Microstructured Hot Film Sensor Array on Flexible Support for Transition Measurement

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ABSTRACT

This paper describes the wind tunnel validation of different arrays of robust microstructured hot film sensors with a high spatial and temporal resolution. Experiments for freestream velocities up to Ma = 0.4 have been performed and the boundary layer transition could be clearly detected with the flexible sensor arrays mounted on the surface of a NACA 0004 profile. The results were consistent with the measurements that were performed with surface hot wire sensors from TU Berlin on an identical model. With this first design of the sensor array we created our own reference to evaluate further developments of the sensor. To enhance the sensitivity of the hot film sensor front end the substrate material was structured to reduce the heat flux into the polymer support. In preparation of flight experiments an improved robustness of the exposed sensors has to be achieved. For this reason a thin passivation layer was deposited on top of the sensor array. Both further developments were tested separately to evaluate the characteristic of each technology.

Keywords: Hot film sensor, Transition, Tollmien-Schlichting Instabilities, Wind tunnel experiments

1. INTRODUCTION

The reduction of friction drag is a very important aspect for aircraft manufacturers [11]. To delay laminar to turbulent transition, the knowledge of the complex flow state is very important [1]. Especially for active flow control it is necessary to use highly sensitive sensors to detect small fluctuations in the boundary layer flow [3]. Sensors that are fabricated using MEMS technology guarantee the high spatial resolution that is needed to detect the small fluctuations [4]. For this application arrays of constant temperature anemometers were developed. The convective cooling of a thin microstructured film is used to sense the changes in the boundary layer flow. Silicon micromachining is widely used for the development of thermal flow sensors [8]. The sensor arrays described here are fabricated on a flexible support and can be easily applied on curved surfaces [2] [9].

In terms of long term flight experiments it is necessary to protect the sensors against environmental impact like erosion, UV-light and water [5] [6]. Therefore the sensors were deposited with a special thin polymeric layer.

To increase the sensitivity of the hot film anemometer the heat flux into the substrate material was reduced through a three-dimensional structuring process. Through this modification the sensitivity and the dynamic response of this thermal shear stress sensor should be increased [13].

Wind tunnel measurements with these sensor arrays have been performed in the transonic wind tunnel at the Berlin University of Technology. In addition to the validation of the hot film sensors, reference measurements with the sensors with passivation layer and the sensors with increased sensitivity were conducted on the same flexible support.

2. EXPERIMENTAL SETUP

2.1 Wind tunnel

The experiments were conducted at the TU Berlin in an open loop low-turbulence wind tunnel up to Ma = 0.4. The freestream Mach number is continuously adjustable up to 0.95 resulting in a maximum Reynolds number Re = 1.3×10^5. Due to the high contraction ratio of 47:1 between the settling chamber and test section, the freestream turbulence intensity is less than 0.15%. The wind tunnel test section has a cross section of 150mm x 150mm at the inlet with adjustable top and bottom fibre-glass walls. These wall adjustments were used in this test campaign to introduce pressure gradients in flow direction that decelerate or accelerate the natural transition process (see Fig. 1). This guarantees that transition is always in the range of the sensor array, independent of the freestream Mach numbers. Therefore, a single model with a fixed sensor position can be used for a range of Mach numbers.

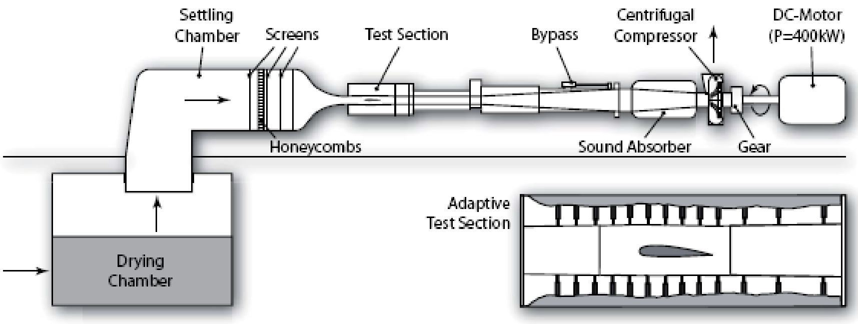

Fig. 1 Transonic wind tunnel TU Berlin

The unswept test wing is a 30mm thick aluminium model with a modified NACA 0004 profile at the leading edge and a flap at the trailing edge (c = 750 mm). The model is horizontally fixed in the centre of the two-dimensional adaptive test section.

