DETECTION OF LAMINAR-TURBULENT TRANSITION IN A FREE-FLIGHT EXPERIMENT USING THERMOGRAPHY AND HOT-FILM ANEMOMETRY

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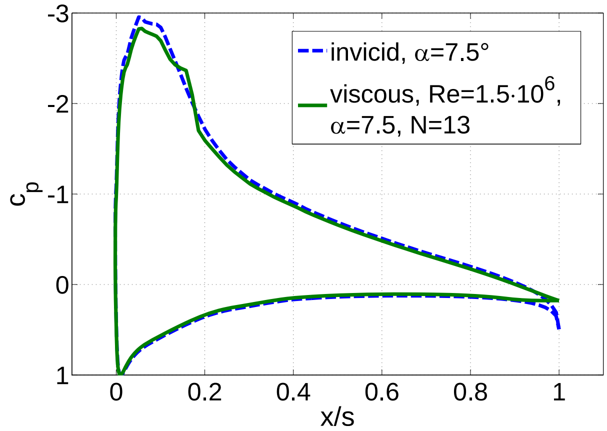
Abstract

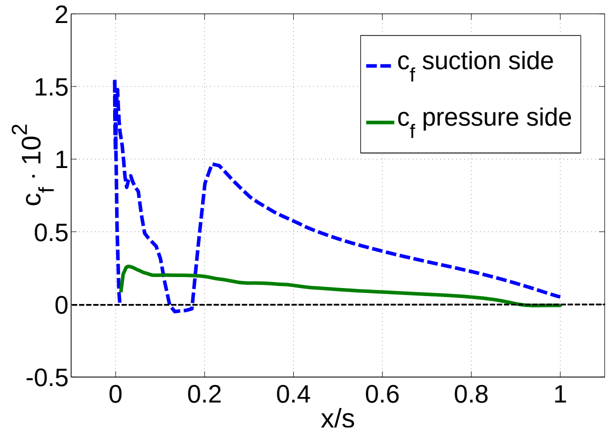
During a student research project in summer 2008 free-flight experiments were carried out in order to detect laminar-turbulent transition in the boundary-layer of a gliders wing. The two-seated plane was equipped with an infrared camera on a tripod above the fuselage and hot-film gauges on the wing surface. The wall temperature distribution as well as a quasi-wall shear stress resulting from the anemometer output voltage were used for locating the transitional zone. A comparison of both techniques showed consistent results for stationary flight attitudes. Due to the high temporal resolution of the hot-film gauges, the influence of atmospheric turbulence on the transition location could be visualized. Regarding the measurements, the angle of attack and hence the pressure distribution are supposed to dominate the transition location on the examined airfoil.

1 Introduction

Skin friction produces about half of a gliders aerodynamic drag. Due to the fact that the wall shear stress significantly increases with the transition to a turbulent boundary layer, increasing the laminar region considerably contributes to the aerodynamic optimization. However, further improvement of the existing designs requires a detailed knowledge of the flow conditions on the planes surface. Unfortunately the atmospheric incidence flow cannot exactly be simulated neither in calculations nor wind tunnel tests.



(a) Pressure coefficient



(b) Skin friction coefficient

Fig. 1 X-foil computation of pressure (c_p) and skin friction (c_f) coefficient

Realistic data can be obtained during free-flight experiments which require adequate measurement techniques. Flight test for detecting the transition location on a gliders wing using infrared thermography were already carried out by

A. Wagner in 2006 [1]. Using this method very good results for stationary flight attitudes could be obtained. During this test campaign it became apparent, that the thermal inertia of the surface does not allow transient measurements.

Preliminary computations of the pressure- and skin friction coefficient using x-Foil indicate a laminar separation bubble downstream the pressure minimum. This separation could not be detected on the infrared pictures. In order to expand the capabilities to transient measurements hot-film anemometry was examined as an additional measurement technique in 2008.

