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Laminar-Flow Instrumentation for Wind-Tunnel and Flight Experiments

Wolfgang Nitsche*
Technical University of Berlin, D-1000 Berlin 10, Germany
and
Joachim Szodruch†
Airbus Industrie, Blagnac F-31707, France

This article reports on selection, adaptation, and integration of advanced measuring techniques for laminar wing testing in wind-tunnel and flight experiments. The aim was to perform high quality experiments with results of sufficient detail and resolution which can be used for theoretical code development and verification as well as for design criteria of laminar wing concepts. Results from various wind-tunnel and flight tests fully support and confirm the quality and potential of the testing techniques employed.

Nomenclature

b = span, m
c = chord, m
c_a = lift coefficient
c_f = skin friction coefficient
c_p = pressure coefficient
E = electric power, W
f = frequency, Hz
geo = geometrical
H = flight level, m
IAS = indicated air speed, km/h
M = Mach number
N = amplification factor
p = pressure, Pa
p' = pressure fluctuation, Pa/s
Re = Reynolds number
RMS = root mean square value, V
t = time, s
u = velocity, m/s
$V_{i,j}$ = voltages, V
w = wall
x, y = coordinates, m
α = angle of attack, deg
β = yaw angle, deg
η = spanwise position
η_k = flap angle, deg
τ_w = wall shear stress, N/m²
Ψ = sweep angle, deg
∞ = freestream condition
$*$ = normalized value

Introduction

ONE of the major potentials for aircraft improvement is the reduction of drag. Since various drag reduction technologies have proven to be beneficial to airline service, these concepts have inspired research for several decades. The idea of laminarizing flow around aircraft components (mainly the wing) is almost as old as the beginning of flight. More than 50 yr of research have passed in this field.[1] The major aim is to save fuel-burn in order to reduce costs and pollution, to extend flight range, or to increase payload. Aircraft-drag breakdown shows that the largest contributor to total drag is skin friction caused by air viscosity. Laminarizing the wing up to 50 or 60% of the chord may result in about 15% of total aircraft-drag reduction. Therefore, the laminar flow concept offers the greatest potential of any single technology in aircraft improvement.

However, e.g., when compared to classical airfoil/wing experiments, the experimental verification of laminar wing concepts requires that the application of all kinds of boundary-layer testing methods must be increased dramatically. Pressure and force measurements, which have dominated traditional experiments up to now, continue to be important in laminar wing experiments. However, the crucial measuring task now concentrates more strongly on a detailed analysis of the state of the boundary layer, flow instabilities, and surface forces. Although such measuring tasks are quite common in experimental flow research they have been neglected in aircraft aerodynamics in the past. Only occasionally have they been used in, e.g., flight tests.[1–3] This situation is the background for the present article which concentrates on measuring technique concepts and their results in laminar flow research. Potential measuring techniques with regard to special applications in the field of laminar wing research are introduced and discussed.

Advanced sensors or data processing is only the first step in finding new measuring methods. The integration and adaptation of advanced measuring techniques in research programs and industrial application are just as important. Hence, examples of successful application of several methods are given in this article on the basis of various wind-tunnel and flight experiments.

Integration of Advanced Measuring Techniques

Transition Detection

Already the fundamental measuring task of a distributed qualitative transition detection raises a major problem with respect to transonic wind-tunnel and flight tests. This is because classical methods of flow visualization (e.g., by means of surface patterns) are too inflexible (under variable test conditions) and cannot be applied in flight test. Recently developed methods, such as the liquid crystal foil technique[4] or the infrared image technique,[2,3] have already shown great

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*Professor, Department of Aeronautics and Astronautics, Marchstr. 14.
†General Manager Research and Technology, 1 Rond Point Maurice Bellonte. Member AIAA.

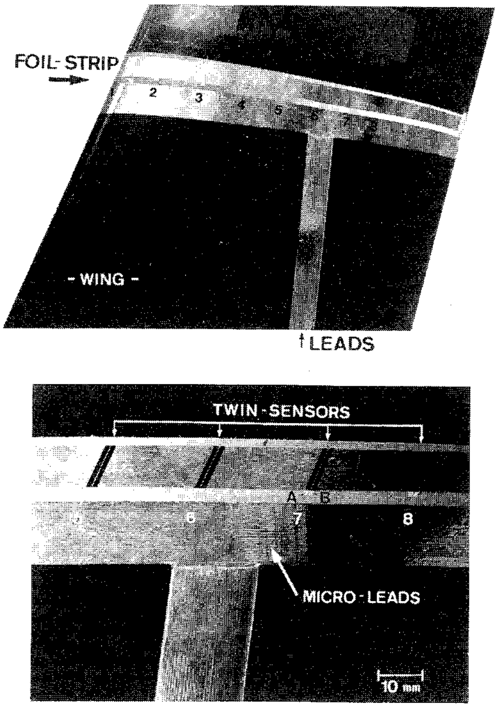

Fig. 1 Piezofoil-array on a wind-tunnel model.

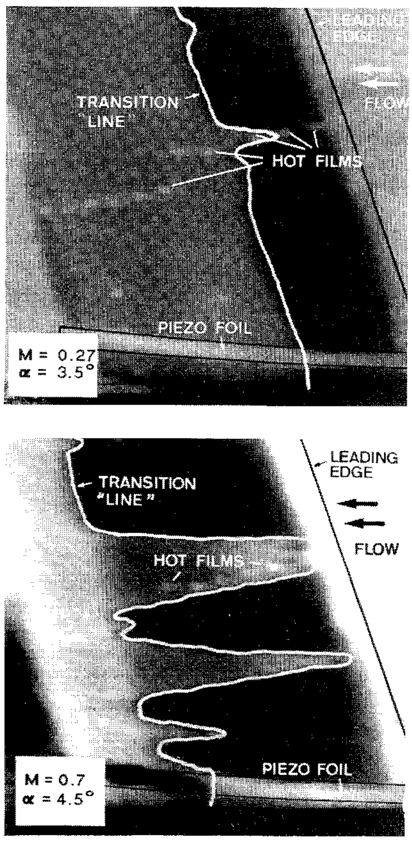

Fig. 2 Infrared images of a laminar-turbulent flow on an airfoil.

