In-flight boundary layer investigations on a Airplane Wing using LDA measuring techniques

by

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ABSTRACT

Research and development work in aircraft aerodynamics to date has been heavily based upon wind tunnel investigations, even though it is known that the test facilities employed impose severe limitations concerning directly applicable design information. For instance, results of wind tunnel studies yielding design parameters for laminar wings have to be verified by flight experiments. This task requires advanced measuring techniques that are nonintrusive and reliable in the harsh environment of flight. Several techniques have been developed in past years for transition detection, e.g., hot film arrays, piezo foils, and infrared cameras. Nevertheless, all of these techniques are only capable of acquiring information directly on the wing surface.

Laser Doppler Anemometry (LDA), in contrary, can provide insight into the complete boundary layer and the surrounding velocity field. However, typical LDA instrumentation does not perform adequately in the environment of in-flight testing. In the present paper the development of a dedicated system for in-flight LDA measurements is outlined. Starting from basic design considerations it finally is shown that LDA is well suited for providing the desired local velocity information, but must be specifically adapted for the various spatial, geometrical, and power constraints imposed by the test aircraft. Laboratory and in-flight measurements studying boundary layer transition on an airplane wing downstream of an excitation source were successfully carried out and a summary of results is presented. Finally, suggestions for further advancements of LDA systems are proposed.

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Fig. 1 Velocity distribution in the laminar boundary layer of the wing glove acqired during inflight tests with the test aircraft GROB 109B

1. INTRODUCTION

Already nowadays the economical success of commercial transport aircrafts is strongly connected to the direct operating costs (DOC) and this will be even more so in the future. From an aerodynamic point of view, the most promising potential for reducing these costs, through a noticeable reduction of the fuel consumption, can be expected from a noticeable reduction of the drag of the aircraft by keeping the boundary layer laminar over most of the aircraft surface This may be achieved by suitable passive or active measures to suppress the laminar to turbulent transition of the flow, i.e. to delay or counteract the Tollmien-Schlichting instability of the boundary layer, the leading edge instability, or the cross flow instability. It is estimated that a laminar wing design will result in a reduction of fuel consumption of the aircraft of up to 15 – 20 %. In addition to the economic aspect by directly influencing the direct operating costs, the reduction of the aircraft drag and, hence, the fuel consumption simultaneously will reduce the environmental impact of commercial transport aircrafts. Thus, a reduction of NO_x and CO_x etc. emissions could be achieved by flow laminarization.

Because of the above mentioned advantages, increased efforts in aerodynamic research and development are presently being observed in connection with the development of the laminar wing technology for commercial aeroplanes. University and governmental research institutes, as well as R&D departments of civil aeroplane companies, are involved in these research efforts and employ experimental and numerical techniques to advance the present understanding of methods of delaying the laminar to turbulent transition and to consider passiv and/or active means of flow laminarisation. But still, reliable methods to predict boundary layer transition are not yet available for realistic flight environments, and the identification and quantification of the relevant parameters, like pressure gradient, wing geometry, surface curvature, sweep angle, Mach number, heat and mass transfer at the surface, etc. are far from being complete. Furthermore, in the studies of laminar to turbulent transition, individual wind tunnels inherently introduce their own specific spectrum of flow disturbances and hence, their transition data can be effected by ‘wind tunnel noise’. Therefore, results of wind tunnel studies aimed to yield design parameters for laminar wings have to be verified by flight experiments. For this task there is a pronounced need for advanced measuring techniques that are nonintrusive and reliable in the harsh environment of flight. Several techniques have been developed in past years, e.g., hot film arrays, piezo foils, and infra red cameras for transition detection. But all of these techniques are only capable of acquiring information directly on the wall surface, whereas LDA shows good prospects for this task and may give an insight into the complete boundary layer and the surrounding flow velocity field. However, typical LDA instrumentation does not perform adequately in the environment of in-flight testing and special optical and electronic systems are required.

