous section.

A. Technical Challenges

In-flight environments generally have structural, vibration, atmospheric and other issues to consider. In the former case, aircraft have flexible and lightweight structures, which can deform significantly during certain flight manoeuvres. In work by Veerman and Hentink [11], this deformation was addressed by using a highly rigid mounting frame inside a Metroliner fuselage and with additional sensors, including accelerometers, which were mounted onto the frame to monitor the structural behaviour during the flight. This approach was adapted further, in the application of image pattern correlation technique (IPCT) measurements, completed by Boden et al. [12], on an Airbus A380 aircraft. In this case, a second framework was mounted inside the cabin, facing the mount camera framework and an optical photogrammetry system, was used to monitor the movement of the main framework. Both approaches allowed live, in-situ corrections to be generated, to improve the accuracy of the optical data.

Aircraft vibration also presents a serious challenge in a light aircraft environment, particularly if the aircraft is powered by a piston engine. In a further application of IPCT [13], this issue of vibration was addressed by pre-testing the complete measurement system on shaker tables before mounting the system for flight. In this case, the instrument casing and circuit boards received significant design attention, to protect the instrument components, from the large accelerations expected during operation.

Further challenges in-flight in aircraft involve Electro Magnetic Interference (EMI). EMI can originate from the ignition system in piston engine aircraft or other electrical systems, contaminating the reference earth connections of test equipment, which usually rely on a common fuselage reference earth. This can be addressed using electrical filters which can be passive or active, analogue or digital [14]. Post-processing techniques can also be used to remove these noise features in the data, and careful positioning and planning of the equipment is needed to minimize these effects [15]. Other approaches to overcome these EMI limitations involve using fibre optic technology, which does not suffer from EMI limitations and allows distribution of sensors over large distances. The principles of these fibre-based techniques have been demonstrated on smaller aircraft for pressure and strain [16].

Cooling issues can also occur as most aircraft in-flight measurements are typically carried out at altitude or have restricted volumes within which the equipment can be installed. If the aircraft flies at 10,000 feet for example, the air density will be 73% of sea level density, therefore reducing the cooling capacity of the instrument cooling systems. It is unlikely that the instrument cooling system will have been designed for this reduced air density and therefore the design may need modification. The same issue relates to atmospheric pressure which will be 70% of sea level and this may affect pumps and laser cavities, which may operate under pressure and risk failure under reduced pressure. If a pressurized aircraft is used, this can reduce these effects, but if a reference pressure is required, it will need to be obtained from outside the cabin, potentially from the aircraft static pressure source.

Operation of lasers will require a safety case and risk assessment, particularly as they are likely to be of higher power and be categorized as a Class 3 or Class 4 laser and pulsed format [6,17]. If the laser is to be projected away from the aircraft, consideration of the operating area and altitude must also be taken into consideration, to avoid endangering other aircraft and persons on the ground. Operation at night may also be required, as outlined in the in-flight particle image velocimetry measurements of Dunker [6]. These approaches will need operational approval from regulatory authorities.

To address a number of these technical issues, if we consider an FRS system design for an aircraft intake, several technologies could be used to mitigate the technical risks. With the optical system, fibre optic delivery of both the laser sheet and imaging system will simplify the installation, in what may be a confined area. Fibre optic imaging bundles offer a proven imaging method, as demonstrated in Doppler Global Velocimetry (DGV) [18]. Also, for pulsed laser delivery, hollow fibre optic designs allow pulsed laser delivery to the flow area [19,20]. Both these methods would allow remote installation of the cameras and lasers away from the flow area, giving more flexibility to the instrument design, allowing cooling and vibration control. These fibre systems could be supplemented by a multi-pass light sheet system, as developed for tomographic PIV [21], to improve the power delivery of the light sheet.

B. Regulatory Considerations

Regulatory considerations are key to permitting a flight trials program to proceed [22]. Early engagement of the regulatory authority in the process is essential and the appointment of a Part 21 design organization is also crucial to complete any research program. Figure 2 provides an overview of a typical process leading to an in-flight research program. The Part 21 will lead the modification of the aircraft used for the flight trials. However, it is important that the instrumentation development occurs in parallel with the appointment of the Part 21, so that the latter stages of instrumentation design, will start to meet regulatory requirements for installation on the aircraft. The final stage of the instrumentation design must satisfy the Part 21, to ensure the instrumentation meets the regulations for flight. The Part 21 may also require the conducting of a series of tests, such as under high g-loads or power measurements, to permit fitting of the instrument on the aircraft. The Part 21 must hold both a Design Organisation Approval (DOA) under Part 21J and a Production Organisation Approval (POA) under Part 21K. In some cases, the Part 21J and Part 21K can be separate companies, but it is generally easier to manage the modifications within the same company. Some parts of the final instrument may need to be manufactured under the POA, before fitting in the aircraft.

