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Hot-wire and hot-film anemometry and conditional measurements: A report on Euromech 132

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The European Mechanics Colloquium, Euromech 132, was held at the Ecole Centrale de Lyon from 2 to 4 July 1980. Specific areas of hot-wire or hot-film anemometry were presented and discussed, more especially the effect of the finite time constant of the wire supports, the use of yawed hot wires in supersonic flows, the possible improvement of vorticity meters, and multi-point measurements of wall-shear-stress fluctuations. Other subjects described during the meeting included a new technique for concentration measurements in flames, developments and new uses of digitization and conditional sampling, pattern recognition analysis of fluid flow from multi-point, multi-time velocity measurements, and new turbulence measurements in complex flows and in fluid-flow machinery.

An exhibition of hot-wire and hot-film anemometers and associated equipment was held during the colloquium.

1. Introduction

Hot-wire anemometry has for a long time been a powerful tool for the investigation of turbulent flows. Its use is of particular value in obtaining continuous time signals and multi-point and multi-component measurements (velocity or temperature). Recent developments in electronic equipment and data acquisition and processing systems, further enhance its advantages, but require at the same time input signals which faithfully represent the physical parameters which are analysed. It appeared therefore necessary to discuss specific areas concerning responses of the sensors and the capabilities of the electronic circuitry. The areas which were selected had also to supplement the topics already considered at two previous Euromech meetings on hot-wire anemometry, Euromech 24 at Prague in 1971 and Euromech 63 at Copenhagen in 1975.

Euromech 132 was attended by 54 participants from 14 countries and 33 communications were presented. The following subjects were discussed:

(*a*) Time constant of the wire supports with regard to the controversy between static and dynamic calibrations.

(*b*) Calibration of multi-sensor probes and related data processing.

(*c*) Turbulence measurements in supersonic flows, mainly with yawed sensors.

(*d*) Attempts to measure fluctuating concentrations, especially in flames.

(*e*) Vorticity, kinetic energy dissipation and other small scale measurements.

(*f*) Velocity measurements near walls and wall shear stress gauges.

(*g*) Conditional sampling.

(*h*) Pattern recognition techniques.

(*i*) Turbulence measurements in complex flows and engineering situations (e.g. separating flows, fans, motors...).

2. Finite thermal time constant of wire supports

It has been pointed out recently that the supports of small hot-wire probes designed to have a good spatial resolution and to reduce aerodynamic perturbations, possess a finite thermal time constant which has to be taken into account in the heat-transfer law of the probe and in the signal it generates (Smits & Perry 1975; Millon, Paranthoen & Trinité 1978; Perry, Smits & Chong 1979). In the case of 'cold' hot-wires used in measurements of temperature fluctuations a systematic investigation was presented by C. Petit, P. Paranthoen & J. L. Lecordier*† (Laboratoire de Thermodynamique, Rouen). Measurements of the transfer function $H(n)$ of the probes were made in the frequency range of interest, $0{\cdot}1 \lesssim n \lesssim 5$ Hz, for ten conventional probes with wires differing in materials, diameters and aspect ratios. The overheat ratio of the wires was around 0·003 in all cases. Each function $H(n)$ which started from 1 for $n \simeq 0$ was found to decrease to a plateau in the range $(n > n_s, n \ll n_w)$ where n_s and n_w stand respectively for the characteristic thermal frequency of the support and of the wire. An empirical fit for all the plateau values H_p (which can be as low as 0·65 in the worst case tested) was suggested, namely $H_p = 1-2l_c/l$ where l_c is the cold hot-wire length already introduced by Betchov (1948) or Corrsin (1963) for static heat losses from wires fixed on infinitely large supports (thus operating at constant temperature). As a consequence, variances of temperature fluctuations whose energy spectra were significantly large in the plateau region were found to be systematically underestimated if static calibrations were not corrected for the frequency dependence of the wire supports. Further details will be presented in a forthcoming paper by Lecordier, Petit & Paranthoen. A similar but limited investigation was undertaken by W. Kuhn & B. Dressler* (Central Institute for Mathematics and Mechanics, Berlin DDR) for wires operating at overheat ratios around 0·8 and used for measurements of velocity fluctuations. R. Cheesewright* (Queen Mary College, London) suggested that the frequency dependence of the wire supports could be a relevant factor when investigating natural convection flows, in particular the turbulent part of a boundary layer along a vertical heated plane surface. According to Hoogendoorn & Euser (1978) the available data examined did not give satisfactory energy and momentum balances. In particular, mean velocities would have to be 30–40 % higher than reported to make the data consistent.

