APPLICATIONS OF DIFFERENT MEASURING TECHNIQUES FOR TRANSITION DETECTION IN LOW AND HIGH SPEED FLIGHT EXPERIMENTS

I. Peltzer[1], J. Suttan[2], W. Nitsche[1]
[1] **Institut of Aeronautics and Astronautics, Technical University Berlin, Germany,**
[2] **MTU Ludwigsfelde Deutschland, Germany**

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Abstract

This paper descibes in-flight measurements at low and high speed experiments to investigate laminar-turbulent transition. The low speed experiments were carried out using a laminar wing glove for a sailplane. High speed experiments on an modified A320 HLF Fin were conducted in close collaboration with Airbus. Different surface sensor measuring techniques (piezofoil, surface hot-wires, wall-microphones) were used in low speed experiments. The piezofoil technique was applied in high speed in-flight experiments to prove the operation robustness, the functional capability, durability and reliability under atmospheric conditions in cruise flight of modern airplanes. All measuring techniques were successfully implemented for the particular task and the laminar-turbulent transition was detected with a high degree of certainty. In contrast to the usual pressure-sensitive measuring techniques (piezofoil), the surface hot-wire sensor shows a decreasing sensitivity with increasing speed, but the best signal to noise ratio in low speed experiments. For the high-speed investigations a complete piezofoil sensor was glued on the fin without observing any interference between the boundary layer flow and the sensor foil. Therefore this technique showed the potential to detect transition in the boundary layer under atmospheric conditions especially in high speed investigations.

1 Nomenclature

β	yaw angle
C	capacity
d_T	pyroelectric coefficient
d_{33}	piezoelectric coefficient
f	frequency
OP	operational amplifier
R	resistance
Re	Reynoldsnumber
t	time
u_∞	freestream velocity
U	voltage
x/c	normalised chord
DFG	Deutsche Forschungsgemeinschaft (German Research Foundation)
FFT	fast fourier transformation
HLF	Hybrid Laminar Flow
MEDAS	Measurement data acquisition system
PVDF	Polyvinylidenfluorid
RMS	Root Mean Square
SNR	Signal to noise ratio
TS	Tollmien-Schlichting

2 General Introduction

The investigations presented in this paper are aimed at finding the laminar-turbulent transition in the boundary layer on an airfoil, in particular the spatial development and growth of the Tollmien-Schlichting (TS) instabilities that lead to transition.

It is well known that the generation of TS waves strongly depends on the environmental flow conditions. It is therefore necessary to investigate the transition under real flight conditions as well as in wind tunnel tests. Based on the experience gained in the Deutsche Forschungsgemeinschaft-funded university group research project [6], where various measuring techniques for in-flight experiments were developed, this paper focuses mainly on measurements with PVDF (Polyvinylidenfluorid)-sensor, surface hot-wire as well as microphone sensor arrays and their feasibility to investigate and detect natural transition. The authors have a lot of experience using surface measuring techniques in wind tunnel tests as well as at low in-flight speeds [11, 2].

For industrial applications, on control of transition, for instance, a simple, robust and consistent measuring technique has to be developed and tested. This was only one reason for the A320 HLF Fin programme, which was initialised by Airbus in the nineties. The programme was multinational as well as multidisciplinary including the extraordinary cooperation of industry, research establishments, universities and suppliers, as an essential part of the overall laminar flow research activities within Europe [3]. Besides the scientific interests on the understanding of flow physics including transition mechanisms both technical and managerial objectives were involved. First of all the A 320 vertical tailplane fin was modified in a way to establish laminar flow over the fin box without modifying the box itself. Furthermore, a suction system was built in the fin nose to induce the hybrid laminar flow. Then measuring techniques based on experience gained in earlier wind tunnel experiments were adapted for the A320 HLF Fin. Among others, an infrared camera, a traversable wake rake, hot-films, an array of PVDF sensors, temperature probes and pressure taps were used to control and monitor the flight experiments [5].

The PVDF sensor array was applied by Technical University Berlin, which could detect the laminar-turbulent transition on the fin. Therefore it could demonstrate the success of the suction system also. This paper will show the results of the high speed tests with the PVDF-foil technique at the A320 HLF Fin. These results will compare with the results from the low speed experiments on the Twin II laminar wing glove with respect to the potentials of the PVDF measuring technique.

