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51. Internationales Wissenschaftliches Kolloquium

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M. Conrath[1], V. Kocourek[2] , Ch. Karcher[1]

Behavior of a liquid metal disk in the magnetic field of a circular current loop

[1] Department of Thermo- and Magnetofluiddynamics, TU Ilmenau
[2] Department of Electroheat, TU Ilmenau

Abstract
In an experiment a liquid metal drop was locked up between two horizontal glass plates and then submitted to the magnetic field of an inductor coil with a frequency in the range 5-50kHz. We report on the twodimensional shapes observed in the experiment which include strongly waved but static patterns. Furthermore, we present an analytical model to predict some aspects of the behavior of the liquid metal disk by means of linear stability theory.

Keywords: electromagnetic shaping, free surface, instability

Introduction

The free surfaces of liquid metals are a crucial point in industrial applications of magnetohydrodynamics. Lorentz forces can shape and support free liquid metal surfaces. But when submitted to a magnetic field, those surfaces often behave unexpected. They occasionally oscillate or fold themselves or pinch or leak through “magnetic holes”. It is therefore important to systematically examine this phenomenon and the coupling effects between magnetic fields and liquid metal free surfaces on which it relies.

Former studies have shown frozen and oscillating wavy deformations. Kocourek et al. [1] has performed experiments on a liquid Galinstan drop which he submitted to a high frequency magnetic field of about 20 kHz. He was able to squeeze his drop up to a critical current before the drop started to oscillate in a mix of modes. Interestingly, the observed oscillations correspond to the capillary eigenfrequencies [2] which is usually far below the magnetic field frequency. An exception was the “starfish experiment” of Sneyd et al. [3] where the frequency of the Lorentz forces acting on a liquid mercury drop matched its eigenfrequencies. The results were very regular single mode oscillations. In an experiment of Perrier et al. [4] a mercury drop was placed in a homogeneous high-frequency magnetic field of about 14 kHz. Here, the drop developed a wavy pattern which remained static. Further current increase lead to pinching and kidney-like shapes of the drop. Another high-frequency experiment was done by Mohring et al. [5] who used an annular gap filled with Galinstan. Lorentz forces on the horizontal free surface on the upside caused short-waved ripples in a first state which irregularly moved. Upon field intensification he observed a superimposed long-waved static deformation as a second state and finally one or several simultaneous pinches at the bottoms of the long wave valleys. The vertical gap of Mohrings annulus allowed only 2D motions and still brought a lot of unexpected results.

Our experiment also deals with a gap, but a horizontal one. Thus the influence of gravity can be neglected. The paper is organized as follows. First, we explain the experimental setup. Second, we present the experimental results. Afterwards, we adapt an analytical model which gives some insight into what happens in the experiment and compare it with the experimental results.

Experimental Setup

Figure 1 shows a sketch of the experimental arrangement. In our experiment we use a liquid metal drop at room temperature. The metal is Galinstan, an alloy of gallium, indium and thin. To prevent corrosion it is covered with a 6% hydrochloric acid. The drop is locked up between two plane horizontal glass plates which allow observation by a camera system from above. Moreover, the plates exclude gravitational effects and restrict the liquid metal motion to 2D. The maximum drop diameter is about 65mm, the heigth is fixed at 3mm. Hence, it can be regarded as a liquid metal disk. A water cooled inductor coil with ten windings surrounds the drop at equal height. The inductor is fed by an electric current which can be varied up to 300 Ampere and a frequency in the range 5-50kHz. Due to the induction losses the drop will rapidly heat up. To remove the joule heat the lower glass plate is water-cooled and in the core of the drop a copper cylinder of 10mm diameter acts as heat bridge to the cold water reservoir. To observe the drop, a high-speed camera is installed above while from below the aparature the drop is elucidated by halogen lights.

Due to the heat production, the measurements in magnetic field were restricted to about three seconds for worst case conditions, i.e. maximum drop diameter, maximum frequency and maximum current. Less extreme conditions often allowed thermal steadiness. In any case, inductor current and frequency were adjusted beforehand and then instantly jumped from zero to its final value. As a result, the drop experiences a switch-on-shock. Before every new “shot”, the current was switched off again.