2 Measurement Techniques

2.1 Fundamental Physics

Both techniques are based on the analogy of local wall shear stress and heat transfer on the surface. For the thermography a in a first approximation constant heat flux from the surface into the flow is assumed. The heat is supplied by solar radiation which is absorbed by the black surface. The laminar-turbulent transition of the boundary layer leads to an improved heat transfer. Since the air temperature is assumed to be constant, this results in abrupt decrease of the surface temperature. The thermography camera detects the electromagnetic radiation emitted by the wing surface in the infrared band. If the wing is modelled as black body emitter and the wave length is constant the intensity of the radiation only depends on the body's temperature.
The hot-film anemometry is based on the convective heat loss of a heated gauge. The sensor is electrically heated as a part of a Wheatstone bridge. A controller regulates the power supply in order to maintain a constant resistance of the Nickel element. Since the resistance and the metal temperature are proportional at the examined conditions, the sensor temperature is also constant. If the local wall shear stress and hence the heat transfer are changing, the heat flux has to be adapted since the temperatures are fix. This change of the power requirements can be measured using the heating voltage E. Because of the small dimensions of the gauge and the larger temperature differences this technique provides a significantly increased temporal resolution.

2.2 Experimental Setup

The measurement equipment was applied to the two-seated glider SZD 9 bis 1E "Bocian" which belongs to the Akaflieg Dresden and was already used in 2006. The wing cross section is a combination of the NACA 43018 airfoil at the root and the NACA 43012A at the wing tip. The experimental setup consisted of a wing glove on the left side, a tripod with the infrared camera above the fuselage as well as racks carrying the power supply and electronics. The latter were placed in the internal storage compartments of the plane. The wing glove is designed as composite sandwich structure. Foam plastic as a sandwich core isolates the surface from the wing structure.

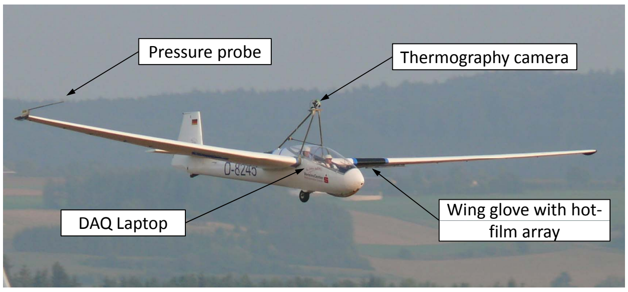


Fig. 2 SZD 9 bis 1E experimental configuration

A matt-black plastic foil was applied to the upper side in order to improve the emissive characteristics as well as to guarantee sufficient heating by solar radiation. The hot-film array provided by Tao Systems consisted of 28 Nickel gauges vapour-deposited on a Kapton carrier foil. It was glued flush to the coated glove surface. As an additional pneumatic measurement technique a Preston tube was applied at 14% of the chord-length. The infrared camera VarioCAM hr head by Infratec Dresden was mounted on a tripod above the fuselage. This stand was build of carbon fibre laminate tubes. The Senflex hot-film gauges were operated at a constant sensor temperature. The power was supplied by a mobile 8-channel anemometer bridge. A multi-hole pressure probe was used for determining the flight attitude including airspeed, angle of attack and yaw. All data was collected and recorded on a laptop and synchronized using the system time.

3 Results

3.1 Data Reduction

The infrared images were processed using the firmware IRBIS 3 professional. For this purpose eight contour lines were defined along the wing surface. The streamwise temperature distributions were exported into ASCII-files and further processed using a separate MATLAB script. The transitional zone is clearly indicated by a rapid decrease of the measured skin temperature.

