Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering 25 (2011) 779 – 782

Procedia Engineering

www.elsevier.com/locate/procedia

Proc. Eurosensors XXV, September 4-7, 2011, Athens, Greece

Artificial lateral-line system for imaging dipole sources using beamforming techniques

Ahmad Dagamseh*, Remco Wiegerink, Theo Lammerink, Gijs Krijnen

MESA+ Research Institute, University of Twente, Hallenweg 15, Enschede 7522NH, The Netherlands

Abstract

In nature, fish have the ability to localize prey, school, navigate, etc. using the lateral-line organ [1]. Here we present the use of biomimetic artificial hair-based flow-sensors arranged as lateral-line system in combination with beamforming techniques for dipole source localization in air. Modelling and measurement results show the artificial lateral-line ability to image the position of dipole sources accurately. Such systems open possibilities for flow-based near-field environment mapping which can be beneficial e.g. to robot guidance applications.

Keywords: Biomimetic hair flow-sensor, artificial lateral-line, beamforming;

1. Introduction

Lately, sensor arrays have become an important research topic with respect to smart sensory systems developments. The estimation of signal parameters using arrays of sensors has been reported, in literature elaborately for various applications [2,3]. In nature, animals can detect events in their environment with varying aptness using different sources of sensory information as it is relevant for their survival. The sensing hairs of crickets and the cilia-based lateral-line system of fish are examples of array-based sensory systems used to detect flows in air and water, respectively.

Recently, a biomimetic approach has been used for insect inspired flow-sensors and Lateral-Line Systems (LLS) [4]. Using Micro-Electro_Mechanical Systems (MEMS) advancements, we developed an artificial hair flow-sensor inspired by the hair flow-sensors of crickets [4a]. The use of artificial hair flow-sensor arrays together with array signal processing techniques (i.e. beamforming techniques) can aid in the understanding of lateral-line operation e.g. with respect to its role in source localization. This work

* Corresponding author. Tel.: +31-53-489-2811.
E-mail address: a.m.k.dagamseh@ewi.utwente.nl.

1877-7058 © 2011 Published by Elsevier Ltd.
doi:10.1016/j.proeng.2011.12.191

differs from previous work [5] as it uses array signal processing and Artificial Lateral-Line Systems (ALLS) with discrete hair-sensors for dipole source localization.

1.1. Artificial hair sensor

In this study, we used artificial hair flow-sensors inspired by the hair flow-sensors in crickets [4a] as the basic array element. Our sensors were fabricated using sacrificial poly-silicon surface micro-machining technology to form a suspended silicon nitride membrane with a ~ 1 mm-long SU-8 hair on top. Aluminium electrodes were integrated on top of the membrane forming capacitors with the bottom substrate (as a common electrode). Due to the viscous drag torque acting on the hairs, the membrane tilts and in consequence the capacitors, on both halves of the sensor, change equally but oppositely. A synchronous demodulation technique is used to recover the original airflow signal from the AM signal. Fig. 1 shows the structure of the mechano-receptive sensory-hair with its source of inspiration.

1.2. Lateral-line system

The LLS is used by fish to detect preys and predators. It consists of spatially distributed hairs sensitive to fluid-flows and arranged in a more or less linear array structure [6]. Biologists try to understand the processes of source localization in fish through various hypotheses. One of these hypotheses is based on reconstruction of the flow fields generated by moving dipole sources by determining the characteristic points [1]. E.g. the distance between a flow-sensor array and a dipole source is encoded in the distance between these characteristic points. A simulated example for the parallel component of a dipole field is shown in Fig. 2.

Previously, we have demonstrated the ability of our hair sensors to reconstruct and localize the position of a dipole source (vibrating sphere) [5]. The characteristic points of the dipole field were used in the source localization. However, this method has some limitations in the estimation of source position when the flow source is not located alongside the ALLS. Additionally, since the zero-crossing of the perpendicular flow-field component is used to determine the source position limited SNR causes large estimation errors. To overcome these limitations different array signal processing techniques and algorithms have been considered. The beamforming technique can provide high-resolution source localization and hence it is implemented in this study.

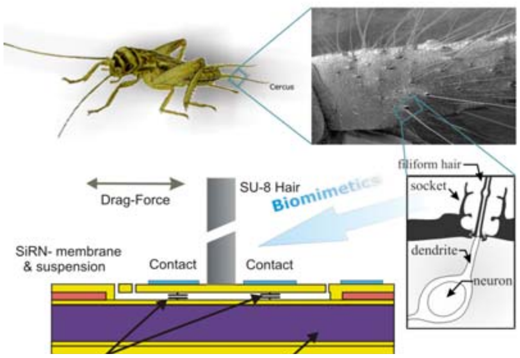

Fig. 1. Artificial hair geometry and its biological source of inspiration.