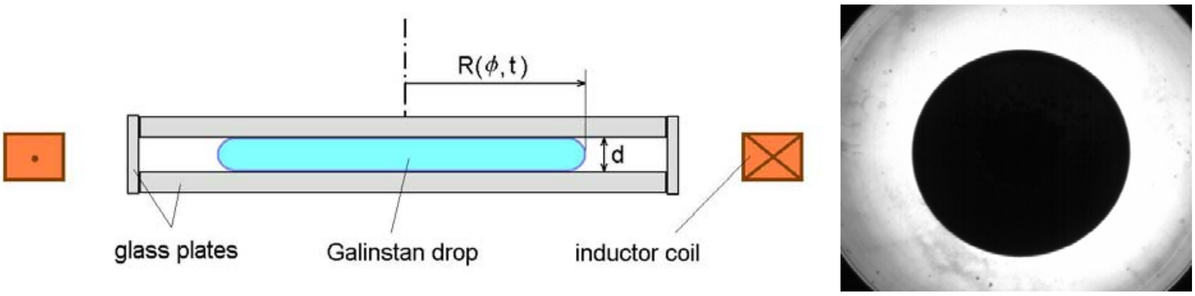

Figure 1: Container of the liquid metal drop surrounded by the inductor (left)
and the drop seen from above in absence of the magnetic field (right)

Experimental Results

Overview experiments. In a first approach, the parameters inductor current, frequency and drop volume were varied in a wide range. Those measurements were less accurate and mainly served to explore the phenomenons to expect. As one can see in the Figures 2 and 3, the observed deformations of the liquid metal disk cover several interesting shapes. All those shapes did not move once they were in place. No oscillations were observed. This is in contrast to the experiments of Kocourek et al [1] and in agreement with the experiments of Fautrelle [4]. The core cylinder obviously caused a center effect. Below a critical current the disk remains circular as is shown on the righthand side of Figurre 1. Above this current a single nose ejects in a random direction and retains this shape without further movement. It seems that this is a new equilibrium shape. As the current increases further the number of noses becomes two, three and four, see Figure 2. Also in these cases, the direction of the noses is randomly. Therefore, three noses can for example form a Latin E or even more strange shapes. Even a separation of a smaller drop was observed during these first experiments, see Figure 3.

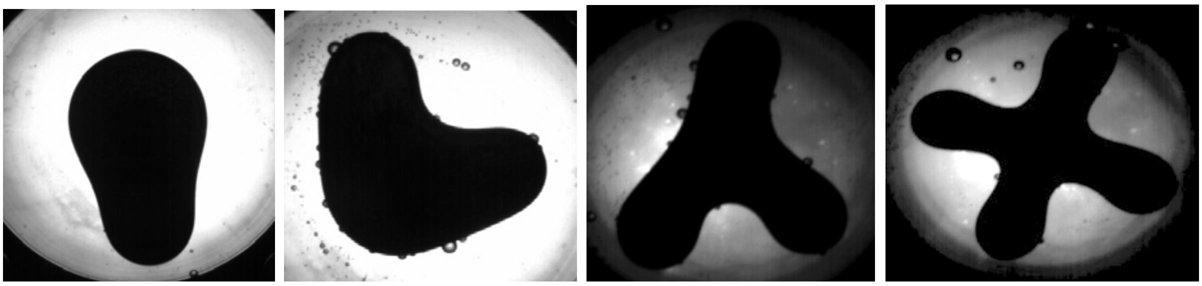

Figure 2: Static deformations of the liquid metal disk with one, two, three and four noses.

