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CONCEPTS AND RESULTS FOR LAMINAR FLOW RESEARCH IN WIND TUNNEL AND FLIGHT EXPERIMENTS

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ABSTRACT

The need for advanced technologies for civil transport aircraft requires intensive research activities. The introduction of a laminar flow wing for future aircraft is expected to reduce the fuel consumption up to 20%. The exploitation of this rather large potential in performance improvement requires the collaboration of industry, research establishments and universities. They are all involved in cooperative national and European research programs in order to prepare theoretical and experimental tools.

Within experimental aerodynamic concepts of testing and measuring techniques have been developed and realized. The aim was to perform high quality experiments with results of great detail and resolution which can be used for theoretical code development and verification as well as for design criteria.

The present paper reports on selection, adaptation and integration of advanced measuring techniques for laminar wing testing. Results from various wind tunnel and flight tests support and confirm the quality and potential of the employed testing techniques. Reference is made to future developments in measuring techniques with respect to applications in performance and suction control systems on aircraft in service.

List of Symbols

b	span
c	chord
c_f	skin friction coefficient
c_p	pressure coefficient
f	frequency
M	Mach number
N	amplification factor
p	pressure
p'	pressure fluctuation
PDF	Probability Density Function
Re	Reynolds number
RMS	Root Mean Square value
t	time
u	velocity
$U_{i,j}$	voltages
$V_{i,j}$	voltages
x,y	coordinates
α	attack angle
τ_w	wall shear stress
ψ	sweep angle

Indices

w	wall
θ	displacement thickness
∞	free stram condition

1. Introduction

Forecasts about the future civil transport aircraft market have already generated an increased competition between aircraft manufacturers. In order to remain successful, aircraft efficiency, safety and comfort must be improved further by employing new technologies. But also restrictions due to environmental limitations have to be observed and solutions developed. It is for all these problems that the classical field of aerodynamics can contribute essentially including rather high performance.

Designing a wing for a commercial aircraft is a complex process that entails finding a wide variety of optimum compromises between conflicting criteria and constraints from the other aircraft-engineering disciplines. Alone, to begin with the complex process of harmonizing the aerodynamic parameters involves a number of iterative steps and necessitates a relatively long developmental time.

Given lead times like these in development and the long service of the aircraft (20 to 30 years), clearly technology has to be improved now, in order to remain internationally competitive up to 2020. These calculations do not include the years of important basic research which must precede pre-development in industry.

This is why all available resources must be exploited to ensure the success of new technologies. The long developmental times are also due to the advanced state of modern technology, the conditions in the industry, the high safety requirements and finally the complexity of the overall system usually refered to as an "aircraft".

These aspects of development time make it necessary that the successful aircraft manufacturer must employ a research strategy for short-, medium- and long-term needs. Market forecasts, different scenarios of competition as well as factors decreasing or endanger the market growth like air traffic have to be accounted for. Thus the main direction of aerodynamic development can be deduced. The concepts necessarily focus on subsonic transport aircraft and in long- and very long-term view include the next generation of supersonic aircraft as well as hypersonic transport.

The aerodynamic technologies are only then fully utilized when their overall integration can be achieved. Furthermore the realization of these aerodynamic concepts is only possible in close cooperation with other disciplines as for example materials (composites), structures and new control and actuator systems.

Major aerodynamic research programs have been defined as following: Wing configuration control (variable camber, wing-engine integration), boundary layer control (laminarized wing, turbulence management, shock-boundary layer control) and due to the future importance, also high-lift configuration control [1 to 3].
Within these research programs the tools of the aerodynamicist as well as experimental and measuring techniques have to be advanced [4]. More sophisticated aerodynamic designs require more detailed knowledge about the flow field which can partly be obtained by CFD. Nevertheless it remains mainly the domain of experimental aerodynamics. Thus improved or new sensor techniques will be required for basic research, development in industrial wind tunnels, in experimental flight testing and for future wing technologies also during the operational life of an aircraft [5]. This situation is the background for the present paper which concentrates on measuring technique concepts and their results in laminar flow research. Laminar flow technology is briefly reviewed since work in this field initiated major achievements in testing techniques during the past years.

Finding new measuring methods, advanced sensors or data processing is only the first step. The integration and adaptation of advanced measuring techniques in research programs and industrial application are equally important. Examples of successful methods are given on the basis of various wind tunnel and flight experiments. The paper concludes with future laminar flow research, utilization of the technology at hand and the required experimental tools.

2. Laminar Flow Research Concepts

One of the major potentials for aircraft improvement is the reduction of drag. Since various drag reduction technologies have proved to be beneficial, these concepts have inspired research for several decades. The major aim is fuel burn saving in order to reduce costs and pollution, to extend flight range, or to increase payload. Aircraft drag breakdown, Fig. 1 shows that the largest contributor to total drag is skin friction because of air viscosity. Laminarizing the wing up to 50 % or 60 % of the chord may result in about 15 % of total aircraft drag reduction. Thus the laminar flow concept offers the greatest potential of any single technololgy in aircraft improvement.

The idea of laminarizing aircraft components, mainly the wing is as old as the beginning of flight. Fifty years of research in this field have passed [6]. However, it is only now that due to advances in aerodynamics and other aircraft disciplines that the introduction of transonic laminar flow wings for next generation of transport aircraft seems at all possible. In order to achieve this aim continuous and concentrated research programs are needed covering basic research, application-oriented investigations and operational as well as manufacturing aspects. In order to find answers to the numerous problems that arise in these areas well adapted, high-quality measuring techniques are desperately needed.

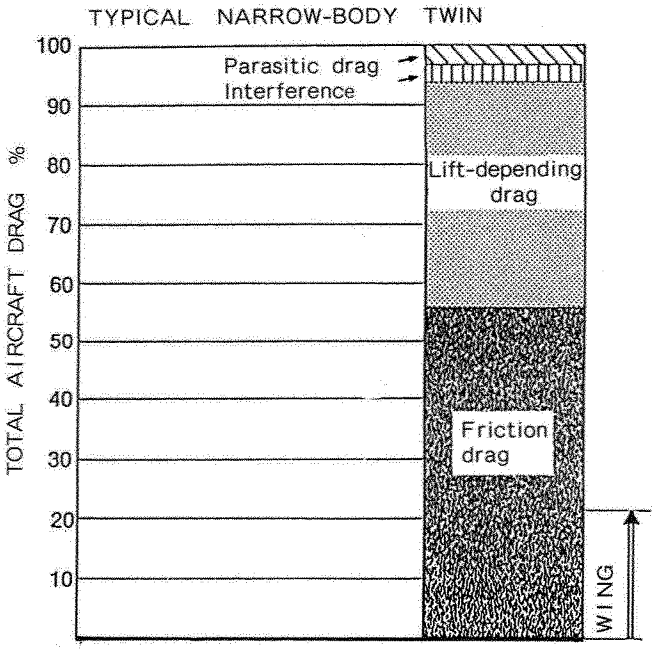


Figure 1: Aircraft drag

The boundary between laminar and turbulent wing flows can be plotted by using the three main parameters leading edge sweep angle, chord Reynolds number and nose radius, Fig. 2. This figure shows that depending on the parameters three instability modes are responsible for the transition of the boundary layer: 1. attachment line contamination as defined by a criterium by Pfenninger/Poll, 2. longitudinal instabilities as described by Tollmien and Schlichting and 3. cross-flow instabilities. The basic physics of disturbed boundary layer flows specially concerning swept wings where cross-flow instabilities and their interaction with other instability modes occur are not fully understood.

