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Laser Doppler Anemometer for In-Flight Velocity Measurements on Airplane Wings

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The development of laminar wing technology for commercial airplanes requires strategies that combine wind-tunnel investigations with numerical flow computations and in-flight measurements. One strategy is outlined; it is explained that instruments are needed to measure local flow velocities in wind tunnels as well as to carry out free flight experiments. It is shown that laser Doppler anemometry (LDA) is most suited to provide the required local velocity information, but special LDA systems need to be developed. Results of LDA system developments are summarized. This program yielded two optical units suitable for in-flight velocity measurements on airplane wings. Laboratory and free flight measurements were successfully carried out with the LDA systems developed, and a summary of results is presented. Applications to laminar wing design are indicated. Suggestions for further advancements of the LDA systems are presented.

Nomenclature

C = concentration, mm^{-3}
c = chord length of the wing, mm
d_M = diameter of the measuring volume, μm
d_P = particle diameter, μm
f = frequency, Hz
f_A = focal length of fiber coupling lens, mm
f_E = focal length of receiving lens, mm
f_S = focal length of transmitting lens, mm
H_{12} = shape factor
l_M = length of the measuring volume, μm
M = Mach number
N = number of fringes
P_L = light power of the laser source, mW
P_M = light power in the measuring volume, mW
P_S = signal power, W
Re = Reynolds number
S = power spectral density, m^2/s
Tu = turbulence intensity, %
t = time, s
u = velocity component, m/s
V_{PP} = voltage peak to peak, V
x, y = Cartesian coordinates, mm
α = angle of attack
Δs = beam spacing, mm
Δx = fringe spacing, μm
Θ = beam intersection angle
λ = wavelength, nm
ν = viscosity, m^2/s
ρ = density, kg/m^3

Subscripts

c = chord length of the wing
max = maximum value
1, 2 = numbers

Superscript

$\bar{}$ = mean value

I. Introduction

THE economical success of commercial transport aircraft is inherently connected to their direct operating costs, and this relationship will intensify in the future. From an aerodynamic point of view, the most promising potential for reducing these costs, through a significant 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 reduction 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 crossflow instability.

So-called laminar flow wings for sailplanes are state-of-the-art, and the knowledge exists on how to design, construct, manufacture, and install such wings. This knowledge is not yet available in the case of laminar wings for large commercial airplanes, although the advantages the laminar wing technology would bring to this class of airplanes are well known. In addition to the economic aspect, the reduction of the aircraft drag and, hence, the fuel consumption would yield environmental advantages. Reduction of NO$_x$, CO$_x$, and other emissions could be achieved by flow laminarization.

Because of the advantages, increased efforts in aerodynamic research and development are presently being observed in connection with the development of the laminar wing technology for commercial airplanes. University and governmental research institutes, as well as research and development (R&D) departments of civil airplane companies, are involved in these efforts; they are employing experimental and numerical techniques to advance our present understanding of methods of delaying the laminar to turbulent transition and/or to consider means of flow relaminarization. Utilizing knowledge of the mechanisms of laminar to turbulent flow transition to delay the occurrence of turbulence, active flow control is also under investigation. All of these efforts could result in new wing geometries for commercial airplanes; however, to ensure success, new developments of instruments (and of computer codes) are needed to support the ongoing R&D activities.

Whereas aerodynamic developments in the past could be entirely performed in laboratory wind tunnels, in-flight experiments are desirable for the R&D work needed for laminar wing designs. To provide laminar flow technology for commercial airplanes, in-flight measurements are required to confirm the applicability of knowledge obtained in wind-tunnel studies (at relatively high turbulence levels and at low Reynolds numbers), to the high Reynolds number flows and low turbulence levels present under free flight conditions. This demand underlines the need for measuring techniques that permit local fluid flow investigations under free flight conditions. One of the techniques that shows good prospects for this task is laser Doppler anemometry (LDA). However, the special working

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conditions for in-flight measurements require special optical and electronic systems to be developed to permit LDA measurements under free flight conditions. Development work along this line has been carried out and has resulted in the LDA optical system described in this paper. The application of the optical system, together with a commercially available LDA signal processor, is demonstrated for laboratory and in-flight local velocity measurements.

In Sec. II, the strategy for laminar wing design developed is outlined, and it is shown to depend strongly on advanced instrumentation for local velocity measurements and high-performance computer codes. These are jointly applied to wind-tunnel studies yielding information on the wing performance under laboratory flow conditions. Flow computations are subsequently used to predict the wing performance under free flight conditions, i.e., at high Reynolds number and low turbulence levels. A limited number of free flight experiments are employed to check the computational results prior to providing the aerodynamic results to the wing design groups of commercial aircraft companies.

To permit the realization of the R&D strategy of Sec. II, the development of special LDA systems for local velocity measurements of the flow around wings was necessary. Such developments were carried out and results are summarized in Sec. III. Section III also describes the LDA signal processing electronics employed. The developments resulted in two LDA optical systems suited for wind-tunnel and free flight experiments. Verification experiments were performed and are summarized in Sec. IV, followed by conclusions and final remarks in Sec. V.

