MEMS SENSORS FOR TURBULENCE MEASUREMENTS AND FLOW CONTROL

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ABSTRACT

This is a review of MEMS (Micro Electrical Mechanical Systems) based sensors for measurements of instantaneous flow quantities. Specifically sensors for fluctuating pressure and wall shear stress are the focus, and for these sensors the requirements from a fluid dynamic perspective are established, some basic design properties are discussed and a brief survey of existing MEMS sensors are given. It is found that the MEMS sensors have some obvious advantages as compared to conventional variants; however, in using MEMS sensors for turbulence measurements and flow control a significant issue is to clarify their uniqueness as compared to conventional sensors.

INTRODUCTION

Normally a MEMS (Micro Electrical Mechanical Systems) sensor is considered to be significantly smaller than 1 mm in size, and this is typically one order of magnitude smaller than traditional sensors used to measure instantaneous flow quantities. Inertial masses as well as thermal capacity are accordingly small, so MEMS sensors are well suited for the measurements in high Reynolds-number flows. In addition, MEMS sensors are produced through micromachining so each unit, which might consist of arrays of many sensors closely spaced on one chip, is fabricated to extremely low tolerance. The combination of small size, close sensor spacing and high quality of each unit are key advantages in mapping instantaneous complex flow phenomena which are of high interest in flow control, transition and turbulence.

MEMS devices are created using specialized techniques derived and developed from IC technology. For fluid dynamic applications, two main technologies are distinguished: bulk and surface micromachining. Bulk micromachining involves different techniques, which use simple, single-crystal, silicon wafers as structural material. Using anisotropic silicon etching and wafer bonding, three-dimensional structures are fabricated. In surface micromachining, the silicon substrate is used as support material, and different thin films such as polysilicon, silicon dioxide and silicon nitride provide sensing elements and electrical interconnections as well as structural, mask and sacrificial layers. The basis of surface micromachining is sacrificial etching where free standing, thin-film structures are free etched on the lateral underlying sacrificial layer. Valuable surveys and references on microfabrication technologies include: Petersen (1982), Linder et al. (1992), Brysek et al. (1994), Diem et al. (1995), and Tien (1997), the books by Madou (1997) and Kovacs (1998).

Sensors based on silicon technology have already been fabricated since the early sixties, and specifically different types of velocity and pressure transducers have been targeted. However, these sensors were relatively large and more or less designed only for measurement and registration of mean quantities. One of the first silicon based sensors that could be classified as a MEMS device for studies of instantaneous flow quantities was the velocity sensors based on the hot wire principle. Löfdahl et al. (1991) were among the first to design such a sensor, and since then several different attempts have been made on making similar devices. An advanced velocity sensor using three wires for measurements of the instantaneours velocity vector was presented by Ebefors et al (1998) and is shown in Figure 1. The principle of the velocity sensors is the same as for conventional hot wires although the advantages of the MEMS technology have been built into the devices. Unfortunately, there are also noticeable drawbacks of the MEMS technology in the hot wire based velocity sensors. A general observation of costs show that MEMS sensors are very expensive in the context of prototype development. However, once the fabrication process is outlined the unit cost is extremely low. As a consequence, when compared to conventional hot wires which can also be fabricated in a spatial scale comparable to the MEMS, the uniqueness of a MEMS based hot wires is questionable for velocity measurements. Comprehensive discussions on MEMS based velocity sensors may be found for instance in Löfdahl and Gad-el-Hak (2000) and for further details on velocity sensors reference is made to this work.

Another complex phenomena associated to MEMS sensors is one that occurs at fluid flows in channels of extremely small dimensions. In such cases, the applicability of the continuums hypothesis is violated since the gas in context may be considered as rarefied yielding, for instance, in the nonfulfilment of the no-slip condition. This phenomenon may typically occur in flows inside small channels, which can constitute one vital part of a MEMS device. Here the Knutsen number, or the ratio between the mean free path and the Kolmogorov scale (the smallest possible length scale of the flow), constitutes a key parameter. A comprehensive discussion on these issues may be found in Gad-el-Hak (2002), and will not be treated further here.