The case of rarefied gases for which convective heat transfer tends to decrease while radiation losses and conductive heat transfer to the support tend to increase, was investigated by L. Gottesdiener* (Laboratoire d'Aérothermique, CNRS, Meudon). A complete and improved procedure for hot-wire anemometry was presented. In particular the heat conduction loss to the support was made negligible by using heated supports (thermistances) whose temperature was controlled by thermocouples with respect to the wire temperature. The radiation losses were determined for each wire temperature by decreasing the gas pressure towards zero in the absence of flow. The

† Asterisks are used to indicate papers presented at the meeting, of which a full list is given at the end of this paper.

procedure was then applied to the wake of a thin flat plate for the following conditions: plate length 12 cm, Mach number $\simeq 2$, static pressure $\simeq 6 \times 10^{-5}$ mm of mercury, Reynolds number $\simeq 1000$ (Gottesdiener 1979).

3. Calibration of multi-sensor probes and related data processing

Most of the work presented dealt with single inclined and dual wire (or film) probes used for velocity measurements. H. H. Bruun & C. Tropea* (Department of Mechanical Engineering, Bradford University and Karlsruhe University) reported an experimental investigation of the combined velocity and yaw sensitivity coefficients of X-wires. Improvements were suggested for the current calibration practice and for the interpretation of the signals of hot-wire probes for cross flow component evaluation. The response of a double wedge probe used in water was thoroughly investigated by J. P. Giovanangeli* (Institut de Mécanique Statistique de la Turbulence, Marseille) for relatively large ranges of flow velocities, fluid temperatures, probe angles and overheat ratios (448 data points). A semi-empirical extension of Collis & Williams' law was proposed. A noticeable difference occurred, however, in the value of the exponent n which expressed the Nusselt-number dependence on the Reynolds number ($n = 0{\cdot}30$ in water compared to $n \simeq 0{\cdot}51$ in air). Previous experiments with a conical hot-film probe also led to the same empirical result. The calibration drift of sensors in water due to dirt accumulation was examined by J. Jimenez, R. Martinez-Val & M. Rebollo* (Universidad Politécnica and I.B.M. Madrid). Two practical methods to take into account the drift were tested, a systematic change in the probe overheat (as suggested by Richardson & McQuivey 1968) and a change in the thermal conductance of the sensor coating as suggested by Morrow & Kline (1974). The latter method was supported by several calibration runs, and turbulence investigation in a plane mixing layer confirmed its validity and applicability.

The difficult case of three-dimensional flows was discussed by J. Cousteix, G. Pailhas and R. Houdeville* (Departement d'Aérothermique ONERA/CERT Toulouse). Measurements of the six components of the Reynolds stress tensor were carried out in the wake which develops behind an 'infinite' swept wing. Two methods were used to increase the level of confidence which can be attributed to the data. In the first method, a single 45° slanting hot-wire probe was successively located at eight roll angles of the probe and the Reynolds stresses deduced from the mean square outputs $\overline{e'^2}$ by a least-square fit. In the second method, a X-wire was used and additional information was obtained from the measurements of the cross-correlation between the signals of the two wires. The interesting situation in which the boundary layer which develops around a cylinder was submitted to a sudden rotation, was presented by E. Arzoumanian, L. Fulachier & R. Dumas* (Institut de Mécanique Statistique de la Turbulence, Marseille). Since in this investigation special attention was paid to the wall vicinity, the presentation of this work is discussed in §7.

Recent advances in multi-channel constant temperature anemometers and data processing were presented by P. Buchhave* (DISA Elektronic A/S). The improvements incorporated into the new system are based on three main principles: (i) miniaturization and simplification of the analog modules, (ii) design of fast digital circuitry able to sample data at a rate of 1 MHz for each channel and to make real time computations of mean, mean square and correlation values, and (iii) design of efficient computer interfacing for data collection and remote control. The system now available may contain up to 16 CTA modules. Conditional sampling or strobing are possible with the digital modules through a reset/hold input.

Finally, a strobing technique designed to follow the motion of particles in turbulence was presented by M. Ayrault, J. L. Balint & J. P. Schon* (Université de St-Etienne and Laboratoire de Mécanique des Fluides, Ecole Centrale de Lyon). It consists of a high-power laser beam (5 W) which swept at known increments of time a section of the flow by means of a rotating cylinder made of sixteen facets acting as mirrors. Small particles injected into the flow (DOP or aloxite, 1 μm in diam.) were illuminated by the beam at each sweep and the photographic records on high-sensitivity films (1500 ASA) showed dotted trajectories for the particles which remained in the section swept by the laser beam. The positions of the particles were then stored in a PDP 11/34 minicomputer by means of a summagraphic digitizer. Lagrangian velocities were computed from the frequency of the rotating laser beam. Extension to a three-dimensional system was considered. The main difficulty was to maintain a high enough illumination of the particles to be traced.