The regulatory route to the flight trials or data collection depends on the nature and duration of the tests and commercial considerations. There are generally two routes to either a certified product or a permit status. Both formats can potentially gather the research data. If the instrument is likely to be used on the aircraft for a long period of time or the aircraft has dual roles, obtaining a supplement type certificate (STC) offers the best approach to the flight trials and data collection. At the end of this process the aircraft will be released with a certified status, which will allow flight within the full flight envelop and flight conditions,

for example instrument flight and/or visual flight. This STC may also then be sold to other aircraft operators, to allow them to use the instrument. The regulatory authority will ultimately issue and approve the STC, once all the design and testing are completed by the Part 21.

The second route that can be taken is using a permit-to-fly process. The permit-to-fly is issued by either the regulatory authority or the Part 21, depending on the status of the modification, which can be minor or major. If the regulatory authority deems the modification as minor, in most cases, the Part 21 is allowed to complete the process and issue a permit. If it is a major modification, the permit will only be issued in conjunction with the regulatory authority. Permits are restricted for certain activities, for example development and testing of an on-board system and they can streamline the regulatory process to fly the equipment and get the required data. However, the issue of a permit contains limitations on the operation of the aircraft, and in some cases, this will include the degree or amount of testing allowed.

Therefore, the research organization carrying out the tests, will need to weigh up the best route and discuss this with the Part 21 and the regulatory authority. In the case of an in-flight FRS system, given the complexity of the equipment, the likely use of a class 4 laser and the number of flights that may be required to satisfy the research output, it is likely that an STC is the best route. The only exception to this situation is if the aircraft is under an experimental category, which may then allow permit only operation, but again with more limitations than a certified in-flight system.

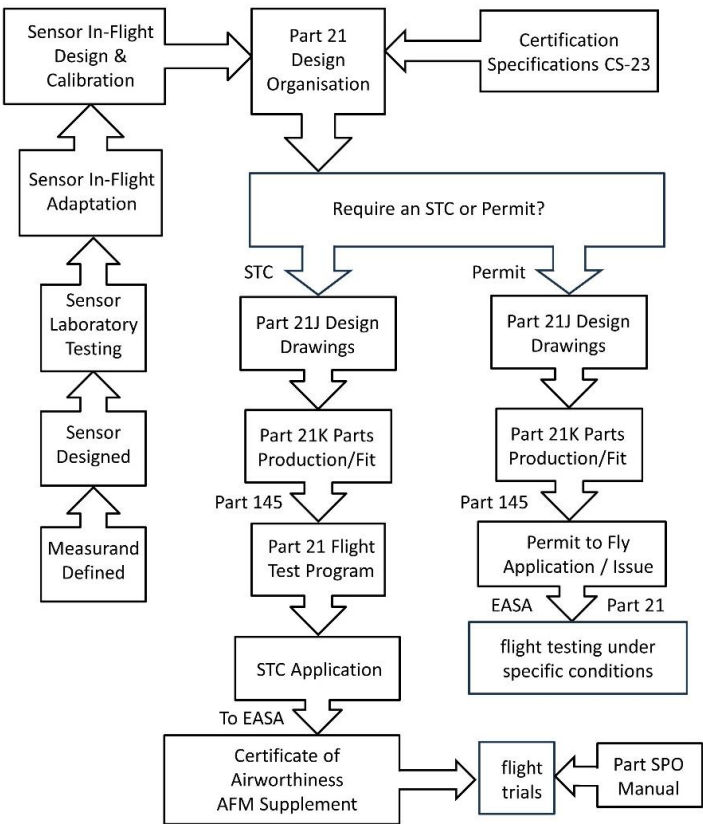


Figure 2: Regulatory process leading to the flight testing of equipment.

4. Conclusions

This paper has reviewed a pathway to FRS in-flight measurement of a complex engine intake configuration. To apply this technique, both technical and regulatory challenges will need to be overcome, with the greatest technical challenge, the implementation of the fibre optic image and light sheet delivery systems, in a set-up which provides a stable set-up in the EMI and vibration of an in-flight environment. The main contribute of this paper to outline a clear and timely pathway for the adoption of Filtered Rayleigh Scattering in in-flight flow diagnostics. By focusing on the conceptual framework, technical considerations, and regulatory context, this paper complements the recent full-length publication and provides forward-looking perspectives that can guide subsequent detailed investigations and experimental efforts. This leverages the novelty of Filtered Rayleigh Scattering as a turnkey diagnostic tool for multi-quantity flow distortion. The potential impact of this study is the reduction of distortion-related propulsion risks in the development phase of novel aircraft configurations.

Competing interest statement

All authors declare that have no competing financial, professional, or personal interests that might have influenced the performance or presentation of the work described in this manuscript.

Ethics statement

No statement required.

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Data availability statement

No new data were created or analysed during this study. Data sharing is not applicable to this article.

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