II. Laminar Wing Design Strategy

R&D work in aircraft aerodynamics thus far has been heavily based on wind-tunnel investigations, although it has been known that the test facilities employed did not provide the required flow conditions to yield directly applicable design information. The sizes of the wind-tunnel test sections employed were usually too small and the velocities too low to yield Reynolds numbers comparable to those in free flight. However, sufficient aerodynamic knowledge of the Reynolds number influence has existed to permit extrapolations of wind-tunnel results to higher Reynolds numbers. This knowledge does not exist, or not to the same extent, for the laminar to turbulent transition investigated in wind tunnels and currently carried out to support the design of laminar wings for commercial aircraft. Reliable methods to predict boundary-layer transition are not yet available for realistic flight environments, and the identification and quantification of the relevant parameters, such as pressure gradient, wing geometry, surface curvature, sweep angle, Mach number, heat and mass transfer at the surface, etc., are far from being complete. For the same reasons, the predictive accuracy for results from present test facilities and wind tunnels is insufficient or at least questionable. For the studies of laminar to turbulent transition, individual wind tunnels inherently introduce their own specific spectrum of flow disturbances, and hence, their laminar to turbulent transition data can be affected by wind-tunnel noise. Hence, results of wind-tunnel studies yielding design parameters for laminar wings have to be verified by flight experiments. Because such experiments are expensive, they have to be reduced to a minimum, and this reduction requires the development of reliable methods to extend wind-tunnel observations to free flight results. A way this transfer can be reliably achieved uses an R&D strategy to be briefly outlined. It is based on wind-tunnel investigations, employs flow computations to predict the flow data of the wind-tunnel experiments, and finally extends the verified computer program to predict the flow for free flight conditions. In free flight, few measurements are needed to assess the flow predictions prior to employing the data for design purposes.

When wind-tunnel investigations are being performed, they are carried out with the laboratory boundary conditions being imposed on the flow. Under these conditions, all of the required flow information can be obtained, for example, by means of hot-wire anemometry and/or LDA. These measuring techniques are available for laboratory investigations and can readily be applied. Numerous aerodynamic studies have been performed in this way.

The laboratory flow can also be predicted using high-performance computational aerodynamic codes with the boundary conditions present in the test flow. Comparing the experimental data with the predictions permits the accuracy of the resultant flow predictions to be assessed. With this accuracy in mind, the flow predictions can be repeated for the flow and boundary conditions that apply to free flight conditions. The predictions obtained then can be checked against data obtained through a small number of free flight experiments. If these comparisons agree within the accuracy obtained from the wind-tunnel results, the code can be employed to support those parts of the aircraft design for which the described aerodynamic investigations were carried out.

Besides the development of the complementary numerical and experimental methodology mentioned, there is a definite need for in-flight tests on boundary-layer transition for assessment purposes. The laminar to turbulent transition process that is to be investigated reacts sensitively to disturbances introduced. This observation implies the need for advanced measuring techniques that should be preferably nonintrusive and must be reliable in the harsh environment of in-flight tests. Several of those techniques have been developed in recent years, e.g., hot-film arrays, piezofoils, and infrared cameras for transition detection. But all of these techniques are only capable of gathering limited information directly on the wall surface, whereas LDA may give an insight into the complete boundary layer and, hence, the entire surrounding flow velocity field. This information is essential to describe input boundary conditions to be employed, as well as for the adjustment and the comprehensive assessment of the numerical simulations.

The realization of the R&D strategy proposed is presently underway with contributions to the following areas:

1) There is development of high-performance computer codes for numerical flow computation to yield direct numerical simulation, large eddy simulation, and Reynolds-averaged Navier–Stokes equations information for aerodynamic flows. All computer codes developed are equipped with multigrid solvers and operate on parallel computers, e.g., see Refs. 1 and 2.

2) Investigations are underway of turbulent wall-bounded flows using LDA measuring techniques to yield local information on time-averaged turbulent flow properties, e.g., see Refs. 3 and 4. These data support analytical studies of wall-bounded flows, mainly to improve the dissipation equation used in turbulence modeling, e.g., see Refs. 5 and 6.

3) Development is underway of measuring techniques to be readily applicable for studies of laminar–turbulent flows, e.g., see Ref. 7. Measuring techniques are also being developed to carry out in-flight measurements, e.g., see Ref. 8.

The work presented in this paper relates to the development work mentioned in the last area.

III. Design of the LDA System

From the beginning of the design of the present 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 studies is a GROB 109B, a two-seated powered sailplane equiped with a wing glove on its starboard 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 to be described. To some extent the LDA systems developed were designed to match the particular demands of the airplane used for in-flight measurements. Nevertheless, the instrumentation shows design features that are of general validity to all similar applications.

In a first approach, an LDA probe with an integral design was adopted; it used an integrated semiconductor laser diode as the light source and a semiconductor photodetector and operated in direct backscatter.[9] The design of this laser Doppler optical system is shown in Fig. 1 in a cross-sectional view. The system incorporated a laser diode and collimator assembly that was temperature controlled by Peltier elements, thereby stabilizing both the wavelength of the laser and the alignment of the collimator. An avalanche photodiode was mounted between the two parallel laser beams, together with its signal amplifiers. The beam paths are diverted by a 45-deg

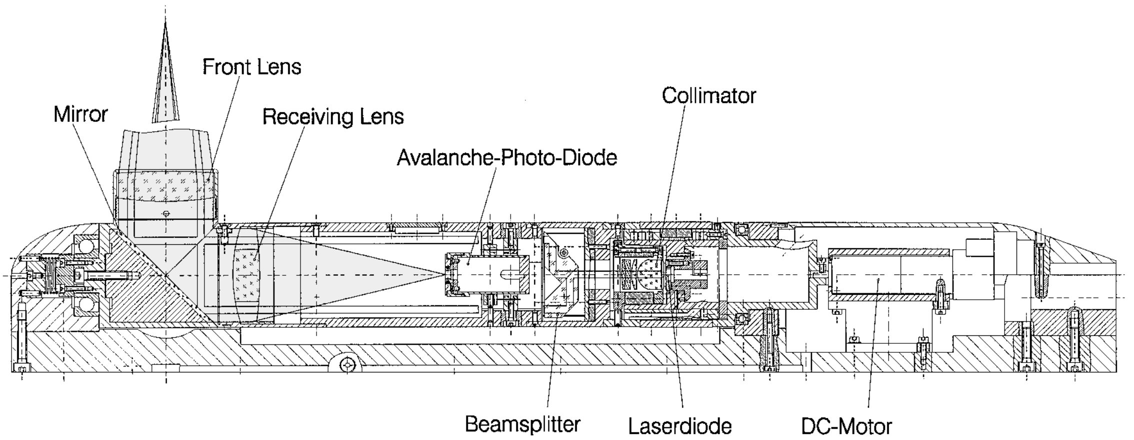

Fig. 1 Cross-sectional view of the semiconductor LDA probe.