improvement. These two technologies are based on measurements detecting variable wall temperatures in the transition region (due respectively to different heat transfer characteristics of laminar and turbulent flows). Apart from the respective electronic effort, the IR-method in particular usually requires artificial structural heating in order to maintain the differences in wall temperature between laminar and turbulent flow regions, and therefore, makes them detectable. These instrumental boundary conditions can cause serious problems, especially on large wind-tunnel models and more importantly, in flight tests. Notwithstanding, the IR-technology has become an indispensable technique in laminar wing experiments. The reason for this is that when using this measuring technique survey patterns can be obtained in a relatively short time. This is, however, only restrictedly possible by means of discrete wall sensors.[2,3]

Significant progress has been achieved in the development of nonintrusive/less-intrusive wall sensors, e.g., the recent developmental work in the field of hot-film arrays[5,6] or the piezo-array technique.[7,8] Both measuring techniques—shown for a 24-sensor piezofoil array on a wind-tunnel model in Fig. 1 are directly mounted on the airfoil surface and selectively detect—in a simple, purely qualitative signal analysis—the heat transfer (hot film) and pressure fluctuations (piezofoil), respectively, which vary significantly in the course of boundary-layer transition. Consequently, they also enable authentic statements about laminar, transitional, and turbulent flow regions. Therefore, combined application of the IR technique and the array techniques mentioned above could be of particular interest in laminar airfoil investigations. The combined application is such that the discrete sensor results can be employed to calibrate gray steps of an IR image, whereas, the IR figures help to detect possible flow disturbances by means of surface sensors. Figure 2 shows two IR figures of a transitional profile flow at $M = 0.27$ and $M = 0.7$ as an example of such tests. Apart from the laminar (dark) and turbulent (bright) flow regions that are clearly visible, the nonintrusion of the piezofoil array and the slightly prelocated transition in the region of the hot-film array can be specifically recognized.

Surface Forces

Naturally, the qualitative detection methods described above only give limited information (in the sense of a yes/no statement) about successful or unsuccessful laminarization. By comparison, much more detailed statements can be expected from the wall sensors already mentioned. This applied especially to experiments where the sensors are used not only for a qualitative analysis but also for direct measurement of local surface forces (pressure, pressure fluctuations, wall shear stress, and wall shear stress fluctuations).

Above all, measuring mean wall shear stresses is of crucial importance since the laminarization that has been strived for particularly aims to drastically reduce this parameter. Unfortunately, it is comparatively difficult even under laboratory conditions to determine this particular measurement quantity accurately.[9] Experimentalists face serious problems when carrying out complex shear stress investigations concerning airfoils. The hot-film technique, e.g., which is a most successful technique in laboratory experiments, only produces reliable wall shear stress results if appropriate in situ calibration techniques are additionally provided. Other techniques such as the laser interferometer method[10] or the application of direct skin friction balance devices[11] seem to be less promising, due respectively, to their great technical effort and limited application.

The computational Preston tube method (CPM3)[12] which, by means of a numerical boundary-layer approximation of the near-wall flow, determines the wall shear stress from the dynamic pressures of three different-sized wall-mounted miniature pitot tubes, is one of the few measuring techniques which can be used immediately without calibration for direct and absolute measurements of the local wall friction in laminar and turbulent flows. This method has already been tested thoroughly in numerous wind-tunnel and flight experiments[2,13,14] (Fig. 3). It is not, however, considered as a nonintrusive technique. Nevertheless, the CPM3 method can be applied rather successfully for certain tasks, e.g., the in situ calibration of other, less intrusive techniques such as hot-film probes. Another promising technique for detecting laminar-turbulent wall shear stress distributions has emerged with the development of shear sensitive liquid crystals.[15] However, due to the great

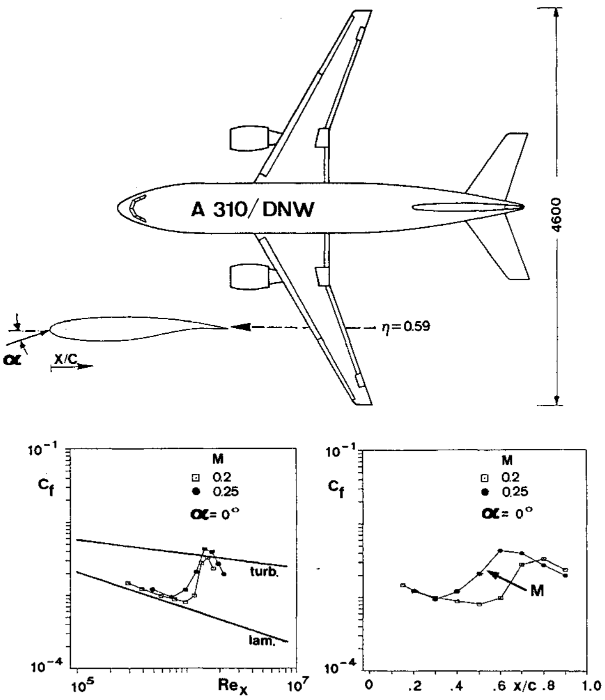

Fig. 3 Skin friction distribution on a wing (CPM3 results).

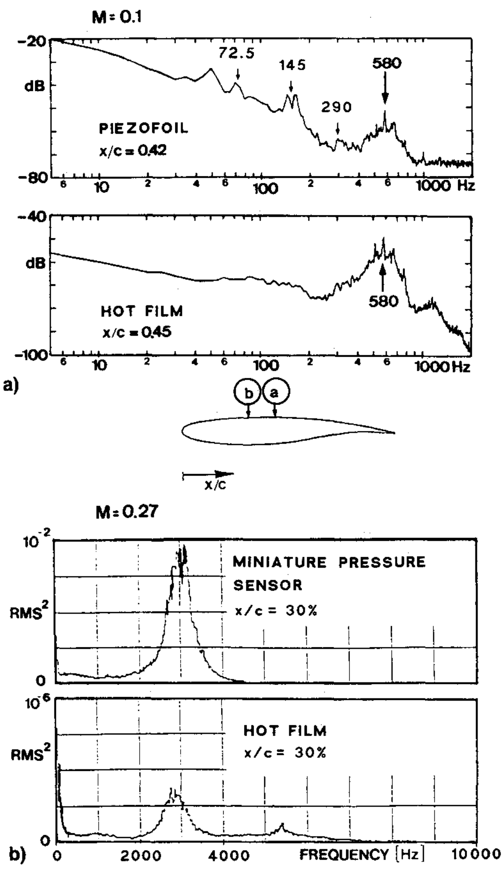

Fig. 4 Power spectra and TS-instabilities: a) piezofoil and hot-film, and b) pressure transducer and hot-film.

effort needed with illumination lamps and cameras, this method will be confined to wind-tunnel tests.