The scope of this paper is limited to cover the use of MEMS based sensors for measurements of fluctuating pressures and wall shear stress. In the following sections, some general remarks are given on the requirements of sensors for the measurement of instantaneous flow quantities followed by the fluid dynamic background of the pressure and wall shear stress sensors. Design criteria are summarized together with some examples of typical MEMS sensors available. Concluding remarks and an outlook for future challenges and possibilities are also included.

SENSOR REQUIREMENTS

Generally it may be stated that the purpose of measurements is to resolve all temporal and spatial scales of the flow field in context, which is realistically impossible. How-

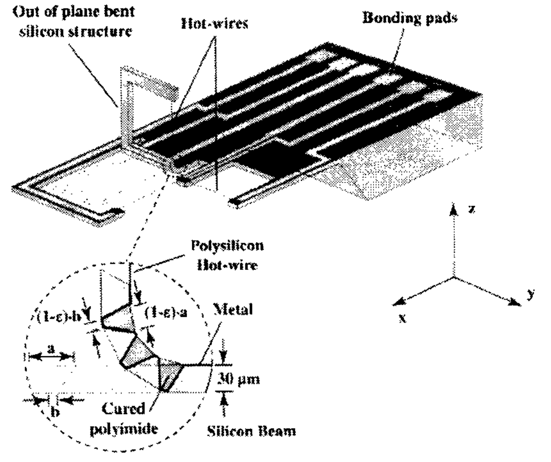

Figure 1: MEMS-based triple wire, Ebefors et al. (1998).

ever, with the access of modern computers, electronics and sensors it is now feasible to map instantaneous flows under certain spatial and temporal restrictions, see Chernoray and Löfdahl (2003). From the sensor perspective, two natural boundary conditions are given by the power spectra. At the lower wave number range, where the largest and most energetic eddies occur, there are normally no problems associated with the resolution since large (conventional) sensors may be distributed over the entire area of interest. However, at the other end of the spectrum a sensor dimension fulfilling both the spatial and the temporal resolutions is a necessity and provides a severe limitation on the sensors available. It can be shown, for example in Tennekes and Lumley (1975) or Löfdahl and Gad-el-Hak (1999), that a relation between the small and large scales of the flow can be obtained by substituting the inviscid estimate of the total dissipation rate into the expressions for the Kolmogorov microscales. This yields:

$$\begin{aligned} \frac{\eta}{\ell} &\approx \left(\frac{u\ell}{\nu}\right)^{3/4} = Re^{3/4} \\ \frac{\tau u}{\ell} &\approx \left(\frac{u\ell}{\nu}\right)^{-1/2} = Re^{-1/2} \qquad (1) \\ \frac{v}{u} &\approx \left(\frac{u\ell}{\nu}\right)^{-1/4} = Re^{-1/4} \end{aligned}$$

where Re is the Reynolds number based on the velocity of the energy containing eddies u and its characteristic integral scale ℓ. The conclusions to be drawn from these expressions are twofold: first, the small temporal and spatial scales are much smaller than those of the larger eddies, and second that the separation in scales widens considerably as the Reynolds number increases. In order to spatially resolve the smallest eddies, sensors which are approximately of the same spatial extension as the Kolmogorov scale for the context are necessary. For example in the self-preserving region of a plane-cylinder wake at a moderate Reynolds number based on the cylinder diameter, of 1840, the value of the Kolmogorov length scale varies typically in the range of 0.5–0.8 mm, see Aronson and Löfdahl (1994). For this case, conventional hot wires can be used to resolve the turbulent quantities. However, an increase of the Reynolds number by a factor of ten, which is a more crucial value from a turbulence perspective, will require a significantly smaller sensor dimension. Another influence of the Reynolds number effect may be found in a simple two-dimensional, flat-plate boundary layer. At a momentum thickness of Re_θ=4000, the Kolmogorov length-scale is typically of the order of 50 μm, and for instance for measurements of fluctuating wall pressure it is necessary to have access to sensors which have a characteristic active measuring length of the same spatial extension.