2.2 Microstructured hot film sensor array

The sensor array consists of 48 constant temperature anemometers. Two rows of sensors are integrated on one thin polyimide foil. The sensor array can be easily applied on the surface of the wing model. To guarantee a flush and robust surface the electronic connections and circuitry are protected by the substrate foil.
Two different enhancements of the sensor array were validated in the wind tunnel entry. During the manufacturing process one row of sensors was equipped with sensors with increased sensitivity or sensors with a passivation layer, the other row was used as reference on both arrays (see Fig. 2).

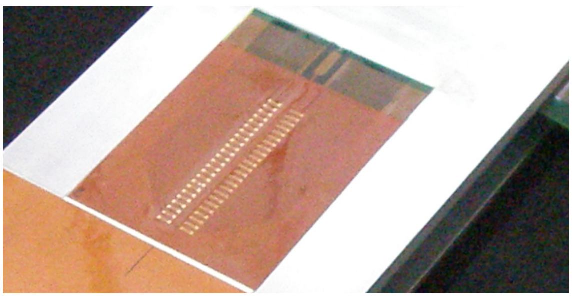

Fig. 2 Microstructured hot film sensor array

The sensor is connected with the electronic board by two flexible and shielded connection ribbons, one for each sensor row. 24 sensors are connected on the first sensor row to get a high spatial resolution, on the other row eight sensors are used as reference. Exchanging the plugs of the two flexible connector strips the first 24 channels could be switched over from the sensor row with increased sensitivity or passivation to the reference sensor.

2.3 Surface hot wire

The surface hot wire from the TU Berlin is used as a reference in these measurements. This sensor was designed to detect smallest fluctuations in the boundary layer and has been tested in flow control experiments and several wind tunnel and flight experiments [10]. A platinum-coated tungsten wire (Ø 5µm) is welded above a narrow cavity (0.075 - 0.1mm) flush to the wing's surface. This arrangement minimizes the heat flux into the wall, therefore resulting in an enhanced signal-to-noise ratio of around five times compared to a conventional surface hot film. The surface roughness of the sensor/cavity is negligible ($k^+ < 5$). The calibration behaviour of the surface hot wire shows a typical hot-element characteristic similar to a surface hot film [7].

2.4 Electronics and data acquisition system

The electronic board includes 32 channels. In order to detect the small fluctuations in the boundary layer, the sensor output signal was separated in an AC and DC circuit. The AC signal path was used with high amplifications in the frequency range above 500 Hz. This was realised using electrical filters. For each channel the amplification and operating point of the controller, that defines the overheat ratio can individually be set.
For digital data acquisition a small system with a sampling frequency of 90 kHz for each channel was used. The sampling time was set to one second for each measurement. To view the measurement data online and to store them for further analysing a program was developed. The time traces and the spectra of all 32 channels can be monitored online. During the signal processing the time signals, the power spectra, the standard deviation and the skewness were evaluated.

3. RESULTS AND DISCUSSION

In order to get information of the quality our sensor array comparative measurements with the surface hot wire sensors from TU Berlin have been performed. Since the measurements showed consistent results, this first design of the sensor was created as our own reference to evaluate further developments. Two modified sensor arrays were tested in direct comparison with our own the reference sensors in different wind tunnel entries. To compare the results during the measurement, one unchanged sensor row is used as reference. Measurements were performed with different wall deflections up to Ma 0.4.
In order to compare the sensitivity of all sensors, a turbulence strip was applied near the nose of the wind tunnel model. This assures equally turbulent flow conditions over the whole sensor array. The sensitivity of each sensor could thus be calibrated with respect to the RMS-value. This was done for all sensor elements.

3.1 Characterisation of the microstructured hot film

In the following the results for one flow velocity (Ma = 0.34) are shown for a row of 24 reference sensors. In the time signals the increase of the amplitude of the signal in downstream direction can be seen clearly. Also the propagation and the amplification of different wave packets are observable.
In Fig. 3 the standard deviation is plotted over the distance to the leading edge. Caused by the higher intermittency the amplitude of standard deviation grows in the transitional boundary layer. The standard deviation reaches a maximum in the transition region and decreases again when full turbulence is attained, albeit to a higher value than before transition.