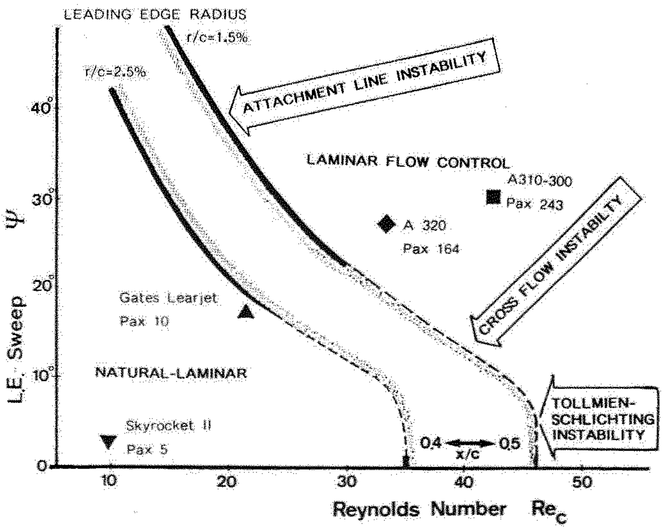


Figure 2: Boundaries for laminarization

The design areas to the right and left of the transition boundary in Fig. 2 also represent different concepts in achieving laminar flow. On the left, the laminar region, natural laminar flow could be realized by shaping the airfoil and the wing geometry accordingly. The area on the right needs active manipulation of the boundary layer flow in order to maintain laminar flow. Suction at the right location and at adequate magnitude can stabilize the disturbed boundary layer and keep it laminar over a considerable wing area. Wings of smaller transport aircraft up to about 120 passengers can be laminarized through natural laminar flow concepts. Larger aircrafts of Airbus size with wings of higher sweep angles and larger chord Reynolds numbers need active devices like suction systems at least at the leading edges to achieve larger laminar areas.

In order to tackle the problems associated with laminarizing transport aircraft Germany started 1985/86 a national research program on transonic laminar wing technology. In an unprecendented manner industry, the DLR's and a number of universities participated in this coherent, collaborative activity. The strategy was to follow a three phase program which would in the end enable industry to incorporate natural laminar wings in their next transport aircraft design, Fig. 3. The first phase has been conducted successfully and important contributions to laminar flow research and application have resulted:

- natural laminar flow of more than 50 % wing chord at Reynolds numbers up to $30 \cdot 10^6$ and Mach numbers up to $M = 0.7$ was achieved on the VFW614-ATTAS aircraft
- a first correlation between wind tunnel and flight experiments at the same Reynolds and Mach numbers was carried out
- design criteria and boundaries for natural laminar flows were established
- theoretical and experimental tools/methods were developed and validated with wind tunnel and flight tests
- first tests with a fluidic de-contamination system were completed
- knowledge concerning the requirements of surface quality was gained.

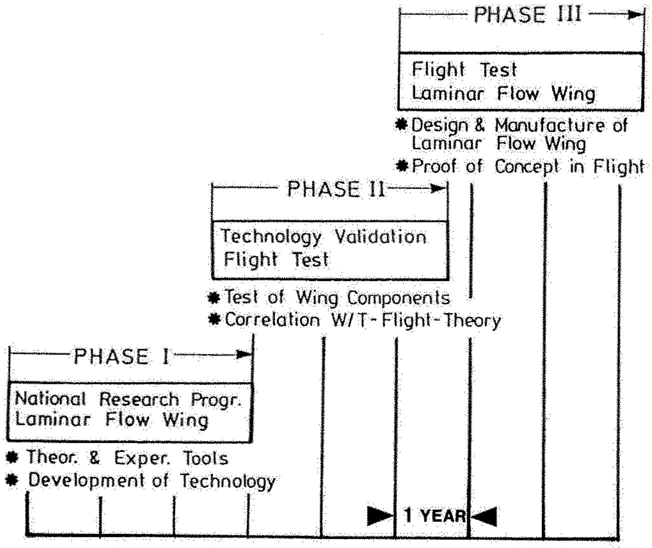


Figure 3: Program schedule for transonic laminar wing

These results were so promising and of such high qualitity that the next phase, mainly proving the technology for performance- and handling-characteristics for laminar wing designs can be begun on a sound basis. It has also been shown that without well-proven measuring techniques and without the development of new measuring methods and sensors as an investment for the future the full potential of laminar flow cannot be utilized when applied to the next generation of transport aircraft.

3. Integration And Adaption of Advanced Measuring Techniques

Compared to for example classical airfoil/wing experiments, the experimental verification of laminar wing concepts requires that the application of all kinds of boundary-layer testing methods is dramatically increased. Pressure and force measurements which have dominated traditional experiments up to now also 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 rather sporadically have they thus been used in, for example, free flight tests [5, 6]. Potential measuring techniques with regard to special applications in the field of laminar wing research are therefore to be discussed in the following.

3.1 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 because classical methods of flow visualization (for example, by means of surface patterns) are too inflexible (under variable test conditions) and not applicable in flight tests at all. Methods developed recently, such as the liquid crystal foil technique [7] or the infrared image technique [8], have already shown great improvement. The two technologies are based on measurements detecting variable wall temperatures in the transition region (which are due to different heat transfer characteristics of laminar and turbulent flows, respectively). Apart from the respective electronic effort, these methods in particular usually require an artificial structure heating in order to maintain the differences in wall temperature between laminar and turbulent flow regions and so make them detectable. It is especially on large wind tunnel models and, more important in flight tests, that these instrumental boundary conditions can cause serious problems. 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 attained in a relatively short time. This, however, is only restrictedly possible by means of any kind of discrete wall sensors [5].

An important progress is also achieved in the development of non-intrusive/less intrusive wall sensors, for example by the recent developmental work in the field of hot-film arrays [9, 10] or the piezo array technique [11, 12]. Both measuring techniques - shown for a 24 sensor piezofoil array on a wind tunnel model in Fig. 4 - are directly mounted on the airfoil surface and selectively detect - in a simple, purely qualitative signal analysis - the heat transfers (HF) and pressure and temperature fluctuations (PF) respectively, which