Apart from mean wall shear stress, unsteady surface forces are of great importance in experiments concerning laminar wings. This is the immediate consequence of the unsteady character of transitional flows [Tollmien-Schlichting (TS) waves or crossflow instabilities] which are not only important for understanding the underlying physics of transition processes

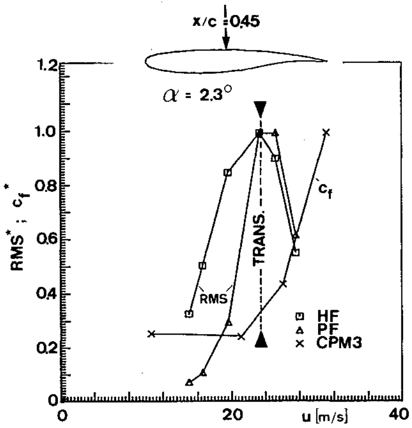

Fig. 5 Hot-film, piezofoil, and CPM3 results in transition.

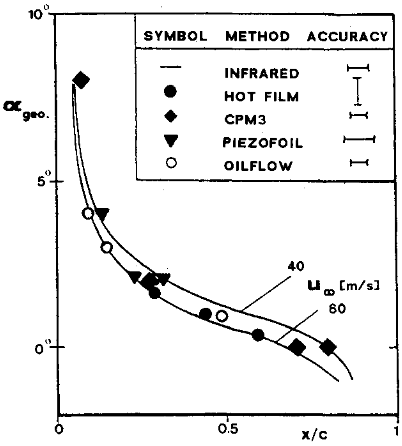

Fig. 6 Transition detection on an airfoil. Comparison of IR-image, hot-film CPM3, piezofoil, and oil flow results.

but also for comparing stability codes (e.g., according to the e^N-method) with the experiment. To begin with, the characteristic frequencies of the flow instabilities are of special interest in such investigations. Moreover, flow amplifications (e.g., N-factors) are also rather important especially when results obtained in different wind tunnels or in comparative wind-tunnel and flight tests are compared with computations.

Among the surface sensors mentioned above, the surface hot-films and the piezofoil sensors are particularly suited for such investigations since both are able to safely detect unsteady flow effects within a wide frequency range. In this context Fig. 4a shows a comparison of the power spectra of a hot-film and those of a piezofoil sensor which were measured simultaneously at $M = 0.1$ in a transitional profile flow. Both sensors show a distinct peak in the range of 580 Hz, i.e., within the range of the Tollmien-Schlichting frequency typical of this test. Comparable results can also be achieved by means of dynamic surface pressure transducers (Fig. 4b). Here data are shown for a wind-tunnel test at $M = 0.27$. They also compare well to the frequency spectrum of a hot-film.

Since each measuring technique detects different flow parameters, the relation of these parameters has to be considered when comparing the results. As an example, the results of a hot-film, a piezofoil sensor, and a CPM3 probe in a transitional profile flow at $x/c = 0.45$ and variable flow velocity are summarized in Fig. 5. While the RMS values of the hot-film and the piezofoil show their distinct RMS maximum at the beginning of transition (at approximately 23 m/s), it is here that the skin friction coefficient (CPM3 measurement) experiences its strong increase from the laminar to the turbulent level. In consequence of these effects (which are due to flow physics) a correspondence suggests a means by which test results concerning transition detection can be made comparable, indicated as a connecting line of the RMS maxima and the beginning of the c_f-increase in Fig. 5. The test results agree well when taking such a correlation into account as shown by a comparative test between infrared technique, hot-film, computational Preston tube, piezofoil, and acenaphthene technique on an airfoil wind-tunel model (Fig. 6).

Boundary-Layer Measurements

Apart from flow visualization and surface force measurements, boundary-layer measurements can also naturally be expected to provide important results to characterize laminar-turbulent flows. Contradicting this, however is, the fact that such measurements require a relatively large instrumental effort as, e.g., due to the probe traverses necessary for measuring boundary-layer profiles. For this reason such boundary-layer investigations have, up to now, only been carried out in exceptional cases and were then confined to wind-tunnel tests. Nevertheless, future laminar wing research will have to put more emphasis on this measuring task. Further developments in the field of nonintrusive boundary-layer measuring techniques, which are suitable for both wind-tunnel and flight tests, are urgently required, particularly in the field of laser Doppler anemometry.

Only a few results need to be mentioned as examples for the importance of such boundary-layer measurements. In Fig. 7, two boundary-layer profiles are shown on the suction side of a transitional profile flow and also the corresponding turbulence intensities, which were determined by means of a traversable hot wire probe. Whereas, the onset of flow instability is hardly recognizable in the boundary-layer profile, the turbulence profiles clearly show a changed intensity distribution which indicates that transition has already started. When comparing computations to experimentation, such measurements are particularly important in order to examine, e.g., the numerical simulation of transitional boundary-layer flows. An experiment that highlights this is shown in Fig. 8. It is here that the boundary-layer profiles, calculated by means of a numerical stability code (SALLY), were verified experimentally just upstream of the instability region.

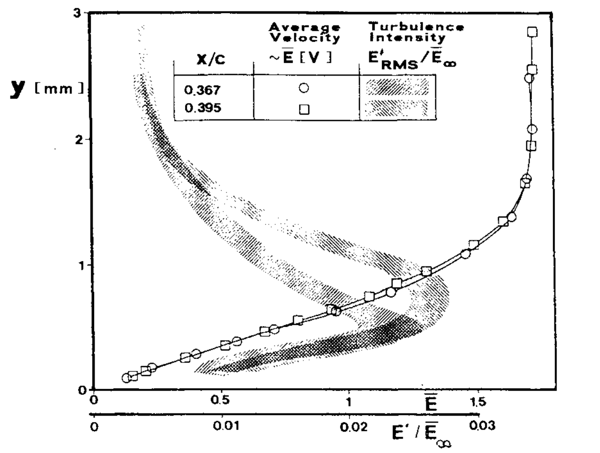

Fig. 7 Boundary layers and turbulence intensities at transition onset.

