

Modelling the Electrolocation of the Weak Electric Fish

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Abstract

As a biological application of physics we discuss the physical relevance of the weak electric fish. We show how it can be used in a basic physics teaching situation utilizing both measurements in an aquarium and computer modelling and simulation. The learning outcome concerns concepts of electric force, field and potential as well as electric material properties. The application serves the purpose of widening the field of physics and so increasing the learning motivations.

Introduction

The elephant nose fish uses weak electric forces to sense its environment. Its natural inhabitation is in muddy rivers of Africa where the use of the vision sense is of limited importance. Using specifically developed muscle cells it makes itself to an approximate electric dipole and locates and identifies foreign objects through electric interactions. These objects are originally electrically neutral but become electrified through the external influence produced by the fish. Since muscles are utilised the electric potential generated will become pulse shaped, maximum 20-30 pulses per second with a duration of 1-2 ms. Close to the fish the potential generated is a few mV.

Along its body, with highest concentration around the head, there are small pits where hair cells are influenced by the electric interaction. By using information from all cells, the fish is able to locate and identify its environment for the purpose of orientation, defense and feeding.

A different class of species of the weak electric fish generates a continuous wave of the potential, resulting in an electromagnetic wave with a frequency of around 300 Hz. This wave is also used for communication, in particular between the sexes.

The understanding of the electrolocation sense is of prime importance in life sciences, connecting to questions concerning evolution and ecology. An important characteristic of this sense, which is very rare in nature, is that the fish generates its own probe to sense the environment. Together with bats and dolphins, which use ultrasound in a similar manner, they form a unique group of species.

The weak electric elephant nose fish is simulated utilizing the Femlab electromagnetic software package (ref 1). We are then able to investigate some important properties of the electrolocation sense such as the effect from the shape and electric properties of a foreign object as well as its distance dependence. Also, we might investigate the importance of the surrounding medium, exploring the fact that this sense has been evolved for water living animals only.

It is quite feasible to keep an elephant nose fish in an aquarium, being aware though of its extreme sensitivity. Measurements of the electric potential can easily be performed and provide input to the simulation.

FIG. 1 Elephant nose fish in an aquarium. Its length is around 20 cm.



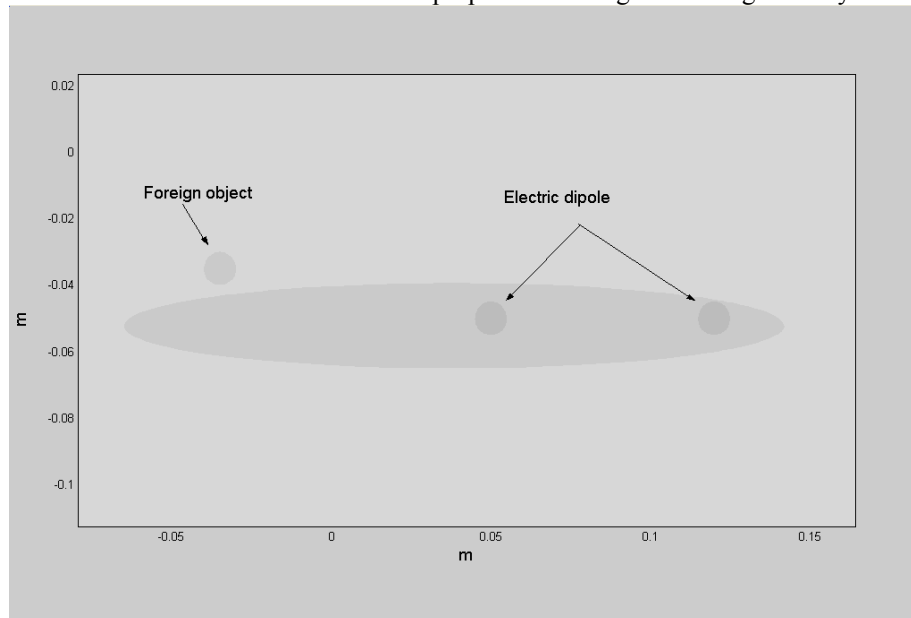
Model definition

Since the time variations of the electrical signals for both classes of fish (pulse and wave) are relatively slow we may approximate the problem as electrostatic, i.e. ignoring magnetic effects. In our first approximation we consider the situation to be plane symmetric, utilizing the 2-dimensional problem solver of Femlab.

From measurements we find that the elephant nose fish can be approximated by an electric dipole. Although in reality its electric generator organ consists of several series coupled flat muscle cells, equivalent to a series capacitor, by simplicity we approximate the fish as an electric dipole (fig. 2). The charge density of the dipoles is adjusted in order to reconstruct the measured potential pattern around the fish. Then we place objects of different shapes and electric properties at different distances in its neighbourhood and check for changes in the potential on the skin where its electroreceptors are placed in reality.

The sensitivity of the electroreceptors is believed to be of the order of 1 μV (ref 2). Using this information it is possible to conclude about the resolution of the sense.

FIG. 2 Subdomain definitions, units in meters. The dipoles corresponds to the electric generator organs, in reality a series of muscle cells. To achieve the proper field strength the charge density is set to 10^{-7} C/m^3



The fish is placed in a surrounding box, which we might imagine as the aquarium borders. Here the potential is assumed to be zero, being at far distance from the fish.