Development work along this line has been carried out at the author’s laboratory and has resulted in a first approach LDA optical system using an integral probe design with a semiconductor laser diode as the light source, a semiconductor photo detector and which operated in direct backscatter arrangement (Durst, Lienhart and Müller, 1992). This LDA system design proved to be reliable and stable, and maintained optical and mechanical alignment at free flight conditions. The experience gained during the in-flight measurements with this LDA design can be summarized as follows:

- local velocity measurements in the flow surrounding a flying aircraft were feasible, however, the data rate in tests performed in the free atmosphere without any hazes or clouds was quite low and not sufficient for some desired studies, e.g. for spectral analytical studies of Tollmien-Schlichting instabilities, and
- it was concluded that this difficulty resulted from the low concentration of aerosols of diameters bigger than about 1 - 2 µm in the atmosphere that were needed as scattering particles.

The completely revised system described in the present paper was therefore designed and developed with the aim to maximise the scattered signal power of aerosol particles that are present in the atmosphere at high numbers but that are of very small diameter. This was achieved by checking all design features and components for prospect advantages in this respect and to limit the inevitable compromises that had to be accepted. The application of the developed LDA system together with a commercially available LDA signal processor was demonstrated for laboratory and in-flight local velocity measurements and some examplary results are presented in the following paragraphs.

2. DESIGN CONSIDERATIONS OF THE IN-FLIGHT LDA-SYSTEM

2.1 Test Aircraft

From the very beginning of the design of the in-flight LDA systems, the space and weight limitations of the research aircraft to be employed had to be kept in mind. The test airplane for the flight campaigns of the present studies is shown in Fig. 2. It consisted of a GROB 109B, a two seated powered sailplane equiped with a ‘wing glove’ on its starboard wing and a flight control system on the port wing. The size and the design of the plane imposed very stringent restrictions on weight and space available to the optical and electronic components, as well as on the power consumption of the measuring system. This situation, in turn, resulted in very special design requirements for the LDA optics and electronics; these requirements strongly influenced the development work described below. To some extend the LDA systems developed were designed to match the particular demands of the aeroplane used for in-flight measurements. Nevertheless, the instrumentation shows design features that are of general validity to all similar applications.

Fig 2 Test aircraft GROB 109B during in-flight tests

2.2 Scattering Particles

In order to not disturb the extremly sensitive transitional flow in the boundary layer it was obvious from the very beginning of the study that no artficial seeding of the air was feasible. Therefore, the only source of scattering particles needed for LDA were the aerosols occuring in the atmosphere. In the lowest atmospheric layer, the troposphere, which reaches up to about 10 km in height, the aerosols originate from natural and man made sources, as well. The actual composition depends on weather and geography, therefore there is no standard size distribution available. Depending on their origins and their behaviour three distinct classes of particles can be identified (Fig. 3). The particles forming the smallest fraction in size are the condensation seeds that range up to about 0.1 µm in diameter, the agglomerations that are built up from these condensation seeds are in the interesting diameter range of 0.1 – 2 µm.

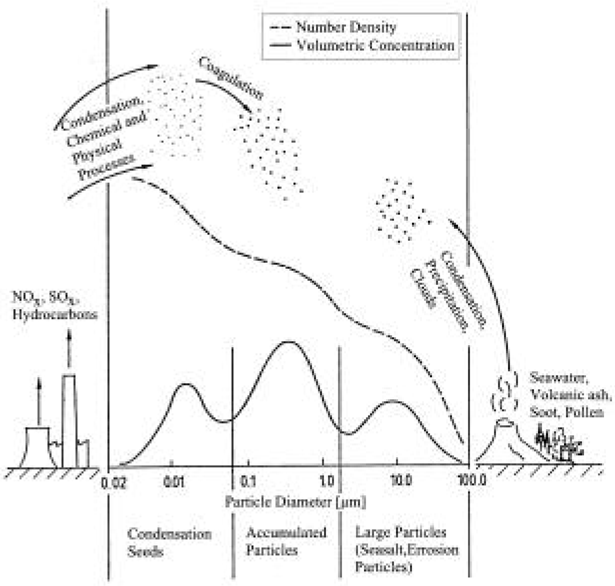

Fig. 3 Origin and size distribution of atmospheric particles

In order to verify the above quoted information on the diameter distribution of natural aerosols in the atmosphere for the actual test flight conditions the particle concentration was investigated using a cascade impactor. In Fig. 4 a particle diameter distribution measured during flight tests is presented. The results showed a very steep increase of concentration for particles of very small size. Therefore the conclusion was clear that, in the absence of artificial seeding, the data rate could only be improved if one succeeded in detecting signals from particles of diameters less than aproximately 1 µm, which was about the limit for the semiconductor LDA probe.