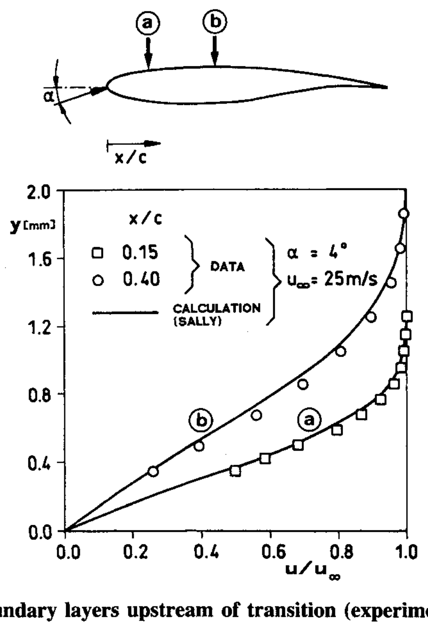

Fig. 8 Boundary layers upstream of transition (experiment-computation).

Integrative Aspects

As described above, the measuring techniques for global and detailed examination of laminar-turbulent airfoil flows constitute a solid base for the necessary experiments concerning the development of modern transonic laminar wings. As indicated, this measurement task requires (due to the complex transitional flow processes) that several measuring techniques should principally be combined. However, it must be ensured that these measuring techniques do not unduly influence each other (e.g., interference of IR photographs due to temperature-loaded sensors such as hot-films; or prelocated transition caused by nonintrusive devices such as boundary-layer probes). In each case the choice of the appropriate techniques has to be made in view of a specific verification experiment on one hand and on the other an experiment orientated more strongly towards the flow physics. Especially for the comparison with numerical calculations, the significant flow parameters like wall shear stress and boundary-layer profiles have to be measured accurately.

Apart from the flow parameters already referred to above, additional measuring parameters might also be significant in such experiments. In this context the respective pressure distribution as well as the distribution of lift and drag coefficients must certainly be mentioned, especially when talking about transonic experiments and shock control on the airfoil. The latter aspect is important insofar as a shock might lead to a destabilization of a laminar boundary layer and can endanger the design tool. In flight tests, the appropriate classical techniques (e.g., schlieren pictures) cannot be used. A promising and rather flexible method emerges with the piezo-array technique[16] as illustrated in Fig. 1 through which the shock position can be determined by detecting the shock oscillation (Fig. 9). With the development of hybrid laminar flow concepts, further requirements concerning measurements are also expected. It is here that suction control must not be forgotten;

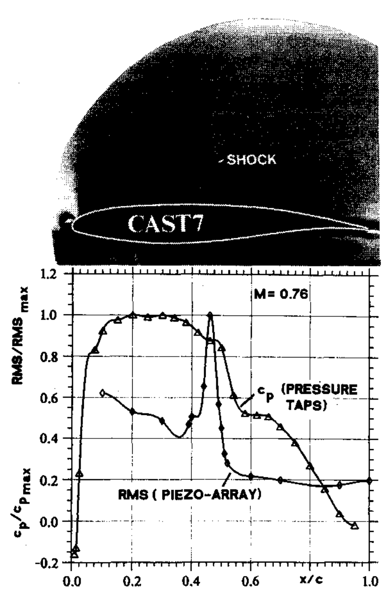

Fig. 9 Shock detection by means of a piezo array.

through which the suction rate required can be controlled in the design phase as well as in practical application. Especially in this field, developments with regard to measuring physics have to be improved and there remains a great need for further development.

Wind-Tunnel and Flight Experiments

Most of the measuring techniques discussed in the previous chapter were examined in the course of German national research programs ("Transonic Laminar Flow" TLF-program of Deutsche Airbus, "Measuring Techniques for Laminar Airfoils" MTLA-program of universities) with regard to their practical applicability to wind-tunnel and flight tests. Some of the results obtained are to be summarized in the following sections. As for the applications, the main emphasis lies in the field of transition detection and the registration of characteristic surface forces (steady/unsteady) by means of surface probes.

Transition Detection on Laminar Wings

In the course of the TLF program, practical tests concerning transition detection were carried out in wind-tunnel (DNW, S1) as well as flight tests (VFW 614-ATTAS). In both cases a laminar glove was used which was mounted on a 1:2 scale wind-tunnel model (Fig. 10) and the aircraft wing, respectively (Fig. 11). Parallel to this, extensive wind-tunnel experiments were carried out in the course of the MTLA program in university-, DLR-, and industrial wind tunnels, as well as first-flight tests which were carried out on a G 109 motor glider (in cooperation with TH Darmstadt). In Fig. 12, the analysis of two ATTAS flight tests shows a first example of the efficiency of the infrared technique regarding transition detection (also see Fig. 2). These tests were carried out under the responsibility of the DLR Braunschweig. Above all, the differences between Tollmien-Schlichting instability (TSI) and cross flow-induced instability (QSI) are clearly recognizable. In each case these differences (depending on the respective flight condition) lead to a characteristic course of transition on the upper wing surface. Apart from that, a number of distinct turbulent wedges can be clearly distinguished, which are partly due to additional measuring devices (hot-film probes, pressure taps) and significantly influence the flowfield in these regions.

Figure 13 shows two results which are typical of transition detection by means of a piezofoil array. While Fig. 13a describes a wind-tunnel test on a TLF model at $M = 0.47$, the results of a G 109 flight test are shown in Fig. 13b. In each case the transition region is clearly indicated by the strong increase in the RMS values of the foil sensors. In contrast to wind-tunnel measurements, the strong decrease in RMS values downstream of the transition region is striking. This decrease could be due to the much smaller turbulence intensity of the flow in flight tests (stagnant air).