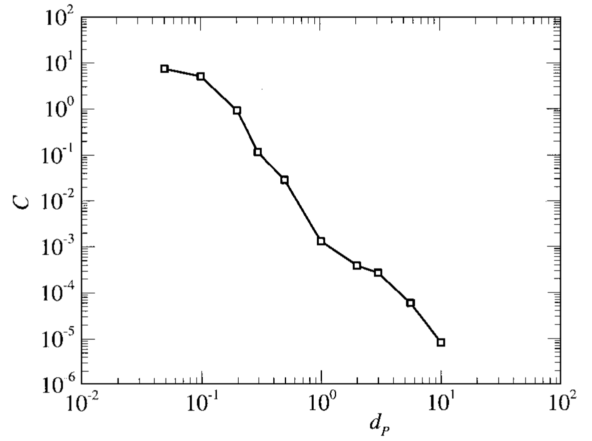

Fig. 2 Particle diameter distribution in the atmosphere measured with a cascade impactor.

mirror, and the entire LDA assembly was mounted in such a way that it became rotatable by a dc motor in a wing pod construction. This construction provided for traversing of the measuring control volume perpendicular to the wing surface and allowed clamping the system on top of the wing glove at an arbitrary chordwise position.

The LDA system shown in Fig. 1 proved to be very reliable and stable in optical and mechanical alignment at free flight conditions. The experience gained during the in-flight measurements 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 hazes or clouds was quite low and not sufficient for some of the measurements, e.g., for spectral analytical studies of Tollmien–Schlichting instabilities. It was concluded that this difficulty resulted from the low concentration of aerosols in the atmosphere that are needed as scattering particles. To examine this hypothesis, the concentration and diameter distributions of natural aerosols were investigated using a cascade impactor device (Aerosol Particle Analyzer, Model PC-2, California Measurements, Inc.). In Fig. 2, a particle diameter distribution measured during the flight tests is shown. It showed a very steep increase of concentration for particles of very small size. Therefore, the conclusion is clear that the data rate could be improved considerably if one succeeded in detecting signals from particles of diameters less than about $d_P = 0.5 - 1\ \mu$m, which was about the limit for the semiconductor LDA probe.

These findings led to the development of an improved LDA system. During design of this system, emphasis was placed on gaining maximum signal power from small scattering particles. To this end, all design parameters influencing the scattered light intensity were analyzed using the theory of light scattering by small particles.[10] The major parameters could be identified to be the following: optical arrangement of transmitting and receiving optics (backward/forward scattering); size of aperture relative to focal length of the receiving lens; intensity of transmitted light in the measuring control volume, a consequence of laser power available and size of the control volume; and wavelength of laser light employed.

Table 1 Optical parameters of the LDA systems

Parameter	Semiconductor LDA	Nd-YAG LDA
λ, nm	830	532
f_S, mm	200	100
Δs, mm	38	30
$\Theta/2$, deg	5.71	7.1
d_M, μm	80×70	50
l_M, μm	800	400
Δx, μm	4.17	2.15
N	19	23
P_L, mW	100	400
P_M, mW	80	200
Signal detection	Direct backscatter	Forward scatter
Signal processing	QSP	BSA

The new system features a laser-diode-pumped frequency-doubled Nd-YAG laser, which provided higher light power at a shorter wavelength, when compared to the semiconductor laser used in the optics in Fig. 1, while still having low electrical power consumption. The scattered power of very small particles is governed by Rayleigh's law and varies with the fourth power of particle diameter divided by wavelength (d_p/λ). Replacing the semiconductor laser ($\lambda = 830$ nm) by a frequency-doubled Nd-YAG-laser ($\lambda = 532$ nm) resulted in an increase of about a factor of 6 in scattered light power. The output power available with an Nd-YAG laser was about 400 mW, but as it was no longer possible to integrate the laser into the probe design, losses of about 40% due to the glass fiber cable needed to be considered. Together with the reduction of the beam waist diameter in the crossing volume, the final gain of light power in the measuring control volume was of a factor of about 12. One major improvement could be expected by altering the optical arrangement from backward to near forward scattering; this gave about one order of magnitude increase in signal power for the smallest particle size and about two orders for the larger ones.

Some deficiencies resulted from 1) a reduction of the receiving aperture forced by geometrical constraints of the space available between the wing of the aircraft and the wing glove, where the probe now was placed; 2) the need for an optical isolator blocking the reflective light from the end of the transmitting glass fiber back into the laser; and 3) the losses due to the receiving fiber. These deficiencies caused a factor of about three reduction in signal power. A comparision of all relevant design parameters is given in Table 1.

Results of a more detailed computation of the signal power to be expected from the new design, based on the theory of light scattering by small particles,[10] are plotted in Fig. 3. Figure 3 shows that the overall gain in Doppler signal power obtained was of two to three

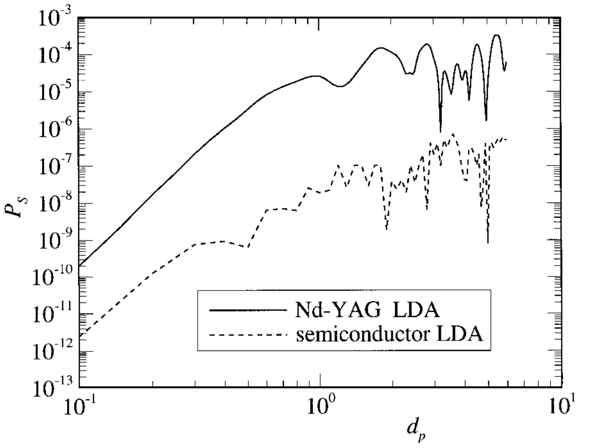

Fig. 3 Signal power calculated based on theory of light scattering by small particles.