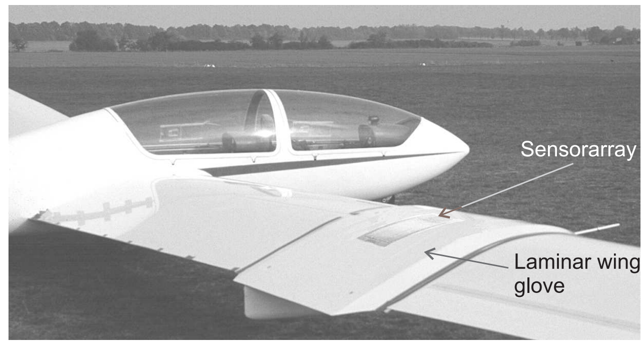

Fig. 1 Sailplane Grob G103 Twin II with the glove

3 Experimental Setup

3.1 Laminar Flow Wing Glove

A laminar wing glove, which was developed for the Grob G103 Twin II two-seater sailplane at the Institute for Aeronautics and Astronautics, Technical University of Berlin, was used for the low speed in-flight measurements (fig.1). The measuring glove has a 2D center part with a $1.0\,m$ span and a chord length of $1.22\,m$. It has an exchangeable wing segment that was equipped with different surface sensors or actuators. One sensor setup is shown in fig.8a). An array of 74 PVDF-sensors was used. A streamwise line of 17 sensors was located from 40 % to 50 % of the chord length for transition detection. Four additional rows of 16 sensors each arranged in the spanwise direction were used. The first spanwise piezo sensor row was located at 46.3 % and the fourth row at 49.6 % of the chord length. There were 14 mm between each row and 7 mm between the spanwise sensors. Furthermore, surface hot-wire and microphone sensor arrays were used on this glove. The flight experiments at the sailplane were carried out at flight velocities from 22.2 m/s to 28 m/s ($1.9 \cdot 10^6 < Re < 3.0 \cdot 10^6$).

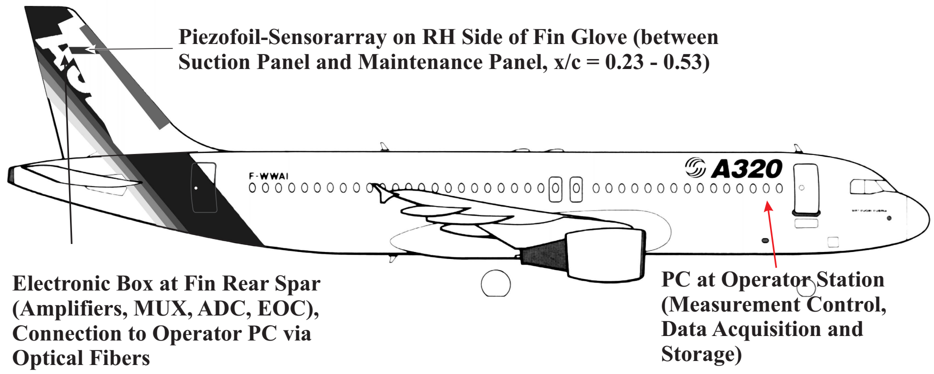

Fig. 2 Sketch of the A320 airplane with HLF-Fin

The measurement system (see also section 4.1) is located in the equipment support underneath the glove. A Prandtl tube, which is also attached underneath the glove, is used to obtain the freestream velocity. The difference pressure between two pressure taps on the glove ($\Delta p_{x1,x2} : [x_1/c = 37.2\%, x_2/c = 52\%]$ and $\Delta p_{x3,x4} : [x_3/c = 2.8\%, x_4/c = 8.5\%]$) are measured to monitor the angle of attack of the glove. A thermocouple and a manometer are used to measure the air temperature and absolute pressure, respectively. These parameters are continuously recorded to obtain the freestream boundary conditions.

3.2 Hybrid Laminar Flow Fin - A320

In close collaboration with Airbus Germany the in-flight experiments at higher Reynolds numbers were carried out on the A 320 vertical tailplane (fig.2). A special PVDF sensor array was built and attached to the upper part of the fin downstream of the suction panel, which were used to control the transition. The geometry of the array was defined through the position on the upper part of fin. The array enclosed 32 sensors in two streamwise lines at a chord length of 23% to 52.6%. The distance between the equally-spaced sensors was 1.97% of the chord length ($\approx 56\,mm$) of the fin (fig.3). The complete sensor array was glued on the fin with a heating layer and was plugged up on the borders. Interferences with the boundary layer flow through the sensor on the fin surface could not observed. The data of the sensor array were reported continuously via a measuring system called MEDAS.