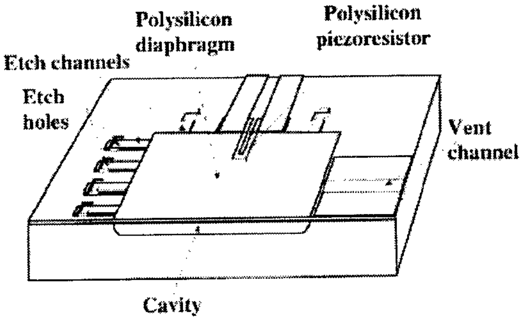

Figure 2: Pressure transducer of Kälvesten (1994).

Severe errors can be introduced in measurements by using sensors that are too large, since such a sensor will integrate the fluctuations due to the small eddies over its spatial extension and the energy content of these eddies will be interpreted by the sensor as an average value. When measuring fluctuating quantities, this implies that these eddies are counted as a part of the mean flow and their energy content is "lost". The result will be a lower value of the turbulence parameter, and this will falsly be interpreted as a measured attenuation of the turbulence, see Ligrani and Bradshaw (1978). However, since turbulence measurements deal with statistical values of fluctuating quantities, it may be possible to loosen the spatial constraint of having a sensor of the same size as the Kolmogorov scale to allow a sensor dimensions which are slightly larger than this scale. For boundary layers, Keith et al. (1992) state that ten wall units or less is a relevant sensor dimension for resolving small-scale pressure fluctuations.

Measurement of fluctuating velocity gradients, essential for estimating the total dissipation rate in turbulent flows, is another challenging task. Gad-el-Hak and Bandyopadhyay (1994) argue that turbulence measurements with probe lengths greater than the viscous sublayer thickness (aproximately 5 wall units) are unreliable particularly near the surface. Many studies have been conducted on the spacing between sensors necessary to optimize the formed velocity gradients see e.g. Aronson et al. (1997) and other references in this work. A general conclusion from experiments and direct numerical simulations is that a sensor spacing of 3-5 Kolmogorov lengths is recommended. When designing arrays for correlation measurements the spacing between the coherent structures will be the determining factor. For instance, when studying the low-speed streaks in a turbulent boundary layer, several sensors must be situated along a lateral distance of 100 wall units, which is the average spanwise spacing between streaks.

PRESSURE SENSORS

In turbulence modelling, flow control and aero acoustics, the fluctuating wall-pressure beneath a wall-bounded flow is a crucial parameter. By measuring this quantity much information can be gained about the boundary layer itself without disturbing the interior of the flow, since the fluctuating wall-pressure is coupled via a complex interaction to gradients of both mean-shear and velocity fluctuations as described by the transport equations for the Reynolds stresses, see e.g. Tennekes and Lumley (1972); Hinze (1975) or Pope (2000). The characteristics of the fluctuating wall-pressure field beneath a turbulent boundary layer have been extensively studied in both experimental and theoretical investigations, and reviews of earlier work may be found in Blake (1986), Eckelmann (1990) and Keith et al. (1992). From the experimental perspective, knowledge of pressure fluctuations is far from being as comprehensive as that of velocity fluctuations, but some general facts have been established for wall-pressure fluctuations, e.g. Harrison (1958), Willmarth and Wooldridge (1962), Bull (1967) Bull and Thomas (1976), Schewe (1983), Blake (1986), Lauchle and Daniels (1984), and Farabee and Casarella (1991). However, a clear shortcoming in many of the experiments designed to measure pressure fluctuations is the quality of the data, since in the high-frequency range the spatial resolution of the transducers limits the accuracy. The main criticism raised is that in many experiments the size of the pressure transducer used has been far too large in relation to the thickness of the boundary layer in context. The ultimate solution is to use small sensors, and for this reason MEMS offers a unique opportunity for reducing the diaphragm size.

Different methods have been refined for the detection of pressure fluctuations, and the principles available are based on detecting the vibrating motion of a diaphragm using piezoelectric, piezoresistive and capacitive techniques. These principles were already known at the beginning of the twentieth century, but the introduction of micromachining methods during the last two decades has provided strong impetus. Another advantage is that this method of fabrication is compatible with other IC techniques so electronic circuitry like pre-amplifiers can be integrated close together with the sensor.