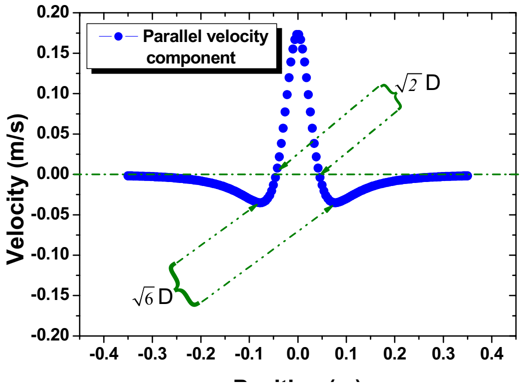

Fig. 2. Simulated velocity fieled $V_{x,//}$ (the parallel component) as function of sensor position along the LLS (*x-axis*). The LLS to dipole source distance (*D*) is encoded within the characterstic points of dipole field.

2. Beamforming

Fig. 3 shows a schematic drawing of the ALLS used in combination with a beamforming technique for source localization. The array is formed by positioning artificial hair sensors in a linear array shape constituting an ALLS. The vibrating sphere is the dipole source emulating (part of) a prey or predator. The current source localization algorithm is based on calculation of a template for the anticipated array responses at each grid point within the area of interest [5] using the dipole source model (eq. 1). The array response is used then to calculate an estimate of a covariance matrix R. Subsequently, a beamforming technique based on Capon's algorithm [7], is used and the associated output power (P_{BF}) at each possible grid point where the source possibly could be determined (eq. 2). Finally, the power amplitudes are used to visualize the grid area and its maximum indicates the most-likely position of the dipole source.

$$V_{x,//}(x) = s\,\omega a^3 (2x^2 - D^2)/(x^2 + D^2)^{5/2} \qquad (1)$$

$$P_{EF} = 1/(A^H R^{-1} A) \qquad (2)$$

where $V_{x,//}$ denotes the theoretical response of each sensor for the field along the *x-axis* at its position, ω is the angular vibration frequency, a is the sphere radius, s is the sphere displacement amplitude, D is the distance between the centre of the sphere and sensor reference line (*x-axis*), A is the array response due to the dipole source at each grid point and A^H is the Hermitian of A.

3. Experimental setup and Results

In this work eight artificial hair flow-sensors aligned in a linear array shape along the *x-axis* were operated in air, imitating the LLS of fish (Fig. 3) [5]. A vibrating sphere (oscillating at 40 Hz with radius of 0.04 m) is used as dipole source. The set goal of this experiment is to determine the distance between the dipole source and the ALLS using the beamforming technique discussed above. This is done afterwards the measurements in an off-line fashion and a power map is generated for the area of interest. The position with maximum power level is the predicted sphere position. Fig. 4 shows a normalized representation of a dipole field measurement as detected by the ALLS, compared with a normalized representation of the parallel component of the flow as given by the theoretical dipole field.

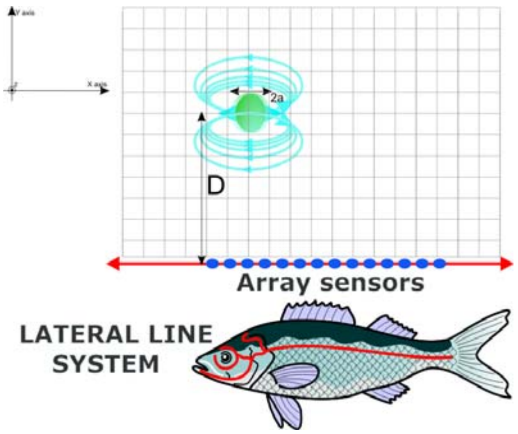

Fig. 3. Schematic drawing of the ALLS and its source of inspiration.

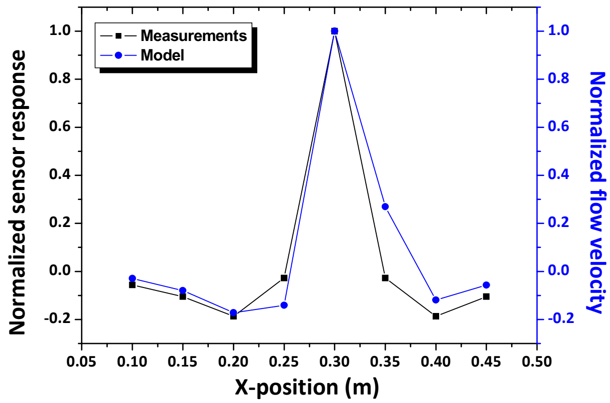

Fig. 4. Flow field measurements (as detected by 8 hair-sensors at x = 0.3 m, D = 0.068 m) versus theoretical model.