The main objective of this small part of TU Berlin within the scope of the A320 HLF Fin programme was to prove the functional capability, durability and reliability of the PVDF sensor technique under real, atmospheric conditions in cruise flight. In particular, that means low temperatures (up to-60° usually at $10000m$ altitude) and high velocities ($Ma \approx 0.8$, $u_\infty \approx 330kt$). Furthermore, the tests focused on investigation of other environmental influences like the noise level, resonance frequencies or acceleration occurring in modern airplanes. The established criterium to ensure transition detection is a sufficient signal-to-noise ratio (SNR, see also section 4.2).

4 Sensor Techniques

4.1 Measuring System - MEDAS

A miniaturised and modularly arranged measuring system especially developed for in-flight measurements was employed in both cases in order to record the data of the dense surface sensors at a high temporal resolution. This multi-channel measurement data acquisition system (MEDAS) consists of two parts. One part of MEDAS (the electronic box) was located close to the sensor array at the rear spar of the fin or underneath the glove of the sailplane. The basics of this electronic box are a two-stage amplifier (charge and power amplifier for each channel) with electroni-

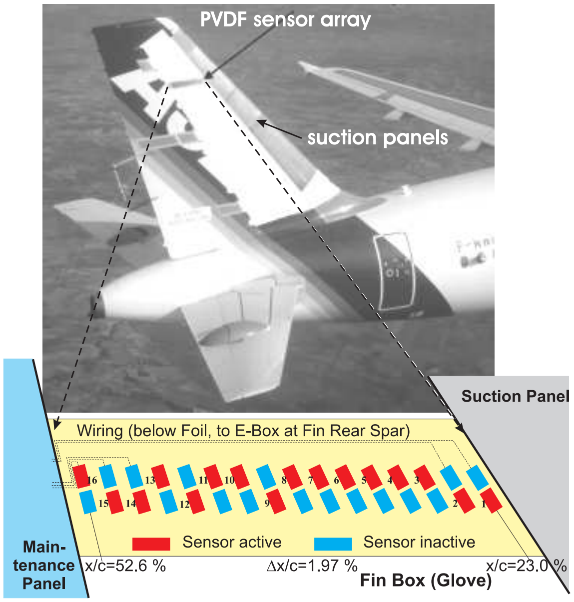

Fig. 3 A320 HLF Fin and the PVDF sensor array

cally adjustable amplifier setting and multiplexer, A/D-converter, E/O-converter next in line. The measuring computer in the cockpit includes the second, board part of MEDAS and makes it possible to control the measurement system at the fin and at the wing respectively during flight. Communication and data transfer for storage between the both parts of the measurement system are carried out via fiber optical transmission. The sampling rate of each channel was about 40 kHz. Further information was described in Suttan [12].

4.2 PVDF Sensor

PVDF sensor and sensor arrays as well-known as the piezofoil sensor also have been successfully employed for measurements of unsteady surface force fluctuations on different applications for several years [8, 11, 6]. A PVDF Sensor array consists of a thin PVDF (Polyvinylidenfluorid) film (9μm to 100μm thick), metallized on both sides. The upper metallic side is used as an electric ground, thereby serving as an electrostatic and electromagnetic shield also. By partially etching one side of the metallic coating, it is possible to create sensor arrays which are customized for a given measurement task. Then each single sensor area is connected to the charge amplifier via thin wires. A single PVDF sensor can be considered as a plate capacitor with very low capacity and mass. The PVDF material has both piezoelectric as well as pyroelectric properties.

When assuming a mechanical (piezoelectric) or a temperature (pyroelectric) change characteristic in laminar-turbulent transition, the sensor material produces small electric charges. The sensor signals can be amplified by means of simple charge amplifiers. The possible frequency range is limited only by the lower limiting frequency of the employed charge amplifier. The choise of the charge amplifier depends on the measuring task. Since the pyroelectric constant (which describes the pyroelectric properties) is some orders higher than the piezoelectric constant, a low temperature gradient ($< 2K$) between sensor and fluid can be employed to obtain a higher SNR [7]. This can be important for the minimization of sensor size and spacing in array measurement techniques. Due to the closed foil on the wing surface, the sensor produces negligible roughness. In this case the experiments showed the successful production of large sensor arrays (areas up to $(1000 * 220)mm^2$) with a smooth and undisturbed surface. The cut-off frequency of the applied PVDF sensor array (including the entire measuring system) was about 30kHz; the sensor was therefore suitable for dynamic measurements at high velocities.

