Modernization of DLR's L2F System Featuring an Air-Cooled Optical Probe Design

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Abstract:

A new optical probe for the well-established Laser-2-Focus (L2F) system at the German Aerospace Center (DLR) has been designed for velocity measurements in the demanding conditions of the DLR's Next Generation Turbine Test Facility (NG-Turb). The new design enables L2F measurements in the vicinity of the turbine's first stage rotor while traversing radially and circumferentially through the test rig's annular space. The optical probe was tested at a free jet flow and featured adequate signal rates and amplitudes. Moreover, the implementation of diode lasers, silicon-based light detectors, and FPGA-based electronics are evaluated. The technological progress in the development of these devices open up new opportunities for enhancing, miniaturizing and simplifying the L2F system's architecture. Accordingly, a new four-color laser system was successfully implemented in the existing L2F system at DLR. Currently, a compact FPGA-based time-to-digital-converter (TDC) is tested and a new software to control the data acquisition is under development. Besides, a supplementary post-processing data evaluation routine enables a more flexible data analysis. The use of silicon photomultipliers (SiPMs) as a replacement of the old photomultipliers (PMTs) will be tested in the near future.

Working Principle of the DLR's L2F System

The goal of experimental investigations of turbomachinery components is to provide a comprehensive image of the flow conditions as well as comparative data for complex flow simulations and design studies. For this purpose, compressor or turbine test rigs are commonly extensively instrumented. Optical measurement techniques have the major advantage of capturing flow field information without physical contact preventing a disturbance of the flow at the measuring point. Furthermore, they can be used to measure in places that cannot be reached by conventional probe measurement technology, for instance in the vicinity of rotating

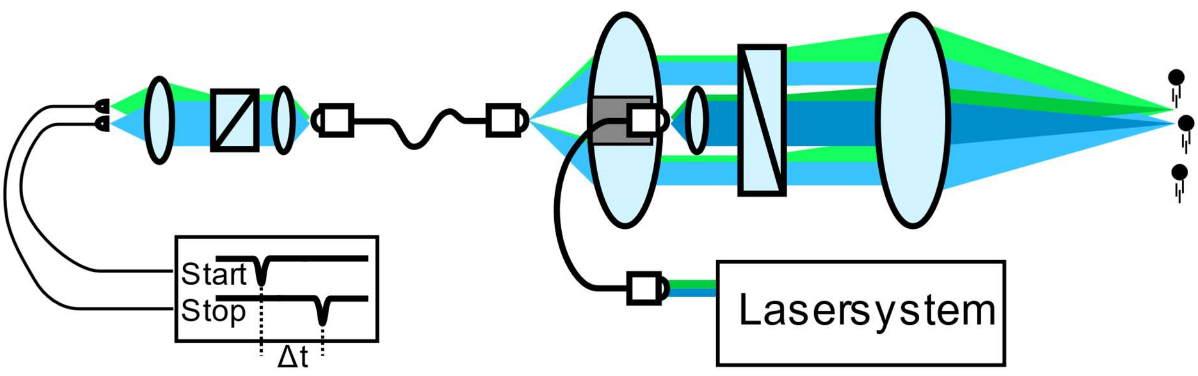

Figure 1: Schematic setup of Two-Color L2F.

components. Nevertheless, the available installation space must be considered, especially due to the diverse requirements of optical measurement techniques.

The Laser-2-Focus (L2F) method was originally developed at DLR's Institute of Propulsion Technology by Schodl [1,2]. L2F is beneficial to measure flow velocities in turbomachinery because the scattered light signals used to measure the flow velocity are detected in reverse direction such that only a single optical access is required. As depicted in figure 1, two laser light beams are guided through an optical fiber to the L2F's front head. The front head's optical setup splits up the laser light in two separated sub beams. This is realized via an Amici prism that spatially separates the initially superimposed laser light beams of different wavelength. These laser light beams are focused into the measuring volume (resembling a photoelectric timing device). The light is scattered by small tracer particles traveling at the speed of the surrounding medium. A significant part of this scattered light is captured by the focusing lens which also acts as part of the receiver optics. The same Amici prism then superimposes the received light. That way, the back-scattered light can be guided through another optical fiber until it reaches the light separation unit. Here, the light is spatially separated again by another Amici prism in order to differentiate the start and stop light pulses and transmit each pulse on a detector, where electric signals are produced. The light separation and detector unit is separated from the actual L2F's front head to keep it as compact as possible. This facilitates positioning the L2F's front head close to a turbomachinery test rig or flow channel since installation space is usually highly limited.