The results show the ability of our hair sensor, when positioned as ALL, to reconstruct the dipole field. The detected field matches satisfactory with the theoretical predictions. The accuracy of the field detection is examined by localizing the source. Fig. 5 illustrates imaging the dipole source position (for the data presented in Fig. 4) using ALLS and the beamforming method. Performance of the ALLS in terms of source estimation accuracy is compared with the real-physically measured distance values (D).

The source localization results show that the estimated distances (D_{est}) between the sphere and ALLS match the set distance reasonably well. Fig. 6 shows D_{est} versus D.

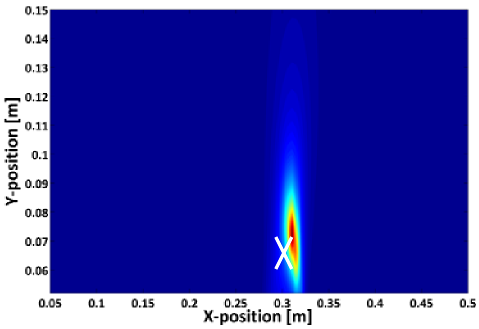

Fig. 5. Dipole source imaging using ALLS. Source positioned at x = 0.3 m, D = 0.068 m (white cross) and the estimated position is X_{est} = 0.31 m, D_{est} = 0.072 m. The red area indicates the area of increased likelihood of the source position.

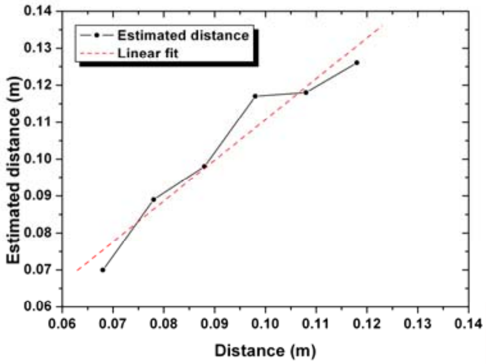

Fig. 6. Dipole source localization determined using the beamforming technique (dots) & linear fit between D and D_{est} (dashed line).

4. Discussion and Conclusions

The above results verify the capability of artificial hair-sensor arrays to localize the dipole source and give some insight in localization mechanisms in fish. However, D_{est} shows some deviation from the set D. Estimation uncertainty can partially be attributed to the deviation between the experimental measurements and predictions of theoretical models. This deviation can be related to the non-prefect matching between individual ALLS elements.

To conclude, a linear array made of eight artificial hair flow-sensors was used to imitate the LLS in fish. Array signal processing in combination with an ALLS show the possibility to localize positions of dipole sources very well. The flow maps constructed by our sensory system open up new possibilities for 3D near field imaging and could aid in understanding nature.

Acknowledgment

The authors would like to thank NWO/STW for financial support in the framework of VICI project BioEARS.

References

[1] Franosch J-MP., Sichert AB, Suttner MD, Van Hemmen JL. Estimating position and velocity of a submerged moving object by the clawed frog Xenopus and by fish-A cybernetic approach. *Biological Cybernetics* 2005;**93**:231-8.

[2] Atmoko H, Tian DC, Tian GY, Fazenda B. Accurate sound source localisation in a reverberant environment using multiple acoustic sensors. *Meas. Sci. Technol.*2008;**19**: art. no. 024003

[3] Yildiz G, Duru AD, Ademoglu A. A comparative study of localisation approaches to EEG source imaging. *In IEEE/NIH Life Science Systems and Applications Workshop, LISA; Bethesda*; 2007, p. 56-9.

[4] (a) Krijnen G, Lammerink T, Wiegerink R, Casas J. Cricket Inspired Flow-Sensor Arrays. *InIEEE Sensors*, *Atlanta, USA*; 2007, p.539-46. (b) Yang Y, Nguyen N, Chen N, Lockwood M, Tucker C, Hu H, et al. Artificial lateral line with biomimetic neuromasts to emulate fish sensing. *Bioinsp. Biomim.*2010;**5**: art. no. 016001.

[5] Dagamseh A, Lammerink T, Kolster M, Bruinink C, Wiegerink R, Krijnen G. Dipole-source localization using biomimetic flow-sensor arrays positioned as lateral-line system. *Sensors and actuators A (Physical)* 2010;**162**:355-60.

[6] Coombs S. Smart skins: Information processing by lateral line flow sensors. *Autonomous Robots* 2001;**11**:255-61.

[7] Capon J. High-resolution frequency-wavenumber spectrum analysis. *In proceedings of the IEEE;* 1969, p. 1408-18.