ULTRASOUND DOPPLER VELOCIMETRY FOR LIQUID METAL BATTERIES

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Abstract : The Tayler instability (TI) due to current flow through a liquid GaInSn column is under consideration here. It is a consequence of electric current surpassing a critical value in the order of a few kA and manifests itself as a stack of vortices. Two ultrasound transducers encased in a copper electrode on top of the column were used to measure the vertical component of the liquid metal flow caused by the TI, which is of the order of several mm/s. UDV measurements were only possible after noise suppression mechanisms were added to the experimental setup. The results of the UDV retrievals will be discussed here.

1. Introduction

Due to the limited amount of fossil and fissile fuels on Earth, as well as the strain on the environment caused by their consumption or disposal, some societies are shifting their reliance onto renewable sources, such as solar and wind energy. This necessitates larger short-term energy storage capabilities, as the production of electrical energy cannot necessarily be adjusted to the demand. Liquid metal batteries are a proposed means of this type of large-scale energy storage. They consist of a solid container holding three phases of liquids, namely an anode metal, a cathode metal alloy and an electrolyte, such as a molten salt, separating the two. The advantages of liquid metal batteries are high current densities, reasonably low projected cost, a long cycle life, scalability, as well as their simple and self-assembling construction. Their disadvantages are low output voltages, high working temperatures required for the metals and the molten salts to remain liquid, as well as magnetohydrodynamic (MHD) instabilities.
As the electrolyte layer needs to be thin in order to have a low resistance, such instabilities could cause fluid motions that displace the electrolyte, bringing the two electrodes of the battery in contact, which would lead to battery failure.

The experiment discussed herein focuses on the pinch-type Tayler instability, which is the incompressible counterpart of the $m = 1$ kink instability of the z-pinch in compressible fluids, such as plasmas [1]. This instability is driven by an axial current flowing through a conducting fluid, which creates an azimuthal magnetic field resulting in an inward radial Lorentz force that “pinches” the fluid. A slight perturbation in a compressible system displaces the pinch locally, bunching the magnetic field together on one side and spreading it out on the other. The radial symmetry of the Lorentz force is broken as a result, causing the perturbation to grow exponentially.

In an incompressible fluid, such as a liquid metal, such small perturbations are counteracted by viscosity and resistivity as long as the current vertically flowing through the conductor remains below a critical value. Above it, the Lorentz forces become too strong for such perturbations to be damped. As a result, a stack of vortices whose axes are normal to the flow of electrical current develops. This is known as the Tayler instability (TI) [2, 3]. In a previous version of this experiment, the vertical component of the magnetic field was measured by fluxgate magnetometers. Above currents of 2.7 kA, B_z grew noticeably, indicating that to be the critical current at which the TI sets in [4]. In the newly modified version of the experiment, the vertical component of the liquid metal flow velocity is directly measured by an ultrasound Doppler velocimeter (UDV).

2. Experimental setup

A 75 cm long and 10 cm wide eutectic liquid gallium-indium-tin (GaInSn) alloy in a cylindrical polyoxymethylene container constitutes the core of this experiment. The top and bottom of the cylinder consist of copper electrodes that are connected to a switched-mode DC power supply unit (PSU) whose switching frequency is 10 kHz. The PSU, the 3 cm wide hollow copper rods delivering current to the experiment as well as the bottom electrode of the GaInSn cylinder are water cooled. The option to water-cool the top electrode exists as well, but was omitted with the aim of reducing thermal convections caused by Joule heating. Two ultrasound transducers (UST) encased within the top electrode are in direct contact with the liquid metal below (fig. 1).