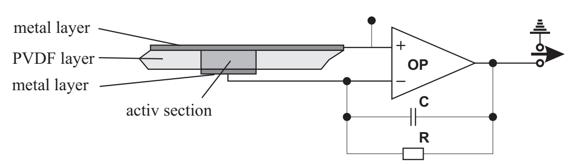

Fig. 4 Sketch of a single PVDF sensor

The specially-made sensor arrays used a 28μm-thick polymer film (with a pyro-coefficient, $d_T = -30 * 10^{-6} C/m^2K$ and a piezo-coefficient $d_{33} = -33 * 10^{-12} C/N$) sandwiched between two 1μm Ni-Cu layers. In basic wind tunnel experiments the upper was coated using a 5μm-thick $TESA^{TM}$ film for protection from abrasive erosion. The sensors were tested coated and non-coated. The results suggest that

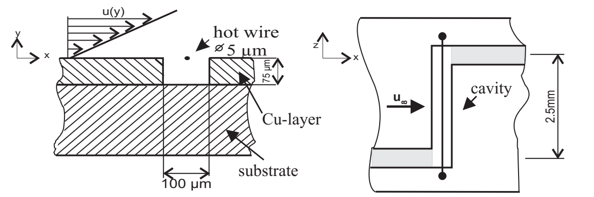

Fig. 5 Sketch of a single surface hot-wire sensor [1]

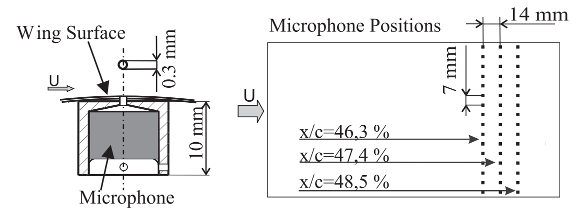

Fig. 6 Sketch of installation and positions of the miniature microphones

the coating layer has almost no effect at both low ($Ma = 0.3$) and high ($Ma = 0.5$) speeds [2]. Therefore the coating can used to protect the sensor surface in real applications.

4.3 Surface Hot-Wire Sensor

A principle sketch of the surface hot-wire sensor is shown in fig.5. A platinum-coated tungsten wire ($d = 5\mu m$) is fixed over a narrow slot ($0.075 - 0.1\,mm$) flush to the surface. For the sensor substrate, a flexible circuit board with a $30 - 75\mu m$ copper layer is used. The slot can be easily shaped in the copper layer using the photo-etching technique. This arrangement produces reduced heat-flux in the structure. Therefore, a higher signal-to-noise ratio is achieved (compared to conventional hot-film sensor arrays) [10, 1]. Modularly arranged hot-wire anemometers were designed especially for in-flight measurements to be able to operate a high number of surface hot-wire sensors during flight in constant-temperature mode. This highly sensitive wall sensor was developed especially for measuring the weakest wall shear stress fluctuations. Therefore, this sensor can be used for measuring the laminar turbulent transition also.

For this special task the laminar wing glove was equipped with a downstream row of surface hot-wire sensors. The spacing of the sensors is similar to the corresponding streamwise PVDF-sensor line mentioned above ($6.5\,mm$ for the sailplane). The position of the first sensor was located further downstream to measure the higher amplified stages of the TS-waves and to observe the transition to turbulence. In this case the sensors were arranged between 45% and 55% of the chord. The surface hot-wire sensor shows the best signal to noise ratio, but has a lower cut of frequency compared to pressure sensitive measuring techniques (PVDF sensors). The distress from damage is especially high in high speed flight tests, however.

4.4 Microphone Sensor

Another possibility to measure TS-waves and observe the laminar-turbulent transition is the installation of miniature microphones. Therefore a microphone sensor array was installed on the exchangeable glove segment. Very small microphones were mounted underneath the surface with a $0.3\,mm$ drilled hole. Fig.6 shows the principle sketch of the construction and the sensor positions. The microphones themselves have a sensivity of $-63\,dB$, a frequency range of $20\,Hz$ to $12000\,Hz$ and are $6.3\,mm$ in diameter and $4.3\,mm$ high. Because of this special construction the microphone array is probably not very useful for in-flight applications on large aircraft and high speed measurements, but they supplied a sufficient data base of the amplification of TS-waves on the laminar wing on the sailplane.