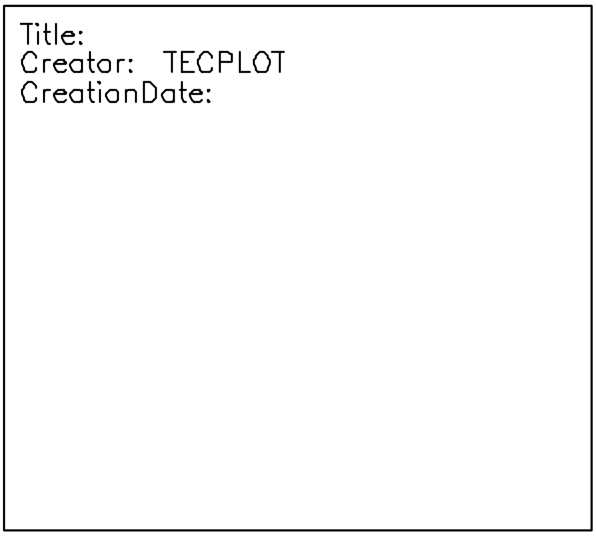

Fig. 4 Measured particle size distribution in the atmosphere

2.3 Optical Layout

The above findings led to the development of a specially adapted LDA system. The emphasis of the design was to maximize the measured signal generated by extremely small particles. To this end, all design parameters influencing the scattered light intensity were analysed using the theory of light scattering by small particles (Naqwi and Durst, 1991). As sketched in Fig. 5 the system finally featured a laser diode-pumped frequency-doubled Nd-YAG laser, which provided higher light power at a shorter wave length, when compared to the semiconductor laser used in the first design, while still having low electrical power consumption. The power of scattered light for very small particles is governed by Rayleigh's law and varies with the fourth power of particle diameter divided by wave length (d_p/l). Replacing the semiconductor laser (l = 830 nm) by a frequency-doubled Nd-YAG-laser (l = 532nm) resulted in an increase of about a factor of six in scattered light power. The output power available with the Nd-YAG laser was about 400 mW, but since it was no longer possible to integrate the laser into the probe design, losses of about 40 % due to the fiber optic cable needed to be considered. This was more than compensated by the reduction of the beam waist diameter in the crossing volume. The final gain of light power transmitted into the measuring control volume was of a factor of about 12. A near forward scattering arrangement was adopted for the receiving optics, which was one major improvement and provided an additional one order of magnitude increase in signal power for the smallest particle size and about two orders for the larger ones. The over all gain of signal power as a function of particle diameter is shown in Fig. 6.