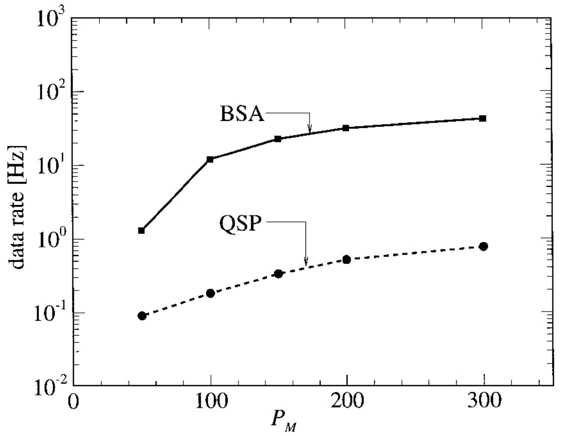

Fig. 4 Comparision of data rate of two different LDA signal processors.

orders of magnitude. This conclusion was verified by wind-tunnel experiments. Studies concerning the complex refractive index of aerosols of rural or maritime origin, respectively, showed no significant influence on signal power for the considered range of particle sizes.

In the semiconductor LDA system, signal processing electronics produced by Quality Signal Processors, Inc. (QSP), were adopted for its low space and power requirements. These LDA electronics consisted of three personal computer boards [transient recorder, hardware fast Fourier transform (FFT), and timer] and the corresponding software. In the initial tests it turned out that this system showed a major disadvantage for its application to in-flight LDA measurements, i.e., in detecting Doppler signals of low signal-to-noise ratio. Because there was only an amplitude trigger at the input of the instrument, the setting of the trigger threshold was extremely sensitive. Either the transient recorder was activated very rarely when a relatively high trigger level was set or it was activated prematurely by noise, thus missing valid Doppler signals during its dead time. Therefore, a signal processor with a more sophisticated burst detection unit was needed. The burst spectrum analyzer (BSA; Dantec Systems Corporation), also using FFT analysis, was tested in comparison to the QSP system for different signal intensities. Figure 4 shows that the data rate achieved was more than one order of magnitude higher. Despite the severe drawbacks of size and weight, the BSA was adopted for the further flight tests.

The severe spatial restrictions imposed by the research aircraft and the demand for a forward scattering arrangement resulted in an unconventional probe design, which is shown in Fig. 5. 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 path; all optics apart from the upper mirrors were placed underneath the wing glove surface, and only these mirrors protruded. Therefore, the distortion of the flow induced by the measuring system was minimal. The requirements for laser beam intersection angle and sufficient receiving aperture area were met by employing optical components cut into narrow slices of $6 \times 40\,\mathrm{mm}^2$. The size of the measuring control volume created was about $50\,\mu$m in diameter and about $400\,\mu$m in length.

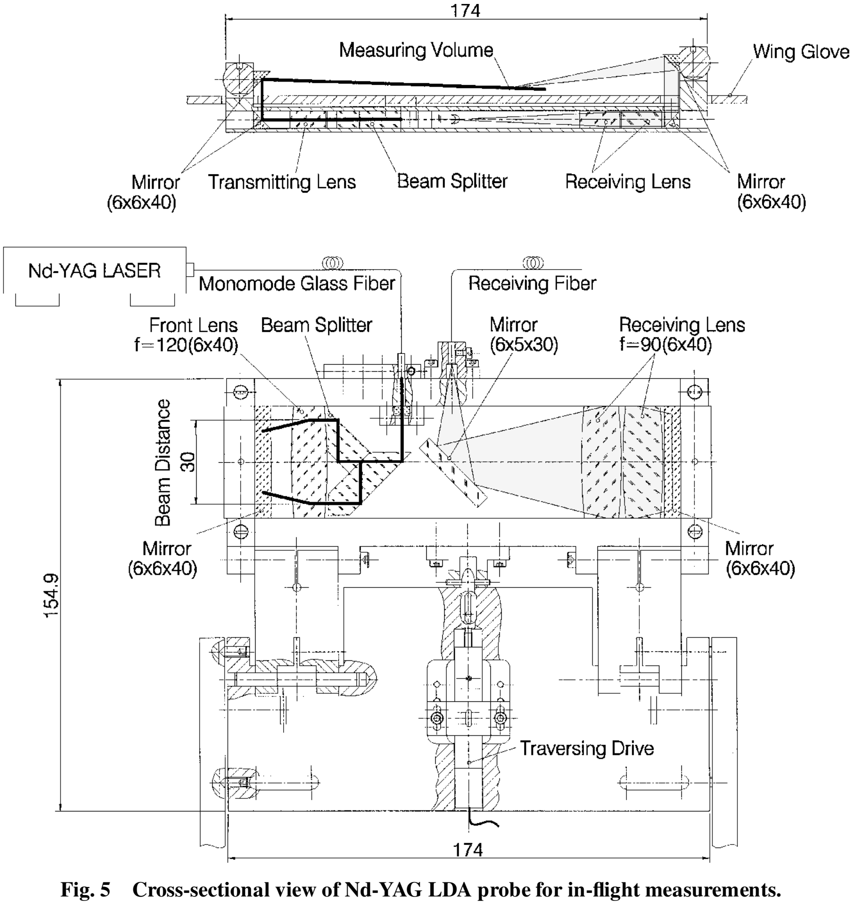

Fig. 5 Cross-sectional view of Nd-YAG LDA probe for in-flight measurements.

The LDA probe was connected to the laser and the photodetector, which were placed in the cockpit of the aircraft, by monomode and multimode glass fiber cables, respectively. 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 misadjustment during flight experiments due to vibration, bending of the wing, and stresses due to changes in temperature. The laser, traversing controller, photomultiplier, power supplies, and signal acquisition and processing unit were installed on an instrumentation platform in the cockpit behind the pilot seats to complete the measuring system.