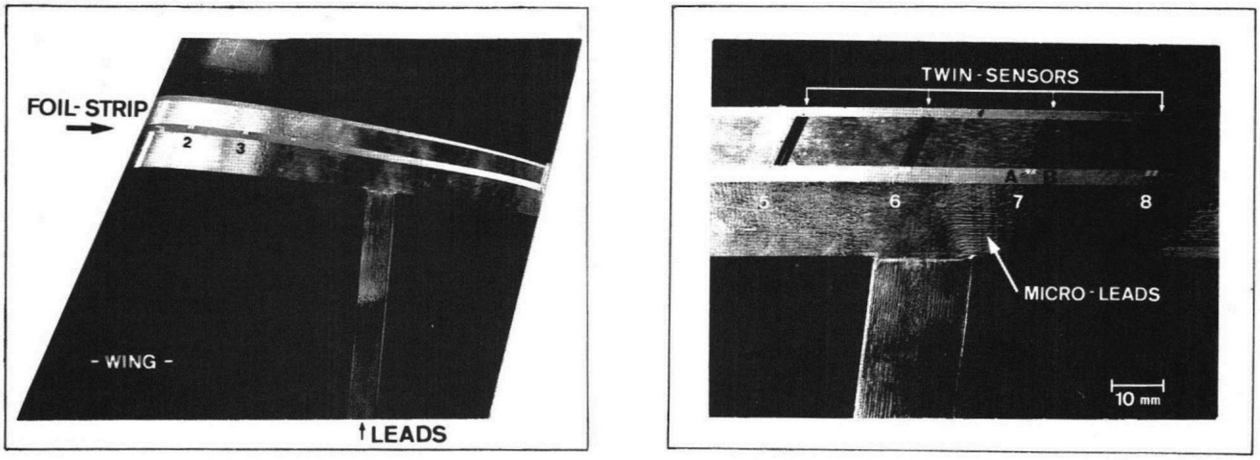


Figure 4: Piezofoil-array on a wind tunnel model

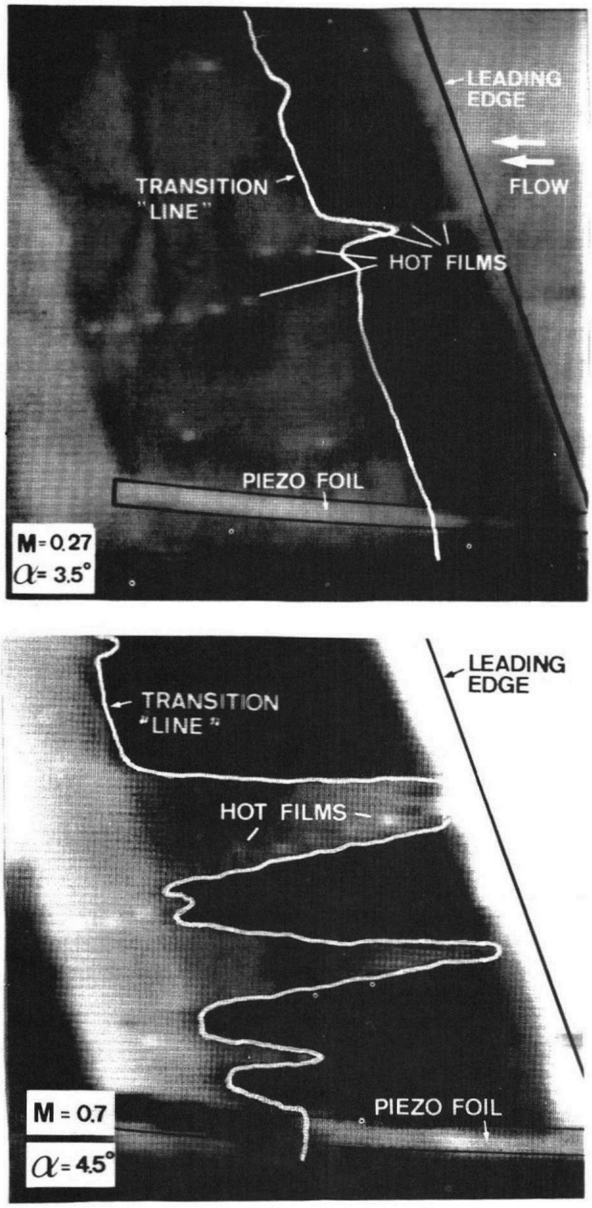


Figure 5: Infrared images of a laminar-turbulent flow on an airfoil

vary significantly in the course of boundary-layer transition. Subsequently they also enable authentic statements about laminar, transitional and turbulent flow regions. Therefore combined applications of the IR technique and the array techniques mentioned above could be of particular interest in airfoil investigations. It is there that the discrete sensor results can be applied in order to calibrate grey steps of an IR image on one hand, whereas, on the other, the IR figures help to detect possible flow disturbances by means of surface sensors. Fig. 5 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 clearly visible, the non-intrusion of the piezofoil array and the prelocated transition in the region of the hot-film array can be specifically recognized.

3.2 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 especially applies 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 here since the laminarization that has been strived for particularly aims at reducing this parameter drastically. Unfortunately, it is comparatively difficult even under laboratory conditions to determine this particular measurement quantity [13]. Experimentalists face serious problems when carrying out complex shear stress investigations concerning airfoils. The hot-film technique, for example, which is a most successful technique in laboratory experiments, only produces reliable wall shear stress results if appropiate in situ calibration techniques are additionally provided. Other techniques such as the laser interferometer method [14] or the application of direct skin friction balance devices [15] seem to be less promising, due to their great technical effort and limited application, respectively.

The computational Preston tube method (CPM) [16] which, by means of a numerical boundary-layer approximation of the near wall flow, determines the

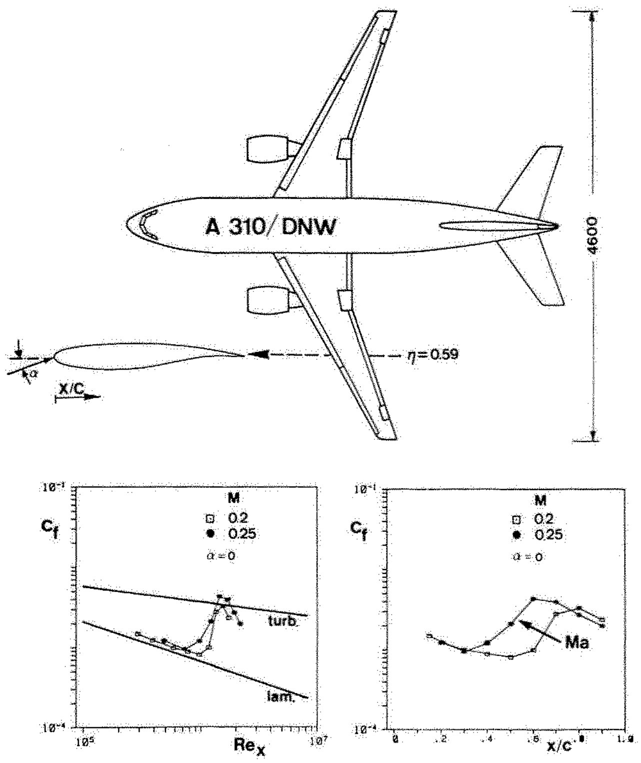


Figure 6: Skin friction distribution on a wing (CPM results)

wall shear stress from the dynamic pressures of three different sized wall mounted miniature pitot tubes, is one of the few measuring techniques which without calibration can be used immediately for direct and absolute measurements of the local wall friction. This method has already been tested thoroughly in numerous wind tunnel and free flight experiments [5, 17] Fig. 6. It is not however considered as a non-intrusive technique. Nevertheless, the CPM method can be applied rather successfully for certain tasks, for example, the calibration of other, less intrusive techniques such as hot-film probes. Another more promising technique for detecting laminar-turbulent wall shear stress distributions has emerged with the development of shear sensitive liquid crystals [18]. However, due to its great effort (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 transitional profile flows. This is the immediate consequence of the unsteady character of flow instabilities (Tollmien-Schlichting waves or cross flow instabilities) which are not only important for understanding the underlying physics of transition processes 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 piezo foil sensors are particularily suited for such investigations since both of them are able to safely detect unsteady flow effects within wide ranges of frequency. In this context Fig. 7a shows a comparison of the power spectra of a hot-film and those of a piezofoil sensor which were measured simultanously at M = 0.1 in a transitional profile flow. The two sensors show a distinct maximum 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. 7b. 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 CPM probe in a transitional profile flow at x/c = 0.45 and

