ASME
Sixth International Thermal Anemometry Symposium
January 8-10, 2001, Victoria University, Melbourne, Australia

A Multi-sensor Hot-wire Anemometer System For Investigation of Wall-bounded Flow Structures.

F.E. Jørgensen[a)]

V.G. Chernoray[b)] [b)], A.A. Bakchinov[b)] and L. Löfdahl[b)]

[a)] *Dantec MT, 2740 Skovlunde, Denmark*

[b)] *Chalmers University of Technology, Thermo & Fluid Dynamics, 412 96 Göteborg, Sweden*

Introduction

The successful implementation of flow control in many practical 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 quasi-periodic with bursting events being both intermittent and random in space as well as in time. The description of such structures cannot be done in terms of Eulerian power and space correlations. It is better done 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 sensor arrays. In this way no information is lost, in contrast to ensemble averaging. The sensors must have high spatial and temporal resolution and provide continuous information about the velocity inside the smallest energy containing eddies close to the wall. Much work has been done studying coherent structures with multi-array probes as reported in [1] and [2) but it has been larger and relatively slowly changing structures due to limitations in digital sampling techniques. The present paper describes the design of a dedicated multi-array hot-wire anemometer system including a traverse mechanism that allows the array to be positioned close to the wall and utilising to-days fast data-acquisition technique. The dimensioning of the wire-array is based on a map of the flow structure created with a single sensor probe utilising ensemble averaging.

System requirements

The measurement 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 approx. 0.5 m/s, and the boundary layer thickness δ = 2 mm, which gives time scales between 0.06 and 0.13 msec, 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.

Selecting measuring principle

A hot-wire anemometer is the obvious choice for this application as it easily meets the frequency and length scale requirements. The bandwidth is normally 20 kHz or more and probes can be made with sensor lengths down to *0.5* mm or smaller. It is a well-established technique, it is relatively easy to use, and it is inexpensive compared with LDA and PIV techniques. As simultaneous measurements are required in many points close to each other, the LDA is not applicable, partly due to practical problems in arranging an array of crossing laser beams, partly due to the high cost of such a solution. The PIV, which might seem ideal for this application being a global technique, does not have sufficient temporal resolution. At present the maximum resolution is about 15 Hz. In combination with the right probes, data acquisition system and data reduction software, a hot-wire anemometer therefore offers the only realistic solution for the mapping of coherent structures in thin, medium-speed boundary layers in air.

System description

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 (CTA) with a 1:20 Wheatstone bridge, servo-loop amplifier

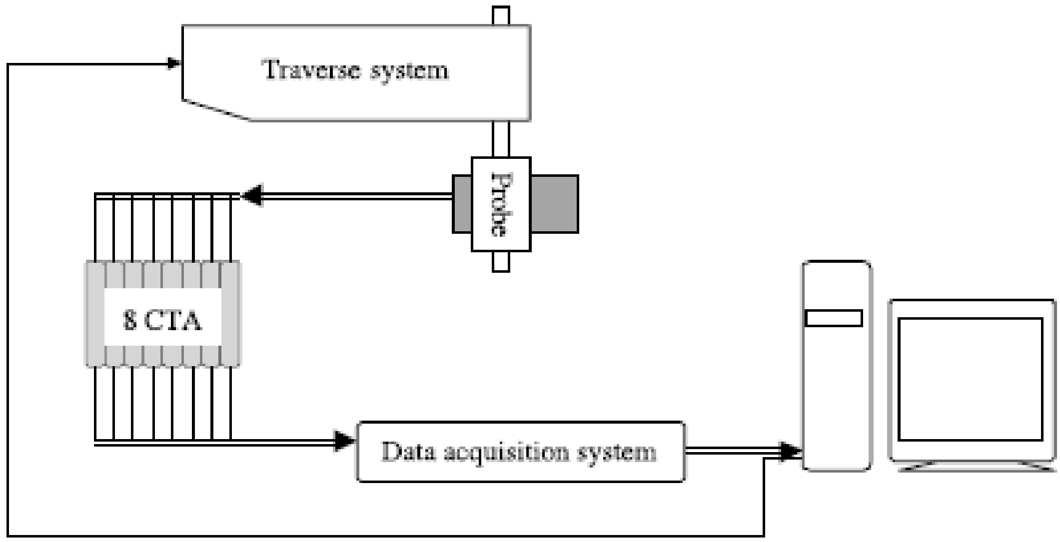


Fig. 1. Layout of multi-sensor anemometer system

and output signal conditioner. The operating resistance, probe current, 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- volts power supplies. The bandwidth is approximately 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 (3x6x11 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. To 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.

Anemometer power supplies:

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 by adding extra noise to the system. In the present case two-channel “Powerbox 3000 A” power supplies are used.

