Graneau's Electromagnetic Submarine

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1 Problem

Discuss the principle of operation of an electromagnetic "submarine" described by Graneau [1, 2], as sketched below. A copper cylinder, blunt on one end and tapered on the other, is propelled in the direction from the tapered to the blunt end by an electric current, DC or AC, that flows parallel to the axis of the cylinder in a conducting liquid which surrounds the "submarine".

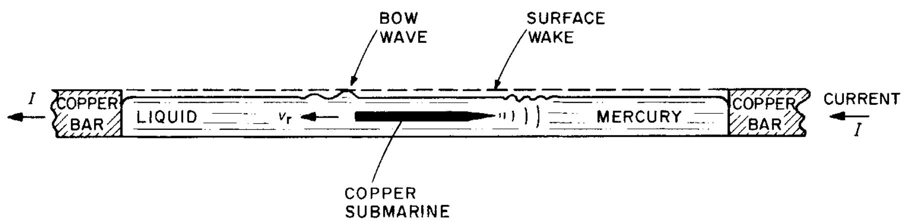

Fig. 2 Copper submarine experiment. Mercury trough length = 30 cm; cross-section 0.5×0.5 inch. Copper extension of troughs 30 cm long, 0.5×0.5 inch cross-section. Remote return circuit. $I = 400$ A. Copper submarine; 5 cm long, 3 mm diameter, 1 cm long taper. $v_r = 15$ cm s^{-1}.

2 Solution

The electric field in the conducting liquid is strong near the tapered end of the 'submarine", and weaker near the blunt end. As a consequence the electric current in the metallic "submarine" is strong near the tapered end and weaker near the blunt end, such that the tapered end heats up more that the blunt end. Then, the conducting liquid heats up more near the tapered end than the blunt end, and the resulting thermal expansion of the liquid near the tapered end propels the "submarine" towards its blunt end, as observed in experiment.

Hillas [3] argued that the current in the tapered end of the "submarine" diverges from its axis, resulting in a $\mathbf{J} \times \mathbf{B}$ force on the taper in the direction of the observed motion of the "submarine". The $\mathbf{J} \times \mathbf{B}$ force on the blunt end opposes the observed motion, but is weaker than the force on the tapered end.

Thus, there are two plausible arguments that are consistent with the observed motion.

2.1 Comments

The conducting "submarine", even if spherical, develops a nonuniform surface-charge distribution in the electric field that drives the current in the conducting liquid, such that the electric force on this charge distribution is in the direction opposite to that of the electric current/field. As the observed effect is independent of the sign/direction of the electric current, this electric-force effect is apparently negligible in Graneau's experiments.

Graneau (something of an "outsider" physicist) did not accept the $\mathbf{J} \times \mathbf{B}$ force law, and instead favored Ampère's original force law between two current elements, $I_1\, d\mathbf{l}_1$ and $I_2\, d\mathbf{l}_2$

,[1]

$$d^2\mathbf{F}_{\text{on }1} = \frac{\mu_0}{4\pi} I_1 I_2 [3(\hat{\mathbf{r}}\cdot d\mathbf{l}_1)(\hat{\mathbf{r}}\cdot d\mathbf{l}_2) - 2\, d\mathbf{l}_1 \cdot d\mathbf{l}_2] \frac{\hat{\mathbf{r}}}{r^2} = -d^2\mathbf{F}_{\text{on }2}, \qquad (1)$$

which has the implication that collinear current elements of the same sign repel one another. In this view, the "submarine" is propelled in the observed direction of motion by the "Ampère force" due to the electric current in the conducting liquid "behind" the "submarine", but retarded by the "Ampère force" due to the electric current in the conducting liquid in "front" of the "submarine". The asymmetry of the "submarine" is such that the net "Ampère force", if it existed, would be in the direction of the observed motion.[2]

References

[1] P. Graneau, *Electromagnetic jet-propulsion in the direction of current flow*, Nature **295**, 311 (1982), http://kirkmcd.princeton.edu/examples/EM/graneau_nature_295_311_82.pdf

[2] P. Graneau, *Electromagnetic Seawater Jet: An Alternative to the Propeller?* IEEE Trans. Mag. **25**, 3275 (1989), http://kirkmcd.princeton.edu/examples/EM/graneau_ieeetm_25_3275_89.pdf

[3] A.M. Hillas; P. Graneau, *Electromagnetic jet propulsion: non-lorentzian forces on currents?* Nature **302**, 271 (1983), http://kirkmcd.princeton.edu/examples/EM/graneau_nature_302_271_83.pdf

[4] K.T. McDonald, *Is Faraday's Disk Dynamo a Flux-Rule Exception?* (July 27, 2019), http://kirkmcd.princeton.edu/examples/faradaydisk.pdf

[5] K.T. McDonald, *Capacitor-Driven Railgun: Magnetic Fields Doing Work* (Dec. 28, 2015), http://kirkmcd.princeton.edu/examples/railgun.pdf

[1]See, for example, Appendix A.12 of [4]. As is well known, the $\mathbf{J}\times\mathbf{B}$ force law and Ampère's force law (1) give the same result for the force between two complete circuits, but differ as to the force between isolated current elements (moving charges).

[2]For discussion of another example that Graneau interpreted as evidence for the "Ampère force", see sec. 2.1 of [5].