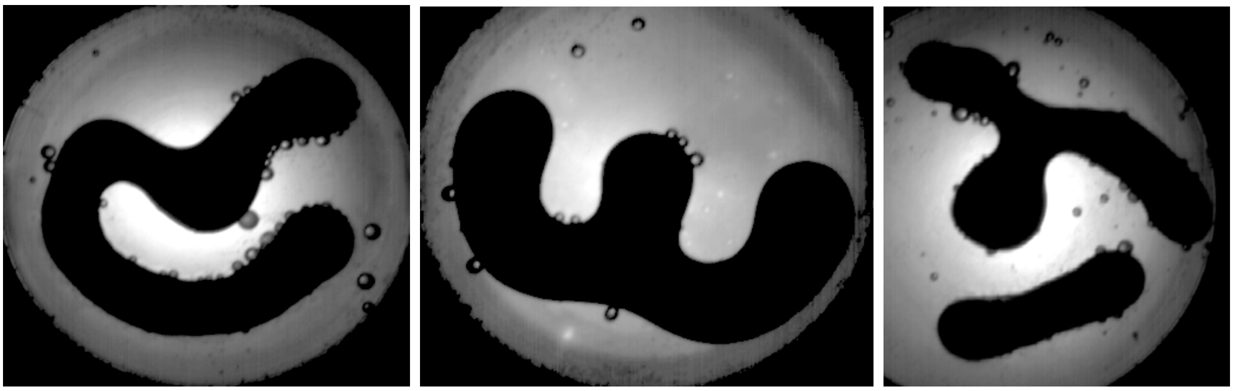

Figure 3: Irregular deformations of the disk

Getting into detail. After getting a first impression of the involved effects and disk deformations, at fixed disk volume, the inductor current and frequency were successively modified to track the parameter spaces in which the different deformations occurred. Thus, a stability diagram for all states of the liquid metal disk was obtained, see Figure 4. But in order to cover the whole parameter range, the stability curves in the diagram were not recorded at maximum precision.