4. Turbulence measurements in compressible flows

Recent progress in the measurement of turbulent shear stresses and turbulent heat fluxes was presented in several papers. Firstly, J. Gaviglio, J. P. Anguillet & M. Elena* (Institut de Mécanique Statistique de la Turbulence, Marseille) gave a well documented survey of the use of yawed hot wires in supersonic flows (Mach number in the range 1–4). They drew attention to specific points such as (i) the advantage of using a single yawed hot wire placed successively at two symmetrical positions with respect to the mean flow direction, instead of an X-probe, in order to reduce the interaction with the wire of the shock waves enveloping the prongs; (ii) the need to check the calibration curve as soon as slack affects the wire and to control the thermal lag compensation if a constant current anemometer is used; (iii) the need to have very large upper frequency limits in order to resolve the fine turbulent scales (e.g. of the order of 300 kHz); and (iv) the need to correct for the deficiency of thermal compensation at high frequencies which is more conveniently done with constant current anemometers than with constant temperature anemometers. Most of these conclusions agreed with the findings obtained independently by Laderman & Demetriades (1979).

V. Mikulla* (GMBH, Munich) reminded the participants that probes were specially designed at the Ames Research Center, NASA, Moffett Field, to be free of strain gauging, slack and wire oscillation even in hypersonic flow conditions ($M \simeq 7$) (Mikulla & Horstman 1975). They consist of 10 μm diam. platinum–rhodium wires mounted on a ceramic wedge. Two main difficulties were however discussed. Firstly, because of the heat loss to the substrate, the steady calibration curve did not easily give the dynamic sensitivity coefficients of the wires. Secondly, the time constant of the wire was not well defined so that it proved necessary to use constant-temperature anemometers.

J. P. Bonnet* (Centre d'Etudes Aérodynamiques et Thermiques, Poitiers) used a constant temperature anemometer to investigate the turbulent wake of a thin plate ($M \simeq 2$). Attention was paid to the frequency response of the anemometer which was tested not only by the usual square wave technique, but also by direct heating of the wire by means of a modulated laser beam (Bonnet & Alziary de Roquefort 1980), a method initially developed at the Franco–German Research Institute of St Louis (X-Bouis) in cooperation with the Ecole Centrale de Lyon (Comte-Bellot 1976). The sensitivity coefficients to mass flux, stagnation temperature and yaw angle were determined very conveniently in a small auxiliary wind-tunnel. Finally, N. Alemdaroglu & P. Ardonceau* (Centre d'Etudes Aérodynamiques et Thermiques, Poitiers) presented a comparison between hot wire (constant temperature) and laser–Doppler anemometry for the case of compressible turbulence in a shock-wave/boundary-layer interaction. Several interesting features were pointed out. For the LDA measurements it was observed that the signal-to-noise ratio varied as $1/U$ so that the optical set-up had to be optimized. A high-power argon laser (6 W) was therefore used and operated in the dual forward scatter mode. A Bragg cell was added to obtain the velocity in reverse-flow regions. The beam splitter was rotated to measure the cross-wire velocity. A typical fringe spacing was 20 μm and the flow was seeded with micron-sized dioctyl phtalate (DOP) particles. The hot-wire system was similar to that previously described by J. P. Bonnet*. Agreement between the two techniques was good except in the transonic region $M \lesssim 1{\cdot}4$ in which the hot-wire operation became unreliable due to the strong nonlinearity of its response (the local fluctuation level reached values of 20 % or more). In conclusion, laser–Doppler anemometry and hot-wire anemometry were considered as complementary rather than competitive techniques. For example, turbulence spectra measurements is possible with hot-wire anemometry in low-turbulence regions, which is almost beyond reach with laser–Doppler anemometry. Conversely, laser–Doppler anemometry provides information in highly turbulent and even separated flows.