Knowing the spatial distance of the focused laser light beams the time difference of the detected start and stop pulses (Time-of-Flight, ToF) yields the speed of the tracer particles in the plane orthogonal to the observation axis. By statistical analysis of the recorded ToF signals the mean velocity (and its statistical distribution) can be derived. Using a stepwise rotation of the prism and thereby the laser foci while analyzing the relative number of start-stop-pairs, the direction of the flow (and its statistical distribution) can be deduced. A detailed analysis of the statistical quantities allows the estimation of the flow turbulence as well.

Since its development and its first implementation in the early 1970s the L2F-method has enabled investigation of flow properties in a wide range of applications [3,4,5,6,7,8]. This was realized by continuous improvements of the existing L2F system by the DLR in cooperation with commercial further development. A successful combination of the L2F-method with Doppler-measurements has been designed to gain information on all three components of the flow velocity while maintaining the compact design of the system [3].

Implementation of Modern Laser Systems

The ongoing development in the field of lasers has facilitated the replacement of the previously used Argon-Ion-laser-system. This laser system was capable of emitting laser light with a wavelength of 476 nm, 488 nm, 496 nm and 514 nm. Today's new solid-state-laser-systems are way more compact, do not need a complex cooling system and are easier to maintain as very little maintenance as well as realignment is required. Besides, solid-state-laser-systems reduce the requirements for setup space, power consumption and shielding against the adverse conditions typical for turbomachinery component testing rigs. Moreover, the measurement system becomes more versatile as solid-state-lasers can be separately adjusted in power and modulated with frequencies in the realm of typical rotor blade frequencies. Nevertheless, disadvantages of these compact laser diodes such as the usually higher bandwidth and the commonly lower laser light power have to be considered. The new laser system used for L2F measurements in the DLR consists of three separate solid-state lasers

(LaserBoxx) manufactured by Oxxius operating at 488 nm, 505 nm and 515 nm whose beams are superimposed via dichroic mirrors. The specified maximum laser light power is 200 mW, 70 mW and 150 mW, respectively. In addition, a laser light beam at 532 nm generated by a high-power CW fiber laser by AzurLight Systems is also superimposed. Being fully remote-controlled the new laser system can be implemented in setups with high technology readiness level (TRL) where strict safety precautions are prescribed. By the selection of a certain pair of laser foci a suitable spatial separation of the foci lowers the measurement time at high turbulence levels. Moreover, a wise selection of the focus separation may decrease the measurement error of flow turbulence, which is relevant to resolve low turbulence levels.

The 532 nm laser system can be frequency-stabilized which enables performing combined L2F-Doppler-measurements. The additional Doppler measurements resolve the velocity component in the propagation direction of the 532 nm laser light beam by analyzing the Doppler shift of the light scattering generated by the particles passing the 532 nm focus. Combining this velocity component with the two-dimensional L2F data allows the determination of all three-dimensional velocity components [3].

Updating the Measurement Electronics (incl. Software)

Recently, the parallel development of modern electronic controls and digital electronic data processing systems enabled the replacement of the purpose-build analog electronics with more precise and still flexibly configurable of-the-shelf electronic components. The use of these devices enables the L2F data acquisition to be more specifically tuned to the expected parameters (e.g. velocity range) and a more detailed analysis of the obtained data in post-processing routines. The most challenging factor for the replacement of electronic components in the L2F measurement system is the high level of integration in the old system resulting from its long-time development and optimization.