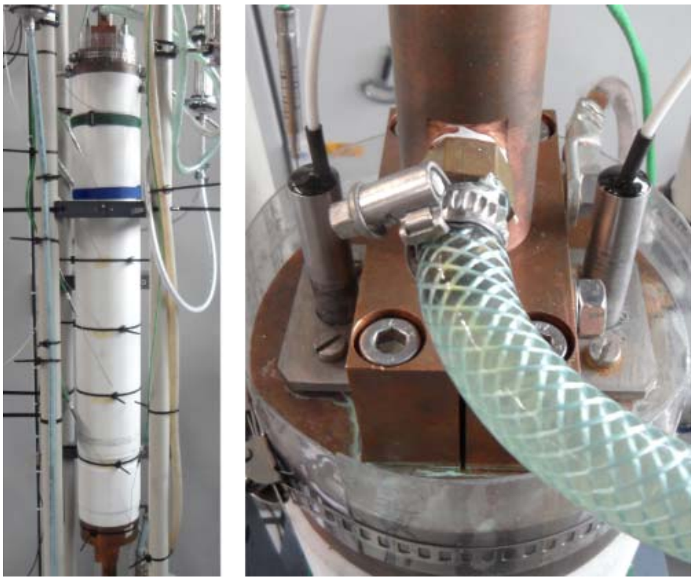

Figure 1: Left: GaInSn cylinder. Right: Top electrode with USTs.

The custom-made transducers, which can function at up to 60 °C, are 12 mm wide and their optimal operating frequency is 6 MHz. They are triggered by an UDV, which also records the echoes they measure and is controlled by a data acquisition computer.
Although the requirements for spatial and temporal resolution permit frequencies as low as 2 MHz, that regime is marred by a larger amount of noise from the PSU. This is due to the rectangular shape of the switching frequency's waveform, as a rectangular wave is equivalent to a superposition of harmonic waves with frequencies that are odd integer multiples of the switching frequency with exponentially decaying amplitudes.

Furthermore, a noise suppression assembly was constructed to ensure that meaningful UDV data can still be gathered from the sensors inside the electrode at currents in the order of several kA. It consists in part of six film capacitors manufactured by Electronicon. They have a self-inductance of 15 nH and are connected to the mains of the PSU in parallel to the TI cylinder, constituting a shunt which damps ripples in the current. Additionally, noise reduction inductors consisting of carbonyl iron and hydrogen-reduced iron powder cores were placed around the copper conductors powering the Tayler experiment. They impede the passage of alternating current through the induction of an opposing voltage. These cores have a high enough inductive reactance in the UDV frequency range to effectively suppress relevant AC ripples. Furthermore, they have a high A_L value, which is related to their inductance L and the number of turns N:

$$A_L = \frac{10^4 L}{(N)^2}. \qquad (1)$$

This is because the energy that can be stored in a magnetic field of an inductor is proportional to the inductance. Here, N = 1 because a straight conductor surrounded by a ring core is equivalent to a coil around a core with a single turn.

The magnetic flux density within the cores is proportional to the applied magnetic field strength, provided it remains below 1 T, above which iron powder materials have their saturation densities. In this linear regime, the inductance is constant. As the maximum possible current that can be generated by the PSU is 8 kA, the ring cores not exclusively used for common-mode chokes (CMCs) were therefore also selected for having an estimated DC magnetic flux density (as calculated with Ampère's circuital law) below 1 T at 8 kA. 14 individual ring cores of three types manufactured by Amidon were used, namely five T225-2, eight T50-2 and a single T650-3. The latter was estimated to reach saturation, if not used as a CMC. Two of the T650-2 cores and the T650-36 core are in fact used as such. The magnetic fields within the cores caused by the opposing DC currents flowing through the conductors they surround nearly cancel each other out. As a result, the flux density within the T650-36 core is well below saturation. The magnetic fields caused by common mode currents travelling through the conductors do not cancel each other out, which is why these currents can be choked by the inductor. The noise suppression assembly is shown in figure 2.