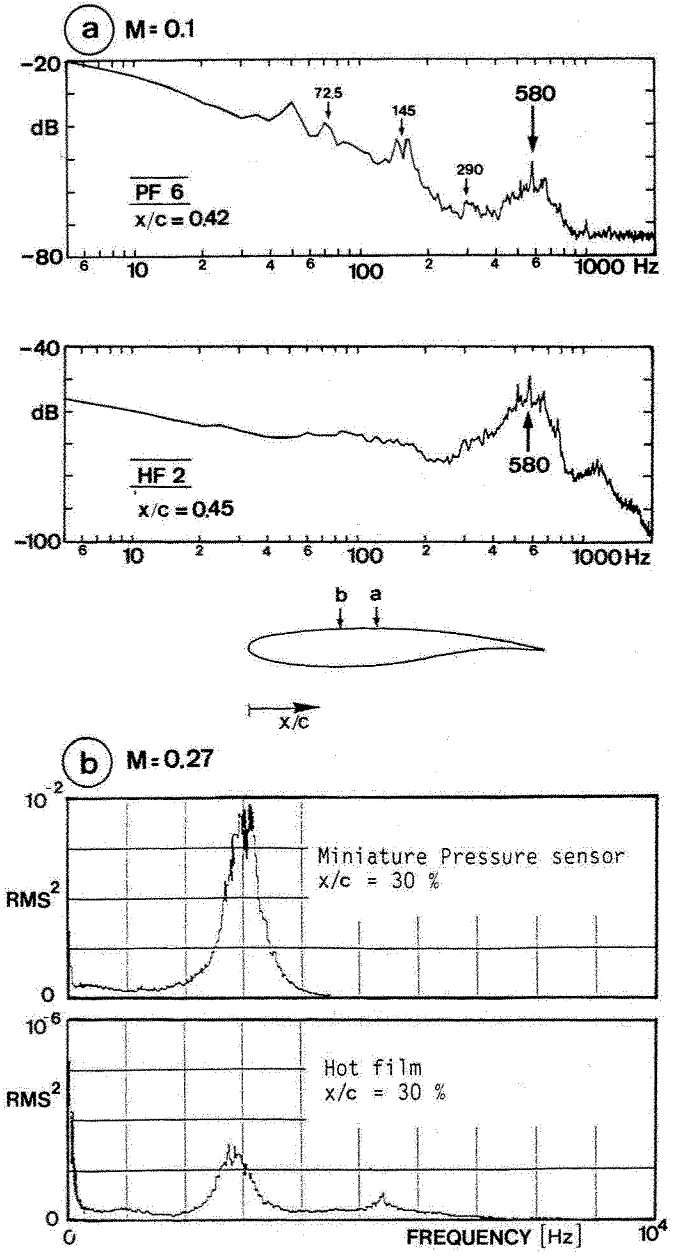


Figure 7: Power spectra and TS-instabilities
a) piezofoil and hot-film
b) pressure transducer and hot-film

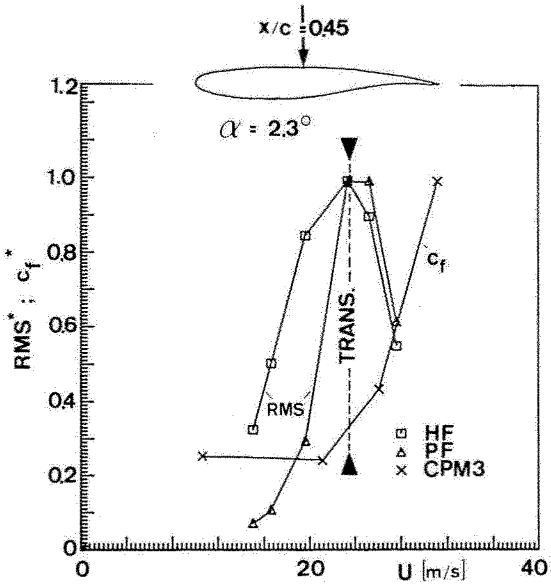


Figure 8: Hot-film, piezofoil and CPM results in transition

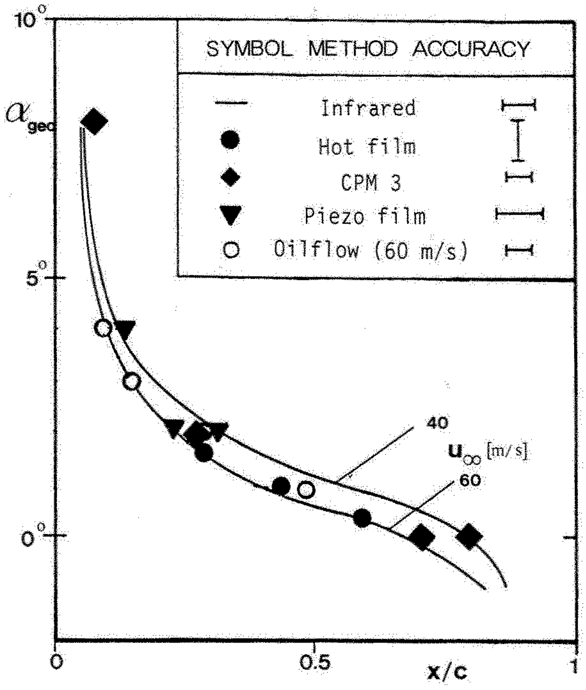


Figure 9: Comparison of IR-image, hot-film and CPM results on an airfoil

variable flow velocity are summarized in Fig. 8: While the RMS values of the hot-film and the piezofoil show their distinct RMS maximum at the beginning of transition (at approximately 23m/s), it is there that the skin friction coefficient (CPM measurement) experiences its strong increase from laminar to turbulent level. In consequence of these effects, which are due to flow physics, a correspondence suggests itself by means of 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. 8. Taking such a correspondence into account the test results agree well as shown by a comparative test between infrared technique, hot-film, Computational Preston tube, piezo foil and acenaphthene technique on an airfoil wind tunnel model, Fig 9.

3.3 Boundary-layer Measurements

Apart from flow visualization and surface forces measurements, boundary-layer measurements can naturally also be expected to provide important results to characterize laminar-turbulent flows. Contradictory to this, is, however the fact that such measurements require a relatively great instrumental effort, for example due to the probe traversings 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. Still future laminar wing research will have to put more emphasis on this measuring task. Further developments in the field of non-intrusive boundary-layer measuring techniques, which are suitable for both wind tunnel and free flight tests, are urgently required for example in the field of Laser Doppler anemometry.

Only a few results are to be mentioned as examples for the importance of such boundary-layer measurements: In Fig. 10, two boundary-layer profiles are shown on the suction side of a transitional profile flow and also

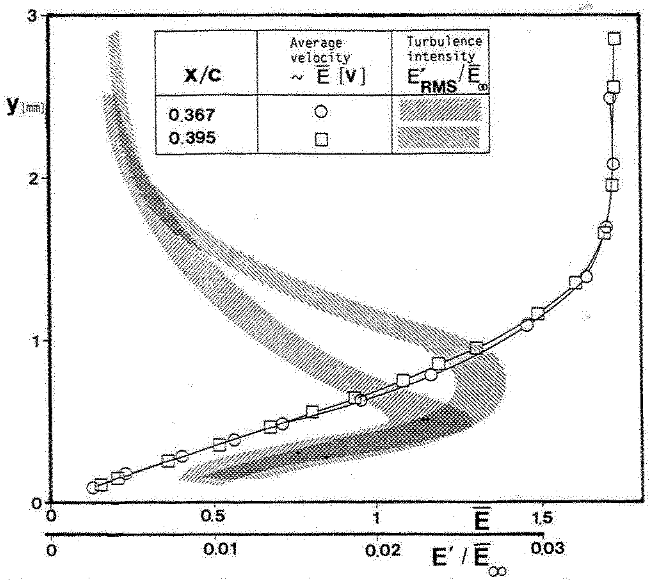


Figure 10: Boundary layers and turbulence intensities at transition onset

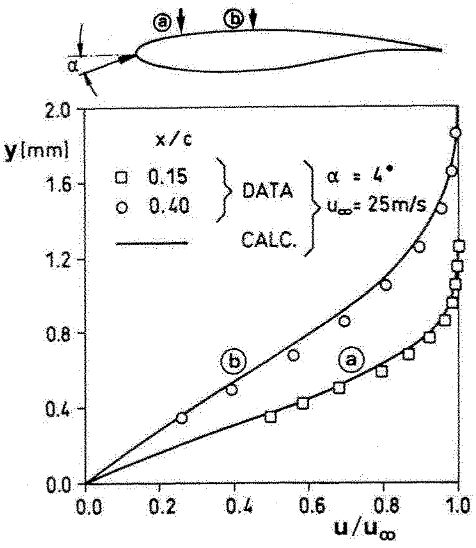


Figure 11: Boundary layers upstream of transition (experiment-computation)

the corresponding turbulence intensities, which were carried out by means of a traversable hot wire probe. Whereas the onset of flow instabilities 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 an experiment such measurements are particularily important in order to examine, for example, the numerical modelling of transitional boundary-layer flows. An experiment that points this out is shown in Fig. 11. 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.

