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A multi-sensor hot-wire anemometer system for investigation of wall-bounded flow structures

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Abstract

This work describes a hot-wire anemometer system and an experimental procedure designed for mapping of the flow structure in disturbed boundary layers. It also briefly presents results from periodically disturbed wing boundary layers. The hot-wire system consists of a number of individual anemometer units, which can be combined to operate multi-sensor probes for simultaneous measurement of velocities in many points. In the present paper, however, only a single probe was used mounted in a dedicated traverse system in order to demonstrate how ensemble averaging can provide knowledge about the growth and decay of organised flow structures, as long as they are periodic in both time and space. The information from this flow structure can then be used in the design of multi-array hot-wire probes for further studies of the non-deterministic stages of the boundary layer transition.

1. Introduction

The successful implementation of flow control in many engineering devices (aircraft wings, road vehicles, ship hulls etc.) requires a detailed understanding of the nature of wall-bounded turbulent flows. The structure of a turbulent boundary layer is normally quasi-periodic with bursting events being both intermittent and random in space as well as in time. If the boundary layer is excited by for example an external sound field, it may stay periodic in both time and space, in which case it may be described by means of ensemble averaged data from a single traversed probe. At the latest stages of transition, however, the flow becomes highly irregular [1], and an analysis of this stage can best described in a Lagrangian framework, where space–time correlations and conditional sampling techniques can be used to follow the generation, growth and decay of organised flow structures. This requires dedicated measurement systems with simultaneous sampling of data from many points at the same time. In this way no information is lost, in contrast to ensemble averaging.

A hot-wire anemometer is suitable for this application as it easily meets the frequency and length scale requirements. The bandwidth is normally 20 kHz or more[1] and probes can be made with sensor lengths down to 0.5 mm or smaller. As simultaneous measurements are required in many points close to each other, the LDA is not quite appropriate, partly due to practical problems in arranging an array of crossing laser beams and partly due to the high cost of such a solution. The PIV being a global technique, which might seem ideal for this application, does not have sufficient temporal resolution. In combination with the right probes, data acquisition system and data reduction software, a hotwire anemometer therefore offers an acceptable solution for the mapping of coherent structures in thin, medium speed boundary layers in air.

Much work has been done studying coherent structures with multi-array probes as reported in [2,3] but it has been confined to larger and relatively slowly changing structures due to limitations in digital sampling techniques. The present paper describes a hot-wire anemometer system including a dedicated traverse mechanism that allows a probe to be positioned close to the wall and procedures for data acquisition and reduction. Results from a single-senor probe in excited boundary layers are presented, which clearly shows K-type breakdown. A more comprehensive

[1] This is determined for wall-remote configuration. For hot-wire in near wall arrangement, one may refer to Khoo et al. [9].

presentation of the results obtained with the measuring system described here can be found in [1]. The map of the flow structure created with a single sensor probe utilising ensemble averaging can be used as a guideline for the dimensioning of sensor-arrays for more advanced measurements.

2. Instrumentation

2.1. Design criteria based on flow characteristics

The measuring system is designed for the mapping of coherent structures in boundary layers on flat plates and wing profiles through a continuous recording of burst events close to the wall.

The main design parameters are the time and length scales of the bursts. The bursts are created through the interaction between decelerated regions (low-speed streaks) and large-scale disturbances (Falco eddies) in the near wall region of the boundary layer. The time scale is a mix between the inner and outer time scales $T_{in} = \nu / U_\tau^2$ and $T_{out} = \delta / U_\infty$ where ν is the kinematic viscosity, U_τ the friction velocity, δ the boundary layer thickness and U_∞ the free stream velocity [3]. The length scale lf may be defined as: $\nu / U_\tau^2 < lf < \delta / U_\infty$. A typical situation would be measurements in a point 0.15 m from the leading edge of a flat plate in air at normal conditions. At a free stream velocity U_∞ = 13 m/s the friction velocity U_τ is 0.5 m/s, and the boundary layer thickness δ = 2 mm, which gives time scales between 0.06 and 0.13 ms, corresponding to frequencies between 7.5 and 16 kHz, and length scales between 0.03 and 2 mm. As not every low-speed streak results in a burst, the time scale for the bursts will be larger, i.e. the burst frequency may in practice be considerably lower although still in the kHz range.