5. Measurement of concentration fluctuations in flames

This difficult area was discussed in one paper only, by M. Trinité* (Laboratoire de Thermodynamique, Rouen) for a hydrogen flame. Use was made of the catalytic combustion which occurred at the surface of a small-diameter platinum cold wire (diameter 4 μm), when the gas temperature was high enough ($\gtrsim$ 473 K). As a result, the wire temperature was increased, and it was possible to show, within not too severe assumptions (negligible radiation loss, fast combustion rate, Schmidt number equal to Prandtl number, diffusion controlled mass transfer), that the temperature increase was a function of the instantaneous hydrogen concentration. The temperature increase of the wire was then obtained from the resistance change of the wire measured by means of a small electric current, as for 'cold' hot wires. The wire was, of course, also sensitive to the temperature fluctuations in the incident gas. A dual platinum-wire probe, with one wire coated to inhibit catalysis, would, in principle, allow for simultaneous measurements of instantaneous concentration and temperature fluctuations. The main difficulty lay in the wire coating, which had to be thin enough to keep the time constant of the wire reasonably small. Experiments in hydrogen were specially difficult because of its high diffusivity, and use of silica coatings was investigated. The short life-time of the wires was also a source of difficulty. The method was, however, used to investigate the intermittency which exists between all-burnt and unburnt products at the edge of a flame. More details will be published by Trinité & Beaudet (1981).

6. Vorticity meters and related small-scale measurements

The Kovasznay vorticity meter designed to measure the streamwise vorticity component ω_x is subject to spurious vorticity signals when operated in flows with high cross-stream velocities (Kistler 1952; Kastrinakis, Eckelmann & Willmarth 1979). Furthermore, no correction can be made for the actual probe because no simultaneous measurement of the cross-stream velocity components is possible. A way around this dilemma would be to use the same wire configuration with each wire held by a separate pair of prongs (a total of eight) and electrically operated independently, as suggested by Kastrinakis *et al.* (1979). A probe of this type was constructed (Cleveland 1979) and results were reported at the meeting by P. Vukoslavcevic, W. G. Cleveland & J. M. Wallace* (University of Maryland, College Park). Systematic tests were done in a gradient-free flow by pitching and yawing the probe. A very good agreement was obtained between the theoretical values of ω_x and the experimental data corrected for the cross-stream components V and W. Additional preliminary measurements were made to study the effect of the velocity gradients $\partial U/\partial y$ and $\partial U/\partial z$ on ω_x and also on the Reynolds stress $-\rho\overline{uv}$. The usual operation of X-arrays was also questioned, supporting therefore a concern already mentioned by Bogar (1975).

A pioneering work aiming at the simultaneous measurement of the three vorticity components along with the three velocity components was presented by W. W. Wassman & J. M. Wallace* (University of Maryland, College Park). A miniature nine-sensor hot-wire probe was designed and built. The wires were arranged in three arrays of three mutually orthogonal wires so that U, V, W, $\partial U/\partial y$, $\partial V/\partial y$, $\partial W/\partial y$, $\partial U/\partial z$, $\partial V/\partial z$, $\partial W/\partial z$ were measured directly and $\partial U/\partial x$, $\partial V/\partial x$, $\partial W/\partial x$ known by means of Taylor's hypothesis. Experiments were made to date in a low-speed flow so that the probe diameter (2 mm) was about 5·6 viscous lengths and the wire length (0·65 mm) was about 1·4 viscous lengths. Each wire was calibrated directly. Special attention had to be paid to the thermal cross-talk between the wires. Reduced over-heat ratios will be used in further experiments.

J. M. Elsner, P. Domagala & S. Drobniak* (Institute of Thermal Machinery, Czestochowa) designed a probe with two hot wires in order to investigate all the terms which appear in the kinetic energy dissipation of turbulent flows. The probe could be rotated around two axes which were defined by the probe configuration and the mean flow field. The difference between the two hot-wire signals was continuously recorded during rotations. All the components $\overline{(\partial u_i/\partial x_j)\,(\partial u_j/\partial x_i)}$ were then computed by means of trigonometric relations within the assumption of small-amplitude fluctuations. The spatial resolution of the probe and the accuracy of the method are to be checked in the near future.

Finally, P. Mestayer & P. Chambaud* (Institut de Mécanique Statistique de la Turbulence, Marseille) investigated some important limitations to the measurements of the small scales of turbulent fields with single and multiple hot-wire anemometers and cold-wire thermometers: probe spatial resolution and end effects, signal contaminations due to parasitic sensitivities, reduction of the effective frequency response by reduction of the signal-to-noise ratio and by probe dirtiness, effects of small uncertainties in probe calibrations when pairs of quasi-identical wires were used. Details were presented in a recent paper (Mestayer & Chambaud 1979).