There exists no simple way for calculating the required pressure range of a sensor for turbulence and flow control applications. Tennekes and Lumley (1972) estimate the fluctuating pressure to be a weighted integral of the Reynolds stresses, so its length scales should in general be larger than those of the velocity fluctuations. Moreover, it is plausible to assume that the order of magnitude of the fluctuating pressure would not be less than the Reynolds stresses, giving a good hint of the intensity of the fluctuating pressure. This intensity depends strongly on the flow in context, but for a typical flat-plate boundary layer at Re_θ=4000, this implies that the fluctuating pressure root-mean-square would be in the order of 10 Pa. (Higher Reynolds numbers yields higher magnitudes of the fluctuating wall-pressure.) There is also a spatial constraint in the sensor design. For the same boundary layer considered here, the Kolmogorov length-scale is about 50 μm, requiring a diaphragm size in the range of 100–300 μm. The required temporal resolution of the pressure sensor is probably the most simple estimate since good turbulence kinetic energy spectra are available and these show that the energy content in the flow above 10 kHz is almost negligible. Based on these physical arguments, a frame for the design of a pressure transducer for turbulence applications can be established, namely that the sensor should have a pressure sensitivity of ±10 Pa, a diaphragm size of 100 μm, and flat frequency characteristics in the range of 10 Hz–10 kHz. The signal-to-noise ratio must be sufficiently high so that ordinary data acquisition can be made. Critical scrutiny of the different principles for designing a pressure sensor shows that the most suitable principle for turbulence applications is piezoresistive since the required spatial and temporal resolutions can easily be achieved. A simple fabrication in MEMS is possible and the temperature drift can be controlled in such a sensor.

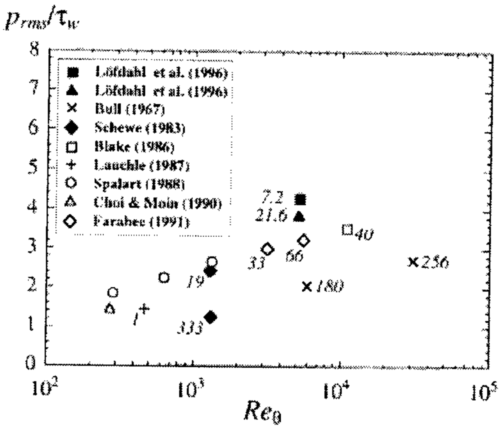

Figure 3: The normalized rms pressure fluctuations as a function of the dimensionless diaphragm, Löfdahl et al. (1996).

Schellin et al. (1995) presented a sub miniature microphone which was based on the piezoresistive effect in polysilicon using only one chip. This sensor was classified as an acoustical sensor which was fabricated with a CMOS-process and standard microfabrication technology. The diaphragm area was one square millimetre and the sensitivity was 0.025 mV/Pa at 6 V, so for a turbulence application this sensor lacks sensitivity and is slightly too large. The frequency response was determined to be flat from 100 Hz to 5 kHz. Unfortunately, no fluid dynamics measurements have been reported with this sensor.

Kälvesten (1994), Kälvesten et al. (1995; 1996a) and Löfdahl et al. (1996) have designed, fabricated and used silicon-based pressure transducers for studies focused on the high-frequency portion of the wall pressure spectrum in a two-dimensional, flat-plate boundary layer. The momentum thickness Reynolds number in their studies was Re_θ=5072. Figure 2 shows a principle sketch of this pressure transducer. A large value of the ratio between the boundary layer thickness δ and the diaphragm side-length d was used, the side-length of the smallest diaphragm used was 100 μm (d^+=7.2), and this gives a ratio of the boundary-layer thickness to the diaphragm side-length of the order of 240 and a resolution of eddies with wavenumbers less than ten viscous units. Power spectra were measured for the frequency range of 13 Hz < f < 13 kHz, and a clear overlap region between the mid- and high-frequency parts of the spectrum was found. The normalized rms pressure fluctuations were shown to depend strongly on the dimensionless diaphragm size with an increase connected to the resolution of the high-frequency region as shown in Figure 3. Classical data in the field are also plotted in the same figure for comparison.