IV. Verification Experiments

In connection with design considerations of laminar wings for commercial airplanes, in-flight velocity measurements are needed to yield information on the naturally occurring laminar to turbulent boundary-layer transition. This transition is very much dependent on the scales of turbulence and on the turbulence intensity present in the flow, as well as on the Reynolds and Mach numbers. This situation readily suggests that a direct transfer of results of wind-tunnel experiments to yield detailed velocity information for in-flight conditions is not completely possible. A special strategy is needed to make wind-tunnel investigations at smaller Reynolds and Mach numbers useful to gaining reliable results for the flowfield around wings of commercial airplanes. The development of such a strategy has been underway at the Institute of Fluid Mechanics.

Within this development work, a wing glove was constructed that was available as a stand-alone airfoil model for wind-tunnel investigations and could be employed for in-flight measurements as well by slipping it over the wing of the research aircraft of the University of Darmstadt. The wing glove was built as a honeycomb sandwich construction of carbon fiber and had an Eppler 580 wing section corresponding to the wing of the test airplane. This configuration resulted in a gap between the airplane wing and the inside surface of the glove (about 15 mm in height) that was available for the instrumentation with the optics and the traversing mechanism of the employed LDA system as earlier described. The overall chordwise and spanwise dimensions of the wing glove were 1.3 and 1.5 m, respectively.

In the wind-tunnel studies, complete surveys of the boundary-layer development on the suction side of the wing glove were measured for different angles of attack. In Fig. 6, examples of velocity profiles in the transitional regime are presented for $\alpha = -1$ deg and $Re_c = 2 \times 10^6$. Beginning with laminar flow, the profiles show inflection points at chord positions of 50–60% and then become turbulent by 65% with a steep increase in boundary-layer thickness. In the wall proximity, the closest distance for which reliable measurements could be obtained was less than 0.1 mm. For comparison with the numerical results, the streamwise variation of integral shape factor H_{12} is plotted in Fig. 7. It is seen that the computations using the boundary conditions measured in the wind tunnel predict the transition significantly more accurately than those using the free flight boundary conditions.

One major objective of the present research in aerodynamics concentrates on the detection of flow phenomena occurring in laminar to turbulent transitional flows. To demonstrate the performance of the LDA system described to detect Tollmien–Schlichting waves, an excitation source for small flow disturbances was installed in the test wing section. This source consisted of a small loudspeaker driver mounted underneath the wing glove upper surface and located at 27% of the chord length. A small chamber in front of the

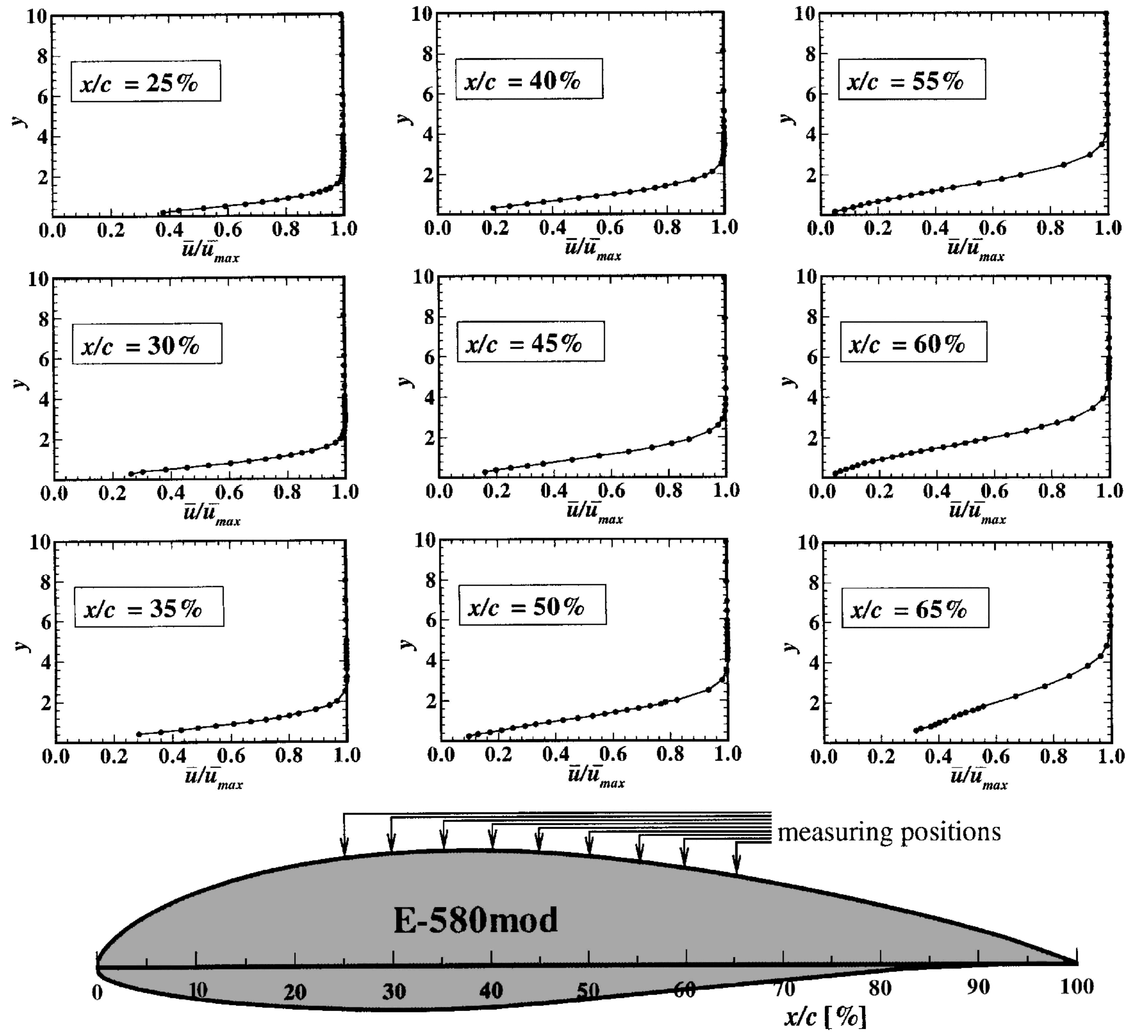

Fig. 6 Boundary-layer velocity profiles on the suction side of the wing glove; $\alpha = -1$ deg, $Re_c = 2 \times 10^6$.