7. Measurements near walls

It is well known that measurements of velocity fields close to walls require, among other things, corrections for the additional cooling of the wire by the wall. A great deal of effort has been expended on this question in the past (e.g. Wills 1962; Oka & Kostic 1972; Alcaraz & Mathieu 1975; Zemskaya *et al.* 1979). M. P. Chauve* (Institut de Mécanique Statistique de la Turbulence, Marseille) has, however, developed a new empirical correction which takes into account the changes of the calibration law of the wire with the distance from the wall. Furthermore, when the calibration law is expressed in terms of the usual King's factors A and B, it is observed that the relative changes of A and B are roughly equal to the relative change of the heating power supplied to the wire without flow ($\Delta A/A \simeq -\Delta B/B \simeq \Delta W/W$). Simplified expressions for the correction terms are then obtained and used successfully in various cases. Some questions, however, are not discussed, such as the effect of the wire aspect ratio, and the error due to the nonlinear response of the wire because of the high levels of turbulence which exist in the wall region. Some work on the wall cooling effect and its correction was also reported at the meeting by S. Burhanuddin & R. S. Azad* (University of Manitoba, Winnipeg).

The case of a movable wall was considered by Arzoumanian, Fulachier & Dumas*. The interest was twofold: (i) the boundary layer which was generated along a rotating cylinder placed in a wind-tunnel was a complex tri-dimensional flow, so that the mean velocity direction had to be determined very accurately prior to any turbulence measurement; and (ii) the wall cooling effect almost vanished for a fixed wire because the velocity remained high close to the moving wall. Check tests were run following the technique developed by Chauve for the mean velocity. Additional tests are under development for velocity fluctuations.

A number of participants were greatly interested in the measurement of instantaneous wall shear stresses by means of hot films mounted flush with the wall. H. P. Kreplin* (Institut für Experimentelle Strömungsmechanik, Göttingen) embedded 12 probes consisting of two mutually perpendicular nickel films in a V-configuration. The magnitude and the direction of the local wall shear could then be determined. Experiments were done on the three-dimensional boundary layer which developed around an inclined body of revolution. Detailed information on the boundary-layer transition and separation was provided by M. F. Fancher* (Douglas Aircraft Company, Longbeach, California) who presented an extensive use of this technique. About 100 sensors were located on an aerofoil by means of a thin plastic film (Kapton or Mylar). Experiments were run in a cryogenic tunnel. The important question of the heat loss to the substrate did not seem, however, to have been examined. For this particular problem, a useful reference is Brison, Charnay & Comte-Bellot (1979).

8. Flow-pattern identification

The technique of flow-pattern recognition was suggested a few years ago (e.g. Wallace, Brodkey & Eckelmann 1977) but has usually been applied only to time traces recorded at single points of turbulent fields. It was only recently (Townsend 1979) that the method was substantially extended to the identification of spatially large flow patterns, hence to the analysis of signals simultaneously recorded at several points in the flow by means of arrays of hot-wire anemometers. Two flows have been already investigated by Townsend (1979): a plane turbulent wake and a two-dimensional boundary layer. At the meeting, J. C. Mumford, A. M. Savil & A. A. Townsend* (Cavendish Laboratory, University of Cambridge) presented the main features of the technique and reported new results for the flow between two cylinders. In principle, flow patterns inferred from a study of the profile diagrams were used in a process of image enhancement. Initially, a profile sequence was assumed and a complete record was scanned to find places where the recorded data had an acceptably high coefficient of fit to the initial profiles. Each time the criterion of fit was met the actual profile sequence was stored, including surrounding profiles, and the average of all the stored sequences was recorded. The process might be repeated using the stored average as an initial sequence. Usually, the first operation led to changes in the dimensions of the pattern and to the appearance of subsidiary satellite patterns, and the second enhancement caused little change. For the turbulent flow between concentric rotating cylinders with the inner cylinder rotating at speeds of around one thousand times the critical value, two very distinct patterns were found from the velocity profiles taken on a parallel to the axis of rotation: (i) a rapid, small-scale turbulent component (time scale $\simeq 2{\cdot}10^{-3}$ s, length scale $\simeq$ 8 mm) and (ii) a low-frequency (0·1 Hz), nearly periodic pattern with a length scale comparable to the separation of the cylinders. Its appearance was related to the presence of toroidal eddies similar to those of the initial Taylor instability. Nearly 20 % of the kinetic energy resided in the toroidal eddies.