WALL SHEAR STRESS SENSORS

For flow control purposes, wall shear stress is an essential quantity to compute and measure. In a turbulent flow the time-averaged values of this quantity are indicative of the global state of the flow along a surface, while the time-

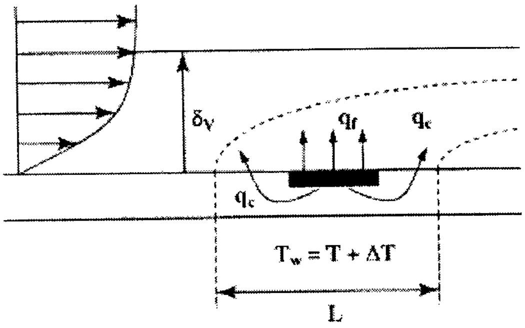

Figure 4: Schematic heat ratio distribution of a flush mounted sensor.

resolved component is a measure of the unsteady structures of the flow field which are responsible for the individual momentum transfer events in the boundary layer. Different methods for the measurement of wall shear stresses have been developed, and most rely on the premise that the mean velocity gradient is proportional to the heat transfer rate at the wall. Numerous experiments have been conducted on this basis, and review papers by Winter (1977), Haritonides (1989), Hanratty (1996) and more recently by Löfdahl and Gad-el-Hak (1999) point out that the success of these efforts depends on the complexity of the flow, the geometry of the solid boundaries, and the limitations of the measuring technique used. A general conclusion to be made is that our knowledge of the wall shear stress, and in particular its fluctuating or time-resolved component, is limited.

A clear trend in all wall shear stress measurements since the mid-1950's is that the sensors used have increasingly smaller active sensor areas in order to improve the resolution. In this process, MEMS fabrication technology has in recent years played a central role. A survey of the methods of wall shear stress measurements, see Löfdahl and Gad-el-Hak (1999), shows that this technology is most suitable for instruments working on either the floating-element mechanical or thermal anemometry principles. Thus far the activities on the floating element devices has had limited success. It is, however, interesting to consult the work of Pradmanhaban (2000) on his recent attempt to develop a MEMS balance, but wall shear stress measurements using floating element devices are outside the scope of the work presented here. Focus of this paper is accordingly put on the thermal sensor, which relies on the principle that the heat transfer from a sufficiently small heated surface depends only on the flow characteristics in the viscous region of the boundary layer adjacent to the heated region. The sensor consists normally of a flush mounted thin metallic film placed on a substrate, and through this film an electric current is passed to maintain it at a constant temperature as heat is continuously transferred from the film to the moving fluid. For certain laminar flows, an algebraic relation between the local shear stress and the heat rate from the sensor can be derived, e.g. Ludwig (1925), Liepman (1950) and Bellhouse (1966). For turbulent flows, however, this relation is not valid, since there is an unknown leakage heat flow that goes through the substrate back into the fluid, see figure 4. This yields an effective sensor area which is instantaneously changing and is also significantly larger than the electrically heated part of sensor. This problem has been pointed out by many researchers, e.g. Blackwelder (1976), Haritonides (1989), Löfdahl and Gad-el-Hak (1999), and more recently by Stein et al. (2000). Attempts have been made to insulate the sensor carefully from the substrate by, for instance, polyimide or a vacuum chamber. Such a conventional flush-mounted hot film sensor was presented by Kälvesten et al. (1996), who used a flush-mounted polysilicon piezoresistor as the heated, sensitive part. Jiang (1994) and Huang and Ho (1996) used the principle of an insulating vacuum chamber and made single as well as arrays of flush mounted wall shear stress sensors. Their sensors consisted of a diaphragm with a thickness of 1.2 μm and a typical side length of 200 μm. On this diaphragm the polysilicon resistor wire was located, and below the diaphragm there was a 2 μm deep vacuum cavity in order to minimize the heat conduction loss to the substrate. However, this principle requires an extremely thin diaphragm in order to minimize the heat flow parallel to the wall. An alternative approach is to use hot wire sensors that are mounted on the wall at a small distance from it. Schematic diagrams of such wall-mounted single or multiple hot wires are shown in figure 5. This sensor design circumvents the use of the above mentioned shear stress-heat rate relationship, and instead employs a direct measurement of the instantaneous velocity gradient normal to the wall. This method will not eliminate the leakage heat flow; however it will reduce it to a known and controllable quantity. This type of wall-mounted conventional hot wire sensors for wall shear stress measurements have been used by researchers such as Alfredsson et al. (1989), Wagner (1991), Nagano (1994), Chew (1994), Fernholz (1996) and Khoo (2000). However, in none of these investigations MEMS fabrication technology was used to produce the sensors.