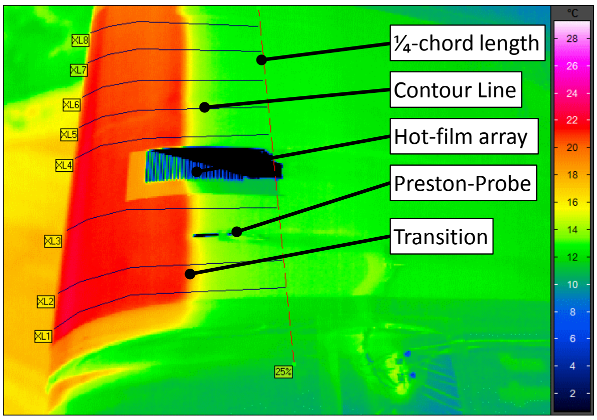


Fig. 3 Infrared image with contour line definition

The minimum temperature gradient was used as mathematical criterion for the determination of the transition location. The heating voltages were also processed using a MATLAB program. At first the voltages were converted into quasi-wall-shear-stresses and then separated into a mean value and fluctuations. The quasi wall shear stress (QWSS) is a proper mean for reproducing the qualitative distribution of the local wall shear stress if the sensors are not calibrated.

$$QWSS = C \cdot \tau^{1/3} = \frac{E^2 - E_0^2}{E_0^2} \qquad (1)$$

Here C is a constant, τ the local wall shear stress, E the heating voltage and E_0 represents the voltage without incidence flow. Since the ambient temperature is changing with decreasing altitude, the QWSS had to be corrected using the formula usually applied for hot-wires. The boundary layer state was evaluated based on the QWSS mean value, the RMS-value and the skewness of the data distribution. The following criteria were defined for determining the transition location: if the position of the sensor and transition are consistent, the RMS-value reaches a maximum, the wall shear stress distribution shows the steepest slope and the skewness crosses zero

3.2 Thermography Results

During the test campaign two flights were carried out using the infrared camera. The measurements showed that the quality of the results strongly depends on the skin temperature induced by the solar radiation.

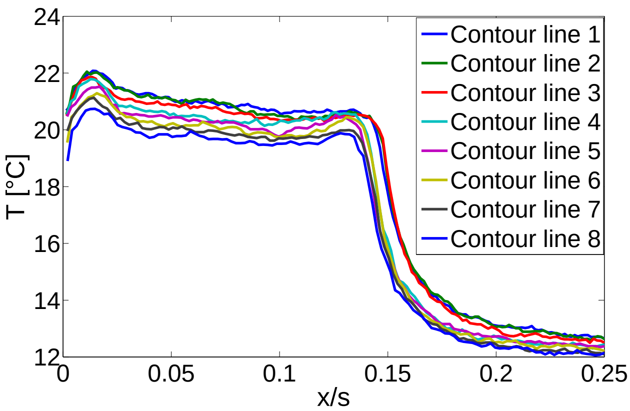


Fig. 4 Exemplary temperature distribution along contour line

The temperature distributions presented in figure 4 show a clear step in the transitional zone. Since the unfavourable weather conditions during the second flight led to noisy temperature data, several techniques for smoothing the curves were tested. Among others the approximation by high order polynomials and running average procedures were examined.

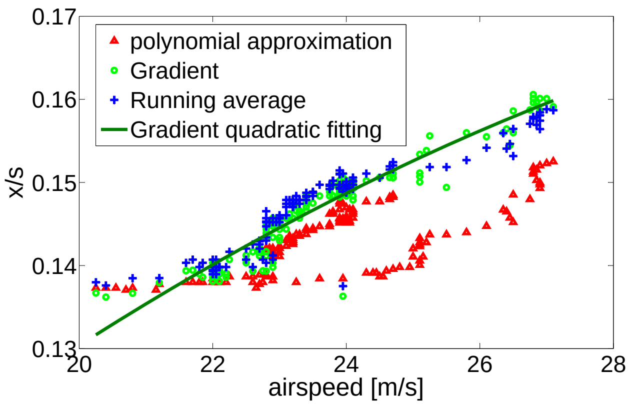


Fig. 5 Thermography results for different noise reduction methods

Figure 5 shows the results processed from the infrared images. If the airspeed is increased the angle of attack is decreasing and the stagnation point is moving further towards the suction side. This results in a different pressure distribution. The measurements showed that the transition location is shifted downstream at higher airspeeds. This suggests a dominant influence of the minimum pressure region. As soon as the pressure increases downstream of this location the boundary layer is destabilized and transition takes place rapidly. It also becomes apparent that only the running average as a smoothing method produces acceptable results. The approximation by polynomials results in significant falsification of the gradient distribution.