2.2. Hot-wire anemometer

The anemometer system is based on the combination of individual single-channel hot-wire anemometers (Dantec MiniCTA, Type 54T30) designed in accordance with the traditional constant temperature principle with a 1:20 Wheatstone bridge, servo-loop amplifier and output signal conditioner. The operating resistance, probe current levels, servo-amplifier gain and cable compensation circuit are designed only for use with wire probes. This very dedicated design makes it possible to miniaturise the anemometer circuit and to reduce the power requirements considerably as compared with general purpose anemometers. All adjustments are made by means of dip-switches and jumpers on the circuit board. The individual units are powered from external 12-V power supplies. The bandwidth is ≈20 kHz with a 5 μm wire probe with 5 m probe cable exposed to 50 m/s, and the noise level (input noise on servo-amplifier) is 3.5 nV/√Hz corresponding to typically 0.2 mV rms. The bandwidth decreases with increasing probe cable length, as the servo-amplifier gain then must be reduced in order to maintain servo-loop stability. The small size of the anemometers (3 × 6 × 11 cm) allows them to be placed close to the experiment, so that long cables may normally be avoided. As the system is based on individual anemometer units, it becomes very flexible and can be expanded at will. For a start a system with 8 units has been established, which will be expanded to 16 units. The number of units is in reality limited only by the data acquisition system. The output from the anemometer units has to be connected differentially to the data acquisition system in order to avoid cross-talk between channels. The system layout including traverse and PC is shown in Fig. 1.

The anemometers are powered from external power supplies, which must be of high quality in order to fully utilise the low noise figures of the anemometers. In the present case two-channel "Powerbox 3000 A" power supplies are used.

2.3. Data acquisition system

The analogue outputs from the anemometer units are digitised in a multi-channel A/D converter and saved as time series in a PC for further data reduction. The two key parameters of the data acquisition system are voltage resolution and sampling rate. In multi-channel applications it is important that the channels are sampled simultaneously, or, if they are sampled consecutively, that the time difference between samples are small enough to avoid unacceptable phase errors. For the present system a high-speed portable data acquisition system (IOtech WaveBook/516) was selected. It has 16bit resolution corresponding to 0.15 mV on a 0–10 V input range. The velocity-to-voltage sensitivity for a standard 5 μm wire probe (overheating ratio = 0.8) is around 0.005 m/s per mV

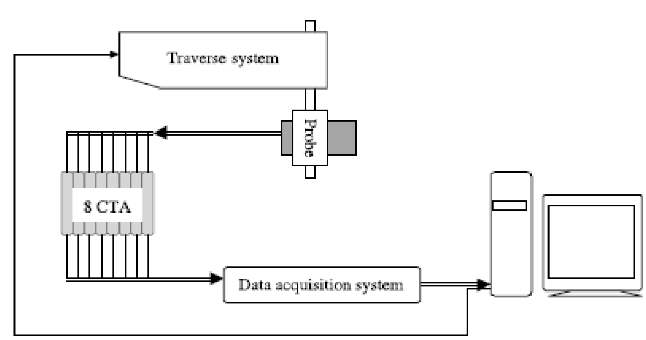


Fig. 1. Layout of multi-sensor anemometer system.

in the actual velocity range of 1–15 m/s. The 0.15 mV resolution of the selected A/D board being of the same magnitude as the anemometer output noise thus gives a velocity resolution of 0.0008 m/s. This is fully acceptable for the application. The IOtech WaveBook samples simultaneously from eight channels with sampling rates up to 1 MHz, which is more than adequate even to resolve the expected 0.06 ms inner time scales.

2.4. Traverse system

A traverse system with 5 degrees of freedom has been designed for positioning of the probe array (see Fig. 2). It moves in *X*-, *Y*- and *Z*-directions of the laboratory coordinate system defined by the wind-tunnel. *X*-, *Y*- and *Z*-are the streamwise, vertical and spanwise directions, respectively. The probe holder can in addition rotate around the *Y*-and *Z*-axis. The *Z*-rotation (θ-angle) makes it possible to position the probe array with an angle between the wire prongs and the wall in order to keep the support out of the boundary layer, while the *Y*-rotation (ϕ-angle) permits the wires to be placed perpendicular to the main flow on swept bodies. In addition the *Y*-, *Z*-rotations also provide the possibility for angular calibrations of *X*- and *V*-sensors to measure simultaneously *uv*- and *uw*-velocity components respectively. The traverse is moved by means of five servomotors coupled with encoders. The system has a linear resolution of 10 μm and angular resolution of 0.01°. The distance from the wire to the wall in its closest position is determined from the mirror image of the wire utilising a measuring microscope. This is tedious but accurate procedure, which allows positioning down to 0.1 mm from the wall with an accuracy of 0.01 mm. The entire traverse system is mounted inside the wind-tunnel test section.