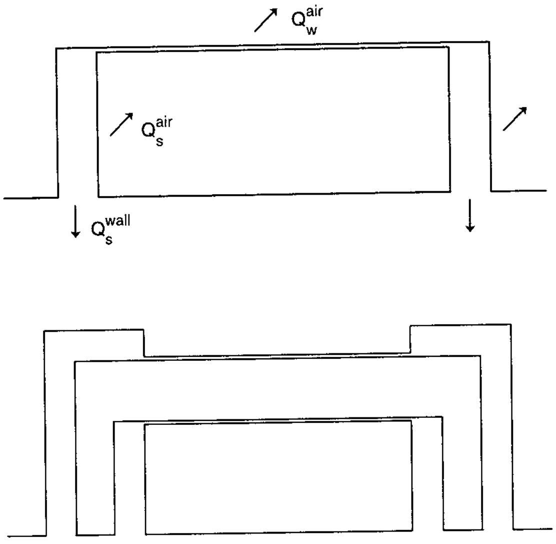

Figure 5: Schematic diagrams of wall-mounted single or multiple hot wires from Löfdahl et al. (2003).

Recently Löfdahl et al. (2003) presented a MEMS sensor designed for the measurements of local time-resolved wall shear stress. This sensor is based on the principle of a single or a rake of hot wires sensors that is mounted on the wall at a small distance from it. Various configurations of wall-mounted rakes consisting of 2–10 hot wires were fabricated and calibrated. Figure 6 shows two examples of these rakes, one double wire (6 *top*) and two five-wire sensors perpendicular to each other (6 *bottom*). The design is based

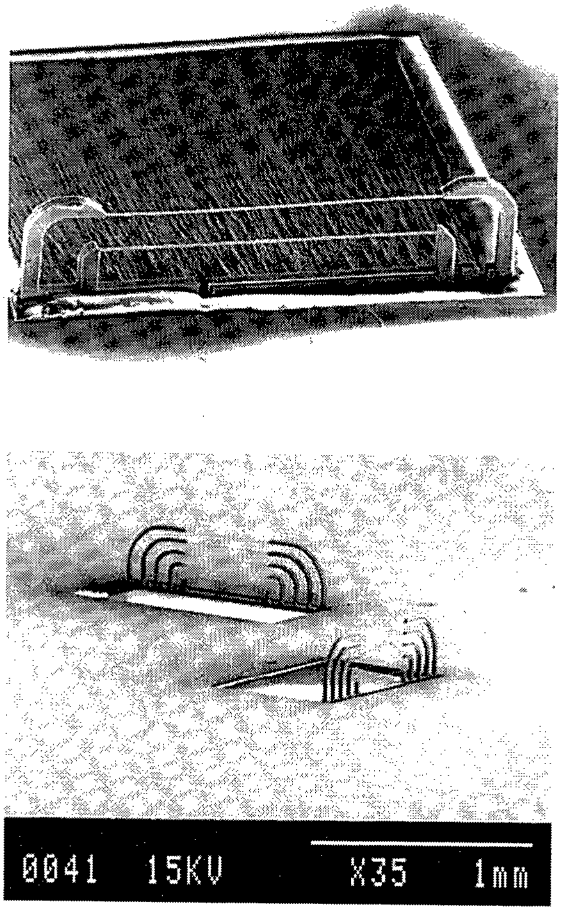

Figure 6: SEM pictures of the fabricated hot wire microsensors, Löfdahl et al. (2003).