9. Conditional measurements

Measurements in intermittent and periodic flows require processing techniques that enable the extraction of relevant information about the nature of the flow field. In a recent survey Kovasznay (1979) discussed the various possibilities of conditional sampling. When combined with ensemble averaging it makes it possible to obtain separate average values for the turbulent flow and for the non-turbulent zone. With the introduction of point averaging it is possible to obtain properties at points located on the interface or at a known distance from the interface. When the sampling criterion is obtained from a periodic signal the above method is called periodic sampling and permits phase averaging. Various examples of conditional measurements were presented at the meeting.

Ensemble averages were reported by Wills* (National Maritime Institute, Teddington), who investigated the air flow over regular trains of water waves both close to breaking and of moderate steepness to investigate the major mechanisms of wave generation. A submerging hot-wire probe was used (Wills 1976) and located close to a wave probe. The output signals were digitized (1 kHz, 12 bits) and transferred to a Commodore PET minicomputer. Velocity signals were then linearized via a look-up table set by the hot-wire calibration and conditionally sampled on a threshold level of water recorded by the wave probe. The location of the point where the hot wire entered the water at the end of its sampling run was also determined and this was then used as the conditional sampling point to align the sampled data. Practical advantages of the processing were underlined, mainly its low cost and its flexibility.

Phase averages were used by Cousteix, Pailhas & Houdeville* when investigating the features of a two-dimensional boundary layer in the presence of a pulsed external flow. In the straightforward case investigated, the synchronization signal was delivered by the mechanical device which generated the pulsation of the flow and used to sample the anemometer signal at the instants of same phase over a great number of cycles. An attractive presentation of the results was shown in the form of plots of streak lines at different instants during one full cycle. Similarly H. C. Boisson, A. Sevrain & M. Braza* (Institut de Mécanique des Fluides, Toulouse) analysed the near wake of a cylinder by using the signals of two wires in accordance with a procedure pioneered by Kovasznay (1949). One probe was used at a fixed location outside the vortex street and it provided the phase reference, while the other was moved to various streamwise and transverse locations. The phase averaging was applied to the velocity and also to the intermittency function in order to separate the front and the back of the bulges. Results were consistent with previous observations.

Finally, A. K. M. F. Hussain* (Mechanical Engineering Department, University of Houston) used his own recent and extensive conditional data for excited jets to test the applicability of Taylor's hypothesis for the large-scale coherent structures. This was done by comparing the spatial distributions of the structure properties with those deduced via Taylor's hypothesis from time-dependent signals obtained with stationary probes. These comparisons showed that the simple use of the local time-average velocity, or even the instantaneous streamwise velocity, produced unacceptably large distortions. Use of the phase average longitudinal velocity as the convection velocity in the hypothesis was not an acceptable solution either. When structure interactions like pairing were involved, no convection velocity could be found with which the hypothesis worked. Only when the structures were passively convected downstream, was the hypothesis tolerable and in fact, acceptable only if a single, constant velocity, equal to the structure centre velocity was used everywhere across the shear flow as the convection velocity in the Taylor hypothesis. The terms neglected in the Navier–Stokes equations when the Taylor hypothesis is used were analysed. The pressure term associated with the coherent field was found large and therefore not negligible. Part of this analysis is already available (Sokolov *et al.* 1980; Hussain, Kleis & Sokolov 1980; Hussain & Zaman 1980) and other papers have been submitted for publication.

10. Investigation of engineering flows

Developments in the understanding of boundary layers on blades of turbomachines were reported in two papers. P. M. Ligrani, B. R. Gyles & F. A. E. Breugelmans* (Von Karman Institute, Rhode Saint Genèse) were concerned with boundary layer separation and its relation to rotating stall in compressors. They designed a wall-mounted four-wire probe combining the thermal-tuft technique (e.g. Moon 1962; Carr & McCroskey 1979) and a crossed-wire arrangement in order to determine the direction and magnitude of the velocity near the surface of a blade. Systematic tests showed that the sensitivity of the probe to flow direction could be increased in highly unsteady flows if the upstream wires were operated at a higher overheat ratio ($\simeq 0{\cdot}6$) than the downstream wires ($\simeq 0{\cdot}1$).

