MHD Propulsion

William Sutcliffe and Tom Neiser, 19th June 2009

Abstract(by Tom Neiser):

This paper investigates the construction of small scale Magnetohydrodynamic(MHD) propulsion systems and the optimisation of engine performance. The experimental thrust of $F = 0.04 \pm 0.01N$ was found to be dependent on the strength of the magnetic field, the salt water resistivity and the engine dimensions. Measurements with a Hall probe were made to determine the magnetic field strength distribution of the component magnets. By combining this data with the factors affecting thrust this paper evaluates the optimum engine width as $16.0 \pm 0.5mm$. Large scale commercial and military MHD propulsion, however, cannot compete with more efficient conventional propulsion systems.

1. INTRODUCTION — Tom Neiser

In the Hollywood blockbuster "*The Hunt for Red October*"[1] a Russian submarine employs a silent MHD propulsion system, making it impossible to be detected. But what is MHD, how does it work and why don't we see it in our everyday life? The field of MagnetoHydroDynamics(MHD) studies the motion of electrically conducting fluids in the presence of a magnetic field. Any conducting fluid such as salt water has free ions that can carry a current. A magnetic field acting perpendicular to the direction of current flow accelerates moving ions at right angles to the directions of both current flow and the magnetic field due to the Lorentz force. According to momentum conservation this creates a thrust which can be harnessed for the propulsion of a vessel, which is explained in Section 2 in greater detail. This project endeavours to design two small vessels propelled by MHD engines. Subsequent measurements of thrust, current flow and the magnetic field strength distribution enable optimum engine dimensions to be determined. Following these investigations the report evaluates the possibility of large scale application of MHD propulsion, which was pioneered by the design[2] of the *Yamato 1*.

2. BACKGROUND THEORY — William Sutcliffe

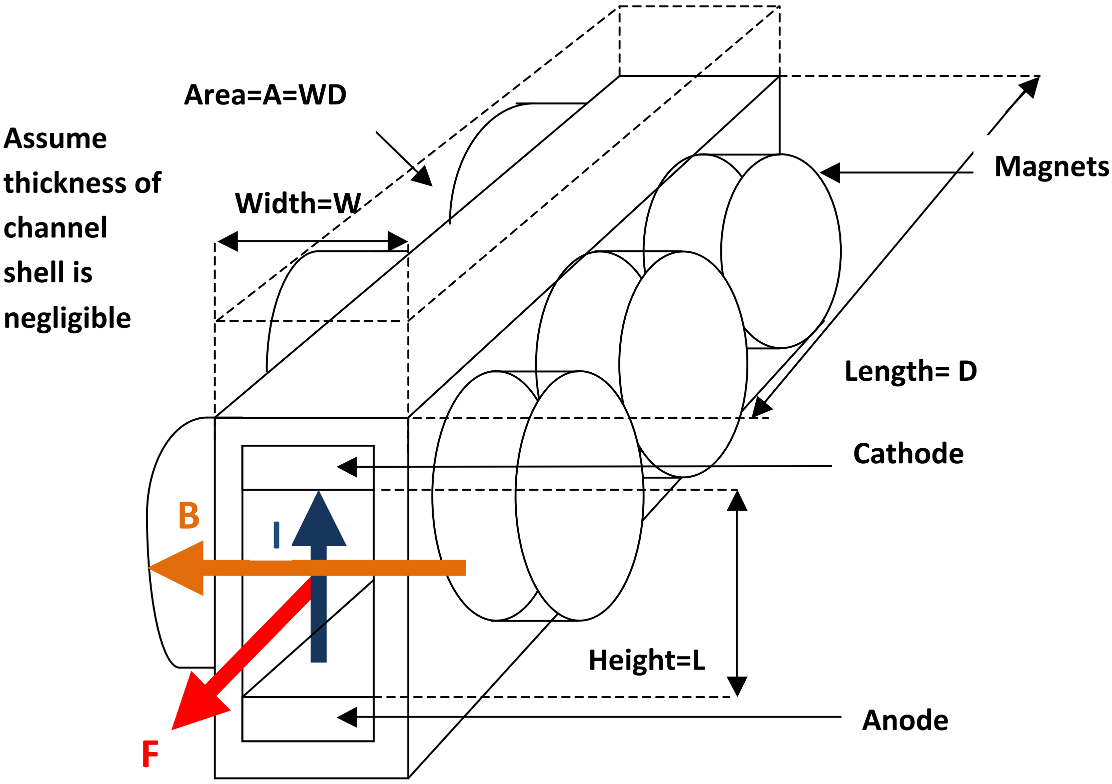
The flow of current, I, through an electrically conducting fluid such as plasma or salt water in the presence of a magnetic field, B, will result in a Lorentz force, F. This will act on the charges carrying the current.

$$\boldsymbol{F} = I\boldsymbol{L}\times\boldsymbol{B} \qquad (1)$$

Where $\boldsymbol{L}$ is the length along which the current acts and is in the direction of conventional current flow. The Lorentz force will be perpendicular to both the magnetic field and the current as $\boldsymbol{L}\times\boldsymbol{B}$ is a vector cross product. This is shown on the rectangular channel in Fig. 1.