The heart of the new measurement electronics is a compact (2-unit-NIM) FPGA-based time-to-digital-converter (TDC) by Surface Concept. This device is capable of recording time-stamps of pulses on up to eight inputs with a digital time bin resolution of 82.3 ps and 40 MHz internal measurement rate. This is in great contrast to the old electronics consisting of a time-to-analog-converter (TAC) and a multi-channel-analyzer sorting the measured ToF into one of 256 channels with a priory chosen fixed maximum ToF. Accordingly, the time resolution of the new system is much higher than the old system which lowers the L2F measurement uncertainty. Besides, the maximum ToF is chosen automatically as a cut-off. Hence, the resolution of recorded ToF data can be chosen more flexibly for the subsequent statistical analysis.

In addition to the improved signal handling and remote-control capabilities of the new measurement electronics, the compact design is of great advantage compared to the former heavy control and data acquisition system built in a high-board 19" rack. The miniaturization of the entire L2F system is one focus of the new development to achieve better handling and reduced setup dimensions in the usually limited space in the vicinity of turbomachinery testing facilities.

A new control and post processing software is currently under development to take full advantage of the new electronics functionality. The new software controls the data acquisition, analyses the recorded ToF in quasi-real time, controls the step motor to rotate the focal plane and records trigger signals to allow a subsequent synchronization with test rig data. A prototype graphical user interface (GUI) could already be successfully tested in a lab-scale environment.

Furthermore, new post-processing software allows a more thorough re-evaluation of the ToF data of the two selected foci with respect to the aforementioned quantities, e.g. by applying more sophisticated noise models when fitting the data.

Replacing PMTs by Solid-State-Detectors

A further step in modernization is the replacement of the ageing photomultipliers with modern silicon-based detectors (silicon photomultipliers, SiPMs). Since regular photomultipliers require high-voltage power supply and comparably big installation space, SiPMs are advantageous, particularly for the development of a miniaturized L2F system. Moreover, SiPMs can handle overexposure much better than PMTs. Thus, SiPMs do not have to be intricately gated when laser light is reflected at moving rotor blades. This behavior facilitates the design of a L2F system to measure the flow velocity in the vicinity of a turbomachinery rotor. Nevertheless, SiPMs feature a higher dark count rate and have to be carefully chosen to match the light frequency of the L2F system to their designed wavelength spectrum. In the past other solid-state detectors such as avalanche photodiodes have been already applied for L2F using laser light in the near-infrared range [4,8]. A well-considered selection of silicon-based detectors considering the wavelength spectrum of the laser system is currently in progress.

New Optical Probe (Application and Design)

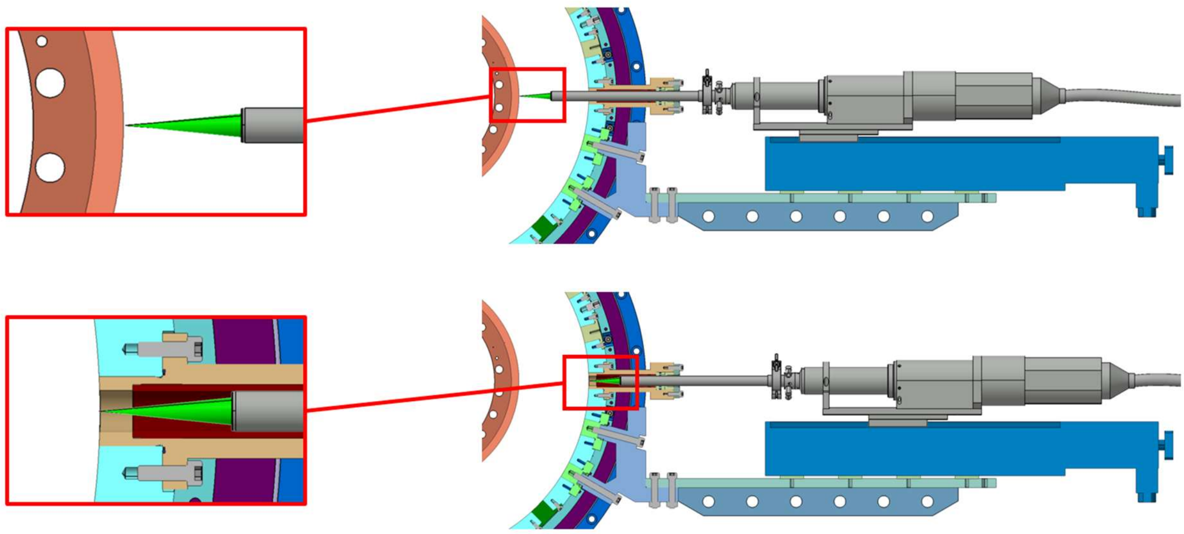

Figure 2: Sectional view of the L2F system's CAD model for implementation of the L2F in a turbine rig. Traversing unit enables radial traversing of the L2F measurement volume over entire channel height. Rotation of outer casing ring allows circumferential traversing of the entire L2F front head.

