Abstract — In this paper we report on the latest developments in characterising and interfacing biomimetic flow-sensor array based on the flow sensitive mechano-sensors of crickets. Capacitive hair sensors have been fabricated using a surface micromachining technology and implemented to detect air flows. We have realized readout electronics to detect the movements capacitively using electrodes integrated on the membrane. A charge amplifier, which produces an output voltage representing the capacitance variation of the selected sensor, is used to pick up the signal. An array of hair sensors is implemented for better and more representative flow signals compared to single sensor measurement. Different schemes for measuring individual sensors in arrays independently are discussed. Frequency Division Multiplexing is found to be efficient for this purpose individual element measurement.

Key Words: Artificial hairs, capacitive readout, FDM.

I INTRODUCTION

Recently, Cricket mechano-sensory hairs have been a common research subjects for between biologists and engineers. These hairs form the sensing part of the cricket’s escape mechanism and are extremely sensitive to air flows in the vicinity of the crickets. The large number of hairs as well as their directivity results in a system capable of complex flow pattern detection with high directional resolution [1].

Inspired from crickets and by the assistance of MEMS techniques, recently, single artificial flow sensors and hair sensor arrays have been implemented successfully in different groups [2][3]. Figure 1 shows a schematic cross-sectional view of an artificial hair-sensor, which is the core of the array structure in this study. Surface micromachined technology has been used to form suspended silicon nitride membranes and SU-8 processing to form the hairs. Capacitive readout is one of the most widely used sensing modalities in MEMS due to its simplicity, high accuracy at a relatively low cost, fast response, long-term stability, low temperature drift and low power consumption when compared to other detection mechanisms, for instance, piezoresistive, magnetic or optical techniques [4]. Therefore capacitive method has been chosen, for our artificial hairs, as readout mechanism.

Figure 1: Schematic representation of artificial hair sensor.

Using the hair structure in figure 1, the conductive electrodes deposited on top of the membrane form capacitors with the common underlying electrode. Due to the viscous drag torque acting on the hair, the membrane will tilt and therefore the capacitors, on both halves of the sensor, will change oppositely. These capacitance changes are measured differentially to provide a means for the tilting angle and, hence, the air-flow in the vicinity of the hair. In literature, many multi-sensor and sensor array systems have been developed since sensor arrays systems provide spatially distributed information. Most notable array sensors are the image sensors, finger print recognition, which has been aided by arrays of capacitive sensors, and arrays of X-rays sensors [5] etc. Figure 2 shows artificial hair flow sensors array.

In biology, sensory information passing into the neural network is a parallel process. Since it is often desirable to perform assays on a large number of samples, methods for rapidly reading
out the sensors array have been considered. Usually, interfacing of large numbers of sensors is attained by using different multiplexing schemes to reduce the number of required connections. Frequency Division Multiplexing (FDM) and, more often, Time Division Multiplexing (TDM) are described in literature to extract the signals individually from hundreds of sensors [6].

Figure 2: Artificial hair sensor arrays placed in different direction for directional sensitivity.

As mentioned above, the potential of these sensor arrays is to measure the flow-pattern rather than single flow observation. Therefore, the sensors have to be examined individually while maintaining limited external connections. Previously, we have shown that these hairs are sensitive to low-frequency sound, using a laser vibrometer setup [7] as well as capacitive measurements [2]. In this work, we present our progress in addressing, characterising and interfacing artificial hair sensor arrays based on these requirements. Different addressing methods are considered. It is pointed out that the most favourable scheme is the FDM mechanism. Different 180° out of phase sinusoidal signals are supplied to the columns, which are the top electrodes of the sensor capacitors in the sensory array. Based on this, the sensor signal is modulating the amplitude of the column’s frequency and hence is coded and distinguishable from other row signals by using different columns frequencies. Such a system would open-up possibilities to measure, characterise and eventually recognise specific amplitude, frequency and flow signatures by extracting individual sensor signals with less interconnects.

II INTERFACING & ADDRESSING ARTIFICIAL HAIR SENSORS

II.1 READOUTS ELECTRONICS

The proposed array sensor system requires special attention with respect to the interfacing electronics. Signals sensitivity, locality and the high signal to noise ratio are the main requirements which have to be considered while interfacing and addressing our array sensor’s-readout scheme. The interfacing mechanisms should not deteriorate the sensitivity or the performance of the sensor. Based on these objectives, a differential capacitive readout technique is used to measure the flow signal. The differential output is acquired by driving the signals 180° out of phase and measuring the reactive current at the common electrode. This provides more sensitivity, high capacitance variation while using high frequency range to maximise the sensor current and reduce the 1/f noise at the sensor-electronics interface. The readout circuit, which consists of a charge amplifier circuit, detects the capacitance changes that vary as a consequence to the applied air-flow. Every row within the array contains one unit of this charge amplifier. Figure 3 shows the schematic of the charge amplifier. The charge amplifier should be sensitive enough and have a high input impedance, low input capacitance and wide bandwidth as well as low input voltage and current noise to detect the capacitance for individual hair sensor which is in the range of 0.05 pF.