5 Results

The process of laminar-turbulent transition on a basically two-dimensional airfoil can be described with three major aspects: receptivity, linear stability and nonlinear breakdown [4]. The first aspect (receptivity) is devoted to the generation of instability waves (TS-waves) in the region from the airfoil's leading edge, where instability waves were amplified. This aspect will not be considered in this paper. The second stage of transition (linear stability) corresponds to the development and amplification of instabilities. This stage shows characteristic structures within the boundary layer. Surface sensor arrays can measure these structures by means of the so-called "footprint" of the boundary layer also. The following sections show the amplification of the instabilities in time traces of streamwise-located sensors as such a footprint. The third stage (nonlinear breakdown) is specified by means of the RMS-values of the streamwise sensor signals. The RMS-values in the first stage are very low, and then they are increased with amplification of the instability. The maximum of RMS-values characterizes the transition (nonlinear breakdown) that is almost finished. Then the RMS-values decrease to a lower level that is higher than in the laminar boundary layer. This means the turbulent stage.

5.1 Laminar-Turbulent Transition in Low Speed Flight Tests

At first, results of the in-flight measurements with the sailplane will be discussed. These experiments were carried out at velocities from $22\,m/s$ to $30\,m/s$ as mentioned above. The RMS-values at different velocities of the streamwise sensor line are shown in fig.7. Each graph has a maximum that indicates the laminar-turbulent transition. The maximum shifts downstream with increasing velocity, since an increasing velocity corresponds with a decreasing angle of attack of a sailplane. Therefore with increasing velocity the transition moves downstream, as to be seen in this figure. Furthermore the RMS-values are on the same low level up to a chord length of 35 %. The increase of RMS-values starts with respect to increasing velocity at a later chord. Since the stability of the boundary layer depends on the pressure gradient, the amplification of instabilities starts depending on the angle of attack. After reaching the maximum the RMS-values decrease again for the turbulent boundary layer.

The employed PVDF-sensor array and significant raw and filtered time traces over $50\,ms$ of 17 streamwise PVDF sensors on the wing glove are shown in fig.8. The signals were measured at a flight velocity of $23.6\,m/s$. Fig.8b) shows the raw data of the PVDF sensors. Up to the eighth sensor the signals are very smooth and no characteristic disturbances or instability waves can be recognized. After that wave packets are occurring, with amplitude that increases with increasing chord length. Furthermore, the temporal phase shift from one sensor to the next becomes apparent, which shows the convective transport process of the instability waves.

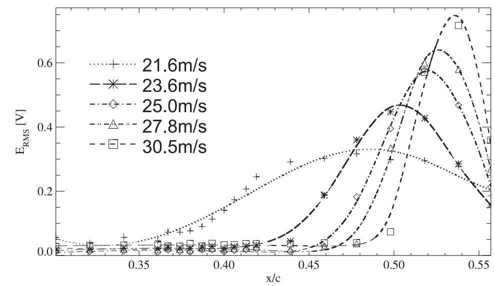

Fig. 7 RMS-values of the streamwise PVDF sensors on the wing glove [9]

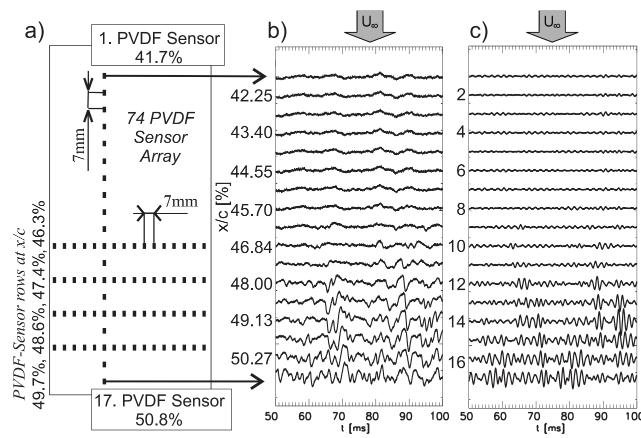

Fig. 8 a) PVDF sensor array, b) raw and c) filtered signals of the streamwise PVDF sensor line at $u_\infty = 23.6\,m/s$

Fig.8c) shows data of the same measurement; the signals are a filtered band pass in the range of $200 - 1800\,Hz$, however. Up to a chord of around 47 % the signals are very smooth again; through the band pass filter the characteristic disturbances (wave packets) with very low amplitudes can be seen. Also the temporal phase shift is more clearly seen. As can be seen so far, the PVDF sensor technique is suitable to detect the transition in low speed in-flight experiments.