As a part of the miniaturization process, a new optical probe for the already existing L2F system was developed. The decision for a new design was driven by the planned L2F-application at DLR's Next Generation Turbine Test Facility (NG-Turb). The objective of the implementation of L2F was to characterize the flow field closely upstream of the first rotor stage of the two-stage turbine test rig. Due to the very complex instrumentation of the rig, there was fairly limited space for an optical access contiguous to the rotor stage. Thus, the outer diameter of the new probe-type focusing and receiving optics was limited to 16 mm in diameter. In order to measure a radial traverse along the full flow channel height, more precisely from hub to tip, the probe's head could be inserted into the rig and moved along the channel height. Figure 2 shows the planned installation of the L2F system at the test rig. The L2F front head is set on a traversing unit which is installed on a rigid support to mount the entire system to the test rig's outer casing. The two images depicted in figure 2 show two radial positions of the new optical probe: an inner measurement position where the focus point is located close to the flow channel's hub and an outer position at its tip, respectively. Moreover, the outer casing ring including the L2F system can be rotated within a maximum angular range of $\Delta\varphi$ = 33°. Accordingly, L2F measurements can be performed along several radial traverses at different circumferential positions resolving a two-dimensional velocity field in the measurement plane.

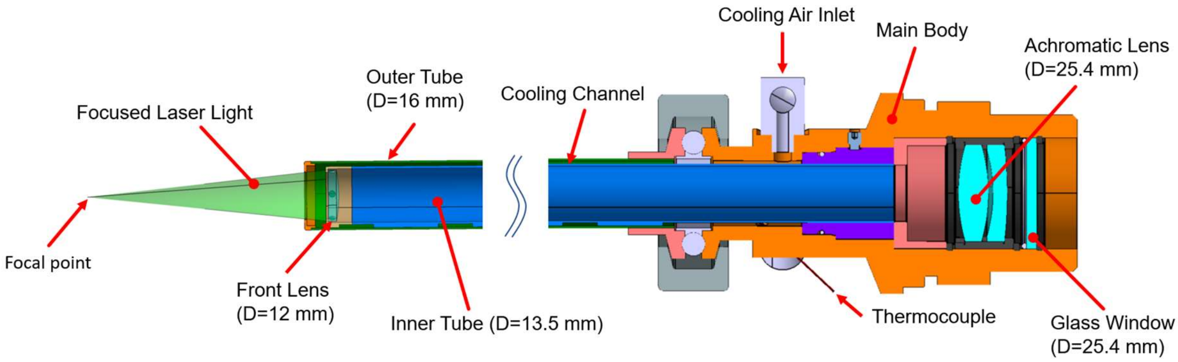

Figure 3: Sectional view of the new L2F optical probe's CAD model for implementation of the L2F in a turbine rig.

The optical probe has to withstand operating temperatures up to T = 250 °C and pressures up to p = 2 bar in the given turbine test rig. Thus, a cooling approach is required in order to prevent the glued connection of the L2F optics from any damage. Based on the design of an inhouse development used for light sheet probes [9], the new L2F probe is built of two concentric tubes as shown in figure 3. The restricted design space leads to a construction with minimal wall thickness (0.5 mm) of the outer tube. While the inner tube carries the front lens with a diameter of 12 mm, the outer tube is used to form a narrow cooling channel, where pressurized air is guided through. This cooling air is injected at three inlet ports evenly distributed around the circumference. It limits the temperature of the gluing point of the front lens and prevents a lens contamination by dust or tracer particles. The front lens is positioned at the tip of the inner tube and focuses the laser light collimated by the achromatic lens in the rear. The generated laser light beams converge in its wavelength-dependent focal points which span the L2F measurement volume. Two thermocouples can be installed in the probe's head to monitor the temperature close to the gluing point of the front lens. A loss of the front lens has to be avoided at all costs, since a foreign object damage of the test rig's stator and rotor blades might have hazardous consequences. Hence, the front lens is installed with positive locking preventing the loss of the lens even if its glue fails. In case of a lens breakage or leakage at the gluing point, hot air would flow from the NG-Turb's flow channel to the L2F's optics or even optical fibers in the rear of the front head. In order to prevent irreversible damage of the front head, the system must be protected from hot leaking air in any case. Therefore, a glass window and additional seals are installed closely behind the achromatic lens.