3.3 Hot-Film Anemometry Results

In order to achieve a good comparability of both techniques the flights with hot-films and infrared camera were conducted early in the morning before thermal updrafts started to develop. The investigation of the transient behaviour was carried out in a slightly turbulent atmosphere.

3.3.1 Stationary Flight Attitudes

The analysis of the quasi wall shear stress and the RMS-values of the hot-film signals yielded a good agreement of both measurement techniques for stationary flight attitudes.

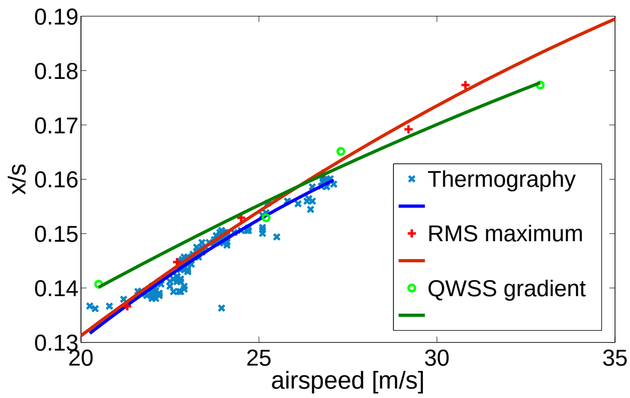


Fig. 6 Comparison of hot-film and thermography for stationary flight attitudes

The deviations which can be observed for the QWSS mainly result from the weak characteristic of the wall shear stress decrease which was used for determining the transition location. The data points for the hot-films represent the position of individual sensors which were passed by the transitional zone while the airspeed was varied.

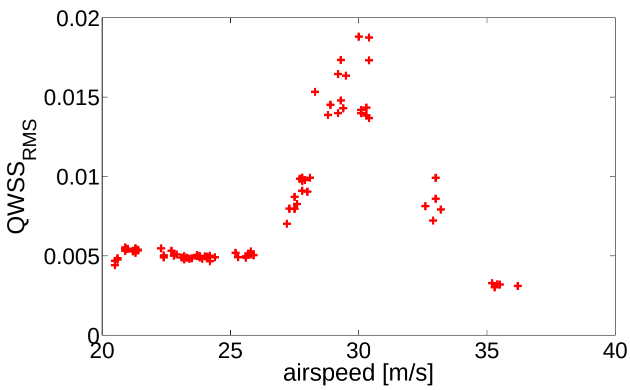


Fig. 7 RMS value distribution, $x/s = 0.177$

Figure 7 shows the change of the RMS value depending on the airspeed for a single gauge. At velocities between 20 and 25m/s the sensor is in the turbulent region of the boundary layer. If the airspeed is increased the transitional zone moves further downstream and passes the gauge. The RMS-value is increasing. The maximum is reached when the boundary layer is about 50% turbulent (cf. [2]). The strong fluctuations result from the large difference of the mean voltage for a laminar or turbulent flow. At high velocities the boundary layer is laminar. The RMS-value is

almost constant at a level slightly below the turbulent fluctuations.
The transition location can also be identified in the distribution of the quasi wall shear stress over the airspeed.