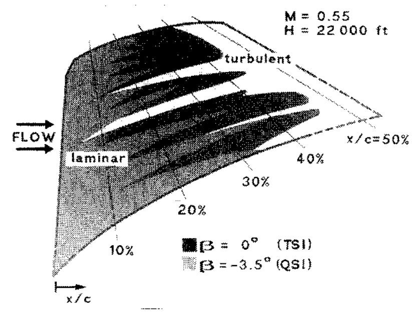

Fig. 12 IR-image results of ATTAS flight tests (DLR Braunschweig).

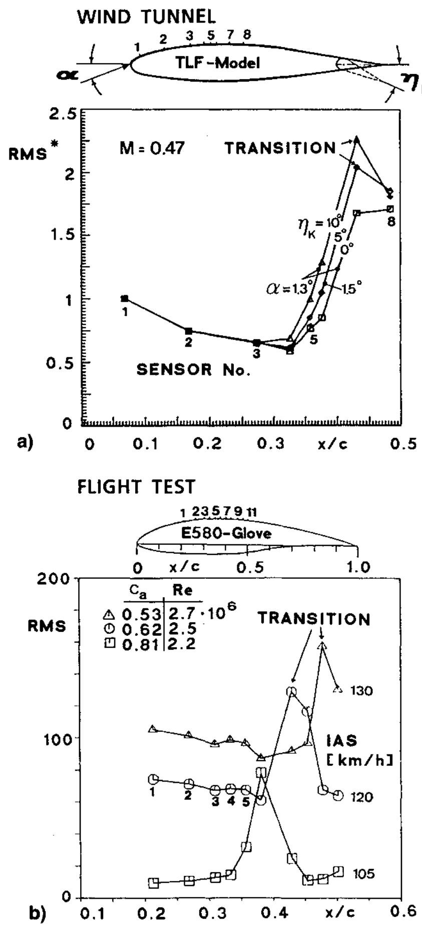

Fig. 13 Piezo-array results in wind-tunnel and flight test.

Fig. 10 Large-scale TLF-test rig with glove in the S1 tunnel.

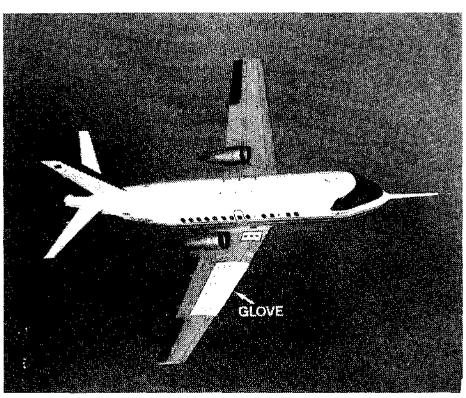

Fig. 11 ATTAS flying test bed with glove.

In Fig. 14 comparable results between the analysis of IR images and that of a piezofoil array is shown from a DNW-/S1 measuring campaign on the TLF test rig. Here the positions of transition are described as a function of the geometrical angle of attack. It is obvious that within a bandwidth due to measuring uncertainty the position of boundary-layer transition corresponds well in the two wind-tunnel tests. It may be clearly distinguished that the piezo array in the case of crossflow-induced transition (negative angles of attack) detects the onset of flow instabilities as early as upstream of the boundary-layer transition—something which could already be derived from Fig. 5—unlike the IR image.

The possibilities of comparing such array measurements to IR photographs according to Fig. 2 or 12 are limited if, as is the case in the measurements shown in Fig. 14 with a sensor structure according to Fig. 1, the line array is confined to a fixed span position. The extension of the piezofoil technique to distributed sensor arrays does not in general raise a problem. This is shown in Fig. 15 for a wind-tunnel experiment with a 6 × 6 matrix array. The number of sensors can be increased at random, and a distributed transition detection can be made. By means of such sensor arrays transition, detection will then provide results which are also comparable to IR photographs. The results summarized at the bottom of Fig. 15 show a series of tests in which the position of transition on a NACA 0012 profile (c = 800 mm) was changed by varying the angle of attack (a and b) and it was also partly prelocated by means of an artificial disturbance at $y/b = 0.35$ (Fig. 15c). Clearly the piezo array detects the general two-dimensional- and three-dimensional-development of transition of evaluating the RMS values of all sensors.

Surface Forces

As discussed previously, measuring steady and unsteady surface forces makes it possible to give detailed information about the position of transition as well as the local conditions of transition. As an example of such measurements the wall shear stresses directly measured by means of the CPM3 method on the TLF test airfoil (S1 campaign) at $x/c = 0.3$ are compiled in Fig. 16 as a function of the angle of attack and the Mach number. In this diagram, the laminar flow regions (low-wall shear stress) and the turbulent flow regions (high-wall shear stress) are clearly recognizable. So a rather good survey on the actual flow conditions is obtained from this selective measurement, which also offers quite interesting possibilities of comparison with, for example, numerical calculations. Figure 17 shows a further comparison of the positions of transition (following from these wall shear stress measurements) with the results of the IR technique, using the DNW/S1 measuring series as an example. As in Fig. 14, the two measuring techniques also correspond well here.

Some results of the CPM3 method obtained in a flight test are shown compared with a numerical calculation in Fig. 18. These tests were carried out on the G 109 glove by means of

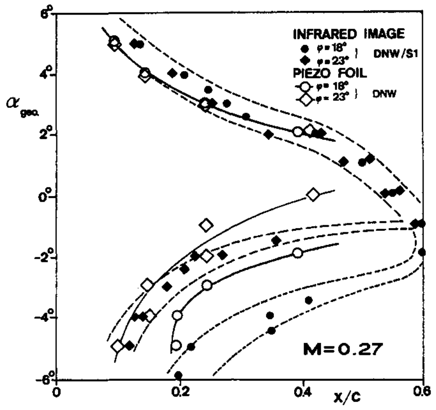

Fig. 14 Comparison of IR-image and piezo-array results (DNW/S1 campaign).