3.4 Integrative Aspects

All in all the measuring techniques for global and detailed examination of laminar-turbulent airfoil flows, as described above, 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. To begin with it must be taken into consideration to a greater extent that these measuring techniques should not interfere negatively (for example, interference of IR photographs due to temperature loaded sensors such as hot-films, pre-located transition caused by non-intrusive devices such as boundary-layer probes). In each case the choice of the appropiate techniques has to be made in view of a pure verification experiment on one hand and on the other an experiment orientated more strongly towards flow physics. Specially here in order to compare it to numerical calculations, the significant flow parameters have to be measured accurately.

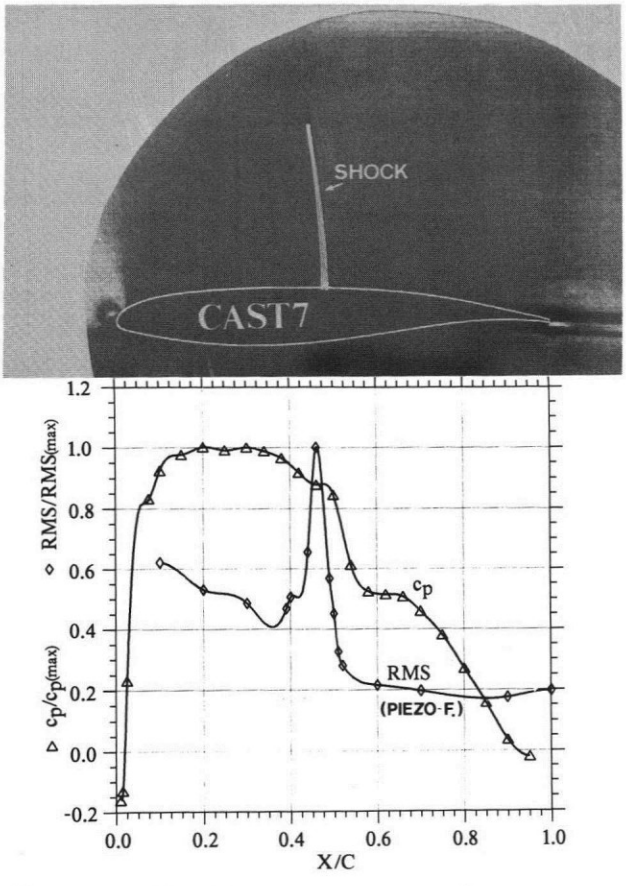


Figure 12: Shock detection by means of a piezo-array

Apart from the flow parameters already refered to above additional measuring quantities might also be significant in such experiments. In this context the respective pressure distribution as well as the lift and drag coefficient must certainly be mentioned, especially when talking about transonic experiments and shock control on the airfoil. The latter aspect is important in so far as a shock might lead to a destabilization of the boundary-layer and, can so endanger the design tool. Especially in free flight tests, the appropiate classical techniques (e.g. Schlieren pictures) cannot be used. A promising and rather flexible method emerges with the piezo-array technique [19] as illustrated in Fig. 4, through which the shock position can be determined by detecting the low-frequency shock oszillation, Fig. 12. With the development of hybrid laminar flow concepts (HLF), further necessities concerning measurements are also to be expected. It is here that the efficient suction control must not be forgotten, 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. There remains a great developmental need.

4. Wind Tunnel and Flight Experiments

Most of the measuring techniques discussed in Chapter 3 were, in the course of national research programs ("Transonic Laminar Flow" TLF-program, "Measuring Techniques for Laminar Airfoils" MTLA-program), examined regarding their practical applicability in wind tunnel and flight tests. Some of the results obtained there are to be summarized in the following. As for these applications, the point of emphasis lies on the field of transition detection and the registration of characteristic surface forces (steady/unsteady) by means of surface probes.

4.1 Transition Detection on Laminar Wings

In the course of the TFL program, practical tests concerning transition detection were carried out in the form of 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 wind tunnel model available (Fig. 13) and the aircraft wing, respectively (Fig. 14). Parallel to this extensive wind tunnel experiments were in the course of the MTLA program carried out in university-, DLR- and industrial wind tunnels as well as first flight tests were made on a G 109 motor glider (in cooperation with TH Darmstadt).

In Fig. 15, the analysis of two ATTAS flight tests shows a first example of the efficiency of the Infrared technique (see Fig. 5, too) regarding transition detection. 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. Depending on the respective flight condition, in each case these differences lead to a characteristic course of transition on the wing. 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 flow field in these regions.

Fig. 16 shows two results which are typical of transition detection by means of a piezofoil array. While Fig. 16 a