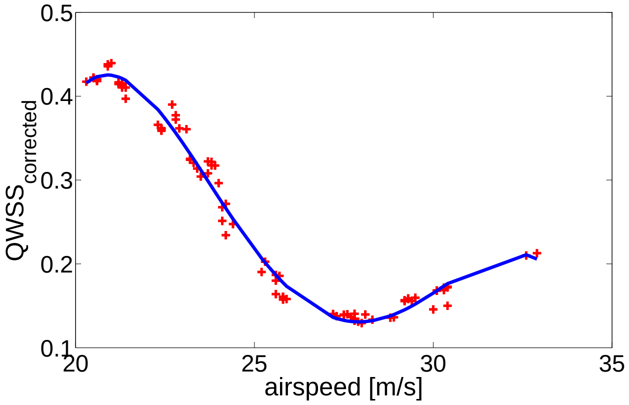


Fig. 8 Distribution of temperature corrected QWSS, $x/s = 0.165$

At low velocities the shear stresses are high because the sensor is overflown by a turbulent boundary layer. As soon as the airspeed is increased and the transition is moving downstream, the QWSS is decreasing until it reaches a minimum at the laminar boundary layer. Further increasing the velocity leads to a reduction of the laminar boundary layer thickness. That is the reason for the slight increase of the QWSS-value during high speed flight.

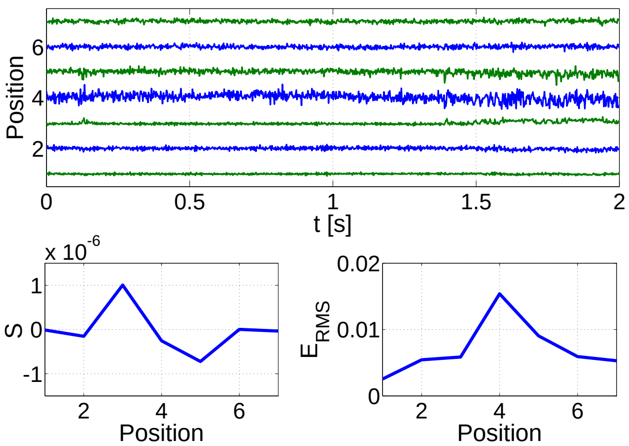
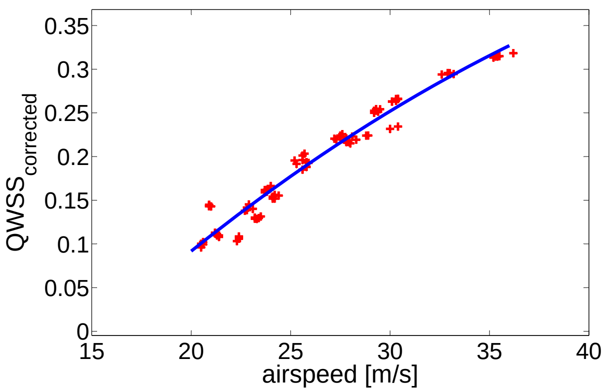
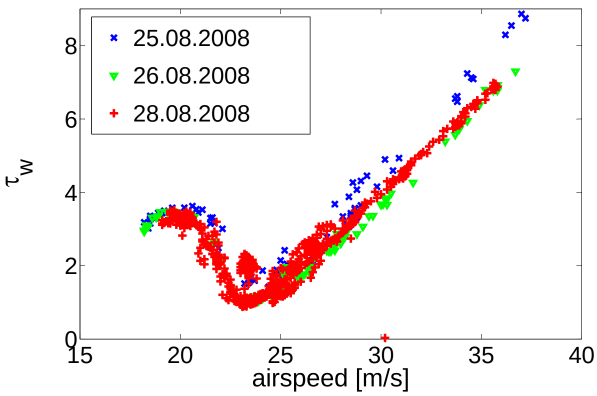


Fig. 9 Signal fluctuations and resulting statistical parameters, $v = 20.6\frac{m}{s}$, $\alpha = 15.7°$

Figure 9 shows the signal fluctuation for a case where the transitional area exactly covers the selected gauges. The skewness distribution allows determining the extension of the transitional zone. The skewness is increasing as soon as initial turbulent spikes appear in the signal. As long as the skewness is positive the boundary layer is mainly laminar. A negative value indicates a predominantly turbulent flow. Downstream of position 6 the boundary layer is fully turbulent. The transitional area in this example extends from 11.5 to 16.5% of the chord length. This equals a distance of 75mm. The development of the RMS-value is comparable to the observations made for figure 7.