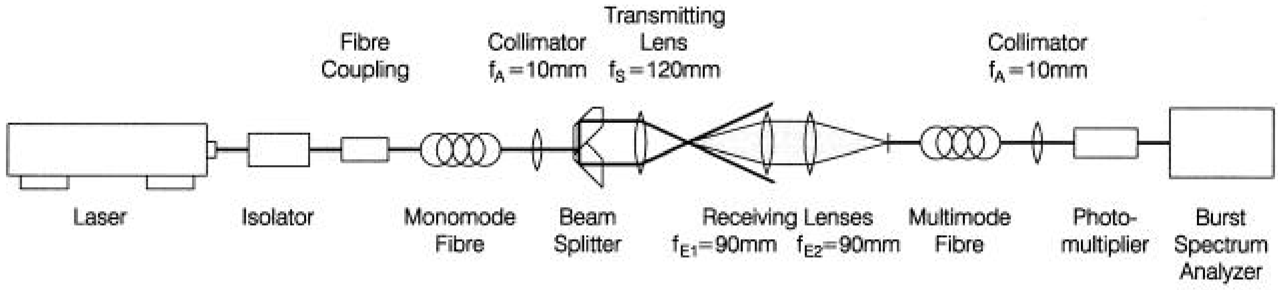

Fig. 5 Schematic view of the optical arrangement

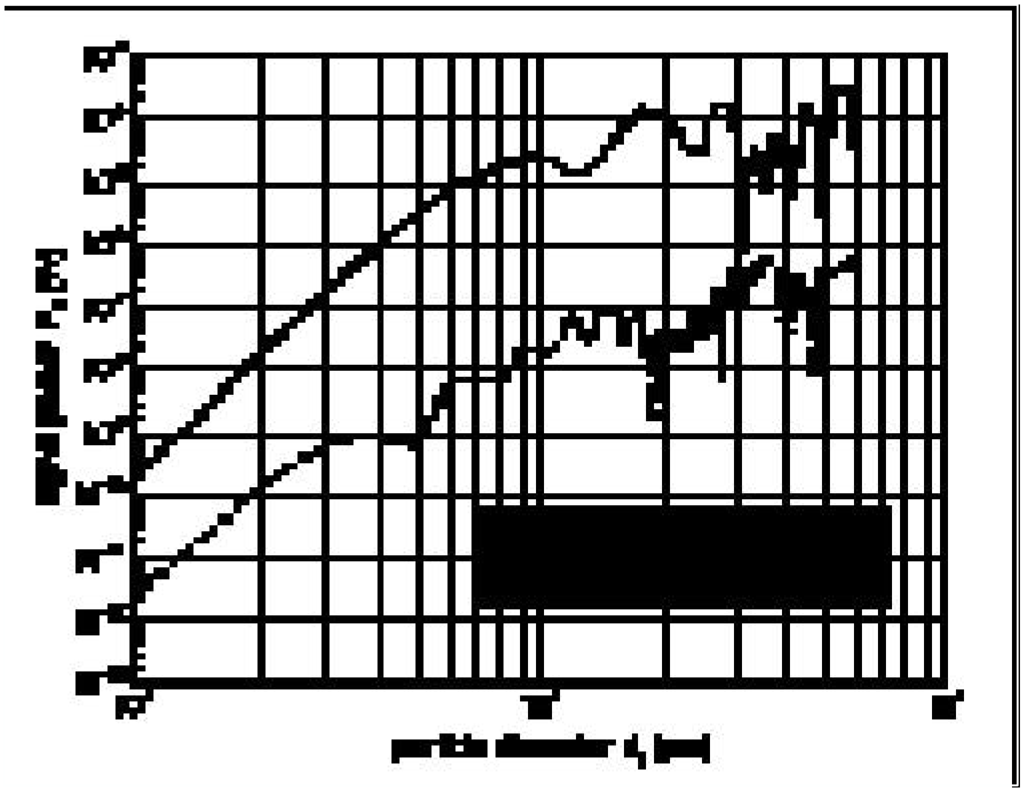

Fig. 6 Signal power calculated using Mie theory

All these constraints and findings resulted in a quite unconventional probe design. It employed the narrow gap between wing and wing glove for the optical components and the beam path was diverted twice by mirrors for both the transmitting and the receiving paths. The optical components consisted no longer of circular lenses etc. but were cut into narrow slices of an aperture of $6 \times 40\ mm^2$. As sketched in Fig. 7 all optics apart from the upper mirrors were placed underneath the wing glove surface and only these mirrors are protruding. Therefore, the distortion of the flow induced by the measuring system was minimal. The optics were mounted on a traversing mechanism that allowed automated measurements of boundary layer profiles. The compact design of the probe, the integral machining of its mechanical structure from titanium, and the way it is clamped to the wing glove ensured mechanical and optical stability and, thus, prevented misalignment during flight experiments due to vibration, bending of the wing, and stresses due to changes in temperature.