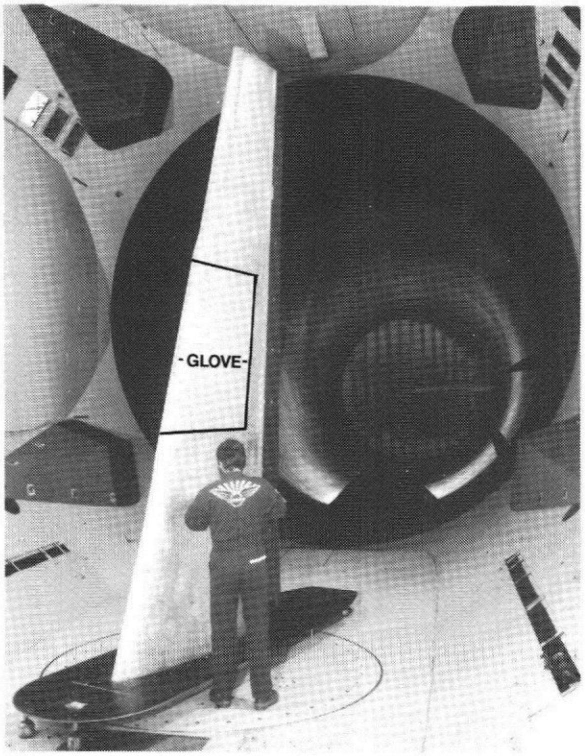


Figure 13: Large scale TLF-test rig with glove

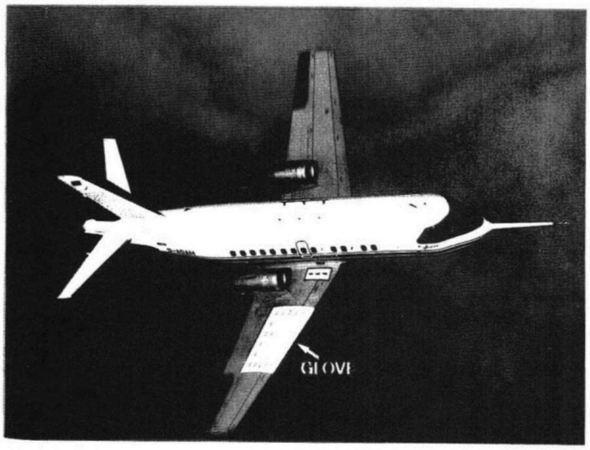


Figure 14: ATTAS flying test bed with glove

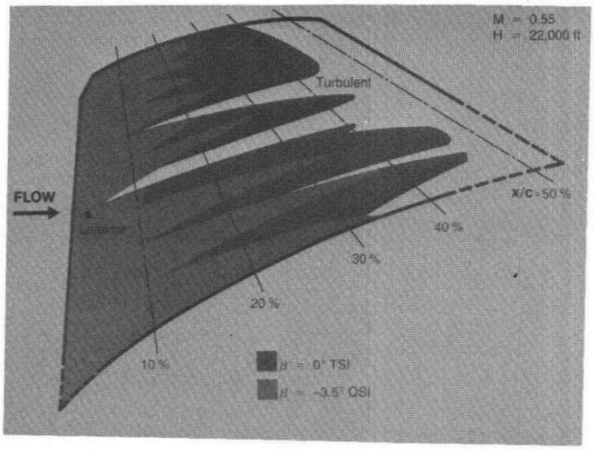


Figure 15: IR-image results of ATTAS flight tests (DLR Braunschweig)

describes a wind tunnel test on a TFL model at M = 0.47, the results of a G 109 flight test are shown in Fig. 16 b. In each case the transition region is clearly distinguishable from 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).

In Fig. 17 a summarizing comparison between the analysis of IR images and results of a piezofoil array is shown for a DNW-/S1 measuring campaign on the TFL 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 which is due to measuring uncertainties the position of boundary-layer transition corresponds well in the two wind tunnel tests. It is clearly recognizable that, especially the piezo array in the case of cross flow-induced transition (negative attack angles), unlike the IR image, detects the onset of flow instabilities as early as upstream of the boundary-layer transition - something which could already be derived from Fig. 8.

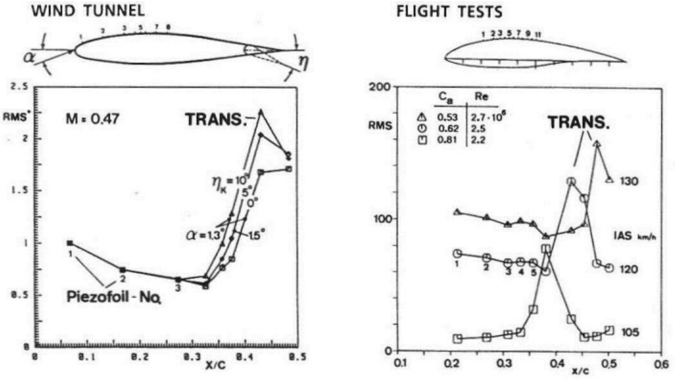


Figure 16: Piezo-array results in wind tunnel and flight tests

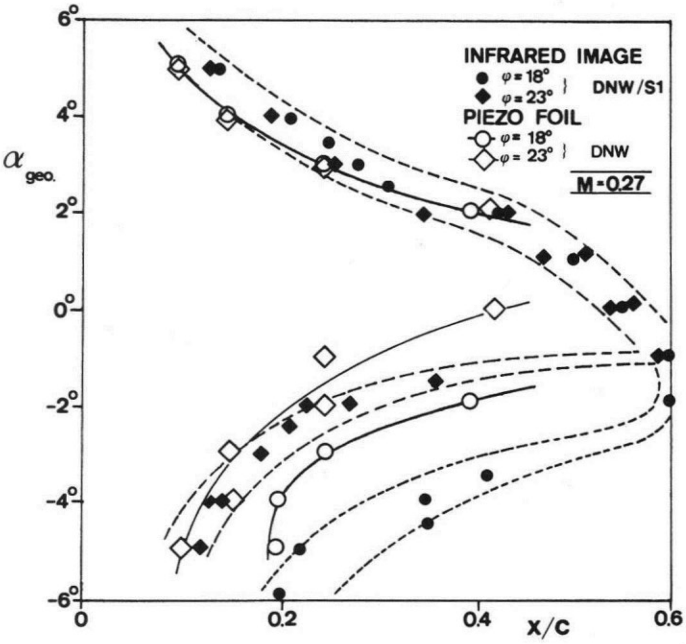


Figure 17: Comparison of IR-image and piezo-array results (DNW/S1 campaign)

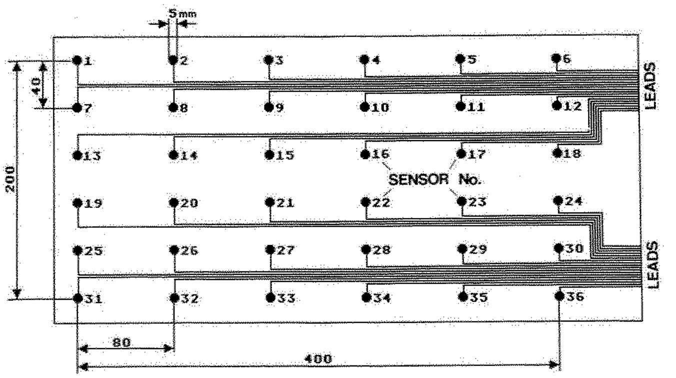
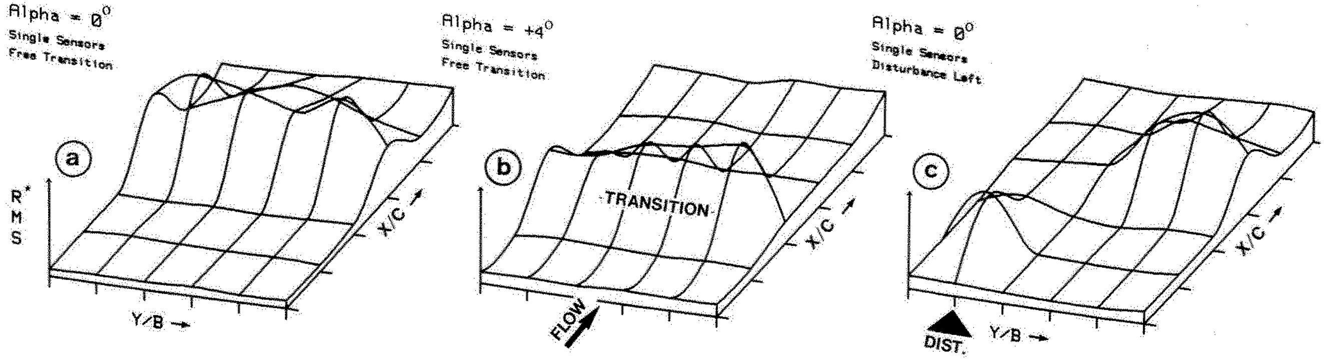


Figure 18:

Piezofoil matrix array on a NACA 0012 test wing



The possibilities of comparing such array measurements to IR photographs according to Fig. 5 or 15 are limited if, as is the case in the measurements shown in Fig. 17 with a sensor structure according to Fig. 4, the line array is confined to a fixed span position. To extend the piezo foil technique to distributed sensor arrays does not in general raise a problem. This is shown in Fig. 18 for a first wind tunnel experiment with a 6x6 matrix array. The number of sensors can be increased at random, and a distributed transition detection can be made. By means of such sensors transition detection will then provide results which are also comparable to IR photographs. The results summarized at the bottom of Fig. 18, show part of 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 pre-located by means of an artificial disturbance at y/b = 0.2, Fig. 18c. Clearly recognizable the piezo-array detects the general 2D- or 3D-development of transition.

