電場定位をする魚の発電器官によって体表面上に形成される物体の電気的イメージ

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概要:弱電気魚は尾部に発電器官をもち周囲に電場を形成し、そのゆがみを利用して周囲の物体を正確に検知することができる。周囲の水と電気的性質（インピーダンス）が異なる物体は、その距離、大きさ、導電性などに依存して魚の周囲の電場をゆがめる。しかしながら、この魚が電場のゆがみのどのような特徴を検知して物体のこれらの情報を知るのか、はまだよくわかっていない。この問題を明らかにする第一段階として、魚の周囲に形成される電場が、物体の様々な状況下でどのようにゆがめられるのか、を正確に知らなければならない。本研究では、魚の周囲の３次元的な電場を正確に計算するモデルを提案する。このモデルは、星宮らのモデルに基づいてつくられ、電場の時空間的変化が計算できるように拡張されている。このモデルをもちいて、我々は、魚の周囲や体表面上に形成される電場を様々な状況で計算した。このような計算から、物体の距離と大きさの情報が体表面上に形成される電場ゆがみの２つの特徴的な量によって表現されることがわかった。

Electric image of object on surface of fish's body induced by electric organ discharge for electrolocation

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Abstract: Weakly electric fish generate electric field around its body using electric organ discharge (EOD) and can accurately detect the location of an object using the modulation of electric field induced by the object. In the present study, we developed a model by which we simulate the spatio-temporal pattern of electric field around the fish body induced by fish's EOD in various situations. Our model was made extending Hoshimiya et al. model so as to calculate the spatio-temporal variation of electric field in 3-dimensional space, because the EOD is generated by electric organ in fish's tail and varies temporally. The present model allows us to calculate the precise temporal and spatial distribution of EOD modulation around the fish body, based on which the fish can locate an object. Using this model, we investigated how the distance and size of an object are represented by the distortion of EOD field. We show that the information of object distance and size can be represented by two characteristic features, the maximum amplitude of EOD amplitude modulation (EOD AM) and the half maximum width of normalized EOD AM. The result provides a useful basis for the study of the neural mechanism by which the fish recognize distance and size of an object.

1 Introduction

Weakly electric fish generate electric field around its body using electric organ discharge (EOD) and can accurately detect the location of an object using the modulation of electric field induced by the object[1]. Objects with electric properties that differ from those of the surrounding water distort the electric field around fish's body depending on the size, distance, and electric properties of objects. The currents across the fish's skin induced by the electric field are sensed by an array of electroreceptors in the skin. The fish must then interpret the 2-dimensional electrosensory images, which are highly dependent upon its EOD AM pattern. It is quite important for understanding the mechanism of electrolocation to clearly quantify and visualize the EOD field on the body surface.

In the present study, we developed a model by which we simulate the spatio-temporal pattern of electric field around the fish body induced by fish's EOD in various situations. Our model was made extending the previous model[2] so as to calculate the spatio-temporal variation of electric field in 3-dimensional space, because the EOD is generated by electric organ in fish's tail and varies temporally. We show that the information of object distance and size can be represented by two characteristic features, the maximum amplitude of EOD amplitude modulation (EOD AM) and the half-maximum width of normalized EOD AM.

2 Model

Figure 1 shows a model of fish body by which we describe numerically the EOD field around fish body. The fish was placed in a water tank, as shown in Fig. 1a. The shape of fish was approximately represented by a rectangle, size of which is 8 cm long, 0.8 cm wide, and 1.6 cm height. The model of fish consists of a fish body surrounded by skin of high resistivity and an electric dipole made by the electric organ, as shown in Fig. 1b. The front end of this organ becomes negative with respect to its rear end. The distance between two poles is 27 mm. The potentials of dipole were set to be -100 and $+100$ potential unit (p. u.) that were the same as those used in Hoshimiya et al. modell[2]. The position of object was fixed or moved parallel to the fish's body axis.