loudspeaker diaphragm was connected to the wing glove surface by a 0.3-mm-diam tap. For a set of measurements in the wind tunnel ($Re_c = 1 \times 10^6$), a 240-Hz excitation frequency was set after stability calculations had predicted that Tollmien–Schlichting waves should be excited by this frequency at this location for the boundary-layer flow. Figure 8 shows power spectral density distributions measured 200 mm downstream from the excitation source with and without excitation, respectively. The wave train introduced into the boundary layer is easily to be identified by the marked peak in the spectral distribution at 240 Hz.

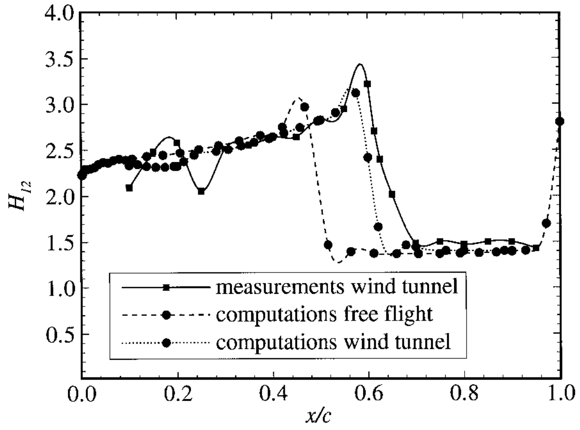

Fig. 7 Streamwise variation of shape factor H_{12}; $\alpha = -1$ deg, $Re_c = 2 \times 10^6$.

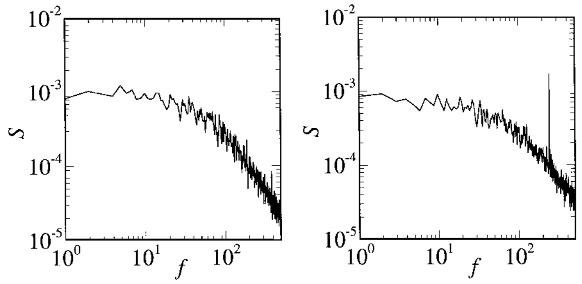

Fig. 8 Power spectral density distributions without and with excitation, measured in the boundary layer 200 mm downstream from the excitation source.

After the successful demonstration of the functioning of the LDA, the entire system was mounted onboard the test aircraft for the flight measurements. The arrangement of the complete instrumentation is shown in Fig. 9. Figure 9 indicates that the LDA probe, traversing system, and excitation source are mounted on the starboard wing glove. The power supplies for the traversing system and excitation source are contained in the underwing station. The laser, photodetector, and signal processor were located on the instrumentation platform behind the pilot seats. The port wing carried the flight data acquisition of the test aircraft, which is described in detail by Erb et al.[11] All systems were controlled by the onboard computer in the cockpit; it ran the different programs in multitasking operation. In this way, simultaneous data acquisition could be performed. The battery that powered the instrumentation lasted for about 30 min of run time per flight.

Figure 10 shows the LDA system in actual flight tests. The alignment of the optical system proved to be extremely stable, i.e., the alignment turned out to be unaffected by aircraft vibrations, temperature changes during flights, etc. Similarly, the electronics performed well during all experiments. The rate of validated velocity data turned out to be approximately 200 Hz for clear atmospheric

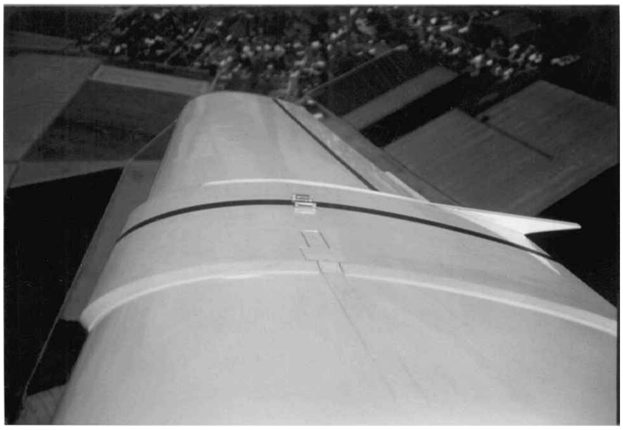

Fig. 10 LDA probe during in-flight tests.