4.2 Surface Forces

As pointed out in Chapter 3 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 CPM method on a TFL test airfoil (S1 test) at x/c = 0.3 are compiled in Fig. 19 as a function of the attack angle 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 which also offers quite interesting possibilities of comparison with, for examle, numerical calculations, is obtained from this selective measurement already. Fig. 20 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. Comparable to Fig. 17, the two measuring techniques also correspond well here.

Compared with a numerical calculation a first application of the CPM method in free flight tests is shown in Fig. 21. These tests were carried out on the original wing without a glove and are therefore confined to five measuring positions. Presently test flights are being prepared in which the CPM probe can be moved along the profile chord by means of a traversable device integrated into the glove. However the preliminary test shown in Fig. 21 already provided

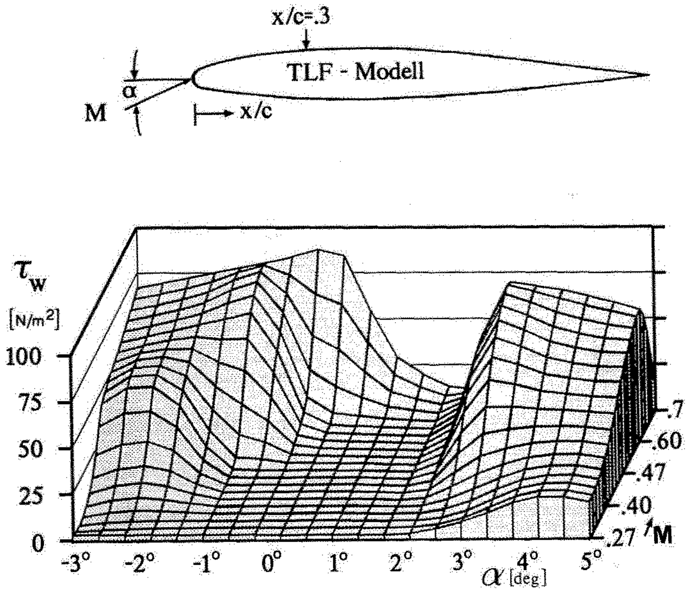
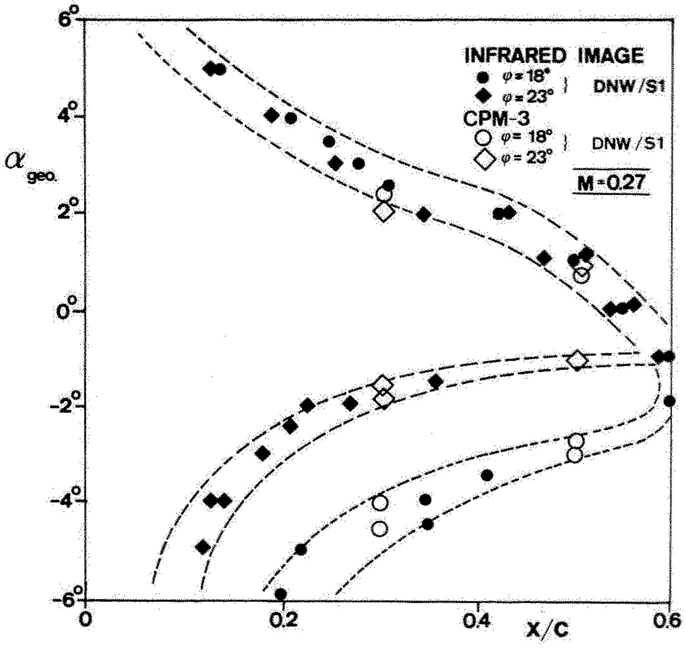


Figure 19: Skin friction dependent on Mach number and attack angle (CPM results)



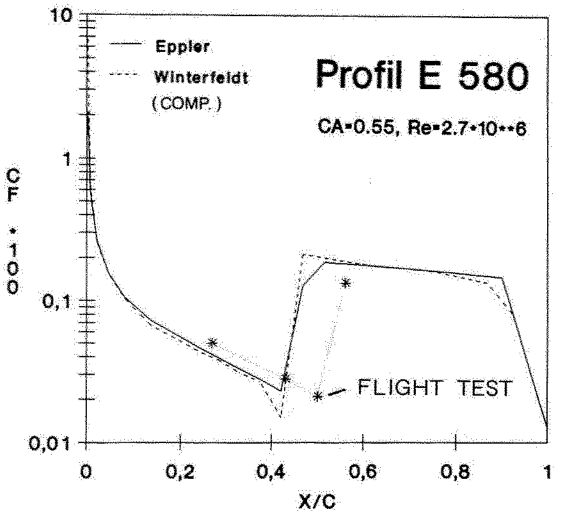


Figure 21: CPM flight tests results and computations

Figure 20: Comparison of IR-image and CPM results

interesting results, for example a distinct relocated boundary-layer transition when compared to 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. 22. In this test the foil signals measured simultanously at five x/c positions are summarized. In the beginning the top line always shows the respective traces over 100 ms. As obvious from the strongly increasing amplitudes, the boundary-layer transition between x/c=0.36 and x/c=0.48 clearly derives from these traces. In the second line the corresponding power spectra are shown which have a distinct peak in the range of the Tollmien-Schlichting frequency (f≈1000Hz) at the position x/c=0.36. These TS waves are also found in the corresponding trace (see detail). Above all they illustrate the piezo sensor's great 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 neighbouring sensors in the form of orbits).

A more detailed analysis of a piezo array test regarding the detection of amplification processes is shown in Fig. 23. First of all the power spectra measured by means of a highly sensitive amplifier system at seven x/c positions are shown in Fig. 23a . In the frequency range of flow instabilities (800<f<1200 Hz), they show a strong increase in amplitude. The amplitude