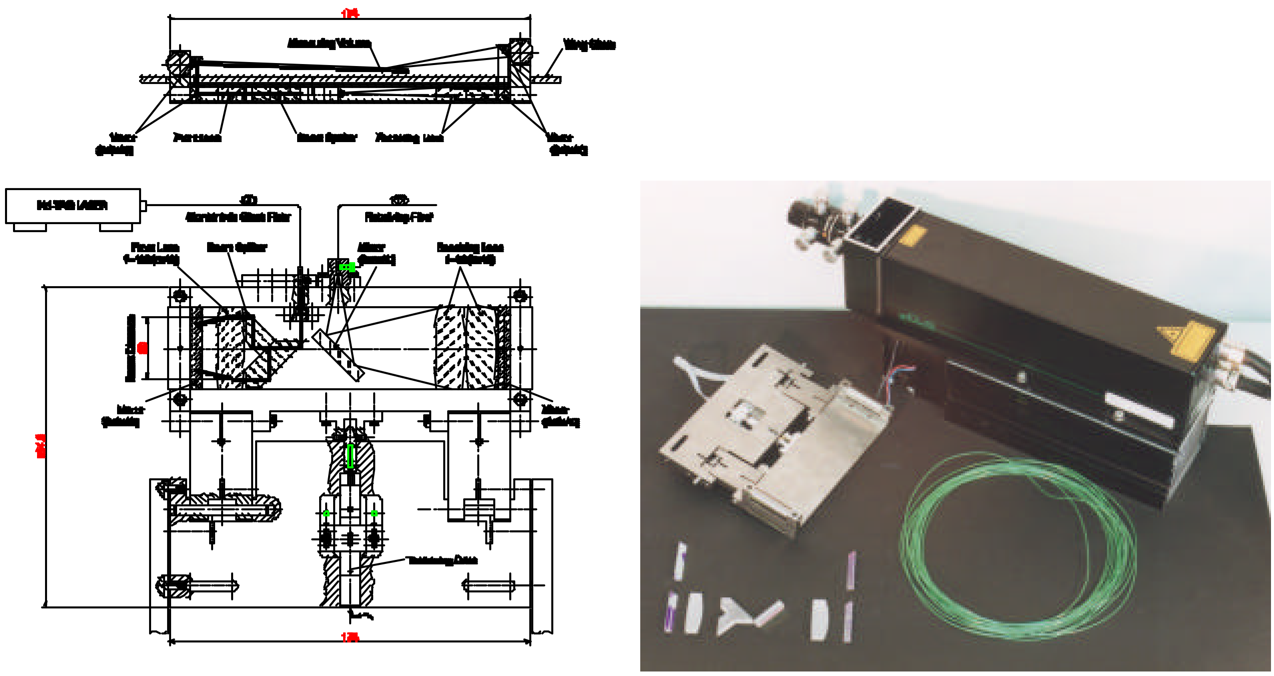

Fig. 7 Optical design of the LDA measurement system

2.4. Arrangement of Instrumentation in the Test Aircraft

For completion of the measuring system the laser light source, the photo multiplier, the power supplies, the signal acquisition and processing unit, and the traversing controller, had to be added. Fig. 8 shows an overview of the instrumentation distributed at different locations of the airplane. It indicates that the wing glove mounted on the starboard wing was equipped with the LDA probe, the traversing system, and the transition excitation source. The loud speaker driver for the excitation source and the controller for traversing were located in an underwing station. The laser, the photodetector and the signal processor (Burst Spectrum Analyzer – BSA) were mounted on the instrumentation platform behind the pilots' seats. The LDA probe was connected to the laser and the photodetector by monomode and multimode glass fibre cables, respectively. The port wing carried the flight data acquisition system of the test aircraft, which was described in detail by Erb, Ewald and Roth (1996). All systems were automatically controlled by the onboard computer in the cockpit. The computer ran the different programs in multitasking operation, in this way simultaneous data acquisition could be performed. The battery that powered the instrumentation allowed about 20 min of run time per flight.