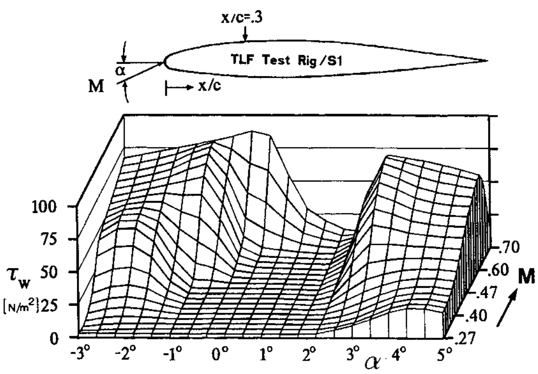

Fig. 16 Local skin friction dependent on Mach number and attack angle (CPM3 results/S1 campaign).

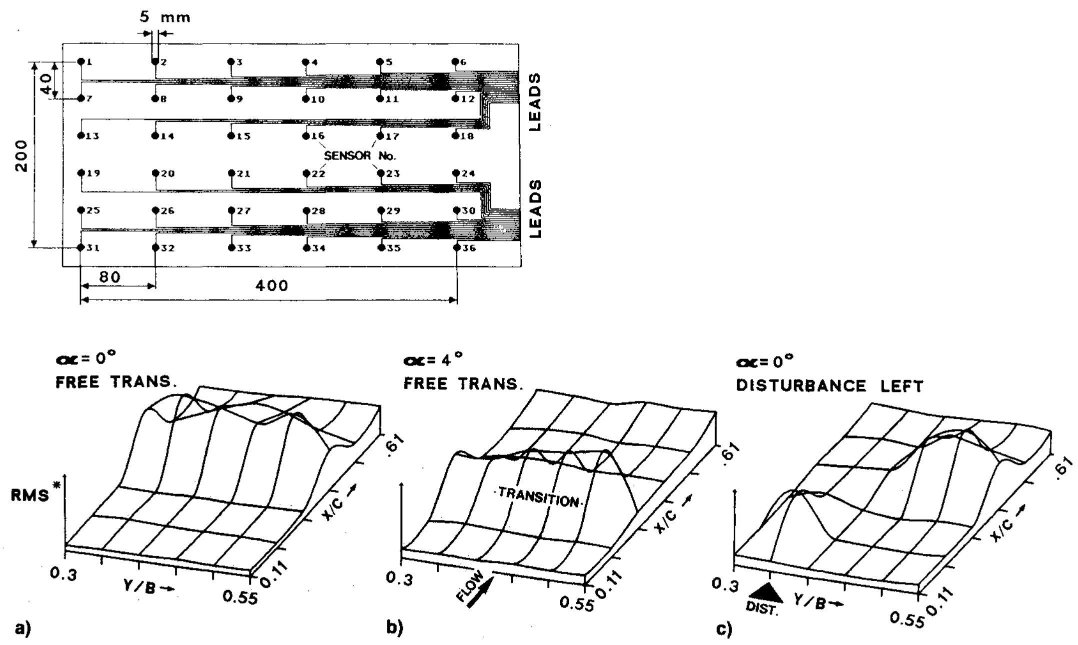

Fig. 15 Piezofoil matrix array on a NACA 0012 test wing and two-dimensional transition detection.

a stepping motor driven CPM3 probe, i.e., the probe could be moved along the profile chord by means of a traversable device integrated into the glove. The test results shown in Fig. 18 provide interesting data, e.g., a distinct relocation of the boundary-layer transition when compared to that of the computation.

For the example of a piezo-array measurement, an analysis of a wind-tunnel test regarding unsteady surface forces in a transitional profile flow is shown in Fig. 19. In this test the foil signals that were measured simultaneously at six x/c positions are summarized. In the beginning the top line always

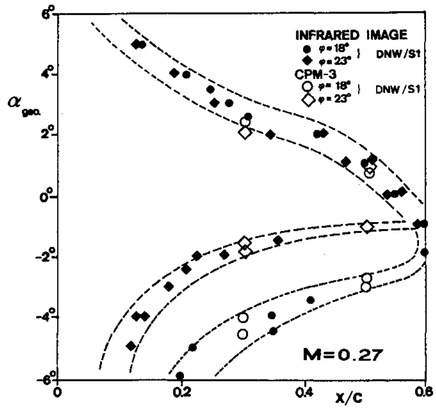

Fig. 17 Comparison of IR-image and CPM3 results (DNW/S1 campaign).

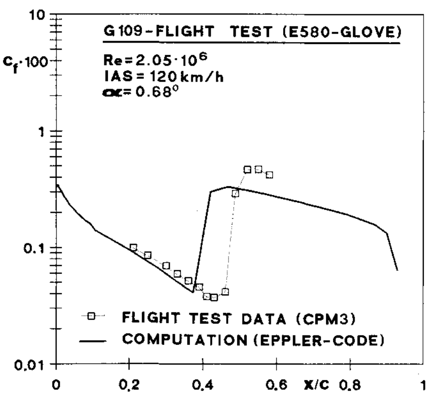

Fig. 18 Comparison of CPM3 flight-test results and skin friction computations.

shows the respective traces over 100 ms. It becomes obvious from the strongly increasing amplitudes that the transition onset starts between $x/c = 0.38$ and $x/c = 0.4$. In the second line the corresponding power spectra are shown which have, for $x/c = 0.36$ up to $x/c = 0.42$, a distinct peak in the range of the Tollmien-Schlichting frequency ($f \simeq 1000$ Hz). These TS waves are also found in the corresponding traces (see detail). Most importantly they illustrate the piezo sensors high sensitivity to amplification processes in a transitional flow. Further possibilities of analyzing the foil signals, (which can also be used for characterizing transition) are shown in the third [probability density function (PDF)] and the fourth line (vectorial plots of two neighboring sensors in the form of orbits). Whereas, the PDF clearly indicates the onset of transition due to its increasing skewness in the range of $0.38 < x/c < 0.42$, and due to its typical two-peak distribution (laminar and turbulent parts of boundary layer flow) in the middle of the transition region ($x/c = 0.48$), the respective orbits directly show the onset of turbulence.