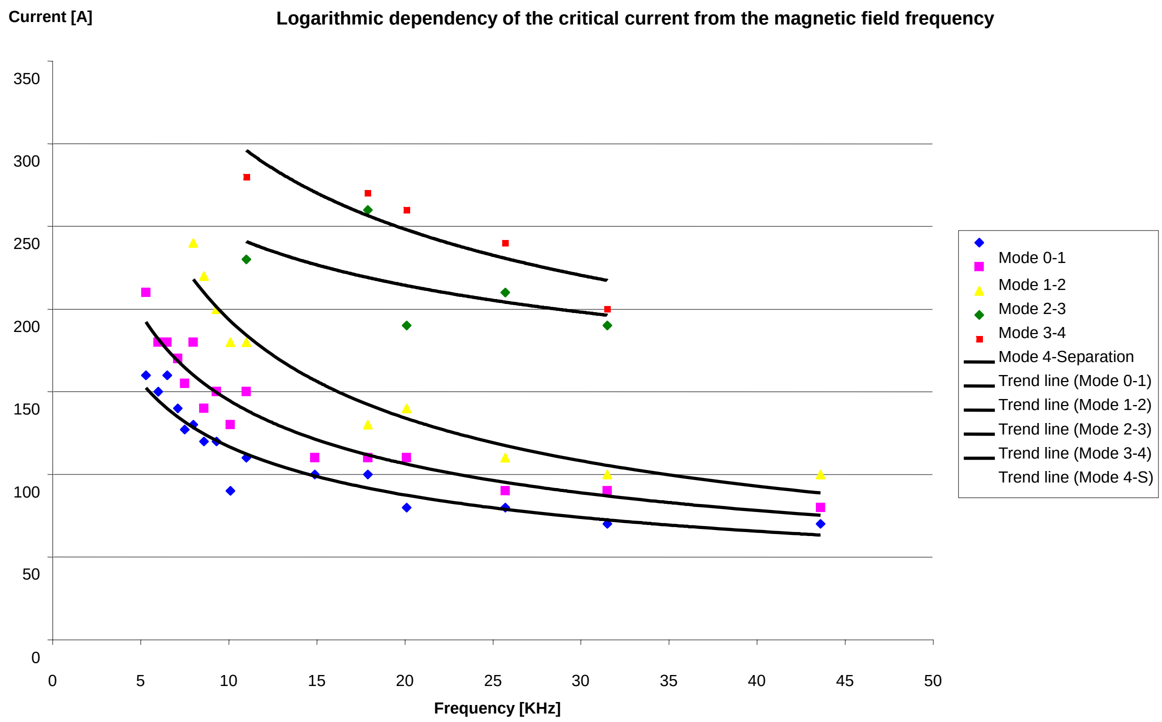

Figure 4: Stability diagram for the liquid metal disk

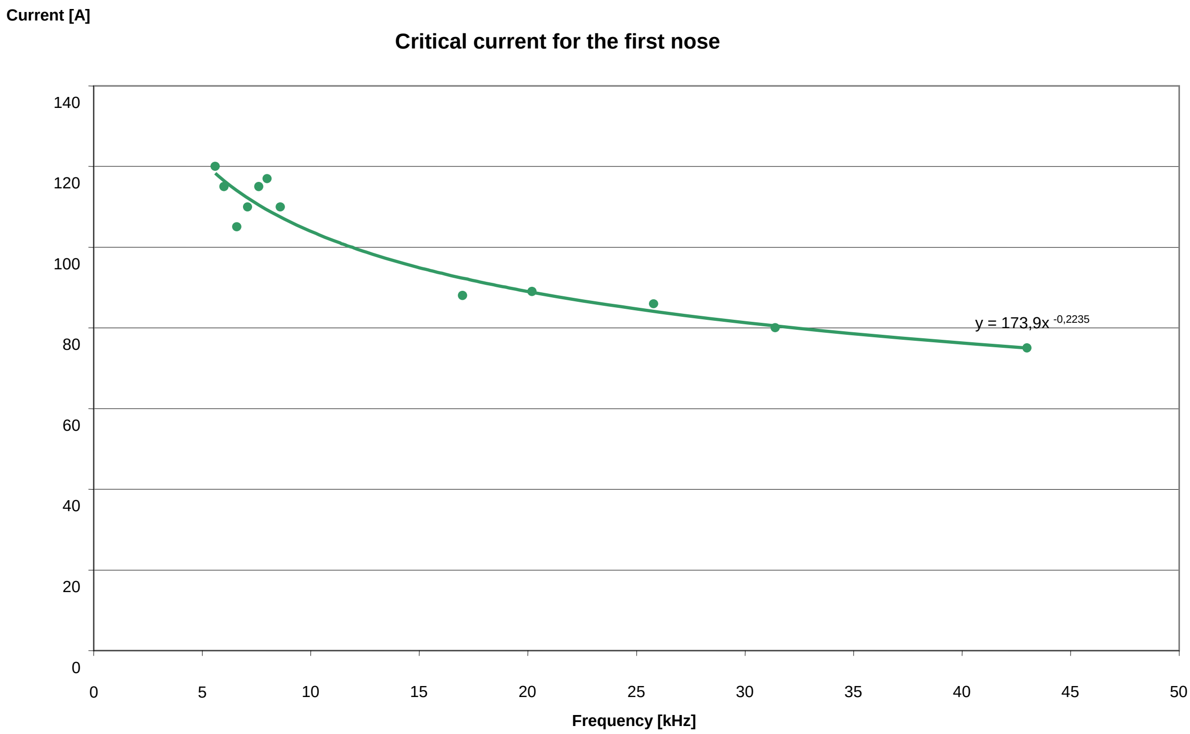

Figure 5: Most precise stability curve for the first nose

An exemplary stability curve at the precision limit is recorded for the occurrence of the first nose as shown in Figure 5. Since this first stability treshold is assumably the most accessible one for theoretial predictions we chose this one. There is a difference between this curve in Figure 4 and Figure 5 which results from the wider mesh of measurement points in Fig. 4. The scattering of the measurement points even at highest precision is due to some practical problems in the experiment. Those include non-constant wetting properties between glass plates and liquid metal, gas bubbles sticking to the liquid metal surface, partial oxidation as well as sensitivity from the initial disk shape and symmetry. However, the trendline in Figure 5 shows a dependency of the critical current from the magnetic field frequency that goes as

$$I_C \propto f\,\hat{}\,(-0{,}2235) \quad . \qquad (1)$$

Summary and Conclusion

We have presented experimental results on a liquid metal disk in the field of a circular current loop. In the experiment the main parameters were inductor current and frequency. The perimeter of the disk was subject to strong deformations that can be described as nose-shaped. After those shapes had formed, oscillations never occurred. We presented a stability diagram for the whole measurable parameter space and one most precisely measured stability curve for the onset of the first nose. The course of this one curve revealed an exponent of -0,2235, conf. Equation (1). Here we see a remarkable resemblance to a prediction of a model of Karcher and Mohring [6]. Their model is based on Hele-Shaw as well as skin-depth approximation and predicts a dependency

$$I_C \propto f\,\hat{}\,(-1/4) \quad . \qquad (2)$$

Unfortunately the cartesian geometry of their model does not match to our experiment. Therefore we aim to properly adapt this model.

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