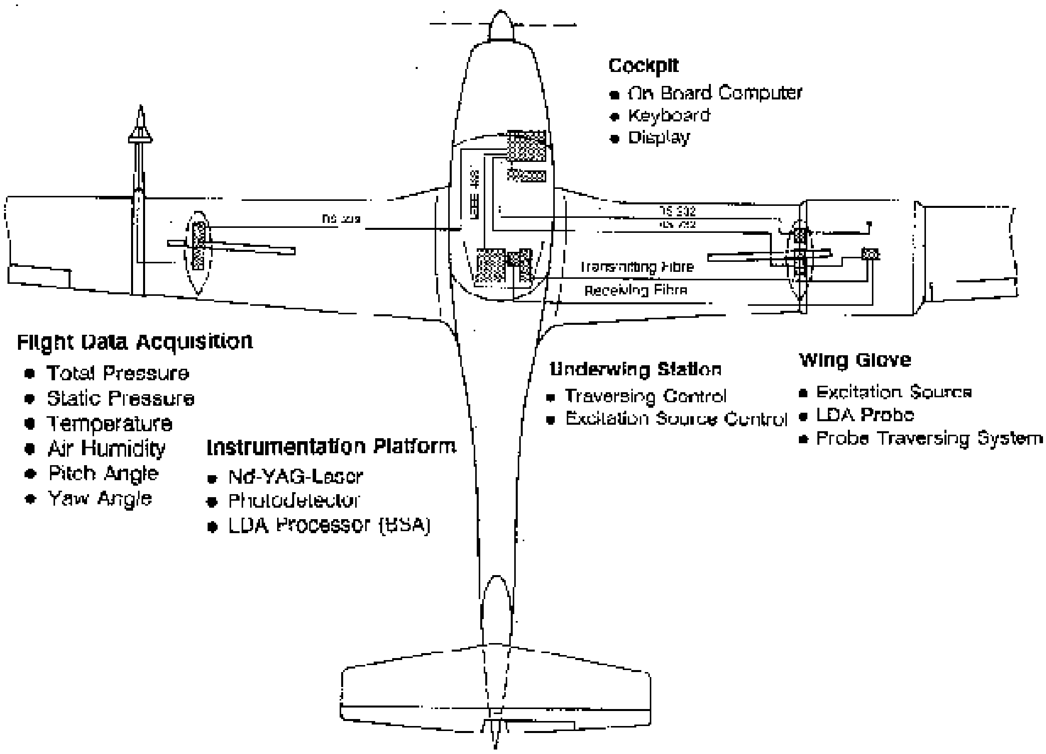

Fig. 8 Arrangement of instrumentation on the test aircraft

3. RESULTS OF IN-FLIGHT TESTS

3.1 Tests of measuring equipment

Before starting the in-flight experiments to study excited boundary layer transition the measuring equipment and the wing glove arrangement was tested in wind tunnel and in-flight tests. The alignment of the optical system proved to be extremely stable and was in no way affected by the aircraft vibrations and the significant temperature changes during the flights, as well. The rate of validated velocity data turned out to be approximately 150 Hz for clear atmospheric weather conditions and several kHz for hazy weather. Fig. 9 shows a typical time series and resulting probability density function. As the major atmospheric parameter influencing the validated data rate the humidity of the air was identified. Nevertheless, in all conditions sufficient data could be obtained during flight experiments to provide useful boundary layer information. Fig. 10 presents boundary layer profile measurements acquired during two different flights in an interval of several days. The reproductivity of the data is excellent as long as the flight conditions could be held constant, i. e. reliable data was gained during times of weak thermal activity in the atmosphere preferably during early morning hours.

