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Noise reduction of ultrasonic Doppler velocimetry in liquid metal experiments with high magnetic fields

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ABSTRACT

The last decades have seen a number of liquid metal experiments on the interaction of magnetic fields with the flow of electrically conducting fluids. The opaqueness of liquid metals requires non-optical methods for inferring the velocity structure of the flow. Quite often, such experiments are carried out in the presence of high electrical currents to generate the necessary magnetic fields. Depending on the specific purpose, these currents can reach several kiloamperes. The utilized switching mode power supply can then influence seriously the measurement system by electromagnetic interference. A recent experiment on the azimuthal magnetorotational instability (AMRI) has shown that a hydrodynamically stable Taylor–Couette flow becomes unstable under the influence of a high azimuthal magnetic field. An electrical current along the axis of the experiment with up to 20 kA generates the necessary field to destabilize the flow. We present experimental results of this AMRI experiment carried out at the PROMISE facility with an enhanced power supply. For this setup, we discuss the elaborate measures that were needed to obtain a reasonable signal-to-noise ratio of the ultrasonic Doppler velocimetry (UDV) system. In dependence on various parameter variations, some typical features of the observed instability, such as the energy content, the wavelength, and the frequency are analyzed and compared with theoretical predictions.

1. Motivation

The classical Taylor–Couette (TC) experiment [1,2] consists of an inner and an outer cylinder with radii r_i and r_o, respectively. These concentric cylinders can rotate independently with angular frequencies $\Omega_i = 2\pi f_i$ and $\Omega_o = 2\pi f_o$. A non-viscous fluid in the gap between two concentric cylinders remains stable against small perturbations if the angular momentum increases outwards. This is described by Rayleigh's criterion [3]:

$$\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2\Omega(r)\right)^2 > 0. \tag{1}$$

In cylindrical coordinates $\{r, \phi, z\}$ the rotation profile of the TC-flow for an infinite cylinder has the following form:

$$\Omega(r) = a + \frac{b}{r^2}. \tag{2}$$

This simple equation (2) describes the ideal TC-flow. It takes the no-slip boundary condition into account and ignores the end effects of finite cylinders. The parameters a and b can be determined from the ratio of the radii $\hat{\eta} = r_i/r_o$ and the ratio of the angular frequencies $\hat{\mu} = \Omega_o/\Omega_i$, so $\Omega(r)$ can be written as

$$\Omega(r) = \Omega_i\left(\frac{\hat{\eta}^2 - \hat{\mu}}{\hat{\eta}^2 - 1} + \frac{r_i^2}{r^2}\frac{1-\hat{\mu}}{1-\hat{\eta}^2}\right). \tag{3}$$

Applying (1)–(3), Rayleigh's stability criterion can then be formulated in the simple form

$$\hat{\mu} > \hat{\eta}^2. \tag{4}$$

Once the condition (4) is fulfilled in an ideal TC-flow, angular momentum increases outwards so that the pressure and centrifugal forces are in an hydrodynamically stable equilibrium state. For the more general setting with an azimuthal magnetic field $B_\phi(r)$ Michael [4] and Chandrasekhar [5] had derived an extended stability criterion for axisymmetric perturbations:

$$\frac{1}{r^3}\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2\Omega(r)\right)^2 - \frac{r}{\mu_0\rho}\frac{\mathrm{d}}{\mathrm{d}r}\left(\left(\frac{B_\phi(r)}{r}\right)^2\right) > 0. \tag{5}$$

This stability criterion is valid for an ideally conducting and inviscid fluid in circular motion. The no-slip conditions at the walls and an infinite domain in axial direction is taken into account

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when applying the TC rotation law (2) to the criterion (5). In the following we consider a central current producing a magnetic field $B_\phi \propto 1/r$ in the fluid, for which the flow remains stable according to (5), if (4) is fulfilled. However, the statement (5) only holds for axisymmetric perturbations, while non-axisymmetric modes are not covered by Michael's criterion. Actually, the interaction of the current free azimuthal field $B_\phi \propto 1/r$ with a hydrodynamically stable rotation law (4) can make the flow unstable against non-axisymmetric perturbations [6,7].

This phenomenon is called azimuthal magnetorotational instability (AMRI), a special version of MRI which is thought to play a key role in destabilizing accretion disks around protostars and black-holes, whose Keplerian rotation profile $\Omega(r) \propto r^{-3/2}$ would otherwise be hydrodynamically stable [8,9]. This magnetic destabilization mechanism enables the outward angular momentum transport and the inward mass transport that is needed to explain the observed high accretion rates of central objects. While the standard version of MRI, with only a vertical field applied to the flow, is extremely hard to study in the liquid metal lab [10,11], AMRI is much easier to observe. The aim of our laboratory setup is to support the well-established theoretical models of AMRI with experimental evidence.

While the main results of our experiment have already been published [12] the focus of the present paper is on the details of the noise reduction of the UDV system which has turned out to be essential for obtaining clean velocity signals for the characterization of AMRI.

2. Experimental setup

The experimental setup is a classical TC device with two concentric copper cylinders that can rotate independently, see Fig. 1.