Figure 3: Schematic diagram of the charge amplifier circuit used to detect capacitance changes for individual hair sensor.

II.2 ADDRESSING ARRAY SENSORS

Normally, capacitive array sensor systems are constructed of rows and columns of conductive electrodes separated by dielectric material. The
capacitances are formed at the row-column intersections. For large arrays, technical challenges arise in making fast and accurate measurements for the entire sensors array. Each sensor should be examined individually with its own electronics; however, this increases the number of connections proportional to the number of array elements. TDM technique, by selecting specific row and column using a control circuit and an analog multiplexer for addressing the array elements sequentially, is another approach [6]. Based on that, the outputs are transferred using single channel to the output stage. This is one mechanism to reduce the channel hardware and its connections by sharing the same channel between different outputs at different time slots. In contrast, certain difficulties, for instance, multiplexing N channels, increase the noise bandwidth, the readout time and decrease the signal to noise ratio (which depends on the number of elements within the array). For these reasons, FDM is considered where different frequencies are provided along the columns of the array. The row signals are modulated with different carrier frequencies and mutually shifted in the frequency spectrum while using less hardware. Simultaneously, in FDM the input signals provided the carrier frequencies are separated by more than the bandwidth of the sensors. By multiplying the summarized output with the same frequency used at the columns side, the information of the individual sensors can be retrieved. Figure 4 presents the implementation of FDM mechanism.

![Figure 4: Possible FDM architecture for readout array sensors.](image)

Furthermore, the system may also include Analog-to-Digital Converter (ADC) to translate the representative voltage in a corresponding bit vector linked to a processing unit.

II.3 DOUBLE FREQUENCY DIVISION MULTIPLEXING

To further reduce the number of signal carrying channels and while using the columns FDM approach, the frequencies of each row can be also shifted again and then combined together in one carrying output channel. This is realized using one multiplier per row. Since the multiplier may generate some noise, the second FDM is more appropriate to be implemented at the output of the charge amplifier which ensures not to affect the weak signal at the sensor-electronics interface. This arrangement, which is called Double FDM, offers tremendous advantages. First, the 1/f noise is significantly decreased by using high driving frequencies. Second, single and double FDM provides a parallel readout capability without increasing the readout time and hence better signal to noise ratio. This provides a live measurement for all of the sensors within the array. Third, the dimensions of the array can be expanded based on the amount of the frequency shifts at the row side and the interval between the columns frequencies. Based on this scheme of double FDM, for instance, it would be possible to combine the signals from an array of 10 columns with 10 rows of sensors. The first FDM can be implemented by using columns-driving frequencies from 1 MHz to 1.9 MHz with 100 kHz intervals. The second FDM can be applied, basically, by shifting the signals of each row with different frequencies starting from 5 kHz with 5 kHz intervals using one multiplier per row while maintaining the signals of the first row without any shift. By doing that, each individual sensor signal is shifted to a different band in the spectrum and the output junction provides a combined output that includes the sum of various frequencies representing the signal of each sensor within the array. Figure 5 illustrates the double FDM architecture for addressing array elements individually. The number of rows, which can be addressed using this architecture, is based on the following formula:

\[
\text{Rows Number} = \frac{\text{Column freq. resolution}}{2 \times \text{Rows freq. resolution}}
\]

In this scheme, the number of the rows and columns are extendable and just depend on the intervals between columns activation frequencies,
amount of frequency shifts at the row side as well as the bandwidth of the sensor’s signal.

![Image of Double FDM architecture for addressing sensors array.](image-url)

**Figure 5:** Double FDM architecture for addressing sensors array.

The double FDM architecture enables using single output channel per array or sub-array, simultaneously. Therefore, this opens the possibility for reducing the hardware by using single high performance Analog to Digital Converter (ADC) as well as single processor. At the signal processing side, each sensor is shifted to a specific band in the spectrum. This can be considered as a signature or a finger print for each sensor which allows mapping, addressing and reconstructing the signal of each sensor with respect to its frequency and magnitude using the Fast Fourier Transform (FFT) algorithm. By acquiring the flow signals from array elements individually, it would be possible to form a real-time flow-picture (pattern) across the artificial hair array. Figure 6 shows the simulated spectrum of different sensor signals in 3 x 3 array using 1 MHz, 1.1 MHz and 1.2 MHz column frequencies and 5 kHz, 10 kHz and 15 kHz rows-shifts.

![Image of Simulated FFT spectrum of 3 x 3 array.](image-url)

**Figure 6:** Simulated FFT spectrum of 3 x 3 array.

### III CONCLUSIONS

We have presented in this contribution our progress in interfacing and addressing artificial hair-array sensors. Different schemes for addressing array elements individually have been considered. It was shown that using single FDM as well as Double FDM multiplexing are the favourable approaches. In future work, pattern recognition has to be considered from a signal processing point of view.

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### REFERENCES