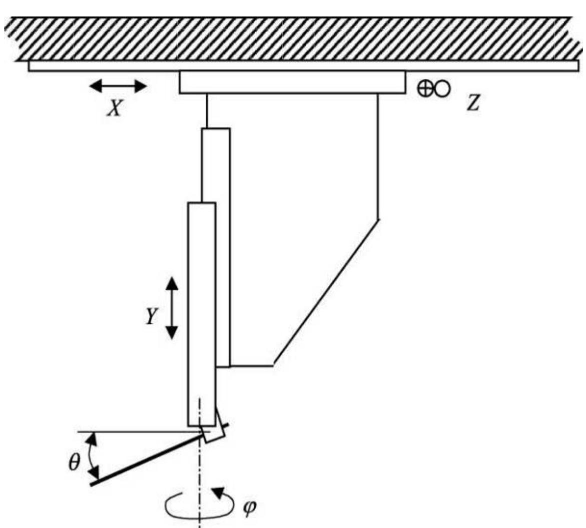


Fig. 2. Traverse system with 5 degrees of freedom.

The software controls the traverse by means of a high performance FlexMotion control board inserted in the computer and positions the probe according to the measurement scheme prior to each set of data acquisition.

2.5. Data acquisition and data reduction software

The dedicated software package is designed on the LabView environment. LabView programs (so-called "virtual instruments") control calibration of the probe, the traverse system and multi-sensor data acquisition. The acquired raw data are converted into velocities and reduced into statistical quantities.

3. Probe calibration

3.1. Calibration procedure

Probe calibration serves the purpose of establishing a transfer function between anemometer output voltages and the velocity acting on the probe. Probe calibrations were carried out in the free stream with a Prandtl tube positioned in the vicinity of the probes as velocity reference. The calibrations were based on about 30 calibration velocities in the range of 1.5–25 m/s. Curve fitting were performed using the relation suggested by Johansson and Alfredsson [6]:

$$U = k_1(E^2 - E_0^2)^{1/n} + k_2(E - E_0)^{1/2}$$

where E and E_0 are the anemometer voltages at velocity U and zero, respectively, and k_1; k_2 and n are calibration constants to be determined for a best fit to the calibration data. The second term in this equation takes into account the effect of free convection at low speeds, which appears below 0.2 m/s. A constant voltage offset, $V_{off,}$ is subtracted from the anemometer bridge voltage, which is then amplified with a factor of 5 in order to utilise the 10 V input range of the A/D converter as much as possible.

The calibration accuracy depends primarily on the accuracy of the micromanometer used together with the Prandtl tube. In the present case it is typically 1–2% of reading under isothermal conditions.

3.2. Check of probe calibration

As hot-wire probes may drift during use, mainly due to contamination, it is important to check the calibration before and after each experiment. Once the basic calibration is performed, it is enough to check the calibration in two points, e.g. at low and high velocity. If the probe has drifted, a new calibration function can be reconstructed on basis of the original function and the new sets of data. Such a procedure reduces the maintenance time of the system considerably.

4. Experimental setup and measuring procedures

4.1. Wings in disturbed cross-flow

Two cases were investigated: One with a uniformly disturbed flow over a swept wing equipped with roughness elements and the other with a flow disturbed by a point source (synthetic jet) over a straight smooth wing. Both experiments were carried out in the recirculating wind-tunnel at Thermo and Fluid Dynamics, Chalmers

University of Technology. In the present experiments the velocity was kept at around 13 m/s. The disturbance was created by a loudspeaker. In the first case it was placed freely in the wind-tunnel in order to create a uniformly disturbed field. In the second case it was placed at the end of a tube having its exit in the wing surface acting as a synthetic jet adding momentum but no mass to the flow. The loudspeaker frequency was 25– 30 Hz.