Experiments on a true compressor are in progress. J. P. Bertoglio, J. P. Melinand & G. Charnay* (Ecole Centrale de Lyon) investigated the effect of Coriolis forces on the development of boundary layer on the driving side and on the trailing side of the blades in a centrifugal impeller. A test facility was specially built, with two symmetric inlets in order to obtain a two dimensional mean flow between the blades. A wall-mounted single hot wire was used. Its angular response was calibrated along with its sensitivity to normal velocity. It was operated at constant current rather than at constant temperature (or resistance) because of the spurious resistance occurring with time inside the slip ring contactor. Measurements were taken for a Richardson number $2\Omega(S-2\Omega)/S^2$ of about 0·1 (S: mean velocity gradient; Ω, angular rotation rate). It was found that the boundary-layer thickness was increased on the trailing side. On the driving side, the presence of a high turbulence intensity conferred stability to the boundary layer which remained thin. These observations were also supported by preliminary measurements of the Reynolds stress terms. More details will be available in Bertoglio, Charnay & Mathieu (1980).

Experiments on the internal aerodynamics of combustion engines were reported by P. Arques & J. F. Delair* (Ecole Nationale Supérieure d'Arts et Métiers, Paris). The velocity signal was obtained by means of a hot wire whose dependence on the temperature was automatically corrected by means of an anxiliary cold wire acting as a thermometer. Calibration was performed in an auxiliary furnace and a wind-tunnel. The observed frequency response of the system was around a few kilohertz. Three successive angular positions were assigned to the hot wire at each measuring point, in order to determine the three components of the velocity field. Work in progress dealt with an externally driven motor that had two cylinders (one for combustion, one for compression) connected by a duct through the head so that a swirling flow existed in the combustion cylinder. On this subject very useful references are Dent & Salama (1975) and Witze (1977).

Attempts to use hot-wire anemometry in highly turbulent flows and rapidly reversing flows were presented in two papers. L. J. S. Bradbury* (University of Surrey) described a new type of shielded hot-wire probe. Two fine wires were mounted within a small tubular shroud. The dimensions of the shroud were such that if one of the wires was used as a hot-wire anemometer, it measured only the magnitude of the velocity component parallel to the axis of the shroud. The other wire was mounted at right angles to the hot-wire anemometer and was operated as a resistance thermometer so that it gave the direction of the resolved velocity vector by sensing either the presence or the absence of a thermal wake of the hot-wire anemometer. Comparisons were made with other types of shrouds (Gunkel, Patel & Weber 1971; Cook & Redfearn 1976), pulsed wires (e.g. Bradbury 1976) and ordinary hot wires. Advances in pulsed-wire anemometry were also reported by J. D. Vagt & P. Dengel* (Technische Universität, Berlin) for the investigation of an axisymmetric boundary layer with zero skin friction generated along the wall of a circular cylinder. The probe was designed according to Bradbury (1976), but with notably smaller dimensions in order that measurements could be taken close to the cylinder wall and also with reduced slack (use of tungsten/platinum-coated wires put under tension when being soldered). Calibration at low speed ($5\,\mathrm{cm\,s^{-1}}$–$1\,\mathrm{m\,s^{-1}}$) were made by means of a specially built carriage traversed along in a duct, a technique which has also been proved convenient and accurate by Baille (1971).

11. Conclusion

The various papers presented and discussed at the meeting permitted an assessment of the recent improvements brought to hot-wire anemometry techniques. For example, the controversy between static and dynamic calibrations has been greatly reduced by taking into account the finite time response of the wire supports. 'Cold' hot wires, operated at low overheat ratios and soldered on tiny prongs in order to be almost free of aerodynamic perturbations, can hence now be used with an increased level of confidence. For the investigation of small turbulent scales and vorticity fluctuations, the spurious signals affecting the vorticity meters have been ascertained and a possible way to correct the errors due to transverse velocity fluctuations was suggested and tested. For wall shear-stress fluctuations, ready-to-fix hot films are available and permit the use of an impressively large number (20 or even 100) of sensors. This procedure has become a valuable tool for the investigation of boundary layers along three-dimensional bodies. Even in the difficult investigation of supersonic flows, hot-wire anemometry remains a useful tool when fluctuating thermal fluxes have to be determined in addition to shear-stress terms. The confidence of slanted wires has been increased by a careful analysis of the factor affecting the frequency response of the sensors. As far as data processing is concerned, a pattern recognition technique based on a multipoint and multi-time analysis of the signals was suggested and successfully used in several flows. Much work along this line is certainly to be expected in the future. Finally, hot wires have been proved useful in a hostile environment, e.g. mounted on rotating blades of turbomachines, when continuous signals are needed. In many situations hot-wire anemometry appears to be complementary to laser–Doppler anemometry rather than competitive. This is specially true when several physical variables are to be measured simultaneously (velocity, temperature...) with low turbulence levels and when spectral measurements are needed in the high-frequency ranges. Future work can be expected along some of the lines just mentioned, but also on less current topics such as the measurement of fluctuating concentrations in reacting flows or the investigation of velocity fluctuations in liquid metals.