Looking forward to the surface hot-wire sensor technique, significant time trace over 50 ms of the streamwise arranged sensors are shown in fig.9. These signals are raw signals at two different flight velocities (22.2 m/s left side and 27.8 m/s right side). Obviously, these signals illustrate the typical TS-wave packets without any filter. From the early beginning amplification stage the instabilities can be observed. Only a few electrical disturbances are in the signals, which could be eliminated easily through a signal conditioner and which do not falsify the flow information.

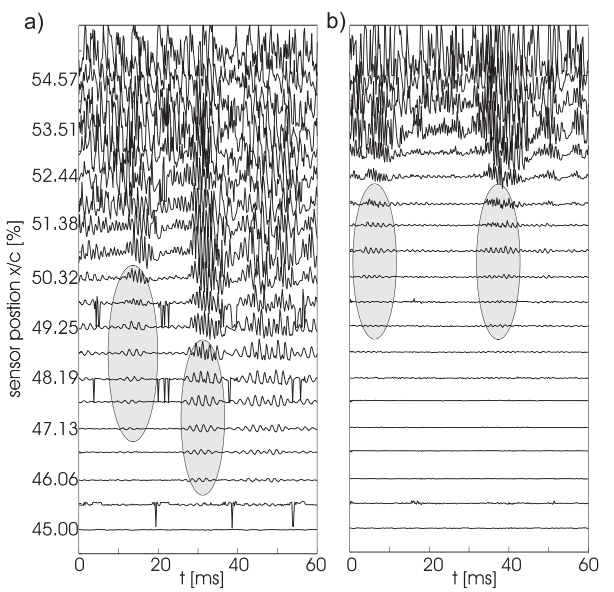

Fig. 9 Raw signals of the streamwise arranged surface hot-wire sensors a) $u_\infty = 22.2\,m/s$ and b) $u_\infty = 27.8\,m/s$

Furthermore, the spectral analysis of the signals can give some more conclusions about the predominant stage of the boundary layer. By looking at the frequency spectrum of a surface hot-wire at a chord length of about 50% at three different flight velocities, three different amplification stages can be registered.

Fig.10 shows three of such frequency spectra. The lowest spectrum shows the frequency band selective amplification of the instable frequencies at about 500 Hz to 1000 Hz (the so-called TS-hump). This frequency band rises till it reaches saturation. In this stage of the boundary layer, the higher harmonic frequencies were amplified also, as can be seen in the spectrum above the lowest one. All frequencies with higher amplitude are represented, but still the fundamental frequency range clearly rises from the spectrum. There are also two more increased ranges. A frequency band limited amplitude increase can be found in the range from 1200 Hz to 1800 Hz and a weaker one is apparent in the range from 2000 Hz to 2300 Hz. These ranges reflect the amplication of the first and second higher harmonic frequencies, i.e. the boundary layer is already in a non-linear amplification stage here. In the third spectrum, the amplification of all frequencies are so much increased that the TS-hump no longer sticks out of the spectrum, i.e. the boundary layer is predominantly turbulent.

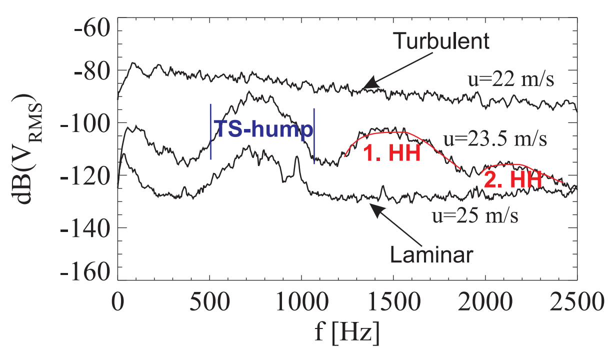

Fig. 10 Frequency spectra of a surface hot-wire sensor at a 50% chord length at three different flight velocities

Next, results obtained from in-flight measurements employing the microphone sensor array are discussed. Fig.11 illustrates filtered time traces from the three spanwise microphone sensor rows at a flight velocity of $u_\infty = 23.6\,m/s$. For a start, the time traces of the first row show typical TS-instabilities with a relatively small amplitude. No temporal phase shifts between adjacent sensors can be observed, so the instabilities propagated are still two-dimensional. In the next chart (fig.11b), the time traces of the second row show increased signal amplitudes. The third row (fig.11c) illustrates beside the increased amplitudes, the amplification of frequencies which are not the fundamental TS-frequency and a temporal phase shift of time traces between adjacent sensors. The temporal phase shift suggests the development of three-dimensional instability structures and the beginning of a non-linear transition stage. This is confirmed by the varying amplified signal amplitudes of the spanwise adjacent sensors in the third row, in contrast to the uniform amplified instabilities in the first row. As said before, the early linear stage of transition is characterized through the spanwise, two-dimensional amplification of instability waves.