4.2. Traverse grid

A traverse grid covering 110 × 50 × 100 mm in the *X*-, *Y*-and *Z*-directions, respectively, was designed. The resolution is 2 mm in both the chordwise and spanwise directions, while it is only 0.4 mm in the *Y*-direction perpendicular to the wall. This gives in total 33,600 measuring points. The *X*-axis follows the cord for both straight and swept wings, which then requires that swept wing results are transformed into the wind-tunnel coordinate system prior to presentation, where *X* lab is in the *U*-direction.

4.3. Data acquisition

The acquisition of the CTA anemometer voltage was triggered by a microphone placed in the flow in order to phase-lock the CTA data. A sampling frequency of 10 kHz and a sampling time of 0.2 s in each point, fit 10 harmonics of 300 Hz main instability wave. The number of samples can be varied from 30 (to fit one period of main frequency) to 30*P* , where *P* is the number of realisations if procedure of ensemble average is applied. In the present examples 50 periods with each 40 samples were employed.

4.4. Data correction and conversion

The raw voltages are converted into velocity by means of the calibration functions for the individual sensors. As the temperature during calibration and measurements only varies 1–2 °C, corresponding to only 2–4% error in absolute velocity, no temperature correction routines are performed. Correction of the anemometer voltage for influence from the wall is not performed. The distance, at which the wall influence starts, is normally around $y_+ = yU_\tau / \nu = 5$ [8], and the friction velocities U_τ in the present experiments is around 0.5 m/s corresponding to a critical distance of y = 0:15 mm. As the smallest distance as defined in the traverse grid between the wall and the sensor is y = 0.4 mm corresponding to $y^+ = 13$, there is no need for any wall corrections. The converted data are stored in the computer in binary file format.

4.5. Data processing and presentation

In our work the behaviour of the disturbed flow is presented as spatial–temporal distributions of different velocity components *u*, *v*, *w*. The notations *u*, *v*, *w* are the velocity disturbances in the *x*-, *y*- and *z*-directions respectively, measured as deviations from the local mean velocities in the undisturbed flow. Both spanwise and