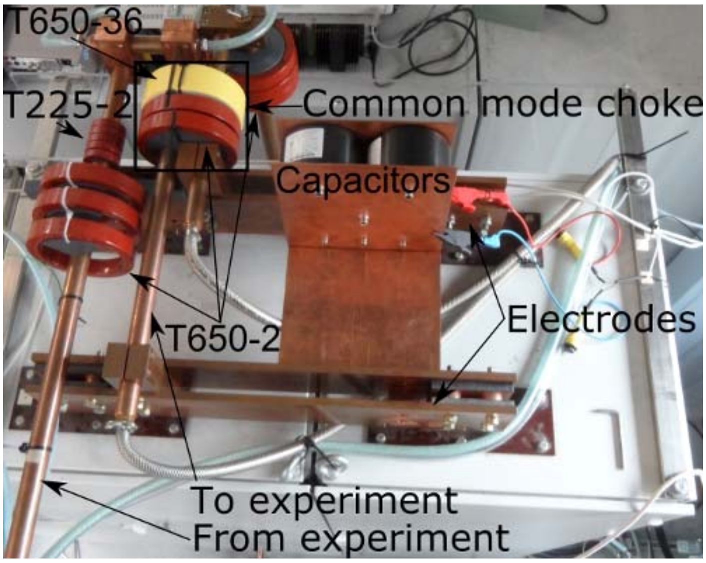

Figure 2: Noise suppression assembly on top of the PSU.

To reduce sheath currents running along the coaxial cables connecting the USTs to the UDV, the cables were wound around toroidal ferrite and split cores.

Moreover, the UDV is decoupled from the electric grid with an isolation transformer, which prevents ground loops from affecting the measurements.

2. Measurements and data analysis

The measurement results consist primarily of the relative intensities and wavelengths of echoes produced by backscattering on metal oxide particles within the fluid. Velocities are computed from the wavelength shifts in real time by the UDV.

The theoretical current threshold above which the TI appears is approximately 2.7 kA. and the wavelength of its vortices is expected to amount to 12.5 cm [3, 4]. Thermal convection caused by Joule heating, as well as electrode-driven electro-vortex flow already appear at much lower currents. The latter is however suspected to be of significance only in the vicinity of the electrodes, rather than across the entire column. The vertical velocity component measured by the two transducers as a function of time and column depth is shown in figures 3 and 4 respectively. Here, the current is switched on at t = 0 and brought to 4 kA in approximately 30 seconds. The vertical wavelength of the velocity fields is approximately twice as large as that of the theoretically predicted value for the TI, but is in agreement with results obtained from the fluxgate magnetometer measurements [4]. Although the cause of this is not well understood yet, aliasing artefacts have been ruled out. Numerical and experimental investigations into other phenomena that are at play here, i.e. the electrode-driven electro-vortex flow and thermal convection are ongoing [5].

To separate characteristic TI modes from other processes, a spectral analysis must be carried out. The Lomb-Scargle method of least squares spectral density estimation is shown in figures 5 and 6 for the velocimetry data from figs. 3 and 4 respectively. Whereas the spatial periodicity of the aforementioned flow patterns, as well as its harmonics are evident in the periodogram, the theoretically determined 8 m^{-1} inverse wavelength of the TI, is overshadowed by a wave twice as long as the predicted value, at approximately 4 m^{-1}. Further analysis will therefore be necessary, such as the isolation of individual wavelength bands and comparisons of their amplitudinal growth rates with one another as well as with the TI's growth rate as determined by fluxgate sensor measurements.

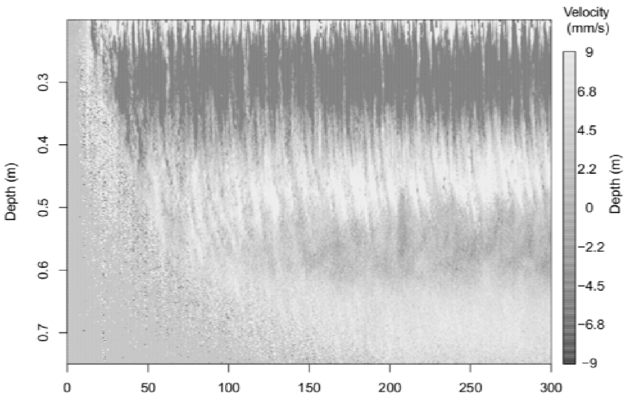

Figure 3: Vertical velocity in the GaInSn column. The current is 4 kA.