[1] Paramount Pictures(1989); "The Hunt for Red October", based on the eponymous novel by Tom Clancy (Naval Institute Press, Annapolis, 1984)
[2] Designed by the Mitsubishi Corp., 1991; see Bibliography

Figure 1: Schematic overview of the MHD propulsion engine



A current can flow, if a voltage, V, is connected across the anode and cathode and the inside of the channel is filled with a conducting fluid (e.g salt water) with resistivity, ρ. The current density, J can be related to the voltage by considering the electric field, E.

$$J = \frac{I}{A} \tag{2}$$

$$J = \frac{E}{\rho} \tag{3}$$

$$(2) = (3) \quad \rightarrow \quad I = \frac{EA}{\rho} \tag{4}$$

For this case since distance between the anode and cathode is L the electric field is

$$E = \frac{V}{L} \tag{5}$$

Substituting (5) and $A = WD$ (see figure 1) into (4) →

$$I = \frac{VDW}{L\rho} \tag{6}$$

This can now be substituted into (1) to give the following magnitude of $\boldsymbol{F}$.

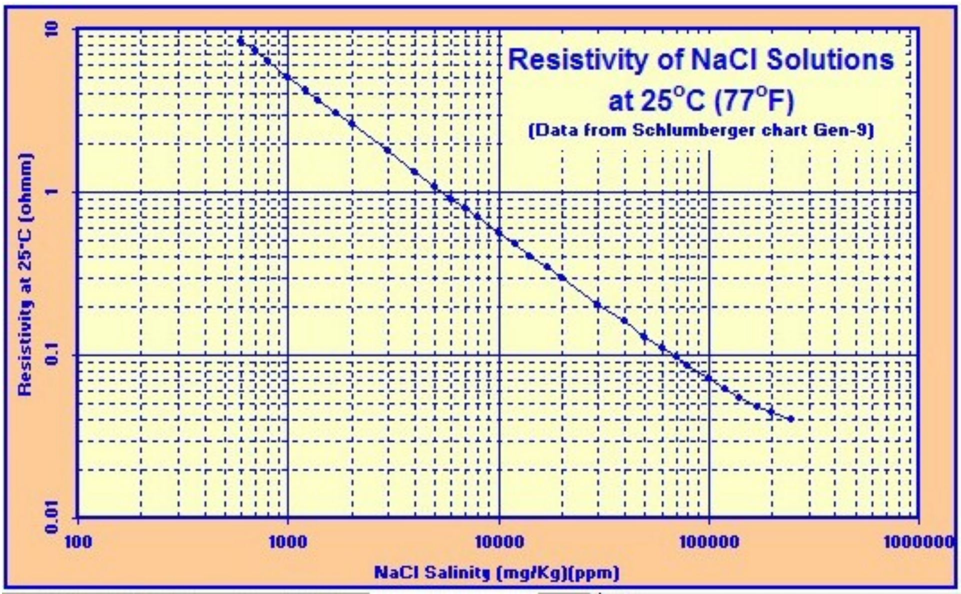
$$|\boldsymbol{F}| = \frac{VDWB}{\rho} \tag{7}$$

This assumes $\boldsymbol{B}$ is uniform throughout the channel which is not the case particularly for circular disc magnets as shown in figure 1. In fact $\boldsymbol{B}$ is dependant on all three dimensions.

In salt water (Sodium Chloride) this force will act on the free ions (Na^+, H^+, Cl^- and OH^-) which carry the current. These ions are accelerated by the Lorentz force and collide with water molecules transferring their momentum to these molecules. Assuming elastic collisions the water will be accelerated out the back of the channel with a force with magnitude equal to that of the Lorentz force. By Newton's third law due to this process there will be an equal but opposite force produced which can be used for propulsion.

The resistivity of salt water will dependent on the salinity of the water. This is a measure of how much salt a body of water contains. The salinity of sea water for instance is 3.5% and its resistivity[3] is 0.22 Ωm.