This report would not be complete without a reference to the manufacturers (Deltalab, France; DISA, Denmark; Thermosystems, U.S.A.) whose equipment was a focal point for demonstrations and further discussions during the Colloquium.

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Papers presented at the meeting

N. Alemdaroglu & P. Ardonceau. Turbulence measurements in a shock-wave/boundary layer interaction by laser-Doppler and constant-temperature anemometry.

P. Arques & J. F. Delair. Anémométrie à fil chaud dans la chambre d'un moteur à combustion interne.

E. Arzoumanian, L. Fulachier & R. Dumas. Utilisation des méthodes numériques dans l'anémométrie à fil chaud en écoulement turbulent sur paroi mobile.

M. Ayrault, J. L. Balint & J. P. Schon. Measurements of Lagrangian velocities in free convection flow by means of a laser visualization system.

J. P. Bertoglio, J. P. Melinand & G. Charnay. Hot-wire anemometry in rotating frames: turbulence measurements inside centrifugal impellers.

H. C. Boisson, A. Sevrain & M. Braza. Statistiques sur les durées des épisodes turbulents au passage des tourbillons émis par un cylindre.

J. P. Bonnet. Turbulence stress measurements by constant-temperature hot-wire anemometry in supersonic flow.

L. J. S. Bradbury. Reverse flow sensing shrouded hot-wire anemometer for use in highly turbulent flows.

H. H. Bruun & C. Tropea. Calibration and signal interpretation of hot-wire probes for cross-flow component evaluation.

P. Buchhave. Multi-channel C.T.A. Signal and data processing.

S. Burhanuddin & R. S. Azad. The effect of the proximity of the wall on hot-wire readings in turbulent flow.

M. P. Chauve. Détermination des contraintes de frottement à la paroi par anémométrie à fil chaud.

R. Cheesewright. Hot-wire anemometer measurements in turbulent natural convection flows.

J. Cousteix, G. Pailhas & R. Houdeville. Use of the hot-wire anemometry for studying unsteady or three-dimensional turbulent boundary layer.

J. W. Elsner, P. Domagala & S. Drobniak. A new hot-wire method for experimental determination of turbulence energy dissipation.

M. F. Fancher. Hot-film anemometry for boundary layer transition detection in cryogenic tunnel.

J. Gaviglio, J. P. Anguillet & M. Elena. Méthodes anémométriques par fil chaud pour l'étude d'écoulements non homogènes en température.

J. P. Giovanangeli. Loi adimensionnelle de refroidissement d'un film chaud incliné dans un écoulement d'eau.

L. Gottesdiener. Utilisation d'un anémomètre amélioré à fil chaud pour l'étude de l'effet du bord de fuite en gaz raréfié.

A. K. M. F. Hussain. Conditional sampling techniques to test the applicability of the Taylor hypothesis for the large scale coherent structures.

J. Jimenez, R. Martinez-Val & M. Rebollo. Hot-film sensors calibration drift in water.

H. P. Kreplin. Measurement of the wall shear stress on a body of revolution at incidence using surface hot-film probes.

W. Kühn & B. Dressler. Experimental investigations on the dynamic behaviour of hot-wire probes.

P. M. Ligrani, B. R. Gyles & F. A. E. Breugelmans. A hot-wire probe for measurement of flow near the surface of a compressor blade.

P. Mestayer & P. Chambaud. Quelques problèmes pour la mesure des micro-structures de la turbulence avec des fils chauds et froids.

V. Mikulla. Recent progress in compressible hot-wire and hot-film anemometry.

J. C. Mumford, A. M. Savill & A. A. Townsend. Identification of flow patterns in turbulent flows.

C. Petit, P. Paranthoen & J. C. Lecordier. Influence de la conduction sur la fonction de transfert des fils froids dans les basses fréquences – Résultats expérimentaux.

M. Trinité. A method for simultaneous measurements of concentration and temperature fluctuations in a hydrogen flame.

J. D. Vagt & P. Dengel. Comparison between hot-wire and pulsed-wire response in a boundary layer with zero skin friction.

P. Vukoslavcevic, W. G. Cleveland & J. M. Wallace. A hot-wire probe for measuring the streamwise vorticity and the velocity components.

W. W. WASSMAN & J. M. WALLACE. A multi-sensor hot-wire probe for measuring the velocity and vorticity components.

J. A. B. WILLS. Hot-wire measurements of air flow over waves obtained via a microcomputer data acquisition system.

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