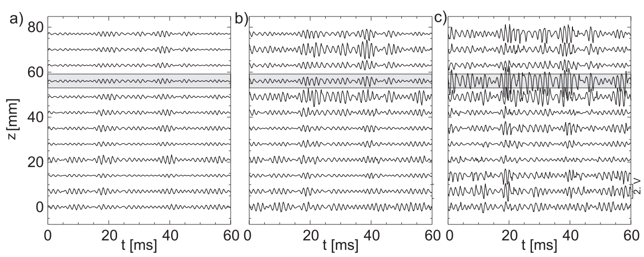

Fig. 11 Filtered time traces of microphone sensors at a velocity of 23.6m/s a) row1, $x/c = 46.3\%$, b) row2, $x/c = 47.4\%$, c) row3, $x/c = 48.5\%$

The middle chart of fig.12 shows the frequency spectrum of the fourth sensor (highlighted in fig.11) of each row. First looking at the highest frequency spectrum (blue in fig.12b), the fundamental TS-hump still dominates the spectrum, the first and second harmonic frequencies increase as well. The spectra of a microphone on the first and second row show similar characteristics at a lower level. Specifically, on the first row at 46.3% of the chord only the first higher harmonic frequencies occur. The increase of the fundamental frequencies from the second to the third row is minimal. Therefore the higher harmonic frequencies increase significantly.

Caused by a lower flight velocity (another pressure distribution, respectively) (fig.12c) all spectra are on a higher level, so that the higher harmonic frequencies almost disappear in the spectra. The transition has proceeded further than at a higher velocity. In the case of a velocity of 25m/s only the fundamental frequencies are amplified (fig.12a). Altogether the spectra in this case are on the lowest level, compared to all shown spectra. The transition is in an early, linear stage. These results correspond clearly to the measurements with surface hot-wires (fig.10, at 50% chord length).

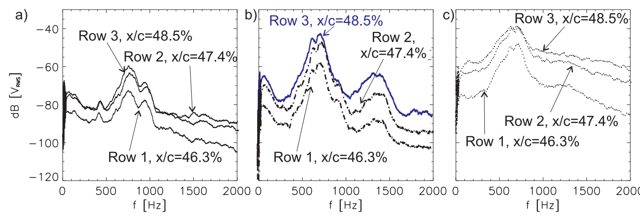

Fig. 12 Spectra of one microphone sensor per row at three flight velocities, a) 25m/s, b) 23.6m/s and c) 22.2m/s

5.2 Laminar-Turbulent Transition in High Speed Flight Tests

Fig.13 shows an example of significant time traces over 800ms of the streamwise PVDF sensors (the over-all time trace length was 6.5s). On the first sensor in the streamwise direction the signal is smooth and shows no amplification of instability waves at all. On the next sensors a small amplification can be observed (linear stage). At a chord length of $x/c = 0.37$ the amplitudes of the sensors are increasingly strong. The first transitional structures like "spikes" or "turbulent spots" are occurring (non-linear stage). The high amplitudes of the signal at 0.39% of the chord represent the last stage of laminar-turbulent transition. At a chord length of 0.41 the amplitudes are decreased, meaning the boundary layer flow is turbulent.