New Optical Probe (Manufacture and Testing)

The new optical probe is manufactured at DLR's in-house Systemhaus Technik (SHT). After its manufacture and assembly, the beam separation and focus size of the new optical probe in the measurement volume were determined by the knife edge method. The beam separation plays an important role in determining the minimum turbulence level of the flow that can be measured by the system and contributes to the systematic L2F measurement uncertainty as well. Mainly, the L2F measurement uncertainty is defined by the focus size of the laser light beams, the time resolution of the electronics and the measurement error of the beam separation. Hence, it is crucial to know these quantities as precisely as possible to lower the overall measurement uncertainty. The DLR's L2F system enables the selection between four wavelengths, which results in several color permutations each resulting in a pair of two laser foci with a well-known beam separation. The resulting beam separation of the new optical probe can be derived by the following figure.

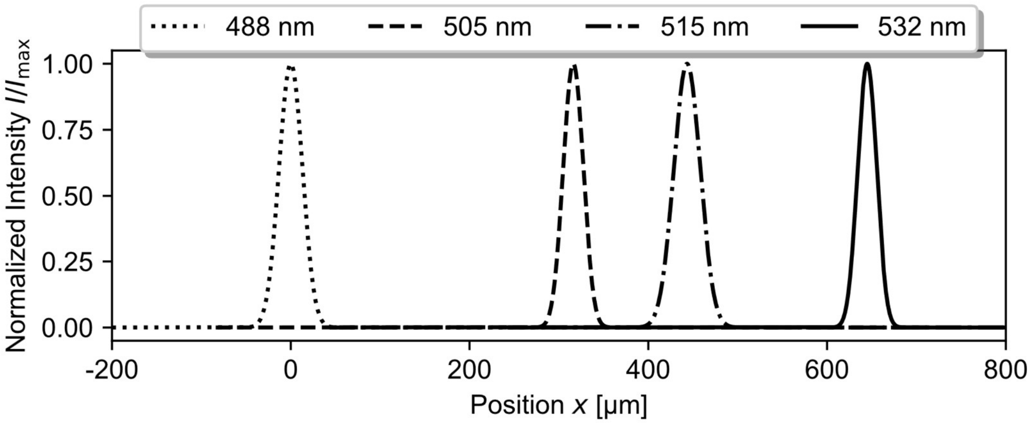

Figure 4: Normalized intensity profiles of the four laser beams determined by measuring the integrated laser power with the knife edge method.

Figure 4 shows the normalized intensity profiles of the four laser light beams superimposed in a single plot. First, the integrated laser power profiles of the laser light beams along the x axis are measured by applying the knife edge method. Hereafter, the integrated power profiles are fitted by a modified Gauss error function and subsequently numerically differentiated to plot the normalized intensity profiles. A closer look at figure 4 shows that the highest beam separation can be achieved by choosing the laser combination 488 nm and 532 nm. As a fairly low turbulence level of about 2 % is expected in the measurement area in

Wavelength Permutation [nm]	488-532	488-515	505-515	505-532
Focus Separation [µm]	645	443.4	127.3	328.9

Table 1: Focus separation of the new L2F setup for different wavelength permutations.

the NG-Turb, the highest possible focus separation would be selected for the L2F measurements to lower the turbulence detection threshold of the system. Table 1 gives an overview of the measured focus separation. According to these values the ToFs for the L2F measurement plane in the NG-Turb test rig can be estimated. The expected mean flow velocity is $\bar{v}$ = 15.4 m/s (derived from numerical simulation of the addressed flow section), hence the ToF is between 8 µs and 42 µs.