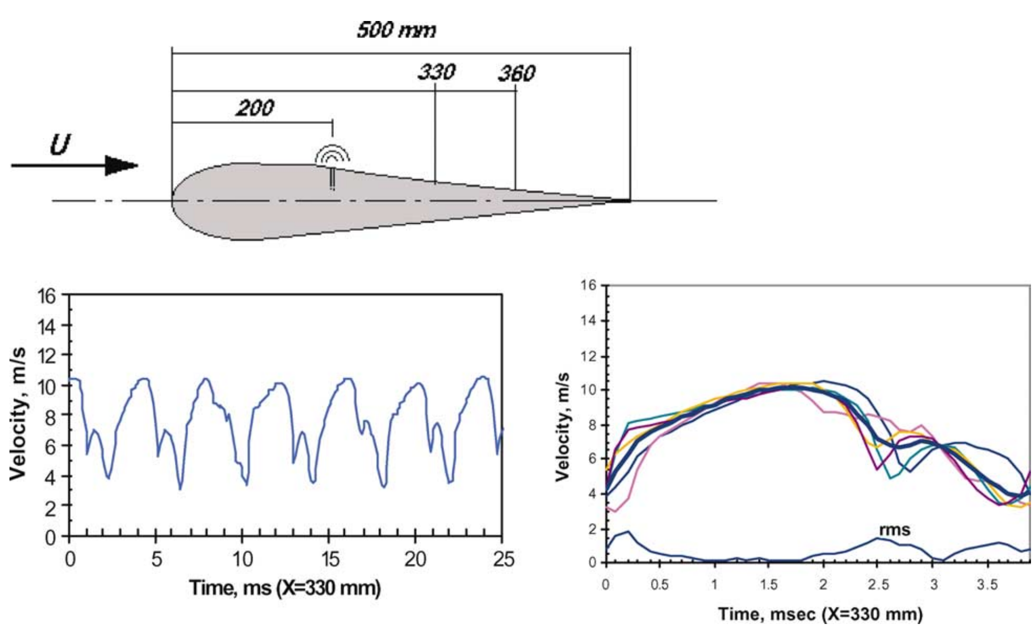
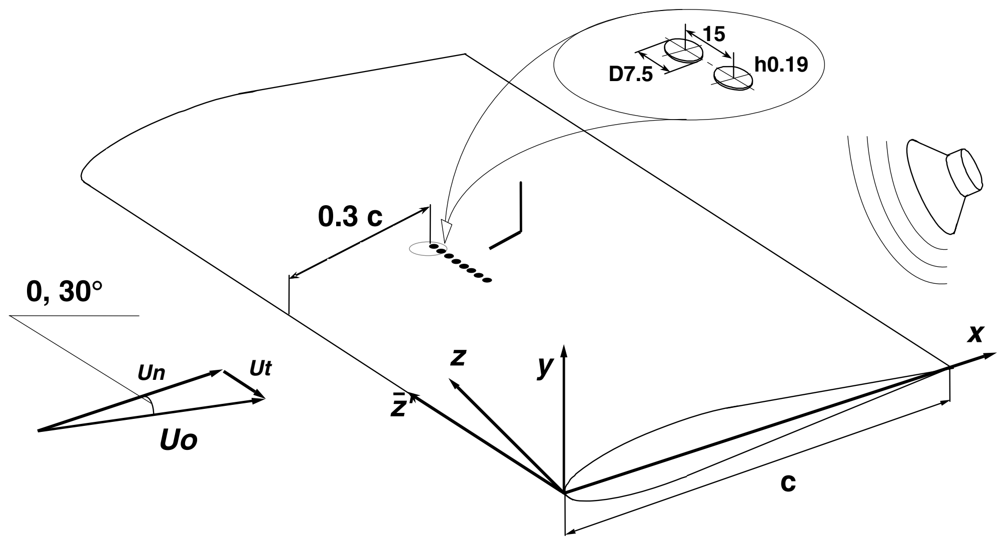
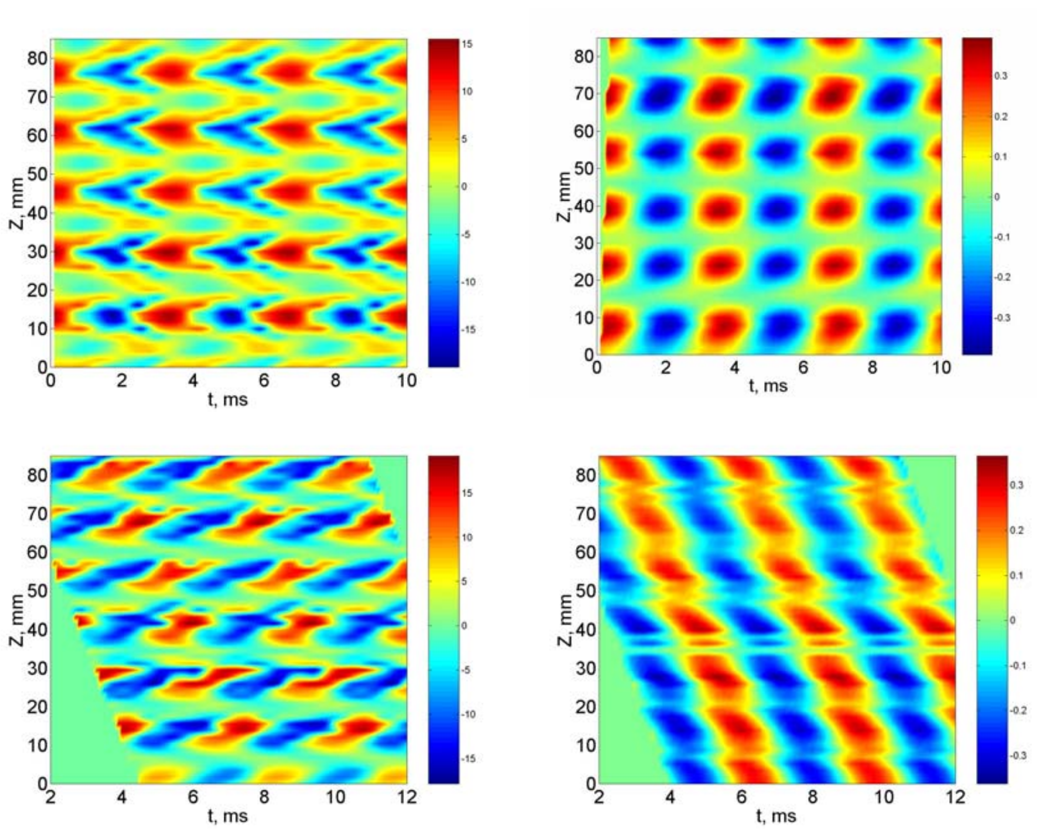


Fig. 3. Time series (left diagram) and phased-locked signals with ensemble average (five periods only) of velocity and standard deviation rms (right diagram).