(a) Hot-film



(b) Preston-tube

Fig. 10 Comparison of local shear stress measurements, $x/s = 0.14$

In addition to the hot-film gauges a Preston probe was attached to the wing glove. The recorded pressures were transformed into a local wall shear stress by means of the Patel calibration (figure 10. This allows getting an idea of the stress magnitudes present on the surface. The measured distribution is similar to the QWSS curve shown in figure 8. Transition takes place at the probe location at an airspeed of approximately 22m/s. The QWSS data for a hot-film gauge located at the same streamwise position does not show signs of a transitional boundary layer. The premature onset of turbulence at the Preston tube might be induced by the pressure rise induced by the stagnation area upstream the probe.

3.3.2 Influence of Atmospheric Turbulence

The conduction of test flights in calm and slightly turbulent air allows drawing some fundamental conclusions on the influence of thermal currents in the atmosphere.

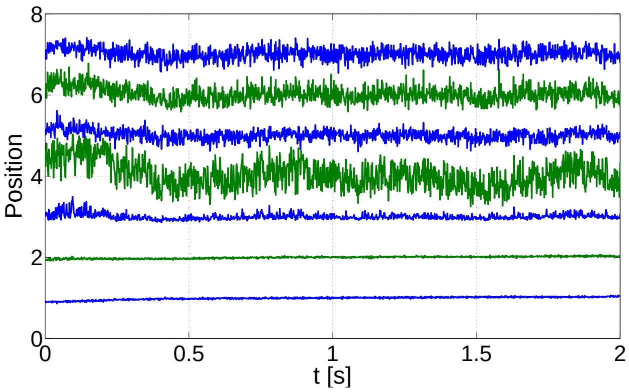


Fig. 11 QWSS fluctuations, $v = 26.5\frac{m}{s}$, $\alpha = 9.2°$, calm air

If updrafts are passed additional vertical velocities act on the glider. They lead to a change of the local angle of attack. Due to the previously described strong influence of the angle of attack on the transition location atmospheric turbulence has to have an impact on the onset of the turbulent boundary layer. Beside that the increased turbulence level of the incidence flow induces additional disturbances to the boundary layer which lead to a premature destabilization. The distributions of RMS-value and quasi-wall shear stress versus the airspeed feature a large scatter and can hardly be analyzed. Although the transition location can be determined for every data point without knowledge of the incidence flow, conclusions on the transition movement comparable to figure 6 are not possible based on the available data.

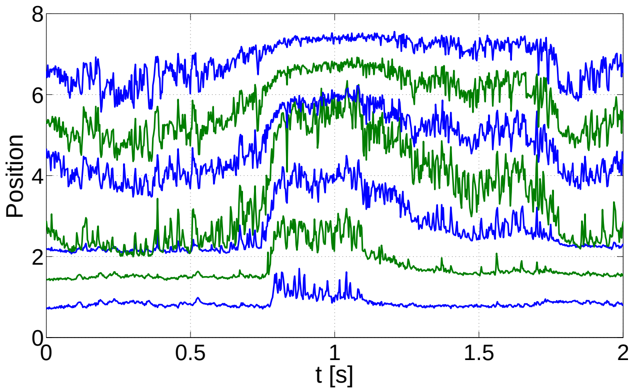


Fig. 12 QWSS fluctuations, $v = 26.5\frac{m}{s}$, $\alpha = 9.2°$, turbulent atmosphere

The figures 11 and 12 show the quasi wall shear stress fluctuation for two different data points. The first measurement was taken in relatively calm air above the cloud base. The second was recorded during the same flight with a strong influence of thermal updrafts. The gauges are located between 14.5 and 17% of the chord length. The signals in calm air are consistent with the results previously presented. The transition location at sensor 4 (15.7% chord length) matches the curve in figure 6. The extension of the transitional zone is small. Figure 12 visualizes the impact of atmospheric turbulence. The measured signals feature very strong low frequency fluctuations. The gauges 1 and 2 which are clearly in the laminar region in the calm air case now show turbulent events exceeding the previously described peaks. These signal characteristics suggest that vertical velocity components largely increase the local angle of attack. This results in a quick upstream movement of the transitional zone. The available data does not allow conclusions on the amplification of disturbances induced by the incidence flow.