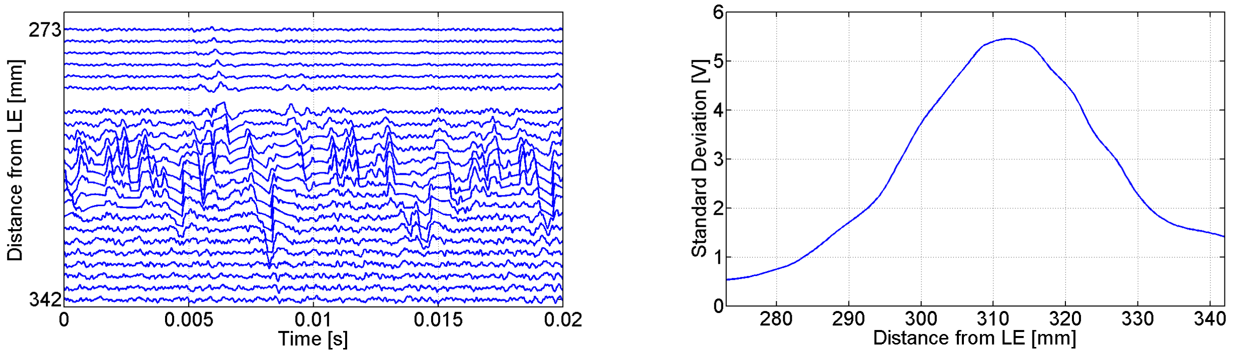

Fig. 3 Time signals (left) and standard deviation (right) of one complete sensor row (Ma 0.34)

3.2 Stages in transition

For different flow freestream velocities the variations in boundary layer flow were analysed. In the following significant examples for Ma = 0.33 are shown. For each stage of transition a typical output signal and the appropriate spectrum gained by Fourier analysis from the signals of the hot film anemometers is shown.

Laminar flow

Fig. 4 shows the time signal and the FFT-analysis (Fast Fourier Transform) of the almost laminar flow. The sensor output voltage is marginal. The peaks in the spectrum are caused by acoustic tones inside the wind tunnel. Frequencies in the signal lower than 500 Hz are damped by the electronic filters.

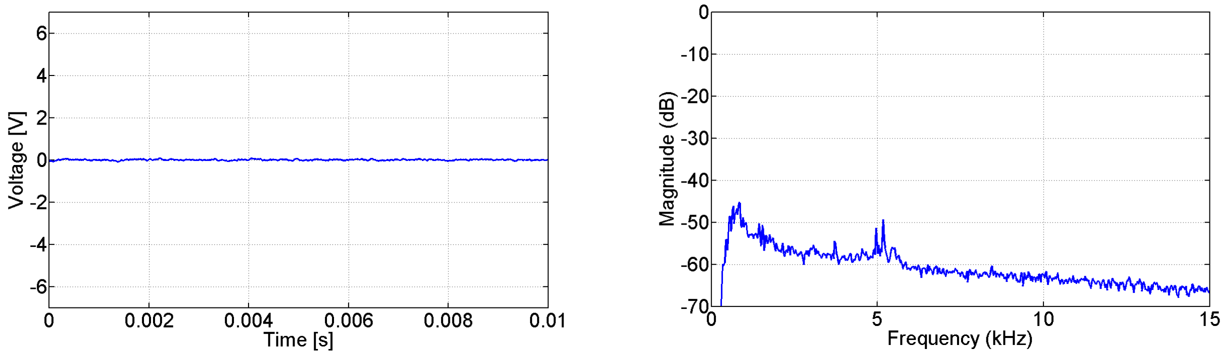

Fig. 4 Time signal (left) and power spectrum (right) of almost laminar flow conditions at Ma = 0.33

Tollmien-Schlichting instabilities

The time signal shows the typical wave packets of the Tollmien-Schlichting instabilities (TS). The wavelength is 6-7mm for this flow velocity. In the power spectrum the typical shape of the excited frequencies can be observed. Even the first higher-order harmonic can be seen in this figure. The acoustic disturbances are also present in this measurement (Fig. 5).
To analyze the time delay between two consecutive sensors the cross-correlation function was calculated. With the known distance between the sensors the propagation velocity of the TS-wave can be calculated. The propagation velocity of the TS instabilities in this test case corresponds to 35.0% of the freestream velocity. This result is consistent with the theoretical calculations [12].