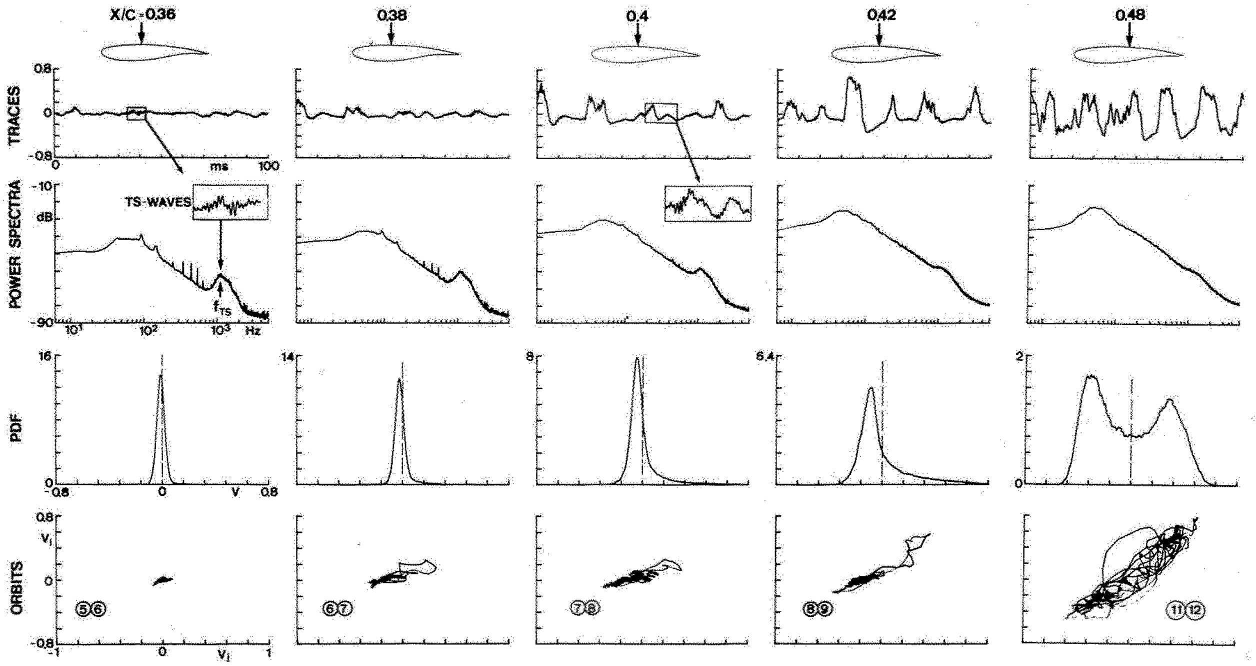


Figure 22: Evaluation of piezo-array data in a transitional airfoil flow

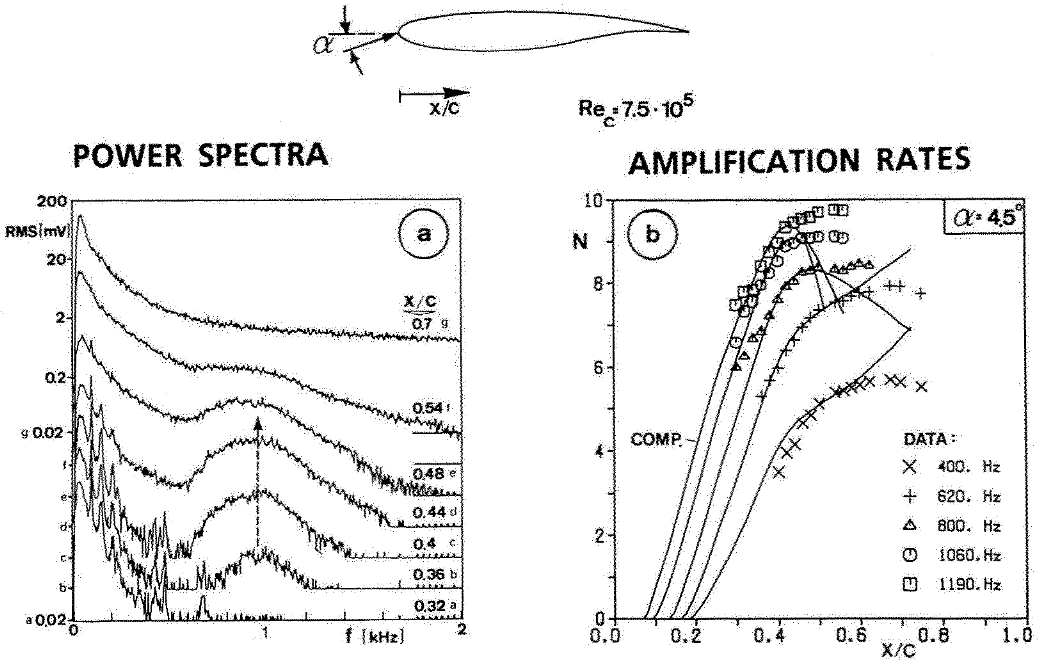


Figure 23: Flow amplifications and n-factors in the course of transition. Piezo-array results

amplifications were achieved at 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 it, the n-factors of the amplification were calculated. As shown in Fig. 23 b, the n-factors 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, for example, hot-film probes, see e.g. [20, 21]. 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).

5. Concluding Remarks

Despite the long history of laminar flow research, the recent successful results and despite the opinion of research establishments like NASA that concepts like "NLF are ready to go" [22] there is presently no transport aircraft in sight on which the laminar flow wing concept might find realization in the near future. The reason certainly lies in the presently low fuel prices and in the effect fuel has on the DOC's. On the other hand operational, manufacturing and certification aspects as well as design philosophy and methods still need to be considered. Related to these problems is the necessity to control and monitor the state of the boundary layer during flight in order to fully utilize the design performance of laminar flow, [2, 5].

However, there still remain a large number of basic research problems connected with laminar flow to be solved, but solutions of these problems will lead to more profound understandig of the entire field of fluid dynamics. The details of leading-edge flows in connection with attachment line and cross-flow instabilities are complex and difficult to assess both in experiments and CFD-simulation. Especially concerning transonic laminar airfoils the shock-boundary-layer interaction region and the recompression area at the trailing edge need further research. The amplification of disturbances in the laminar boundary layer, their frequencies and amplitudes as well as the significance of linear and non-linear regions in the transition process (bearing in mind that presently only the linear stability theory has been successfully applied) require further research. Finally for the introduction of laminar wing new design and prediction methodologies are needed. Wind tunnel results alone are probably not sufficient, flight testing will become a further important step during the development phase. This simultanously allows testing closed-loop control and manipulation systems for optimum use of laminar flow. Thus reliable and suitable measuring methods and sensors for transonic flight environment are required.

The typical results of various measuring techniques for laminar wing tests introduced in chapter 4 indicate their potential but also state clear requests for further improvement and development. The situation is different for wind tunnel and flight testing. For wind tunnel experiments a number of measuring techniques have been employed for transition detection and detailed boundary layer investigations. Less progress has been made in flight tests, owing to the fact that especially there, the step from pure qualitative measurement to quantitative methods is 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 for example holds for the entire field of non-intrusive boundary layer and flow field measuring methods like LDA or L2F. Up to now they have not been included in standard testing procedures.

Furthermore there is also a lack of surface sensors giving quantitative information on details of strongly three-dimensional shear layers and transition effects like cross-flow instabilities over larger wing areas. Promising developments can be seen in surface hot-film arrays as well as in the piezofoil array technique. Both methods, however, still require a more simple and standarized data evaluation philosophy for industrial application. As mentioned earlier the instabilities in laminar boundary-layers are of prime importance in order to validate corresponding theoretical analysis so that these sensors will hopefully be able to meet the great expectations in the near future.

In flight test only a few advanced measuring techniques have been employed, although these experiments decide on the successful laminar 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 the flight experiment has to take place under extreme conditions due to the physics, the environmental effects, the limited space for electronic equipment and also due to 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 possibilty of independent parameter variation cannot be offered [23]. Nevertheless especially the laminar flow concept needs flight testing and advanced high-qualitiy measuring techniques.

Apart from verifying laminar wing designs measuring techniques are also required for performance control or suction control. This especially applies to hybrid laminar flow concepts. For wind tunnel and flight testing as well as for standard in-service flights special sensors need to be developed and coupled to adequate data reduction and evaluation systems in order to control on-line suction rates or other relevant parameter like flap settings for optimum pressure distribution. Thus the flow around laminar airfoils should be permanently monitored by robust, reliable sensors for optimum utilization of laminarization in all flight conditions independent of the concept employed.

The complex measuring task for laminar flow investigations poses a major challenge to experimental fluid dynamics. To find solutions the close cooperation of universities, research establishments and industry will be needed. Consequently German universities (Darmstadt, Erlangen, Aachen and Berlin) cooperate within the national research program on laminar wing technology to investigate and develop measuring techniques specifically suited to free-flight testing. Research focuses on hot-film arrays, laser diode applications, piezo foil arrays and other methods and forms the basis for future industrial application.

In Europe larger transport aircraft are developed and manufactured by more than one country and company. Therefore it is consistent that the Commission of the European Community supports an aeronautical program in order to keep European companies and their research to be able to compete on the world market. One of the major research programs is laminar flow investigation. Here wind tunnel and flight experiments are supported by high-quality measuring techniques and further advanced methods are investigated. The European program offers the possibility of coordinating and directing future research and advance in the development of measuring techniques.

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