A more detailed analysis of a piezo-array test with regard to the detection of flow instabilities is shown in Fig. 20. First of all the power spectra measured by means of a highly sensitive amplifier system at seven chordwise positions are shown in Fig. 20a. In the frequency range of flow instabilities ($800 < f < 1200$ Hz), they show a strong increase in amplitude. These amplitude amplifications were achieved in a frequency selected manner from these power spectra. After having calibrated the basic amplitude A_0 by means of a numerical stability calculation, the amplitude ratio A/A_0 and, following from $N = \ln A/A_0$, the N-factors of the amplification were calculated. As shown in Fig. 20b, these N-factors that are dependent on frequency compare quite well with the computations (SALLY code), although it has not yet been possible to detect the range of smaller N-factors here which, under certain circumstances, can be decisive for the physics of transition.

Relating to the examples, the investigations concerning characteristic unsteady surface forces will have to be confined to the application of the piezofoil technique. Comparable results can also be obtained by means of, e.g., hot-film probes, see Refs. 6, 17, and 18. However, the advantage of the piezofoil certainly lies in the sensors flexibility with regard to the shape and structure. In addition, piezofoil arrays produce less interferences in a laminar flow. The electronic effort diminishes in comparison to hot-film measurements, since the foil is an active transducer which needs less supporting electronics (only micro-amplifiers but no electronic bridges).

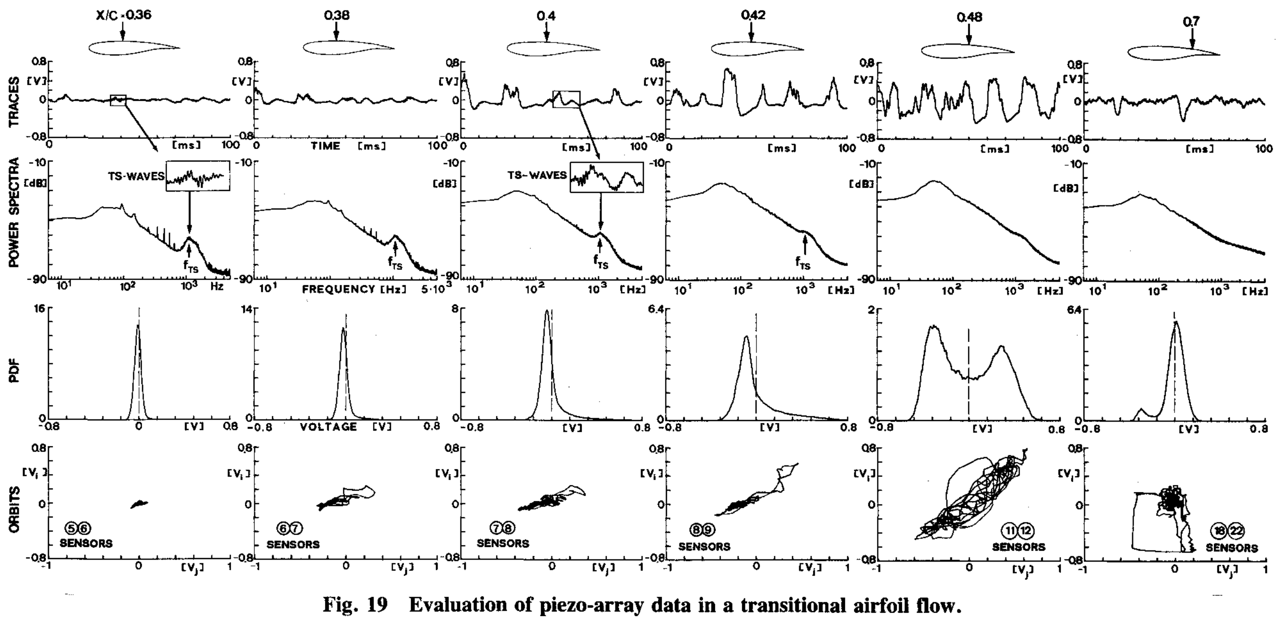

Fig. 19 Evaluation of piezo-array data in a transitional airfoil flow.

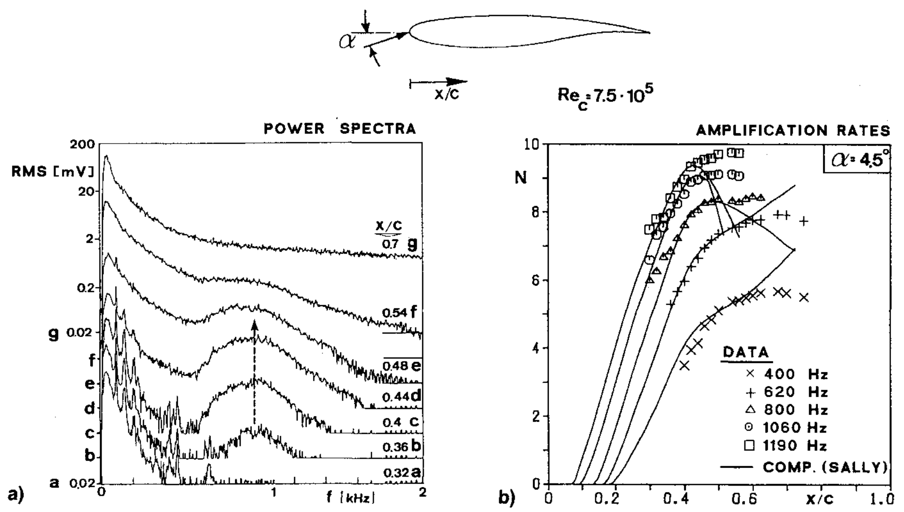

Fig. 20 Flow amplifications and *N*-factors in the course of transition. Piezo-array results compared with computations.

Concluding Remarks

The results of various measuring techniques for laminar wing testing outlined in this article indicate their potential but also state clear requirements for further improvement and development. The situation is different for wind-tunnel and flight testing. In wind-tunnel experiments, a number of measuring techniques have been successfully demonstrated for transition detection and detailed boundary-layer investigations. Less progress has been made in flight tests, indeed, the development steps from pure qualitative measurements to quantitative methods are still the exception.

Despite the overall positive results for wind-tunnel measuring methods, further research is needed to account for the tough environment in industrial wind-tunnel testing and to adapt the techniques developed in the laboratory. This is necessary, e.g., for the entire field of nonintrusive boundary layer and flowfield measuring methods like LDA and L2F. Up to now they have not been included in standard laminar wing testing procedures.