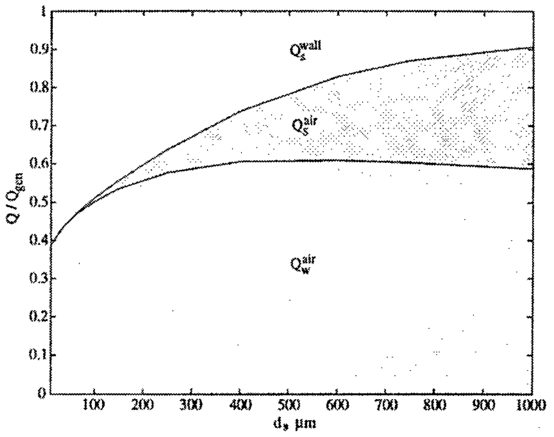

Figure 7: Heat rates of the microsensor for different support lengths; τ_0=1 Pa, Löfdahl et al. (2003).

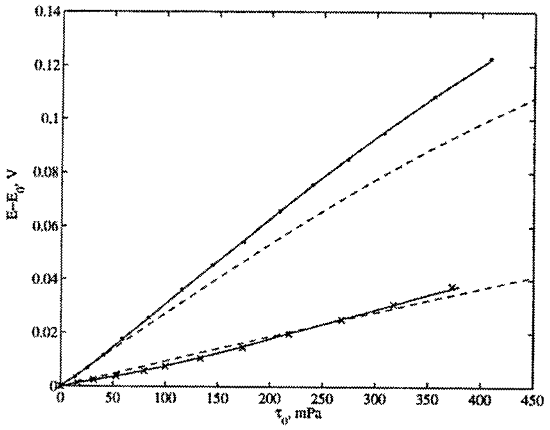

Figure 8: MEMS sensor calibration curves. Crosses: wire at 50 μm from wall, dots: 100 μm. Solid lines: King's law approximation with wall correction, dashes: computed calibrations, Löfdahl et al. (2003).

on estimates of heat rates, and using the software package Matlab the different contributions to the heat balance were estimated. Figure 7 shows normalized heat rates as a function the wall distance at a constant value of the wall shear stress, in this particular case $\tau_0 = 1$ Pa. As is evident from the figure, a good sensitivity of the wire to the flow velocity and a low sensitivity to the temperature variation, the convective heat transfer from the wire to the air, Q_w^{air}, should be large as compared to the other terms. Figure 7 shows that for the current MEMS sensor the convective heat transfer from the wire constitutes about 50–60% of the total heat generated. According to Bruun (1995), a conventional hot wire has a corresponding value at 80–85%, however for the current wall-mounted hot wire the conduction out of the wire is greater. Using the computed characteristics it was also possible to estimate theoretical calibration curves. These were compared to experimental calibrations, and figure 8 show the result of such a comparisons. As is apparent from this figure the agreement is very good.

The MEMS sensor by Löfdahl et al. (2003) was used for measurements in a laminar Blasius boundary layer where it was calibrated versus mean wall shear stress. The possibility to perform time resolved wall shear stress measurements was a main objective in designing this MEMS sensor, and a first practical application was to detect some phenomena, events in the laminar-turbulent transition process was demonstrated. For this purpose the laminar flow breakdown was artificially triggered to provoke the flow breakdown. The disturbance is introduced in an initially laminar boundary layer by localized periodic blowing and suction through a hole located about 80 mm upstream of the MEMS sensor. Frequency of the artificial disturbance was fixed at 260 Hz, and in figure 9 measured by microsensor velocity traces that are shown for three different values of the free stream velocity. To obtain these measurements, the recorded instantaneous voltages were converted to velocities and ensemble averaged over 25 realizations. In the figure, four periods of obtained transitional flow traces are shown and it is clearly visible how the disturbance in the boundary layer grows and how the transition is promoted as flow Reynolds number increases. Initially sinusoidal disturbance starts to lose its periodicity, then is distorted by the appearance of higher harmonics and increasing randomness. It is worthwhile to note that the amplitude of the instability wave at 13 m/s was fairly small, about 0.5% of the free stream velocity. This was the first experiment where MEMS-based wall-mounted sensor was able to register weak eigen disturbances of the boundary layer during the transition process.