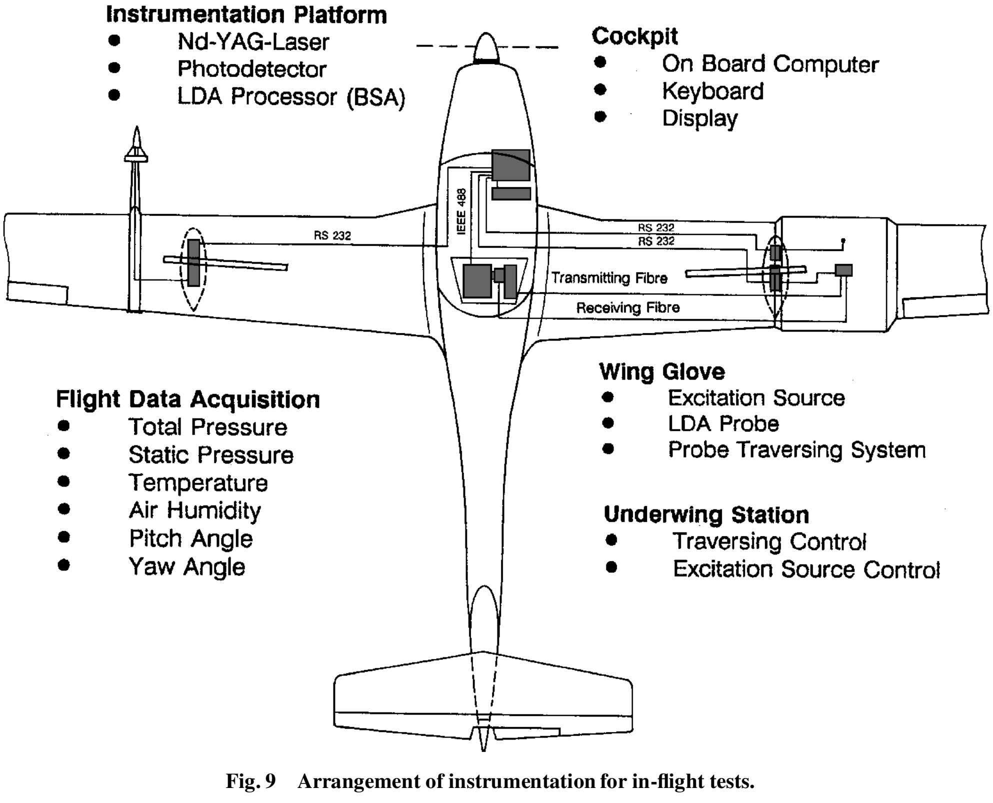

Fig. 9 Arrangement of instrumentation for in-flight tests.

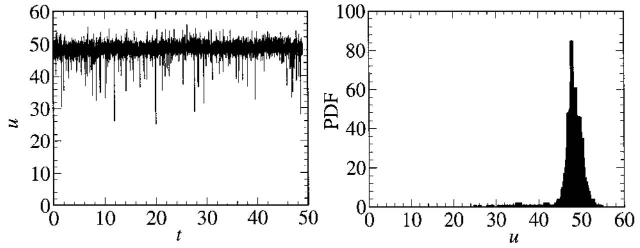

Fig. 11 Typical time series of instantaneous velocity and PDF; $x/c = 42.5\%, y = 2$ mm, 7759 samples, 160-Hz data rate.

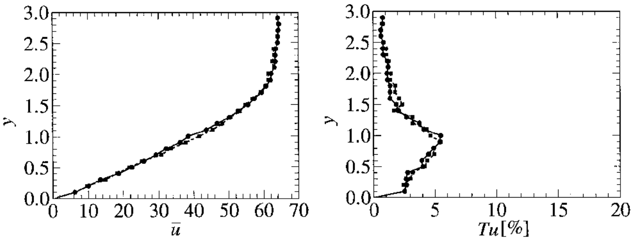

Fig. 12 In-flight velocity and turbulence intensity profile measurements; $x/c = 42.5\%$, $\alpha = -1.5$ deg, IAS = 154 km/h.

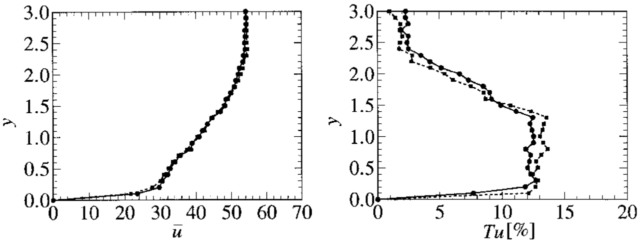

Fig. 13 In-flight velocity and turbulence intensity profile measurements; $x/c = 42.5\%$, $\alpha = 0$ deg, IAS = 138 km/h.

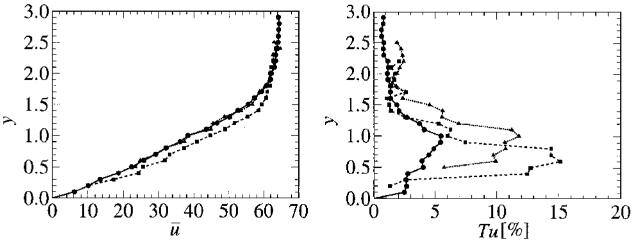

Fig. 14 Velocity and turbulence intensity profiles of an apparently laminar boundary layer without and with excitation of two different amplitudes; $x/c = 42.5\%$, $\alpha = -1.5$ deg, IAS = 154 km/h: a) ——, no excitation; b) ----, $f = 2000$ Hz and $V_{PP} = 1$ V; and c) · · · ·, $f = 2000$ Hz and $V_{PP} = 0.5$ V.

weather conditions, whereas for hazy weather data rates up to several kilohertz were obtained. The major atmospheric parameter influencing the validated data rate was the humidity of air. Experiments carried out at flight levels above the inversion layer yielded significantly lower data rates than flights below the inversion. Nevertheless, in all conditions sufficient data could be obtained during flight experiments to provide useful boundary-layer information. A typical set of velocity measurements is shown in Fig. 11. It shows a time series of instantaneous velocity and the derived probability density function (PDF), respectively. This specific measurement was taken in the boundary layer on the wing glove at a distance of about 2 mm from the surface and a chordwise position of 42.5%. The position was chosen to be in the region of laminar to turbulent transition.

Traverses of the measuring control volume perpendicular to the wing surface were carried out, and the results were plotted in boundary-layer profiles. In Figs. 12 and 13 resulting profiles of mean velocity and turbulence intensity are shown. The data were measured at the same chordwise location ($x/c = 42.5\%$) but at different indicated airspeeds (IAS) of the aircraft, yielding different angles of attack. Each measuring point marked represents an average of 5,000 to 10,000 samples. For a boundary-layer thickness of about 3 mm and a step width between the equidistant measuring points of 0.1 mm, one flight was sufficient for acquiring up to two complete profiles. In Figs. 12 and 13, results of two different flights are plotted, showing the excellent repeatability of the measurements. Whereas the velocity profile at $\alpha = -1.5$ deg (Fig. 12) appears to be laminar, the turbulence intensity profile reveals that the boundary layer was already in a transitional stage. The characteristic maximum of turbulence intensity appeared at 35% of boundary-layer thickness. For $\alpha = 0$ deg (Fig. 13), the boundary layer at the measuring position had become fully turbulent, which is easily to identify in the velocity and turbulence intensity profiles as well.