4 Discussion

The laminar-turbulent transition could successfully be determined using thermography as well as hot-film anemometry. The obtained results show a good match for stationary flight attitudes. The calculated transition locations suggest that the angle of attack and hence the surface pressure distribution are the main actuating variables. By means of the hot-films a significant impact of atmospheric turbulence could additionally be observed. Although the low frequency fluctuations of the signals 2 and 3 as well as the local QWSS-minimum at gauge 4, shown in figure 13, might be explained by a separation, a definite prove of the supposed laminar separation bubble could not be found with neither of the techniques.

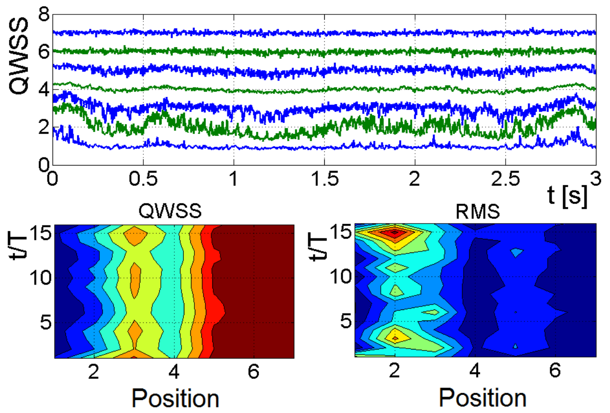


Fig. 13 Supposed laminar separation bubble, $v = 19.1\frac{m}{s}$, $\alpha = 19.3°$

The contour plots show the temporal development of the QWSS and RMS values. T represents the total duration of the recording. The diagrams show, that the sensor arrangement which was chosen in order to detect transition does not cover a sufficiently wide part of the wing surface. The little effort that is necessary to operate the infrared camera and to record the images is a clear advantage of this technique. In contrast positioning the camera is problematic. Although the camera mounting was approved by the airworthiness authorities it still affected the aerodynamic characteristics of the glider considerably. The hot-film anemometry requires less complicated external installations. Theoretically, the carrier foil could directly be applied to the wing surface. But the setup of the electronics and the adaption to the sailplane are clearly more complex. If a calibration of the sensors is intended the effort again increases. The power supply can be ensured independent from the onboard supply system if additional accumulators are carried. The data acquisition is uncomplicated for both measurement techniques. The limiting factor for the hot-film anemometry was the available number of channels.

The analysis of the measurements showed that the advantages of both techniques complement one another very good. The thermography provides an overview of large surface areas and allows determining a transition line. The weaknesses are the qualitative character of the observations and the large thermal inertia of the surface.

The hot-film anemometry provides detailed information about the boundary layer state. The high temporal resolution allows investigating transition and instability mechanisms. Beside that calibrated sensors can be used to measure local wall shear stresses.

5 Future Work

During the work on the presented project experiences on the use of thermography and the hot-film technique could be gained. The problems which arose and the experiences which were made were described an can now be considered in the planning of new experiments. This mainly includes a simplification and improvement of the equipment. The hot-film gauges require a larger number of acquisition channels featuring a higher sampling rate and resolution. This would allow a direct connection of the anemometer bridges to the data recorder and possible sources of error like the amplifiers can be omitted. The analysis of the test flights brings up questions that motivate a further investigation of the topic. An additional characterization of the free-stream conditions using hot-wires would provide deeper insight in the influence of atmospheric turbulence. In combination with high-frequency hot-film data a correlation of incident turbulence and boundary layer instabilities should be possible. The supposed laminar separation bubble could also be subject of future experiments. Beside that the experience could be used to approach new problems like the flow around the fillet wing fuselage or the tail.

Acknowledgements

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[2] Brunn, A., Nitsche, W. *Stroemungsmesstechnik 2. Auflage*. Springer, Berlin Heidelberg, 2006.

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