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 (TOtech WaveBook/516) was selected. It has 16-bit resolution corresponding to 0.15 mV on a 0-10 Volts input range. In the case of a standard 5 μm wire probe operated at an overheating ratio of 0.8 (corresponding to a wire over temperature of approx. 230 °C) the relative velocity-to-voltage sensitivity variation, $(dU/dE)/U \cdot 100$, $\% \cdot Volt^{-1}$, varies typically from 800 to 300 $\% \cdot Volt^{-1}$ in the velocity range 1-15 m/s. The 0.15 mV A/D board resolution, which is of the same magnitude as the anemometer output noise, gives a velocity resolution between 0.12 and 0.045 %. The Iotech WaveBook samples simultaneously from 8 channels with sampling rates up to 1 MHz, which is more than adequate even to resolve the expected 0.06 msec inner time scales.

Traverse System:

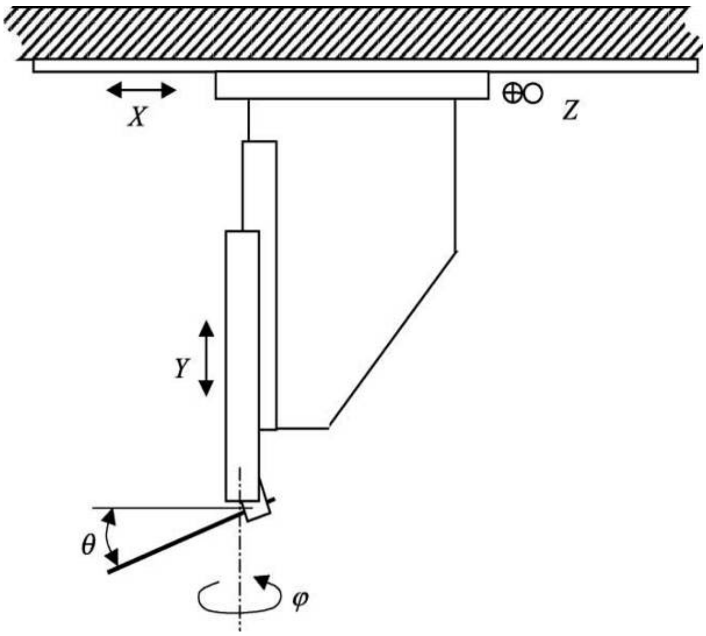


Fig. 2. Traverse system.

A traverse system with 5 degrees of freedom has been designed for positioning of the probe array. It moves in *X*-, *Y*- and *Z*-directions of the laboratory coordinate system defined by the wind-tunnel. *X*-, *Y*- and *Z*- are the stream-wise, vertical and span-wise 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. 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 servo motors coupled with encoders, the system have linear resolution of 10 μm and angular resolution of 0.01°. The entire traverse system is mounted inside the wind-tunnel test section. 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.

Multi-wire probes:

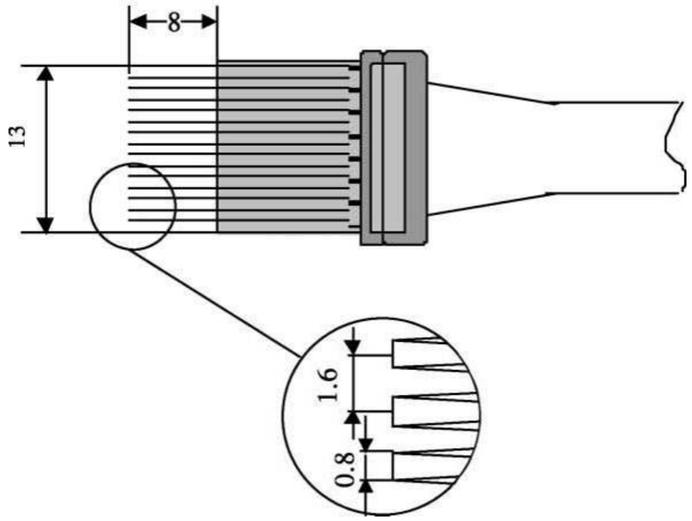


Fig. 3. Multi-array hot-wire probe with 5 μm diameter wire sensors

The dimensioning of multi-array probes is partly based on calculations of expected length scales basically on preliminary measurement of the structure in the boundary layer by means of a single-sensor wire probe. Ensemble averaged streamwise velocity in the (t, Z)-plane measured with a single wire probe in a disturbed boundary layer show so-called Λ-structures with a width of approx. 13 mm [6], For the continued study of this phenomena, a probe with 8 wires, each 0.8 mm long, placed on a line with 1.6 mm between their centres, was designed. 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 8 coaxial probe cables (2.5 mm in diameter) connect the wires to their respective anemometer module.

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.

Measurement Procedure

Basic Probe calibration:

The probes were calibrated in the free stream with a Prandtl tube positioned in the vicinity of the probes. The velocity was varied in the range of 1.5 — 25 m/s, and about 30 calibration points were usually taken. The calibration function was taken from Johansson & Alfredsson [5]) given by:

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

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, *Voff*, 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. It is worthwhile to note that the standard procedure for analytical temperature correction of the anemometer output voltage is not valid, if an offset has been applied prior to calibration. In this case the signal is no longer proportional to the square root of the heat transfer from the probe.

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.

Probe traverse:

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.