Experimental investigation of K-type transition in straight and swept wing boundary layers.
Scheme of the experimental set-up and the coordinate system.



Patterns of the ensemble averaged streamwise velocity disturbance component in (t, z)-planes demonstrating two the scenario of K-type transition in straight (a, b) and swept (c, d) wing flows. X / c = 0.48 (a, c), X / c = 0.66 (b, d). The flow direction is from right to left.

Fig. 4. Two scenarios of K-type transition observed over an airfoil exposed to a uniform acoustic field. The top row presents evolution over straight wing, whereas the bottom row reveals the K-type of breakdown observed in swept wing configuration (sweep angle = 30°). Flow direction is from right to left. From [7].

normal distributions were measured, in which a set of isocontours in the planes (*y*, *t*) and (*z*, *t*) is referred to as vertical and horizontal disturbed flow structure, respectively. The isocontours represent, unless other wise mentioned, the streamwise perturbation velocity, $u = u'/U_{mean} = Tu$. The mean velocity and the standard deviation rms are calculated from phase-locked ensemble averaging of time series over *P* periods:

$$\overline{U}_E(t) = \frac{1}{P}\sum_{p=1}^{P} U(t, p)$$

$$u'_E(t) = \left\{ \frac{1}{P}\sum_{p=1}^{P} \left[U(t, p) - \overline{U}_E(t) \right] \right\}^{0.5}$$

where *t* = 0:39 ms in increments of 0.1 ms. Fig. 3 shows an example of cyclic velocity variations over a straight wing with a point source disturbance represented as a velocity time series and a group of five phase-locked velocity cycles. They reveal a strong periodicity with a clear disturbance from the front edge of the wing.

All analysis have been done using the standard Matlab packet.

5. Experimental results

5.1. Uniformly disturbed flow field

Experiments by Grek et al. [7] showed that the crossflow could cause the formation of non-symmetry in streaky-structures. In their experiments a solitary streaky-structure was generated in the boundary layer by injecting a portion of air through a transversal slot on the swept wing surface. To check those results experiments on the stability of three-dimensional boundary layers on the straight and swept airfoils have been conducted. The disturbance was created by a loudspeaker, which was placed downstream from the profile in the free flow field. It should be noted that the non-symmetry of the basic (mean) boundary layer flow (for the swept wing) results in non-symmetry of the disturbance flow patterns at non-linear stage of evolution of the waves. Detailed measurements of the streamwise velocity field in (*y*,*z*) planes, as well as the 3D frequency–wavenumber spectra have revealed linear and non-linear evolutions of the disturbances generated by an external acoustic field in the airfoil boundary layers. Signals from the hot-wire anemometers were triggered with external sound measured with the microphone. The signals have then been ensemble averaged (over 300 realizations) and stored in a PC for a subsequent analysis. It was found that the Tollmien–Schlichting waves, excited by the sound, were dominant in both configurations, and the disturbance flow field remained highly deterministic and periodic both in time and space until the latest stages of the transition. The K-type transition was identified with the aligned order of so-called Lambda-patterns at non-linear stage of the transition (Fig. 4).

5.2. Flow with an acoustic point source

In this case the disturbance was a point source placed 0.4 cord lengths from the leading edge of the profile. The source was a hole in the profile surface connected via a tube to a loudspeaker. In this way momentum was introduced into the boundary layer with the loudspeaker frequency.

The results are presented as isokinetic surfaces of the velocity perturbation *u'* (*u'* = Tu in % related to free stream velocity U_0) in the *X*-, *Y*-, *Z*-space, one surface for each time frame. In this way it is possible to see the temporal development of the disturbed wall bounded flow in three dimensions. The flow on both the straight and the swept wings were dominated by Tollmien–Schlichting waves like in the case of the uniform disturbance. The waves moved as a train along a line in the free stream direction overlapping each other in the *Y* direction and increasing in length and width with the distance from the disturbance point. On the straight wing the waves were almost symmetrical in the linear range, while they were highly irregular on the swept wing due to the three-dimensional nature of its boundary layer (Fig. 5). The study of the latest stages of transition indicates a chaotic behaviour.