We used a finite-element-method to calculate the EOD field [2]. The space of water tank and fish body were divided into small cubes, the side length of which is $L0(=1\text{mm})$. Each small cube has the resistivity and capacitance relevant to the occupied material. The electric potential of small cube at position (i,j,k) , $U(i,j,k;t)$, is determined by

$$\sum_{X=i\pm1} I(X,j,k;t) + \sum_{Y=j\pm1} I(i,Y,k;t) + \sum_{Z=k\pm1} I(i,j,Z;t) = 0, \tag{1}$$

$$\begin{aligned} I(X,j,k;t) = & (C(X,j,k)+C(i,j,k))\frac{d}{dt}(U(X,j,k;t)-U(i,j,k;t)) \\ & + \frac{1}{(R(X,j,k)+R(i,j,k))}(U(X,j,k;t)-U(i,j,k;t)), \end{aligned} \tag{2}$$

$$\begin{aligned} I(i,Y,k;t) = & (C(i,Y,k)+C(i,j,k))\frac{d}{dt}(U(i,Y,k;t)-U(i,j,k;t)) \\ & + \frac{1}{(R(i,Y,k)+R(i,j,k))}(U(i,Y,k;t)-U(i,j,k;t)), \end{aligned} \tag{3}$$

$$\begin{aligned} I(i,j,Z;t) = & (C(i,j,Z)+C(i,j,k))\frac{d}{dt}(U(i,j,Z;t)-U(i,j,k;t)) \\ & + \frac{1}{(R(i,j,Z)+R(i,j,k))}(U(i,j,Z;t)-U(i,j,k;t)), \end{aligned} \tag{4}$$

where $I(X,j,k;t)(X=i\pm1)$ is the electric current from the cube at position (X,j,k) to that at position (i,j,k). $I(i,Y,k;t)$ and $I(i,j,Z;t)$ have similar definition to $I(X,j,k;t)$, $(Y=j\pm1$, and $Z=k\pm1)$. $C(i,j,k)$ and $R(i,j,k)$ are the capacitance and resistivity of the material occupied in the small cube at (i,j,k), respectively. $C(X,j,k)$, $C(i,Y,k)$, $C(i,j,Z)$, $R(X,j,k)$, $R(i,Y,k)$, and

$R(i,j,Z)$, are defined by similar way to $C(i,j,k)$ and $R(i,j,k)$. The boundary conditions are given by

$$\begin{cases} U(0,j,k)=0, & U(L_x,j,k)=0, \\ U(i,0,k)=0, & U(i,L_y,k)=0, \\ U(i,j,0)=0, & U(i,j,L_z)=0, \end{cases} \tag{5}$$

This means that the electric potential is measured with reference to walls of water tank.

In the case where the object has only resistivity, we used the iteration method to solve eqn. (1) numerically. It was assumed that the computation converged if the condition,

$$|U_{k+1}(i,j,k) - U_k(i,j,k)| < 10^{-4}$$

was fulfilled for all (i,j,k), where k is the iteration number.

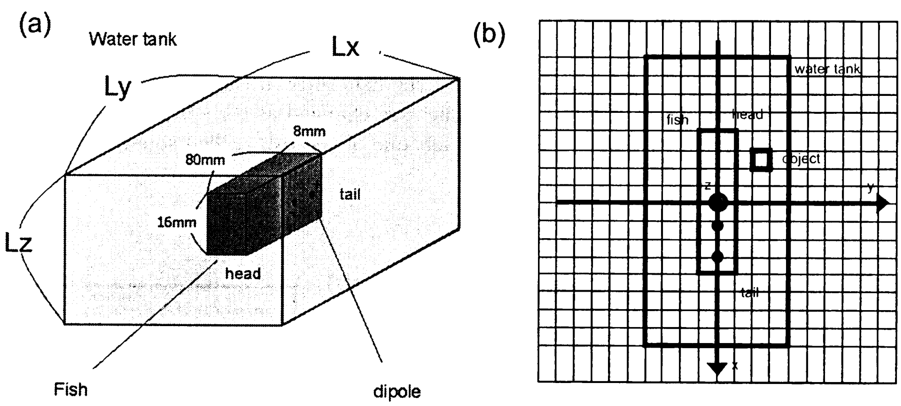

Figure 1: (a) A model for the simulation of electric field around fish body induced by its own EOD and an object. $Lx = 200$ mm, $Ly = 100$ mm, and $Lz = 100$ mm. (b) The space around the fish is divided into small cubes. The EOD current is generated by the potential dipole consisting of $-V$ at $X = 102$ and $+V$ at $X = 129$. $V = 100$ and 1p.u. = 0.125mV.