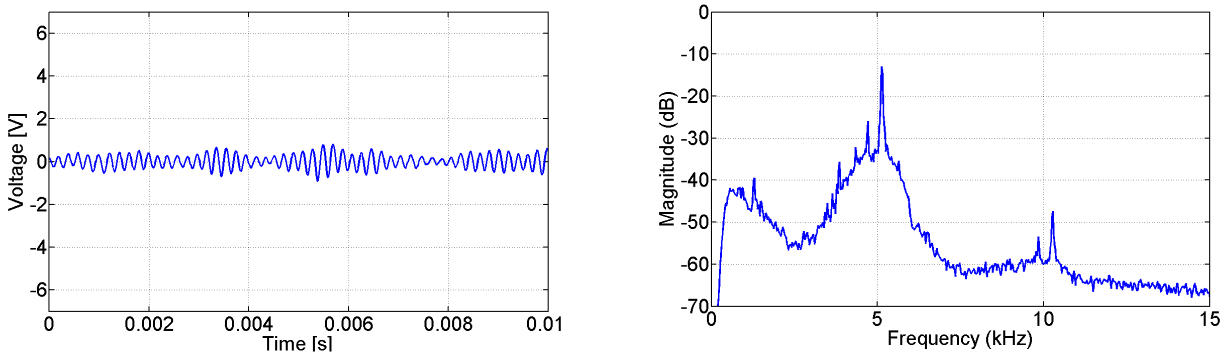

Fig. 5 **Time signal (left) and power spectrum (right) of Tollmien-Schlichting instabilities at Ma = 0.33**

Transitional flow
An explicit increase in the amplitude and the fluctuation of the sensor output voltage is one of the criterions for transitional flow in the boundary layer. This can also be identified in the increase of the FFT-signal (see Fig. 6).

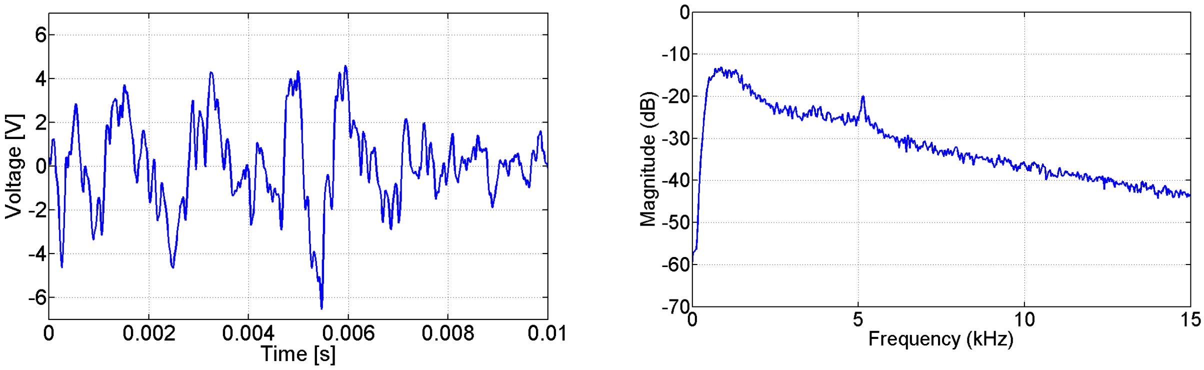

Fig. 6 **Time signal (left) and power spectrum (right) of transitional flow conditions at Ma = 0.33**

Turbulent flow
For the turbulent flow conditions the RMS-value of the sensor output decreases again. No specific frequencies can be observed in the spectrum. The decrease in the frequency is caused by the characteristics of the hot film anemometer (Fig. 7).

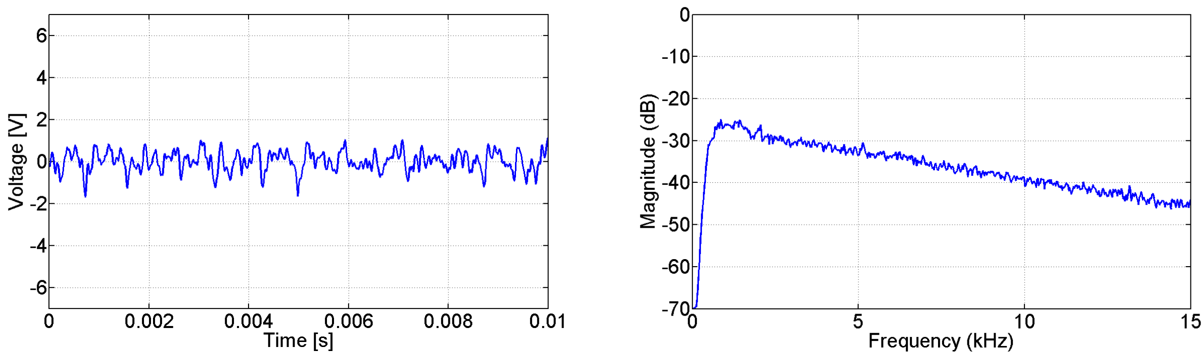

Fig. 7 Time signal (left) and spectrum (right) of turbulent flow conditions at Ma = 0.33