The Femlab program solves for the potential which obeys the Poisson's equation

$$\Delta V = \frac{\rho_0}{\epsilon_r \epsilon_0}$$

where ρ_0 is the charge volume density, ϵ_0 is the electric permeability and ϵ_r is the electric relative permittivity, also called dielectric constant. The electric field and displacement are then obtained through

$$\vec{E} = -\nabla V$$

$$\vec{D} = \epsilon_r \epsilon_0 \vec{E}$$

Results and discussion

Figure 3 shows the result of a calculation with a foreign object included, with a relative permittivity of 4. We observe the typical dipole pattern of the field lines, the "distorsion" of the dipole field close to

the object and the continuity conditions at the interfaces between different media. By comparing with a calculation done without the foreign object we observe a change in potential of a few microvolts, i.e. in the range of the fish's sensitivity, see figure 4.

FIG. 3 Result of the calculation. The potential is illustrated with colours with scale to the right. The electric field is visualized with arrows and flowlines. The length of the arrow is proportional to the strength of the field. Along the head a line is defined where the potential is plotted, see below.

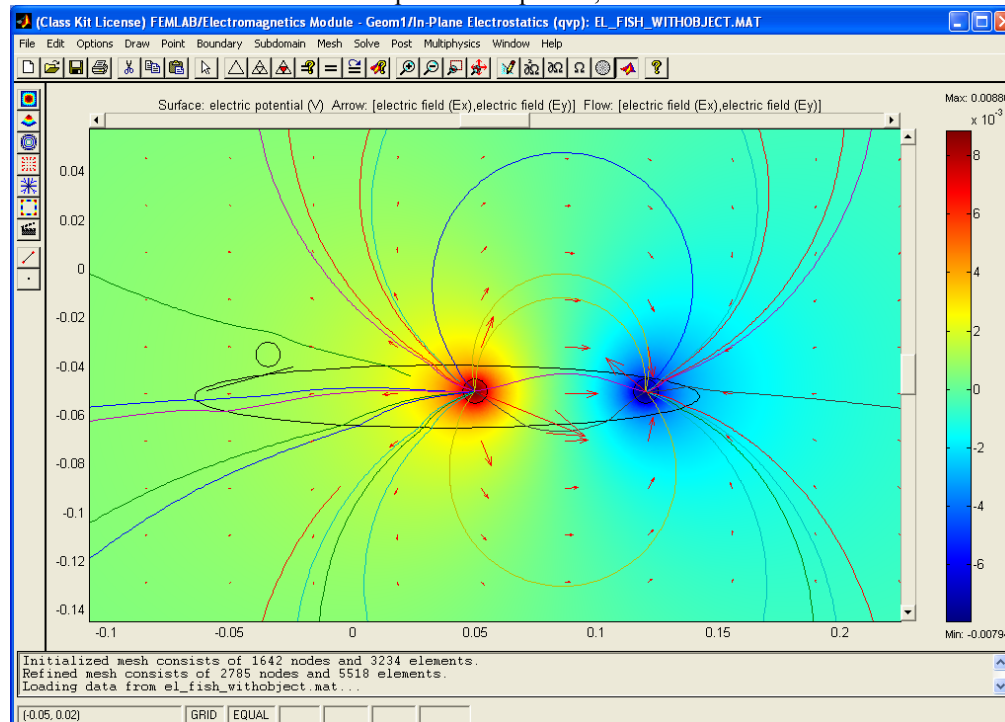
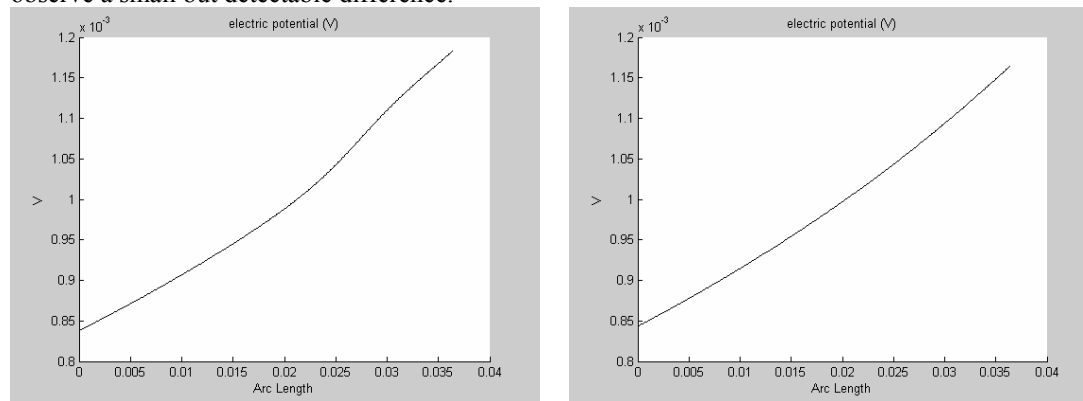


FIG. 4 Potential along the line marked in figure 3 with object (left figure) and without object (right figure). We observe a small but detectable difference.



Pedagogical Aspects

Traditionally, physics is predominantly applied to technology. Presumably this is connected to the male dominance of the subject. The low and decreasing interest for physics in the world community might be related to this unnecessary concentration of a single aspect of the subject. Widening its application towards e.g. biology, as in this work, serves the purpose to attract people with interests in life other than technology. Since the interest for the science of living systems is widely spread it might result in an increasing attraction for physics in general. Specifically, one would hope to adjust the gender unbalance of physics, which is one important symptom of a basic system error of the subject. The biological applications help to alter the reputation from dull and abstract to a living and modern subject. It makes physics alive.

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