An electrically insulated copper rod carries a current up to $I_{\max} = 20$ kA through the center of the cylinders. The azimuthal magnetic field in the liquid metal between the cylinders can then be approximated by

$$B_\phi = \frac{\mu_0}{2\pi}\frac{I}{r} \tag{6}$$

which gives a maximal field strength at the inner cylinder radius r_i of $B_\phi(r_i) = 100$ mT, if I_{max} is applied. The central TC unit in Fig. 1 is surrounded by an additional solenoid (yellow, only on the left panel) which had been used in previous experiments [13,14] on the so-called helical MRI (HMRI) with an additional axial field component B_z. For the first AMRI experiments, with a pure B_ϕ – field, this axial field component is not necessary and has been switched off. The electrically conducting fluid in use is the eutectic alloy $Ga^{67}In^{20.5}Sn^{12.5}$ (GaInSn). This metal composition is completely molten at room temperature. Its physical properties at 25 °C are as follows [15]: density $\rho = 6.36 \times 10^3$ kg/m^3, kinematic viscosity $\nu = 3.40 \times 10^{-7}$ m^2/s, electrical conductivity $\sigma = 3.27 \times 10^6$ $(\Omega\,\text{m})^{-1}$. The magnetic Prandtl number is then $Pm = \mu_0\sigma\nu = 1.40 \times 10^{-6}$.

The installed vacuum-insulation, shown in Fig. 1a – (1), prevents heat exchange between the current-carrying copper rod (Fig. 1a – (3)) and the TC vessel itself. It has been installed after previous experiments without that thermal insulation had given evidence that the small periodic changes of the cooling water temperature influence the velocity. The top (Fig. 1a – (2)) and bottom motors (Fig. 1a – (10)) drive the cylinders. The relevant volume of GaInSn is limited by split rings at the top and the bottom (Fig. 1a – (6) and (9)), which reduce the global effect of Ekman-Pumping [13]. These rings are fixed to the corresponding cylinders.

A typical parameter set for the experiment is given in Table 1,

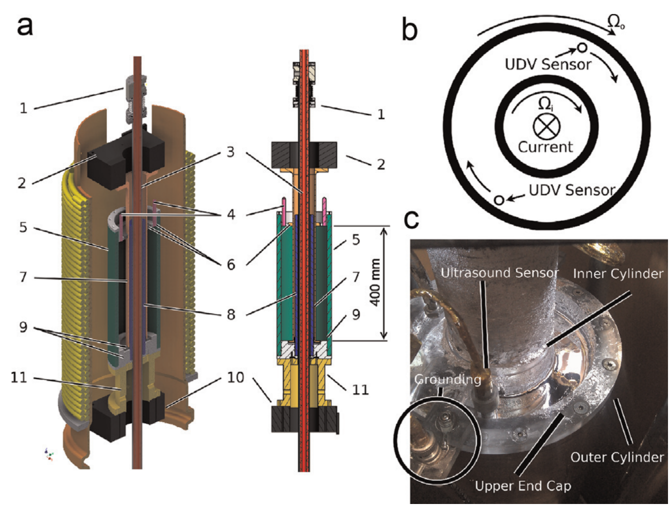

Fig. 1. (a) Sketch of the PROMISE facility with main dimensions $h = 0.4m$, $r_i = 40$ mm, $r_o = 80$ mm. (a) (1) Vacuum insulation; (2) upper motor; (3) current carrying copper rod; (4) UDV-sensors; (5) outer cylinder; (6) top acrylic glass split rings; (7) inner cylinder; (8) center cylinder; (9) bottom split rings; (10) bottom motor; and (11) spacer. (b) and (c) Schematic sensor mounting and a look inside the facility. The free surface of the liquid washes over the upper end cap. The UDV-sensors are fixed with the upper outer splitting (6), so that they are co-rotating with the outer cylinder. An additional grounding keeps the potential of the GaInSn and the UDV shielding at 0 V.

Table 1
Typical parameters for hydrodynamically stable operation of the PROMISE experiment.

Parameter	*Value*
Inner rotation	$f_i = 0.1$ Hz
Outer rotation	$f_o = 0.026$ Hz
Rotation ratio	$\hat{\mu} = \Omega_o/\Omega_i = 0.26$
Geometry	$\hat{\eta} = r_i/r_a = 0.5$

which corresponds to the most interesting case: a hydrodynamically stable TC flow satisfying condition (4). The destabilization of the flow by AMRI is then to be investigated.

Once the instability sets in, axial velocity components v_z are excited which can be measured along the height of the cylinder by UDV.

2.1. UDV instrumentation

As shown in Fig. 1a – (4), there are two focusing 4 MHz ultrasound transducers (TR0408LS-F10 by Signal Processing SA) installed on the top of the container pointing downwards parallel to the cylinder axis. Each of them is equipped with a 8 mm diameter piezo. Both sensors are fixed at the outer top ring, and are flush mounted at the interface to the GaInSn. The velocity component to be measured is v_z. Since the outer top ring is fixed to the outer cylinder, the sensors co-rotate with the same rotation rate Ω_o. Fig. 1b gives a simplified sketch of the sensor installation. In addition to that, Fig. 1c gives a look on the top of the free surface, which washes over the upper end cap. In this picture one UDV-sensor is visible whereas the other one is hidden by the inner cylinder (see Fig. 1a – (7)).

It is obvious that the measured time series of the co-rotating sensors contain information which depend on z, ϕ and t. Since the angular sensor position $\phi(t) = \Omega_o t$ is a linear function of time the velocity can only be represented by the measured 2D-time series $v_z = f(z, t)$. This point becomes important when analyzing the data

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