3.3 Comparative measurements with the surface hot wire

To investigate the quality of the hot film sensor array, a comparison with surface hot wire sensor measurements from TU Berlin were made for the same type of models.

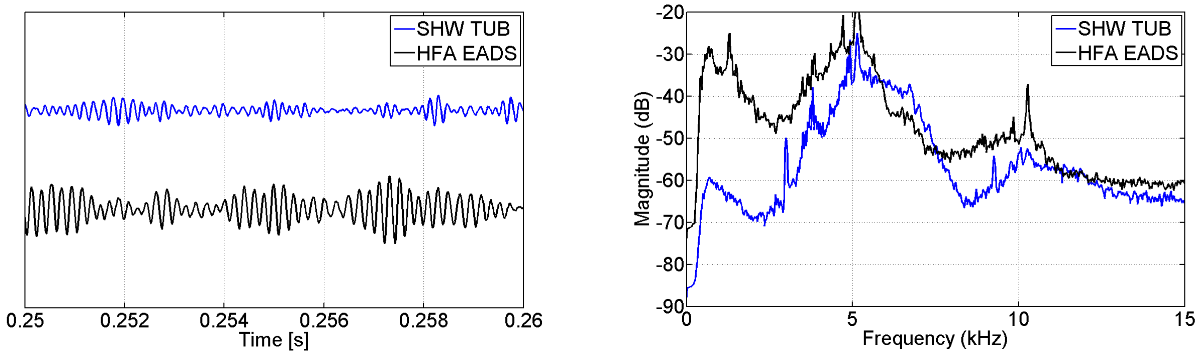

Fig. 8 Time signals and appropriate spectra of the microstructured hot film sensor array (blue) and the surface hot wire sensor (black) (Ma = 0.33)

The measurements were performed on identical wing models. The time signals and power spectra are taken from the sensors at the corresponding transition positions (see Fig. 8).
The feature of transition in the micro structured hot film arrays is comparable with the results of the surface hot wire measurement. According to the construction the surface hot wires show a higher sensitivity and an enhanced signal to noise ratio. It is difficult to increase their robustness

3.4 Sensors with passivation

In comparison to the reference sensor, the thin polymeric passivation layer results in a low frequency dependent damping. Despite this damping the TS instabilities are clearly observable in the time signal and the corresponding power spectrum (Fig. 9).

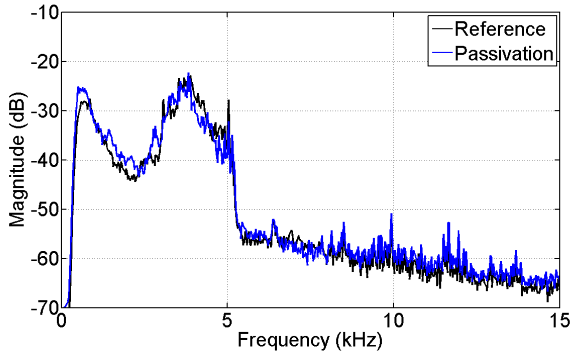

Fig. 9 Spectrum of one sensor with passivation layer (blue) and the corresponding reference sensor (black) (TS instabilities Ma at 0.30)

3.5 Sensors with increased sensitivity

In this wind tunnel entry a hot film sensor array with improved sensitivity was investigated. In this modified version of the sensor the heat flux into the substrate material was reduced. The improved sensors are implemented in a neighbouring row.