Fig. 9 Time series and probability density function

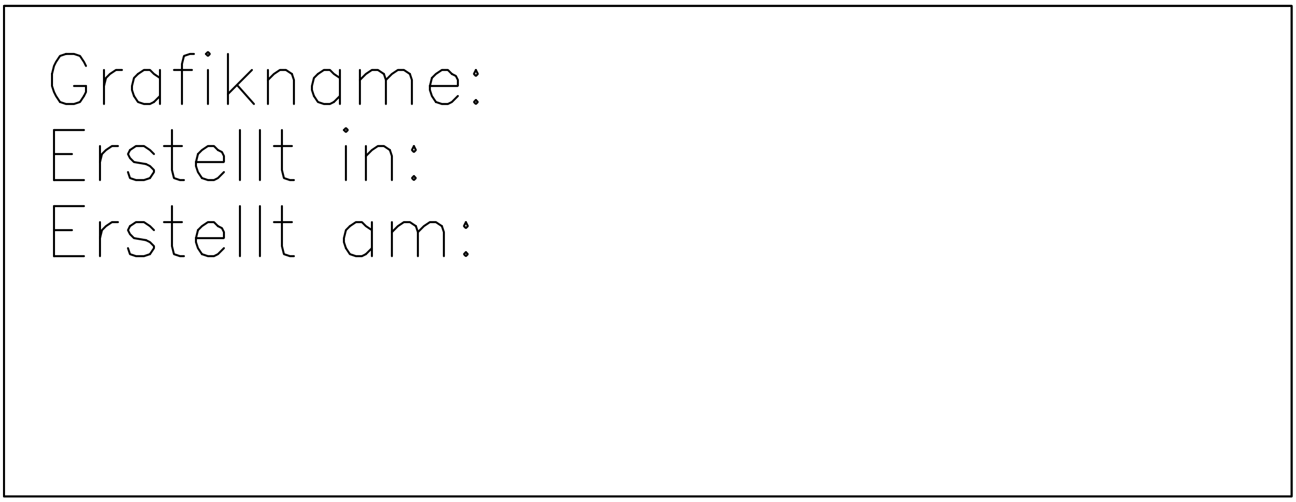

Fig. 10 Reproductivity test of boundary layer measurements

3.2 Transition measurements

Prior to the in-flight investigations the measuring system and the processing of the data were tested in wind tunnel experiments (e. g. Lienhart and Becker, 1994, Becker, Lienhart and Durst, 1999). In order to prove the performance of the LDA system to detect Tollmien-Schlichting waves an excitation source for introducing small flow disturbances into the boundary layer was installed in the test wing section. There were actually six sources along a span-wise line at 27 % of the chord length, each consisted of a small circles of holes of 0.3 mm diameter. These circles were connected to a loudspeaker driver mounted in the underwing station. The excitation frequency was set to 900 Hz that corresponded to the frequency of maximum amplification according to a stability computation. To map the span-wise velocity distribution of the boundary layer, the six circles were successively excited rather than traversing the LDA system.

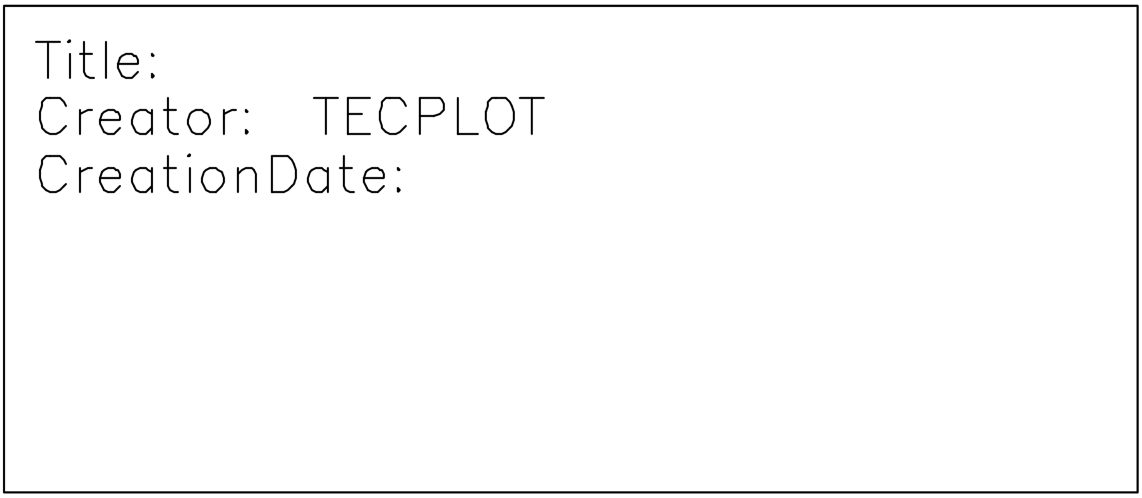

Fig. 11 Velocity distributions and turbulence intensities at different spanwise locations, without and with excitation