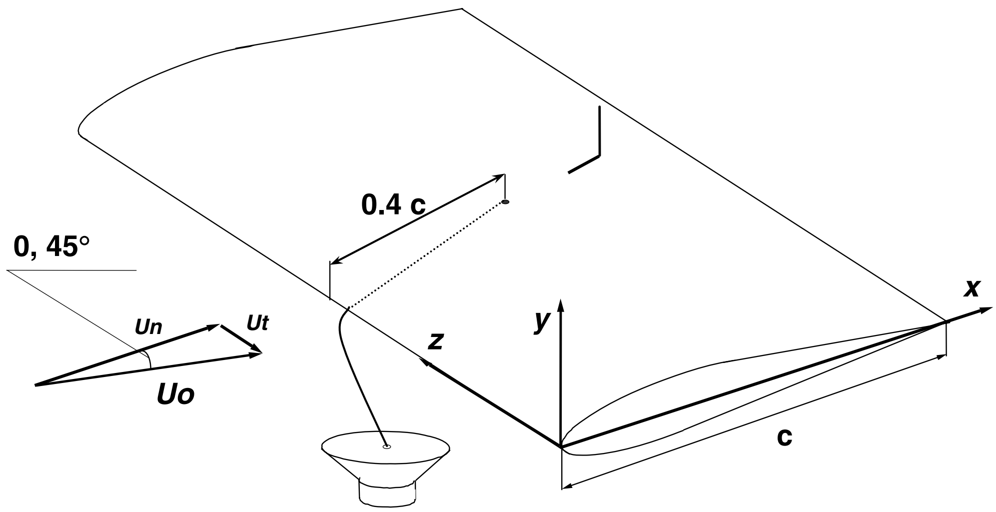
A more comprehensive description of the measuring results is given in [1].

6. Future developments

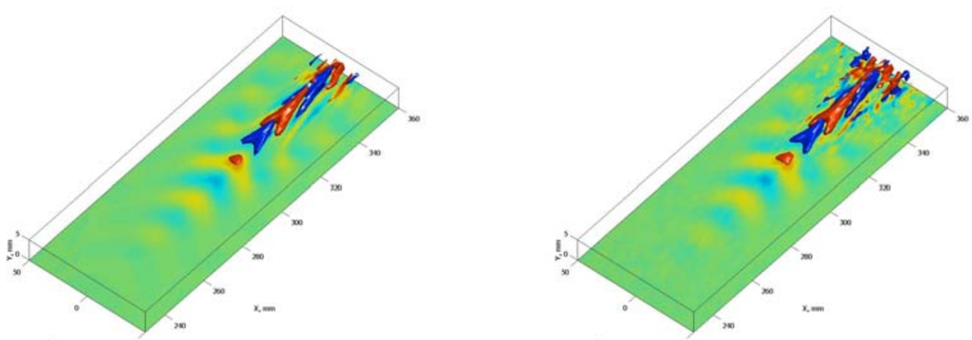
6.1. Multi-wire probes

To obtain real representation on all stages of the fluid motion a multi-wire probe is needed instead of the single-wire probe used so far. In the linear range multi-wire probes would reduce the experiment time considerably, while the transition process in 3D flows could not be mapped without simultaneous measurements in many points. A probe with eight wires will reduce the total measuring time in the present 33,600 points grid from about 30 h to less than 4 h.