As soon as time-resolved measurements are considered, an issue of the dynamic response of the sensor becomes important. The response of thermal sensors to high frequency

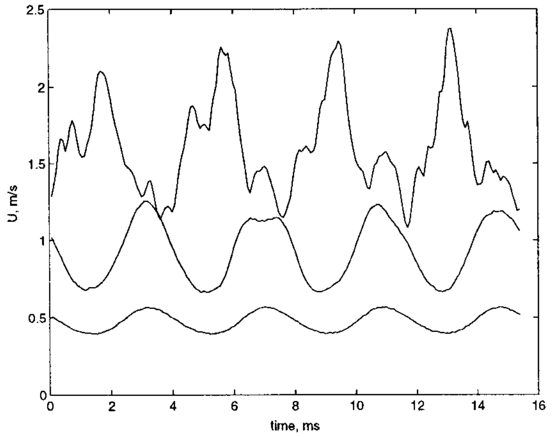

Figure 9: Velocity traces of laminar-turbulent transition measured by a MEMS sensor. Free stream velocity 13, 20 and 24 m/s (from bottom to top), Löfdahl et al. (2003).

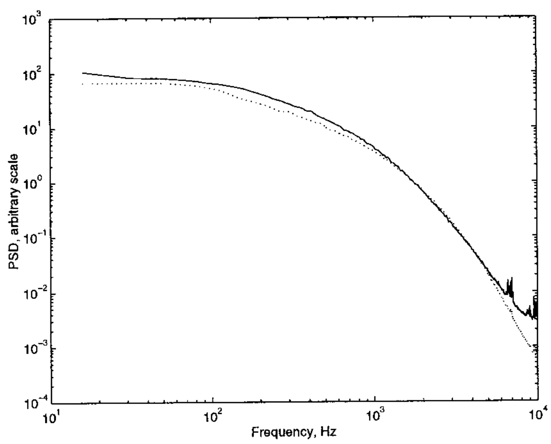

Figure 10: Power spectral density measured with MEMS sensor (solid line) and with conventional hot wire (dotted line) in turbulent boundary layer, Löfdahl et al. (2003).

fluctuations has long been considered as a limitation; see e.g. Hinze (1975). In this perspective the present MEMS sensor is no different from an ordinary hot wire when used for relatively high wall shear stress where the wall influence disappears. For low wall shear stress, the signals obtained from high intensity and high frequency fluctuations will be somewhat distorted by the nonlinear nature of the interaction between the fluid dynamics and the temperature field. Recent studies on this have been made by Khoo et al. (1998), Chew et al. (1998), Khoo et al. (1999) and Teo et al. (2001). To evaluate the frequency response of the current microsensors a spectrum of fluctuations in a fully turbulent boundary layer was measured. In figure 10 a comparison of two spectra, one measured by a conventional hot wire and the other by a microsensor are shown. Since the MEMS calibration does not extend to high values of the wall shear stress, which are present in turbulent flow, the spectra are represented in arbitrary scale. The two spectra demonstrate almost the same shape except for small spikes in the spectrum obtained by MEMS sensor at frequencies higher 6 kHz, and most probably this is due to the noise within electrical circuits. So it may be concluded that for frequencies less than ~5 kHz the MEMS sensor has a similar dynamical response as a conventional hot wire.

CONCLUDING REMARKS

The requirements and background for the design of MEMS based sensors for the measurements of fluctuating pressures and wall shear stresses have been outlined. Some typical MEMS based sensors are reviewed as well. In these sensors the combination of small size, close spacing and high quality of each unit has been built in through the MEMS fabrication. The pressure sensors discussed might today be considered as relatively mature MEMS sensors and can be used as a tool in turbulence and flow control. Recent MEMS-based wall shear stress sensors seem to have the ability to control the unwanted leakage of heat flow that goes through the substrate back into the fluid. However, much work remains on these sensors in order to qualitatively measure the fluctuating wall shear stress, specifically focused in the processes used for the dynamic calibration.

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