3 Results

Figure 2a shows the EOD field around the fish body in the absence of object. The spatial distribution of fish's own EOD is symmetric to the center-line of fish's longitudinal axis. The electric organ causes extremely large electric potentials nearby the electric organ, while it does slowly decrease of potentials in rostral half-body. The rostral isopotential lines are more parallel to the body surface rostrally. The fish must recognize the environment with reference to the intrinsic EOD field around fish body. As shown in Fig. 2b, the object elicits a local distortion of the EOD field around the object.

Figure 3 shows the dependence of maximum amplitude of electric image and the half-maximum width of normalized electric image on the object distance and size. The object used is a cube. It is seen in Fig. 3a that the maximum amplitude (E_m) of the electric image is increased with decreasing the object distance and increasing its size. As shown in Fig. 3b, the half-maximum width (σ) of normalized electric image shows a strong dependence on the object distance, while it shows only a slight change depending on the object size. The results indicate that the object size could be mainly determined by the maximum EOD AM, while the object distance could be determined by the combination of E_m and σ.

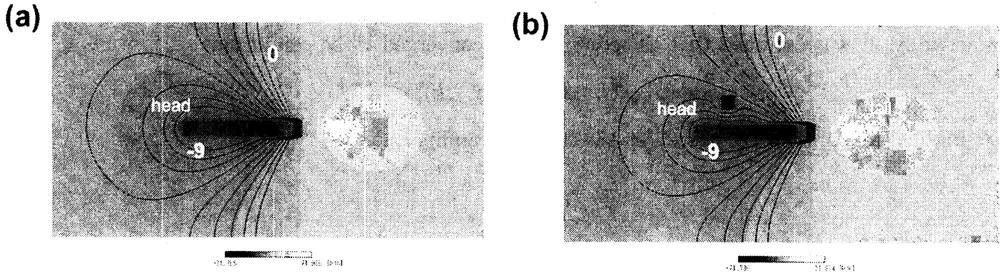

Figure 2: Contour plot of EOD field around the fish body in the absence of an object (a) and in the presence of an object (b). Contour values are changed as 0 - -9 p. u. in 1 p. u. steps (1 p. u. = 0.125 mV) from the right side to the left one of the fish. Filled square nearby the fish is the object.

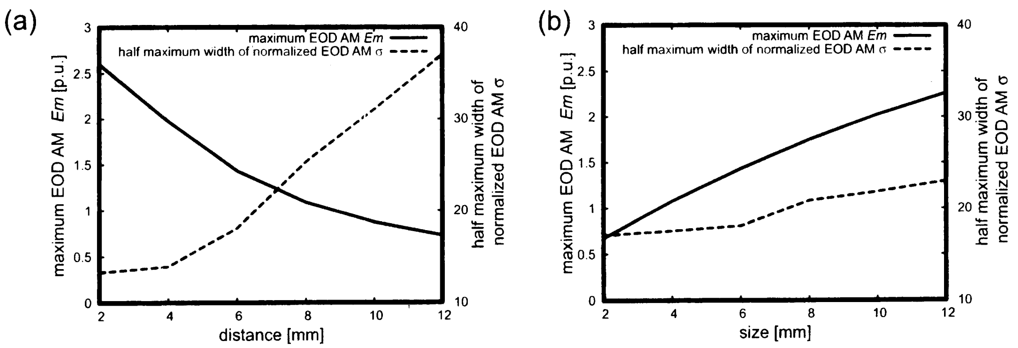

Figure 3: Dependence of the maximum amplitude of electric image and the half-maximum width of normalized electric image on distance and size of object

References

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