Figure 2: Graph of resistivity vs. Salinity of salt water solution



PPM- Parts Per Million

As illustrated on logarithmic scales in Fig. 2, increasing salinity leads to decreasing resistivity at a diminishing rate. For example using the graph above if salinity increases from 10% to 25% resistivity will decrease from 0.07 Ωm to 0.03 Ωm.

In order for later analysis of displacement time graphs the equations of uniform accelerated motion can be used. For constant acceleration, a_0, integrating twice with respect to time, t, gives the following:

$$x = 0.5a_0t^2 + v_0t + x_0 \quad (8)$$

Where x is displacement; v_0 is initial velocity and x_0 initial displacement.

The complete equations of MHD combine Maxwell's equations of electromagnetism and the Navier Stokes continuity and momentum equations for fluids. These shall not be use in this report as they are difficult to solve requiring computer solutions.

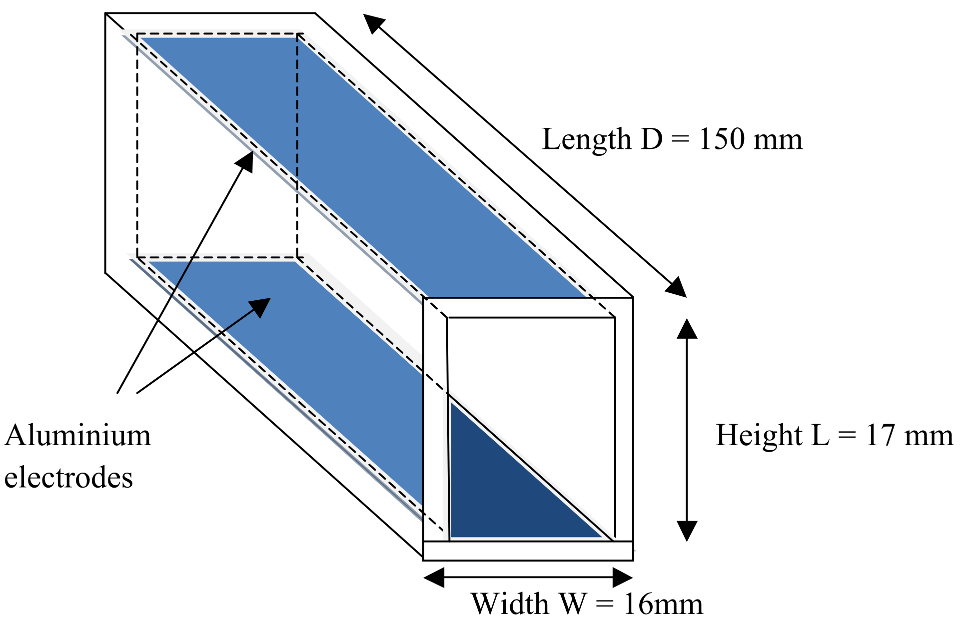
[3] Henderson Petrophysics, http://www.hendersonpetrophysics.com/SalinityConversion.html; date accessed: 14th June 2009

3. EXPERIMENTAL METHOD Tom Neiser

The method of this project was divided into two sections epitomised by the construction of the two MHD propelled vessels and the investigations into the MHD engine's properties.

Firstly, the two MHD prototypes consisted of a long single propulsion engine and a vessel with shorter twin engines inspired by the design[4] of the *Yamato 1*. Both models were constructed using a similar method, which can be illustrated using the example of the single engine craft. In order to accelerate salt water under the influence of a current and a magnetic field, we used a hollow, rectangular plastic channel with the following dimensions(see Fig. 3):

Figure 3: Water channel for MHD propulsion



The length D of the channel was dependent on the length of the plastic box intended for the hull of the craft. As illustrated above, Aluminium electrodes were attached to the top and bottom surface on the channel's inside in order to transport the current vertically within the channel. Despite its susceptibility to corrosion, this metal was chosen because it could be easily made into electrodes by rolling Aluminium foil around a thin wooden rod before pressing the resulting cylindrical shell into a light, thin, rigid sheet of metal. Several of these electrodes were produced as a replacement once pairs of anode and cathode have corroded. Potential alternatives to Aluminium included Copper sheets, which were even more vulnerable to corrosion, and Brass sheets, which were more resistant to corrosion but also impractically heavy. Gold leaf was also considered as a light, non-corroding and highly conducting substitute to Brass and Copper, but unfortunately it was so thin that it detached itself from the electrodes during operation.

The magnetic field was produced by 18 permanent neodymium cylindrical magnets with a magnetic field strength of **0.34 Tesla** on each face. These magnets were attached on two opposite sides of the channel to create an approximately uniform magnetic field

[4] See Appendix 1 for pictures of the two different MHD engines and the Yamato 1