A measured boundary layer velocity profile without any excitation is presented in Fig. 11. It displays mean velocity distribution and turbulence intensity, as well. This measurement was taken in the boundary layer on the wing glove at a chord length position of 42.5 %. The position was chosen to be in the region of laminar flow. Some results of flight tests with a wave train introduced by the excitation source are added in Fig. 11. Whereas the influence of the wave train in the mean velocities could hardly be identified, the turbulence intensities were significantly increased with introduced excitation and showed the characteristic peaks of a transitional stage. There are profiles of mean velocity and turbulence intensity at different span-wise positions given. The highest increase of the turbulence intensity was observed at a distance of 20 mm from the symmetry plane. This corresponded to an angle of lateral growth of the disturbance of about 6° which is in good agreement to published data.

In favourable weather conditions data rates could be achieved that allowed a direct calculation of the power spectral density function from the velocity-time series via Fourier transformation. For lower data rates, amplitude and phase angle of the Tollmien-Schlichting wave at any location in the boundary layer were analyzed using harmonic analysis of the time series. Fig. 12 shows the amplitude of the Tollmien-Schlichting wave in comparison to the results of the Direct Numerical Simulation (DNS) carry out by Stemmer, Kloker and Wagner (1998). It shows remarkable good agreement with the numerical results in the location and the size of the peak turbulence intensities of the boundary layer, as well. There is poor agreement close to the wall, which probably is caused by starting three-dimensional deformations of the wave train at the measuring position that is located near to the end of the linear amplification regime.

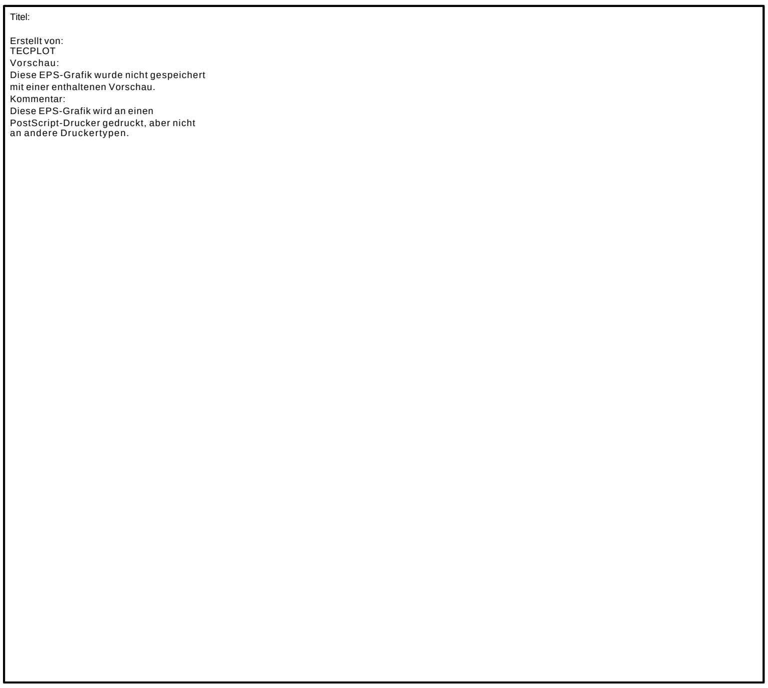

Fig. 12 Harmonic content of the velocity fluctuations

4. CONCLUDING REMARKS AND OUTLOOK

The present paper summarizes the development of an LDA optical system for in-flight applications that was optimized to be small, light, robust, and capable of detecting signals from very small scattering particles. It proved to perform very well under the rugged conditions and to be reliable and stable in long term test campaigns. The presented results of boundary layer studies give evidence of its capability to provide useful velocity data from flight tests not only in terms of mean velocity profiles but also in detecting subtle developments in the transitional boundary layer.

But there is still room for further work. Whereas the optical system design presented can be regarded as quite sophisticated, conventional LDA signal processing equipment was employed. Therefore, future work should concentrate on developing LDA electronic systems that are small in size, light in weight, and robust, so that they can be reliably operated under flight conditions. It should also aim for a reduction of power consumption of the electronic systems to permit long duration measurements in small airplanes of the kind employed in this research work.

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