After optimizing the L2F front head's optical fiber adjustment to the optical setup of the new optical probe, the system was successfully tested in a lab-scale environment at a free jet flow. That flow is analytically well-known and hence commonly used as a reference flow case. Figure 5 illustrates a recorded L2F start and stop pulse from which the flow velocity of the free flow jet can be determined. The oscilloscope recording shows adequate amplitudes while the L2F

GALA e.V., Karlsruhe, Germany, ISBN 978-3-9827594-0-1

electronics measured high signal rates. Thus, the new setup features a high signal-to-noise ratio (SNR) as well as a low measurement time (for a sufficiently dense tracer particle concentration) at a free jet flow. Since the tracer particle concentration as well as the background noise (reflections on metal surfaces, e.g. flow channel walls) highly effect the measurement time and SNR, the system might behave differently measuring the flow velocity at the NG-Turb. In addition, figure 5 shows a two-dimensional Gaussian distribution of the number of events *N* plotted over the ToF and L2F angle α. This plot represents the L2F measurement results after performing an angle traverse by rotating the front head’s Amici prism over a symmetrical angle range $\alpha_0 \pm \Delta\alpha$, where α_0 represents the L2F central angle.

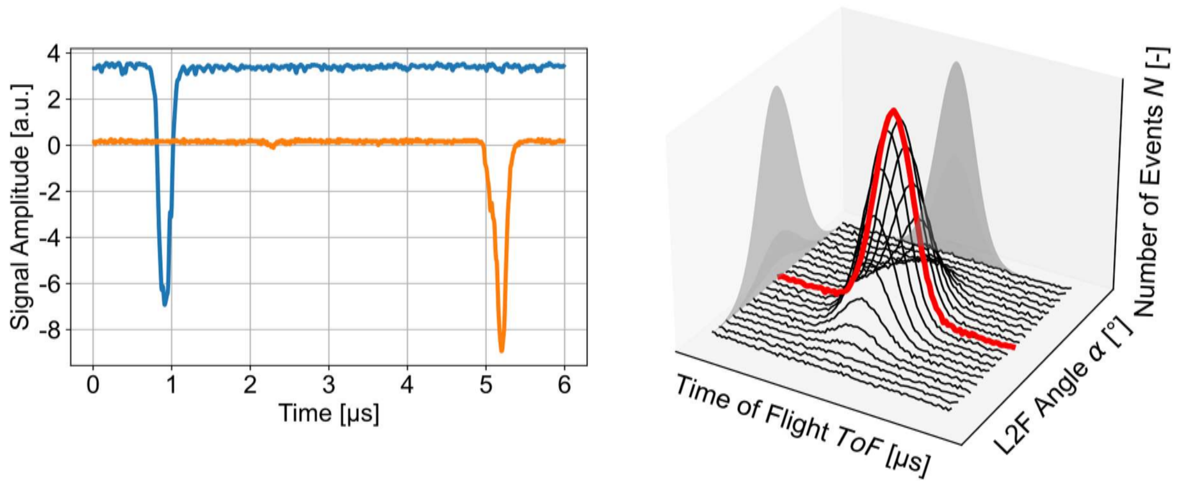

Figure 5: Oscilloscope recording of L2F start and stop pulse at the free flow jet (left). Two-dimensional Gaussian distribution of the number of events plotted over the ToF and L2F angle $\boldsymbol{\alpha}$ (right).

Conclusion

The modernization of the DLR’s L2F system is currently in progress. The implementation of new diode lasers was successfully realized. The new FPGA-based TDC was tested and enables new possibilities to handle ToF data. A new control and evaluation software are under development to achieve a more user-friendly and agile operation as well as flexible data evaluation routines. Moreover, SiPMs were evaluated replacing the still used PMTs and will be tested in the near future. As a part of the miniaturization process, a new optical probe was designed to perform L2F measurements at the DLR’s NG-Turb. After manufacturing, assembling and adjusting the optics the L2F system was tested at a free jet flow. The L2F system showed adequate signal rates and amplitudes. As a next research step, the application of the new optical probe to measure the velocity at the NG-Turb is targeted.

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