Some results of flight tests with a wave train introduced by the excitation source are shown in Fig. 14. Demonstrated in the diagrams are profiles of mean velocity and turbulence intensity without any excitation and with excitation at two different amplitude levels at the same flight conditions as in Fig. 12. Whereas the influence of the wave train in the mean velocities could hardly be identified, the turbulence intensities were significantly increased with increasing excitation level and showed the characteristic peaks of a transitional stage.

V. Concluding Remarks and Outlook

The increased efforts in the aerodynamic development of laminar wings for commercial airplanes has triggered the research to work on a strategy to utilize modern experimental and numerical techniques to obtain velocity information on the flow around wings. Within these research efforts, LDAs were developed and were employed both for wind-tunnel measurements and for in-flight boundary-layer flow investigations. The present paper summarizes the outcome of the LDA system development yielding a miniaturized optical system optimized to be small, light, and robust and to be able to detect signals from very small scattering particles. Typical results of the wind-tunnel experiments and of in-flight measurements are presented. The mean streamwise velocities, rms values of turbulent velocity fluctuations, and energy spectra of the fluctuating components were measured. The results presented demonstrate the successful completion of the development. The LDA system is now available for aerodynamic studies of flows showing laminar to turbulent transition. Through understanding the basic mechanisms of the natural transition to turbulence, work on the optimization of the wing geometry will be supported. The authors hope that this knowledge will lead to optimum wing geometries, which permit laminar flow to remain over most of the wing surfaces for commercial airplanes.

There is still room for further development and related work.[12] Whereas the optical system design dominated in the present research efforts, conventional LDA signal processing equipment was employed. 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 time measurements in small airplanes of the kind employed in this research.

The authors have no doubt that laser Doppler systems suitable for wind-tunnel and in-flight measurements will be the basis for advanced aerodynamic studies in the future. When combined with numerical prediction procedures, with multigrid solvers and implemented on parallel vector computers, LDA systems of the kind described here can be powerful tools for aerodynamic research in general and for laminar flow wing research in particular.

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References

[1] Drikakis, D., and Durst, F., “Computation of Aerodynamic Flows Using Improved Parallelization Procedures,” *Parallel Computational Fluid Dynamics: New Trends and Advances*, Elsevier Science, New York, 1995, pp. 109–116.

[2] Durst, F., and Schäfer, M., “A Parallel Block-Structured Multigrid Method for the Prediction of Incompressible Flows,” *International Journal for Numerical Methods in Fluids*, Vol. 22, No. 6, 1996, pp. 549–565.

[3] Durst, F., Jovanovic, J., and Sender, J., “LDA Measurements in the Near-Wall Region of a Turbulent Pipe Flow,” *Journal of Fluid Mechanics*, Vol. 295, July 1995, pp. 305–335.

[4] Durst, F., Jovanovic, J., and Sender, J., “Detailed Measurements of the Near Wall Region of Turbulent Pipe Flow,” *ASME Symposium*, FED-Vol. 146, American Society of Mechanical Engineers, New York, 1993, pp. 79–87.

[5] Jovanovic, J., Ye, Q.-Y., and Durst, F., “Statistical Interpretation of the Turbulent Dissipation Rate in Wall-Bounded Flows,” *Journal of Fluid Mechanics*, Vol. 293, June 1995, pp. 321–347.

[6] Jovanovic, J., Durst, F., and Johnson, T. G., “Statistical Analysis of the Dynamic Equation for Higher-Order Moments in Turbulent Wall Bounded Flows,” *Physics of Fluids*, Vol. 5, No. 11, 1993, pp. 2886–2900.

[7] Lienhart, H., and Becker, S., “LDA Untersuchungen in transitionalen Grenzschichten,” *Proceedings 9. DGLR-Fach-Symposium* (Erlangen, Germany), DGLR, DGLR-Bericht 94-04, Bonn, 1994, pp. 25–31.

[8] Ewald, B., Durst, F., Krause, E., and Nitsche, W., “In-Flight Measuring Techniques for Laminar Wing Development,” *Zeitschrift für Flugwissenschaft und Weltraumforschung*, Vol. 17, No. 7, 1993, pp. 294–310.

[9] Durst, F., Lienhart, H., and Müller R., “Application of a Semiconductor LDA for Inflight Measurements,” *Proceedings of the 6th International Symposium on Application of Laser Techniques to Fluid Mechanics,* Instituto Superior Tecnico, Lisbon, 1992, pp. 11.3.1–11.3.4.

[10] Naqwi, A., and Durst, F., “Light Scattering Applied to LDA and PDA Measurements, Part 1: Theory and Numerical Treatments,” *Particle and Particle Systems Characterization*, Wiley–VCH Verlag GmbH, Weinheim, Germany, 1991, pp. 245–258.

[11] Erb, P., Ewald, B., and Roth, M., “Flight Experiment Guidance Technique for Research on Transition with G109b Aircraft of the Technische Hochschule Darmstadt,” *New Results in Numerical and Experimental Fluid Mechanics*, Vieweg Verlag, Brunswick, Germany, 1996, pp. 143–150.

[12] Jentink, H. W., Beversdorff, M., and Förster, W., “Laser Anemometry for In-Flight Investigations,” *Proceedings of 16th ICIASF Conference* (Dayton, OH), *ICIASF ’95 Record*, Inst. of Electrical and Electronics Engineers, Piscataway, NJ, 1995, pp. 23.1–23.4.

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