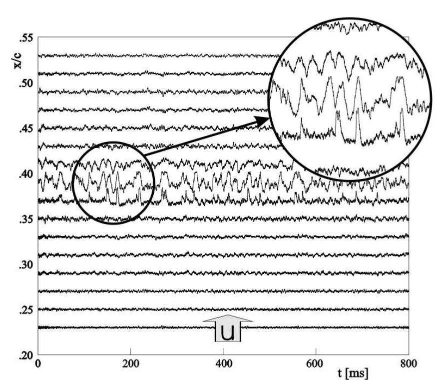

Fig. 13 Time traces of the PVDF sensors on the A320 HLF Fin

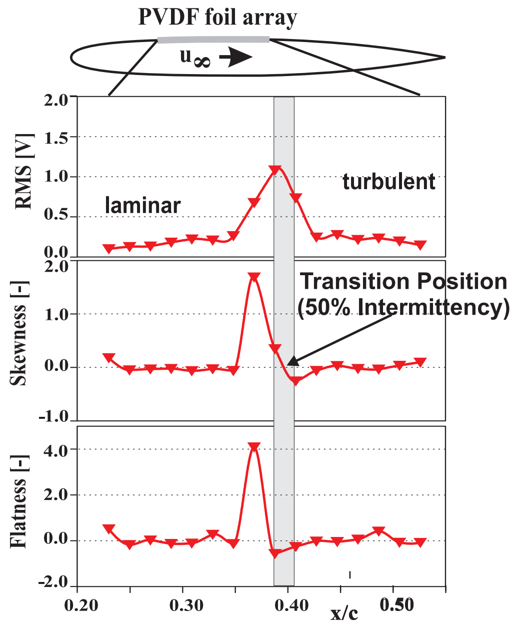

Fig. 14 Transition detection on the fin with RMS-values, skewness and flatness

The averaged data and the results of the statistical data analysis are shown in fig.14. Analogous to the analysis of the in-flight measurements on the sailplane, the RMS-values of the 16 streamwise arranged PVDF sensors for one single measuring point are shown in the first chart of this figure. The RMS-values start at a very low level, then increase because of the amplification of instabilities. They reach a maximum and decrease on a lower level. Therefore they indicate the transition location. Further statistical analysis was performed by means of skewness and flatness. The skewness describes the asymmetry of the distribution of the amplitudes based on a Gauss distribution. In the laminar boundary layer the skewness is close to zero and has a maximum in the late stage of transition (25% intermittence). At transition (50% intermittence) the skewness has zero-crossing. The flatness describes the width of amplitude distribution and can be considered as a rate of the power dispersion of the system. Therefore, the maximum of the RMS-values together with skewness and flatness are sufficient criteria for transition detection. A similar signal performance was observed at almost all other measuring points.

Further experiments investigated the influence of variation of the yaw angle of tailplane and the suction rate of the integrated suction system. Fig.15 shows the results of one case of variation of yaw angle and suction based on the RMS-values of the streamwise PVDF sensors. Clearly, the influence of the variation of the yaw angle on the transition is much higher than a variation of suction. The suction variation shifts the transition about 2%. Different yaw angles can indicate a transition shift in a range of 15% of the chord length. These successfully accomplished

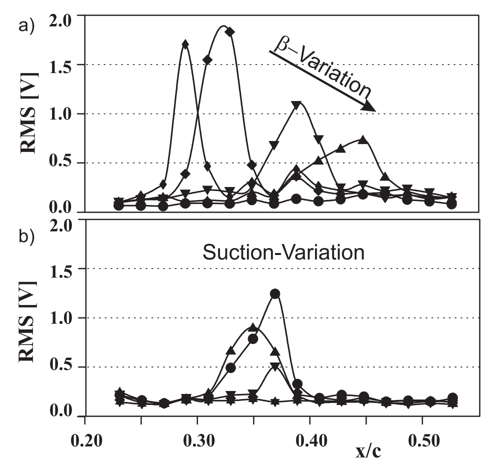

Fig. 15 Influence of the yaw angle on transition

high-speed flight experiments proved the reliability of the PVDF sensor technique under real, atmospheric conditions in cruise flight.

6 Conclusion

Low speed in-flight experiments were carried out on a sailplane using a laminar wing glove and different sensor techniques were implemented and compared. All applied measuring techniques are suitable to detect transition. The low speed experiments clearly show instabilities in an early stage of growth, also the amplification of these instabilities, the convective transport of wave packets and the transition to turbulent structures in the boundary layer. In close collaboration with Airbus high speed experiments were conducted, using the piezofoil measuring technique on the A320 fin. The results obtained on the A320

HLF fin clearly show the amplification of instabilities and the transition to turbulence in the boundary layer as well. The cut-off frequency of the here applied PVDF Sensor system was about 30kHz; the sensor is therefore very suitable for dynamic measurements at a large range of Reynolds numbers. Furthermore, the investigations show the potential of the PVDF-foil measuring technique under atmospheric conditions to detect, for instance, transition or other phenomena in the boundary layer. Finally this sensor almost does not disturb the surface of the wing and the space required for the electronic equipment is minimal due to the passive measuring method.

Acknowledgements

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