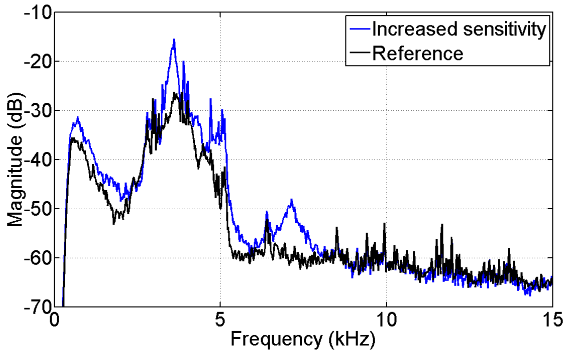

Fig. 10 Spectrum of one sensor with increased sensitivity (blue) and the corresponding reference sensor (black) (TS instabilities at Ma 0.30)

The sensors with improved sensitivity show a clear increase in the signal to noise ratio and the sensitivity up to 49% in the special configuration investigated (Fig. 10). Furthermore, with this arrangement it was possible to identify even the first higher harmonic mode. This improvement was found to be largely independent on the frequency over the observed frequency range.

4. CONCLUSION

The results show that boundary layer transition and Tollmien-Schlichting waves can be definitely measured with the microstructured hot film sensor array. The time signals, the power spectra and the standard deviation exhibit all indicators and all phases in the development of transition. The feature of transition in the microstructured hot film arrays is comparable with the results of the surface hot wire measurement.
As expected the passivation layer has a damping effect on the sensor signal. The passivation is necessary in terms of robustness of the sensor array. Despite the damping the transition can be clearly identified.
The reduction of the heat flux into the substrate through a three-dimensional structuring clearly enhances the sensitivity of the sensor array (49%). In the technological tests and experiments before this wind tunnel entry a method was figured out to realise this additional step in technology with minimum effort and costs. The amplification in the signal is higher than the damping the investigated passivation layer.
Wind tunnel validations up to transonic speed on a different airfoil model are planned for the future.

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REFERENCES

[1] A. Berns, E. Obermeier, X. Wang, J. Domhardt, J. Leucker, W. Nitsche: AeroMEMS Sensor with Integrated Pressure and Hot-Wire Sensor for High-Frequency Transition Detection, 47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition, 2009.

[2] U. Buder, R. Petz, M. Kittel, W. Nitsche, E. Obermeier: AeroMEMS polyimide based wall double hot-wire sensors for flow separation detection, Sensors and Actuators A, 142, 130–137, 2008.

[3] M. Engert, A. Pätzold, R. Becker, W. Nitsche: Active Cancellation of Tollmien-Schlichting Instabilities in Compressible Flows Using Closed-Loop Control, IUTAM Symposium on Flow Control and MEMS, 2006, Imperial College London.

[4] M. Gad-el-Hak: Flow Control – Passive, Active, and Reactive Flow Management, Cambridge University Press, 2000.

[5] F. Hausmann, W. Schröder: Transition Detection in Cruise Flight Using a Resistant Multisensor Hot-Film Technique, 42nd AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 2004.

[6] G. A. Johnson, M. J. Hucker, H. Holden, C. Trigg, C. Warsop: Development of MEMS Hot-film Sensors for use in the Integrated Wing Project, 26th AIAA Aerodynamic Measurement Technology and Ground Testing Conference, Seattle, Washington, 2008.

[7] J. Leuckert, J. Domhardt, W. Nitsche, J. Quest: On Application of Surface Measurement Techniques for Cryogenic High Reynolds Number Investigations on Wind Tunnel Models, 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 2008.

[8] F. Mailly, A. Giani, R. Bonnot, P. Temple-Boyer, F. Pascal-Delannoy, A. Foucaran, A. Boyer: Anemometer with hot platinum thin film, *Sensors and Actuators A*, Vol. 94, 32-38, 2001.

[9] C. B. McGinley, L. N. Jenkins, R. D. Watson, A. Bertelrud: 3-D High-Lift Flow-Physics Experiment – Transition Measurements, 35th AIAA Fluid Dynamics Conference and Exhibit, Toronto, Ontario Canada, 2005.

[10] I. Peltzer, W. Nitsche, J. Suttan: Low- and High-Speed Flight Experiments on Transition Detection, Journal of Aircraft, Vol. 45, No. 6, 2008.

[11] J. P. Robert: Drag reduction: An industrial challenge, AGARD R-786, Special Course on Skin Friction Drag Reduction, 1992.

[12] H. Schlichting, K. Gersten: Boundary Layer Theory, Springer, 2003.

[13] M. Sheplak, L. Cattafesta, T. Nishida: MEMS Shear Stress Sensors: Promise and Progress, 24th AIAA Aerodynamic Measurement Technology and Ground Testing Conference, Portland, Oregon, 2004.