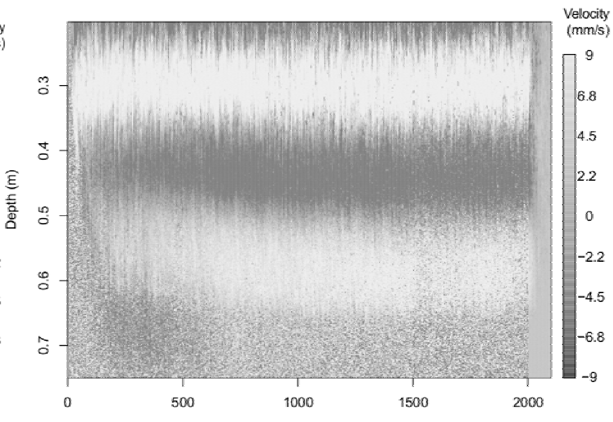

Figure 4: Vertical velocity in the GaInSn column measured by the other UST under the same conditions.

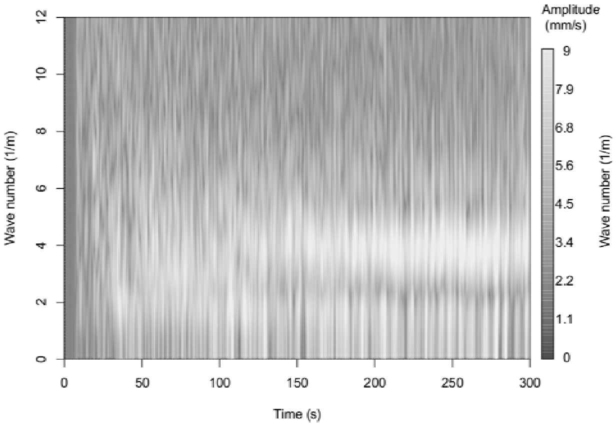

Figure 5: Lomb-Scargle periodogram of the velocity time series in fig. 3.

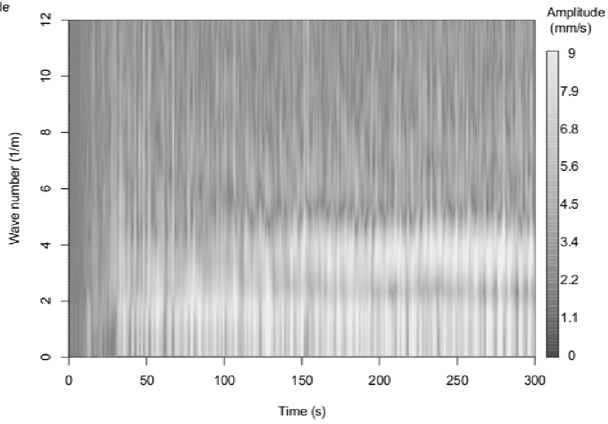

Figure 6: Lomb-Scargle periodogram of the velocity time series in fig. 4.

3. Conclusion and outlook

The basic feasibility of UDV within a high-current environment has been demonstrated and the preliminary results are in general agreement with those found with B_z-measurements [4]. However, the TI growth rate has yet to be determined and compared with the previous results. Two additional USTs will be added to measure the vertical flow 90° off the positions of the current sensors, which will allow a clearer monitoring of the flow structure. More in-depth analysis of the collected data will be performed as well, especially in the first few hundred seconds, during the growth time of the TI, before natural convection becomes more pronounced.

4. Acknowledgements

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5. References

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