Furthermore, there is also a lack of surface sensors giving quantitative information on the details of strongly three-dimensional shear layers and transition effects like cross-flow instabilities over larger wing areas. Promising developments can be seen in hot-film arrays as well as in the piezofoil array technique. Because the instabilities in laminar boundary layers are of prime importance in order to validate corresponding theoretical analysis, these sensors will hopefully be able to meet the performance expectations in the near future.

In flight test only a few advanced measuring techniques have been employed up to now, even though these experiments will decide the successful laminar wing concept in the end. This discrepancy is partly due to traditional strategies in which only airfoil and wing data from wind-tunnel experiments were used to predict flight performance. In contrast to the wind tunnel, a flight experiment has to take place under extreme conditions due to the flow physics, the environmental effects, the limited space for electronic equipment, and with limited energy on board the aircraft. Furthermore, flight tests are inevitably more expensive, they are less able to be repeated, are less accurate (at least they were in the past), and also the possibility of independent parameter variation available in a wind-tunnel experiment cannot be offered. Nevertheless, the laminar flow concept requires flight testing, and therefore, advanced high-quality measuring techniques, and further research activities.

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References

[1]Wagner, R. D., Maddalon, D. V., Barlett, D. W., and Collier, F. S., "Fifty Years of Laminar Flow Flight Testing," *Proceedings of the Aerospace Technology Conference and Exposition*, SAE-Paper 881393, 1989, pp. 1.195–1.1019.

[2]Dziomba, B., Henke, R., Münch, F. X., and Szodruch, J., "Laminar Wing Testing Techniques in Wind Tunnel and Flight," International Congress on Instrumentation in Aerospace Simulation Facilities '89, Göttingen, Germany, 1989.

[3]Körner, H., "Natural Laminar Flow Research for Subsonic Transport Aircraft in the FRG," *Zeitschrift Flugwissenschaft und Weltraumforschung*, Vol. 14, No. 4, 1990, pp. 223–232.

[4]Hippensteele, S. A., Russell, L. M., and Torres, F. J., "Use of Liquid-Crystal, Heater Element Composite for Quantitative, High-Resolution Heat Transfer Coefficients on a Turbine Airfoil, Including Turbulence and Surface Roughness Elements," NASA TM 87355, May 1987.

[5]Johnson, C. B., and Carraway, D. L., "A Transition Detection Study at Mach 1.5, 2.0 and 2.5 Using a Micro-Thin Hot Film System," *International Congress on Instrumentation in Aerospace Simulation Facilities '89 Record*, IEEE, New York, Sept. 1989, pp. 443–449.

[6]Feyzi, F., Kornberger, M., Rachor, N., and Ilk, B., "Development of Two Multi-Sensor Hot-Film Measuring Techniques for Free-Flight Experiments," *International Congress on Instrumentation on Aerospace Simulation Facilities '89 Record*, IEEE, New York, Sept. 1989, pp. 443–449.

[7]Nitsche, W., Mirow, P., and Szodruch, J., "Piezoelectric Foils as a Means of Sensing Unsteady Surface Forces," *Experiments in Fluids*, Vol. 7, 1989, pp. 111–118.

[8]Nitsche, W., Mirow, P., and Dörfler, T., "Investigations on Flow Instabilities on Airfoils by Means of Piezofoil-Arrays," *Laminar Turbulent Transition*, Springer-Verlag, New York, 1990, pp. 130–135.

[9]Nitsche, W., Thünker, R., and Haberland, C., "Comparative Investigations on Friction Drag Measuring Techniques in Experimental Aerodynamics," *Proceedings of the 14th Congress of the International Council of the Aeronautical Sciences*, Vol. 1, ICAS/AIAA, New York, Sept. 1984, pp. 391–403.

[10]Monson, D. J., "A Non-Intrusive Laser Interferometer Method for Measurement Skin Friction," *Experiments in Fluids*, Vol. 1, 1983, pp. 15–22.

[11]Nguyen, V. D., et al., "The Determination of Turbulent Skin Friction Behind Flat Plate Turbulence Manipulators Using Servo-Controlled Balances," *Proceedings of the 14th Congress of the International Council of the Aeronautical Sciences*, Vol. 1, ICAS/AIAA, New York, 1984, pp. 404–409.

[12]Nitsche, W., Thünker, R., and Haberland, C., "A Computational Preston Tube Method," *Turbulent Shear Flows 4*, Springer-Verlag, New York, 1985, pp. 261–276.

[13]Weiser, N., Mirow, P., and Nitsche, W., "Statische und Dyna-

mische Meß-verfahren zur Transitionsbestimmung an Laminarflügeln," *DGLR-Jahrbuch I*, Deutsche Gesellschaft für Luft- und Raumfahrt, Bonn, Germany, 1989, pp. 427–434.

[14]Ewald, B., Durst, F., Krause, E., and Nitsche, W., "Flugmeßtechnik für die Laminarflügelentwicklung," *DGLR-Jahrbuch III*, Deutsche Gesellschaft für Luft- und Raumfahrt, Bonn, Germany, 1990, pp. 1261–1273.

[15]Gaudet, L., and Gell, T. G., "Use of Liquid Crystals for Qualitative and Quantitative 2-D-Studies of Transition and Skin Friction," *International Congress on Instrumentation in Aerospace Simulation Facilities '89 Record*, IEEE, New York, 1989, pp. 66–81.

[16]Nitsche, W., Swoboda, M., and Mirow, P., "Shock Detection by Means of Piezofoils," *Zeitschrift Flugwissenschaft und Weltraumforschung*, Vol. 15, No. 4, 1991, pp. 223–226.

[17]Meier, H. U., Michel, U., and Kreplin, H. P., "The Influence of Wind Tunnel Turbulence on the Boundary Layer Transition," *Perspectives in Turbulence Studies*, Springer-Verlag, Berlin, 1987, pp. 26–46.

[18]Kreplin, H. P., and Höhler, G., "Oberflächenheißfilmmessungen am ATTAS-Laminarhandschuh im Freiflug und Windkanal," *DGLR-Jahrbuch II*, Deutsche Gesellschaft für Luft- und Raumfahrt, Bonn, Germany, 1990, pp. 903–910.