Data acquisition:

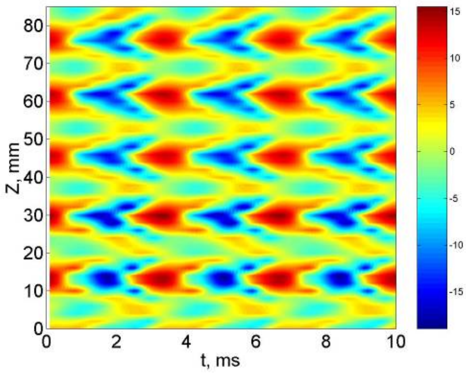
Example: Swept wing at 13 m/s. Typical sampling frequency is 10 kHz to fit 10 harmonics of main instability wave of 300 Hz. Number of samples can be varied from 30 (to fit one period of main frequency) to $30 \times N$, where N is the number of realisations if procedure of ensemble average is applied.

Data conversion:

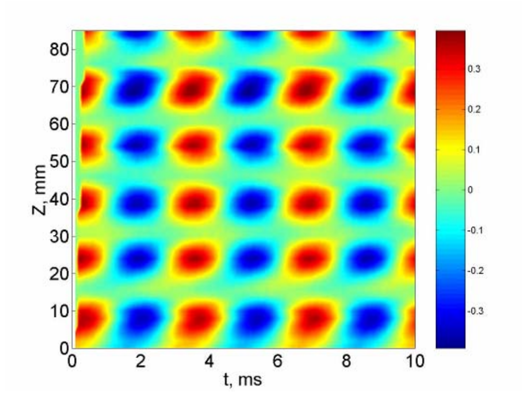
The raw voltages are converted into velocity by means of the calibration functions for the individual sensors. As the temperature during calibration and measurements only varies 1-2°C, corresponding to only 2-4% error in absolute velocity, no temperature correction routines are performed. Correction of the anemometer voltage for influence from the wall is not performed because wood made model always used. The converted data are stored in the computer in binary file format.

Data processing and presentation:

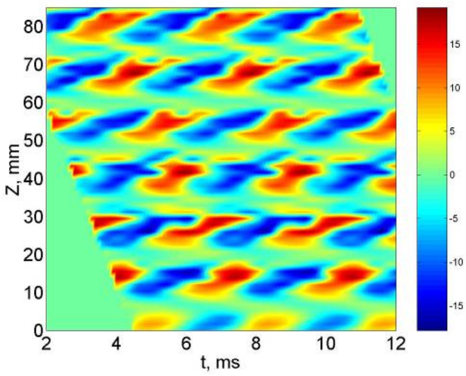
In our work the behaviour of the disturbed flow is presented as spatial-temporal distributions of different velocity components u, v, w. The notations u, v, w are the velocity disturbances in the x-, y- and z-directions respectively, measured as deviations from the local mean velocities in the undisturbed flow, Both spanwise and 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 otherwise mentioned, the streamwise perturbation velocity, u. All conventional procedures of analysis have been applied to the files of data. In the present case the standard Matlab packet is used.



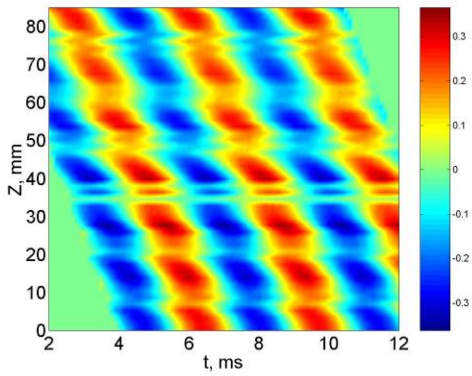
X = 311 mm



X = 241 mm



X’ = 380 mm



X’ = 280 mm

Fig. 5. Two scenarios of K-type transition observed over an airfoil. 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.

Experiments by Grek et al. [7j showed that the cross-flow could cause the formation of non-symmetry in streaky-structures. In their experiments a solitary streaky-structure was generated in the boundary layer by means of injection of 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. 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. 5).

Conclusion

A multi-array hot-wire anemometer system has been designed for measurement of coherent structures in wall bounded flows. It consists of 8 individual constant temperature anemometer modules a fast 8-channel data logger with simultaneous sampling at up to 1 MHz and a PC with a dedicated software package for calibration, probe traverse, data acquisition and data reduction. A multi-array probe with 8 wire sensors, *5* 1um diameter — 0.8 mm long, placed in-line has been developed for near wall measurements. A high-precision traverse system with 5 degrees of freedom moves the probe around in the boundary layer. Preliminary measurements in a disturbed boundary layer on a swept wing profile at a free stream velocity of 13 m/s with a single wire probe showed clearly so-called Lambda-structures having a width of approx. 13 mm and a time length of approx. 3 msec. This information was used as design parameters for the multi-array probe to be used in the same application. Testing of the multi-array probe is planned to take place in the nearest future.

Acknowledgements

The authors wish to thank Professor Viktor Kozlov at Institute of Theoretical and Applied Mechanics, Novosibirsk for valuable discussion on manufacturing and using multi-sensors in aero-physical applications. We wish to thank Mr. Uno Hansson for helping with the manufacturing of the experimental set-up The support from the Royal Swedish Academy of Science (KVA) is also gratefully acknowledged.

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