A simulation study of the dipole source localisation applied on bio-mimetic flow-sensor linear array

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Abstract— In flow-sensor arrays, elements are distributed at different positions and each sensor locally constructs the flow field components. In this paper, we report the developments of the bio-inspired artificial flow-sensors in array structures. The source localisation mechanism in fish, using the flow pattern generated from prey, is modelled. We computed the flow velocity components (parallel and perpendicular), generated by a dipole source, at the array position and based on the structure of our flow sensor. The ability of our sensors, arranged in arrays, to detect flow patterns was investigated. The model results were found to be in an excellent agreement with the measurements along virtual lateral-line and successfully demonstrate the source-distance determination.

Index Terms— Artificial lateral-line, hair flow-sensors, source localisation.

I. INTRODUCTION

Sensors arrays are used to measure field components rather than single or average measurement to obtain more information. In nature, there are various examples of highly sensitive hairs arranged in array structures assisting animals to survive. Crickets [1], spiders [2], scorpions [3] and fish [4] all have flow sensors in the form of hairs or (in cupula embedded) cilia that detect tiny fluid movements assisting them in locating preys and avoiding predators even in noisy environments. Specifically, the lateral-line in fish has received great attention in the literature for understanding the source localisation process [5].

The lateral-line is a natural mechano-sensory system consisting of spatially distributed neuromasts to detect fluid velocity (superficial neuromasts) and fluid acceleration (canal neuromast). Many efforts have been made to understand the localisation and tracking of moving objects by detection and reconstruction of flow patterns as performed by lateral-line systems [6,7].

II. DIPOLE SOURCE LOCALISATION

Since the characteristics of dipole sources are well-known from literature [8], a vibrating sphere generating a dipole velocity field can be conveniently used to analyse object – sensor array interactions. Once the dipole-field characteristics are determined, information about the source can be retrieved. In an ideal fluid, a sphere vibrating parallel (//) and perpendicular (⊥) to a linear array line (parallel to the x-axis) generates a flow velocity in the direction of the x-axis with amplitudes [8]:

\[
V_{x,//}(x) = s \omega a^3 \frac{2x^2 - D^2}{(x^2 + D^2)^{3/2}}
\]

\[
V_{x,⊥}(x) = s \omega a^3 \frac{D x}{(x^2 + D^2)^{3/2}}
\]

where ω is the angular vibration frequency, a is the sphere diameter, s is the sphere displacement amplitude and D is the distance between the centre of the sphere and sensor reference line (x-axis). Fig. 1 shows the velocity profile generated by a vibrating sphere and Fig. 2 shows the parallel and the perpendicular velocity components, at the position of the lateral-line as typical receptive field plots.

The velocity components uniquely encode the distance to the source irrespective of the fluid properties, vibration frequency, amplitude, direction and dimensions of the moving object [7,9]. The distance D can be determined in various ways: for \( V_{x,//} \) the distance between the two zeros equals \( \sqrt{2}D \) and the distance between the two minima is \( 6D \), while for \( V_{x,⊥} \) the distance between the maxima and minima equals D as shown in Fig. 2. Depending on signal-to-noise ratios and orientation of the sensors the most suitable method can be chosen.
In this work and based on mimicking the lateral-line system in fish, we simulated the effect of various source parameters on the source-distance determination to assess the ability of the hair sensor in detecting flow patterns. Once the field characteristics are known, Artificial Neural Network (ANN) can be used to extract information about the source.

III. THEORETICAL MODEL

The flow velocity field generated by dipole source and directed to the flow sensor was modelled. An array of hairs is shaped as a lateral-line system in which each single element (called cerci) contains a 124 hairs (31 rows by 4 columns aligned in 45° with the x-axis) to increase the detected signal. The flow velocity field is calculated based on equation 1 and 2 at the position of each single hair element. To re-produce the flow velocity field, the output from each cerci is plotted as function of position along the lateral-line (aligned parallel with the x-axis). The source-distance is determined based on the characteristic points of the detected velocity fields as illustrated in Fig. 2. The simulations show that the integration of the detected fields by various elements within a single cerci can be represented by the field located at the centre point of the cerci as illustrated in Fig. 3 a and b.

![Fig. 1](image1.png)

Fig. 1. Sketch for the dipole velocity field and measurements setup. The maximum sensitivity axis of the hair sensor is aligned to be parallel with the x-axis.

![Fig. 2](image2.png)

Fig. 2. Simulated velocity amplitude Vx as function of sensor position along the x-axis (the parallel and perpendicular components).

![Fig. 3](image3.png)

Fig. 3. The velocity fields (Vx) at the front, mid and back of the cerci compared with the integration of the fields detected by a 124 hairs within the cerci using the same vibration conditions (a) the parallel field (b) the perpendicular field.

We were able to accurately determine the distance to the source from the front, mid and back of the cerci. The estimation accuracy depends on the number of lateral-line elements. The effect of different source parameters on the determination of the source-distance was investigated. The modelling results show that vibration frequency as well as sphere diameter has no influence on the characteristic points of the velocity fields (Vx// and Vx⊥) as shown in Fig. 4. The velocity amplitude has a maximum at the closest position to the source and gradually decreases while decreasing both vibration frequency and sphere diameter. On the other hand, the influence of varying D on the characteristic points is shown in Fig. 5. The velocity amplitude decreases while increasing distance to the source and the distance between the zero-crossing points increases. This confirms that D is the only parameter which affects the source-distance estimation using velocity field detected by the lateral-line system.
We plotted the estimated distance \((D_{est})\) as function of \(D\), using the theoretical model, to compare the effect of various source parameters on source-distance estimation. Fig. 6 shows a clear linear relation between the \(D\) and \(D_{est}\). The procedure done on the parallel component of the velocity field is applicable to the perpendicular component with \(D_{est}\) the distance between the peaks of the perpendicular plot.

IV. EXPERIMENTAL RESULTS

To verify the theoretical model, we demonstrated the source localisation mechanism using artificial hairs arranged in virtual lateral-line system. The experimental setup, the definition of distance \(D\) and the reference coordinate points at the sensor and sphere positions are shown in Fig 1. The theoretical model was fitted to the experimental data with less than 3 % fitting error and used successfully to localise the dipole source as shown in Fig. 7.

![Fig. 6. Relation between \(D\) and \(D_{est}\) using the theoretical model with different vibration conditions.](image)

![Fig. 7: The typical parallel and perpendicular components of the dipole velocity-field (measured and simulated) at a distance of \(D = 0.056\) m using the same vibration conditions.](image)

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V. DISCUSSION AND CONCLUSIONS

We have shown the ability of our hair flow-sensor to reconstruct the velocity field generated by dipole source. Using the hair sensor in virtual lateral-line it was possible to accurately detect both the parallel and perpendicular velocity components and as a demonstration to determine the source distance. We investigated the effect of different source parameters to determine the field characteristics needed for the distance determination. The results show that the dipole source position is encoded in the velocity field along the (virtual) lateral-line system. As an example of pattern recognition system, the dipole characteristic points could be used as an input vector to the ANN for determining various source parameters. Such a system can, for example, be used for guiding purposes in robotic applications.

REFERENCES