Small silicon based pressure transducers for measurements in turbulent boundary layers

L. Löfdahl, E. Kälvesten, G. Stemme

Abstract Small silicon based sensors for the measurement of wall-pressure in turbulent flows have been designed and fabricated using microelectronic technology. The sensor diaphragms have a side length of 100 and 300 µm, and polysilicon piezoresistive gauges were used for detection of the deflection. A two-dimensional flat plate boundary layer was employed to determine the performance of the pressure transducers, and comparisons with established data from the literature were made. A threshold value for the pressure fluctuations of about the double Kolmogorov length scale was estimated independently from the probability distribution as well as from the power spectra. In good agreement with theoretical predictions of Blake (1986), the slope of the power spectra was found to be $\omega^{-2}$ in the intermediate and $\omega^{-3}$ in the high frequency range.

1 Introduction

Wall-pressure fluctuations beneath a turbulent boundary layer are one key issue in studies of the dynamics of boundary layers. The pressure fluctuations are coupled to the velocity fluctuations via complex interactions with the mean shear as well as with the velocity fluctuations themselves. These phenomena have been a challenge for many investigators through the years, and have been studied both theoretically and experimentally. Reviews of earlier work can be found in e.g. Willmarth and Wooldridge (1962), Bull (1967), Bull and Thomas (1976) and Schewe (1983). From these experiments some general facts have been proposed like the order of the magnitude of the pressure fluctuations and a general form of the power spectrum. However, one main criticism that can be raised on most of these works is that the size of the pressure transducer is too large compared to the local thickness of the boundary layer where the transducer is employed. More specifically, the ratio between the pressure transducer size and the smallest important length scales of the flow should be as small as possible, since a too large transducer would attenuate the high frequency/small scale components of the pressure signals due to a spatial and temporal averaging over the face of the transducer.

The introduction of silicon technology into fluid dynamics offers new possibilities in the design of extremely small sensors for the study of turbulent phenomena. Silicon based sensors for the determination of mean and fluctuating velocities have been developed, fabricated and tested by Löfdahl et al. (1992). These sensors were found to have an accuracy and an area of applicability comparable to hot wires. An extension of these efforts was to develop a silicon based pressure transducer with a resolution that makes it feasible to capture the aforementioned high frequency pressure fluctuations of a turbulent flow. A first generation of small silicon based pressure transducers was developed and tested by Löfdahl et al. (1993). The important issues were to find a reliable method to detect the diaphragm deflection, to determine the resolution and to manage the operation of a sensor with a diaphragm thickness less than one micron.

In the present paper further developments of the earlier pressure transducers are presented, i.e. the design, fabrication and testing of a second generation pressure transducers are described. Compared to the first generation the new sensors are fabricated employing more complex and sophisticated methods, yielding even smaller sensors and thereby an increased spatial and temporal resolution. The performances of the second generation pressure transducers are tested in a well-defined turbulent two-dimensional flat plate boundary layer, and all the results are discussed and compared with the established data from the literature. Influence of the improved resolution of the probability density distribution and the power spectra are issues of special interest, which are addressed in the present paper.
2 Silicon sensor design

The classic way to detect pressure fluctuations is to use a cavity covered with a diaphragm. A stable static pressure is maintained on one side of the diaphragm, while the other side is exposed to the fluctuations. The deflection of the diaphragm, which is a measure of the fluctuations, can be detected in many ways. Most commonly, capacitive (Bourouina et al. (1992)) and piezoresistive (e.g. Schellin and Hess (1992)) methods have been employed, however, more complex methods based on the reflection of laser beams have been suggested as well (e.g. Warkentin et al. (1987)).

In accordance with the results of Löfdahl et al. (1993), polysilicon piezoresistive gauges were chosen to detect the deflection of the diaphragm. The possible disadvantage of high temperature sensitivity of these gauges is solved by placing four equally designed gauges into a Wheatstone bridge close to the diaphragm. Two of the gauges are located where the diaphragm stresses are at maximum, which is in the middle of the square diaphragm edges, and the other two are placed outside the diaphragm to serve as reference gauges for temperature compensation. A verification of this temperature compensation is that identical results are obtained at measurement temperatures which have varied about ±3 °C.

To accomplish a measuring unit of the silicon sensor chip, the basic ideas of Löfdahl et al. (1993) were employed, i.e. the chip was mechanically fixed to, and electrically connected via the bonding pads to a small printed circuit board. To reduce the disturbances the bonding pads are located far away from the diaphragm, of the order of 3 mm. All sensors are equipped with a vent channel starting at the cavity and emerging at the opposite side of the chip. The dimensions of the diaphragm, the cavity and the vent channel are important issues for the performance of the transducer, and the design of these are described in Sect. 2.1.

Figure 1 shows a principle drawing of the second generation of pressure transducers. The different parts like the diaphragm, polysilicon piezoresistive gauges, conductors, vent channel and bonding pads are clearly indicated in the figure. As compared to the first generation of pressure transducers the present transducers are considerably smaller. The side lengths of the diaphragms are 100 and 300 μm and the thickness is 0.4 μm. This should be compared to 1000 and 1 μm, respectively, for the first generation.

2.1 Design criterion

Some main criteria must be fulfilled in the design of transducers capable of determining fluctuating pressures of turbulent flows. A transducer sensitivity large enough for the pressure signal to overcome the noise level of the sensor is a basic requirement. The overall size of the diaphragm is another important issue. Since the side length has to be of the same order as the smallest high frequency eddies of the flow, i.e. the Kolmogorov length scale, extremely small diaphragms are needed in turbulent laboratory experiments. For the present flow case, a flat plate at an approximate Re number of 2×10^5, this length scale was estimated to be of the order of 50 μm. According to Tennekes and Lumely (1972), the pressure fluctuation could be interpreted as a weighted integral of the fluctuating velocities and the former tends to have a length scale larger than the latter. Due to this statement, it is plausible to assume that a characteristic length scale for pressure fluctuations would be by some factor larger than the Kolmogorov length scale. For the present case a side length, a, of 100 μm (implying a diaphragm thickness of 0.4 μm) was chosen of the fabricated pressure transducer. For comparison purposes, a transducer with a side length of 300 μm was fabricated as well.

To optimize the dimensions of the pressure transducer, the frequency response was simulated with a method using discrete acoustical impedances. The relationship between the geometry of the mechano-acoustical elements and their corresponding impedances have been treated by Rossi (1988). In this model, an electrical analogy is used where the pressure is equivalent to a voltage, the volume flow to a current and the acoustic masses to inductances. The damping is due to the viscosity of the flow, and is described by resistances. Furthermore, properties like diaphragm flexibility and compressibility are equivalent to capacitors. For the present transducer the input pressure at the diaphragm and the vent channel are represented by two voltage sources, Pd and Pw, respectively. A simplified equivalent circuit diagram of the present pressure sensor is shown in Fig. 2, and the use of this analysis indicates that the frequency response is very good for the developed sensors.

In the lower frequency range, disturbing pressure fluctuations passing through the vent channel, Pw, may limit the frequency performance. For the present flow case, the lowest interesting frequency was estimated to be of the order of 1 Hz. Using the aforementioned acoustic analogy, the corresponding lower cut off frequency, fL, of the transducer was calculated