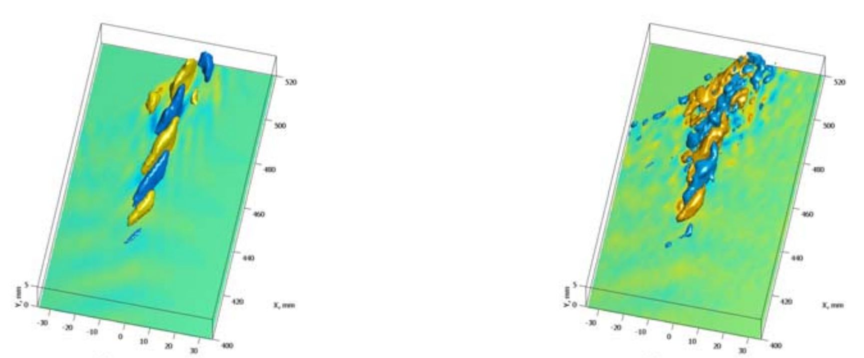
The dimensioning of multi-array probes is based partly on calculated length scales and partly on preliminary measurement of the structure in the boundary layer carried out by means of a single-sensor wire probe. In one of the reported experiments ensemble averaged streamwise velocity in the (*t*,*Z*)-plane measured with a single wire probe in a uniformly disturbed boundary layer show so-called Λ-structures with a width of ≈13 mm [6]. For the continued study of this phenomena, a probe with eight wires, each 0.8 mm long, placed on a line with 1.6 mm between their centres, will be designed (see Fig. 6). The wires are spot-welded to 0.4 mm diameter nickel prongs which are positioned parallel with each other and glued together with epoxy 8 mm downstream from the tip. The probe is equipped with a multipin connector, from which eight coaxial probe cables (2.5 mm in diameter) connect the wires to their respective anemometer module.



Experimental investigation of disturbances from point source in straight and swept wing boundary layers.
Scheme of the experimental set-up and the coordinate system.



Straight wing, U_o = 12.8 m / s, disturbance from point source, isosurfaces of u' =7.8 % U_o
Comparison of ensemble averaged and instantaneous signal.



Sweep angle 45°, U_o = 12.8 m / s, disturbance from point source, isosurfaces of u' =5.0 % U_o
Comparison of ensemble averaged and instantaneous signal.

Fig. 5. Isokinetic surfaces on straight and swept wing at U_0 = 12.8 m/s. Disturbance from a point source, isosurfaces of u' = 7.8% U_0

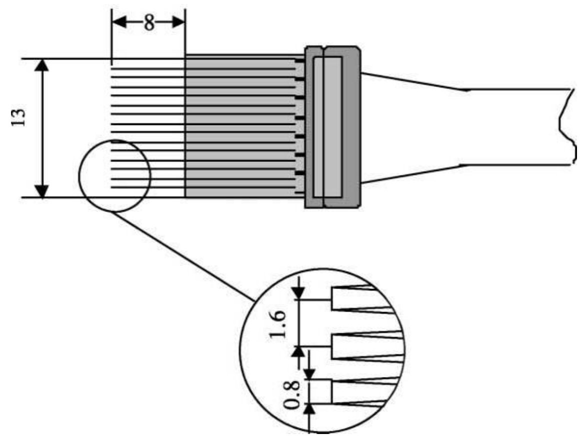


Fig. 6. Multi-sensor hot-wire probe.

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References

[1] V.G. Chernoray, A.A. Bachinov, V.V. Kozlov, L. Lofdahl,o€Experimental study of the k-regime breakdown in straight and swept wing boundary layers, Phys. Fluids 13 (7) (2001).

[2] C.W. Van Atta, Multi-channel measurements of high-order statistics, in: Proceedings of the Dynamic Flow Conference 1978.

[3] H.H. Bruun, Multi-probes and higher moments, in: Proceedings of the Dynamic Flow Conference 1978.

[4] H.H. Bruun, Hot-wire Anemometry Principles and Signal Analysis, Oxford University Press, 1995.

[5] L. Löfdahl, M. Gad-el-Hak, MEMS applications in turbulence and flow control, Prog. Aerosp. Sci. 35 (1999) 101–203.

[6] A.V. Johansson, P.H. Alfredsson, On the structure of turbulent channel flow, J. Fluid Mech. 122 (1982) 295–314.

[7] G.R. Grek, M.M. Katasonov, V.V. Kozlov, V.G. Chernoray, Modelling of streaky-structures in two-and three-dimensional boundary layers, Inst. Theoret. Appl. Mech., Russian Acad. Sci., Novosibirsk, 1999 (in Russian); Preprint No. 2-99.

[8] K.S. Hebbra, Wall Proximity Corrections for Hot-wire Readings in Turbulent Flows, DISA Information No. 25, 1980.

[9] B.C. Khoo, Y.T. Chew, C.J. Teo, C.P. Lim, The dynamic response of a hot-wire anemometer: III. Voltage-perturbation versus velocity-perturbation testing for near-wall hot-wire/film probes, Meas. Sci. Tech. 10 (1999) 152–169, Readings in turbulent flows.