Ultrasonic flow measurements in a downscaled water mockup of a large scale precession driven dynamo experiment

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The DREsden Sodium facility for DYNamo and thermohydraulic studies (DRESDYN) is planned to become a platform both for large scale experiments related to geo- and astrophysics as well as for experiments on thermo-hydraulic and safety aspects of liquid metal applications in energy related technologies. The most ambitious project in the framework of DRESDYN is a homogeneous hydromagnetic dynamo driven solely by precession. The detailed knowledge of the flow structure in the precessing cylindrical vessel is of key importance for the prediction of the dynamo action. In this paper we present UDV measurements of the velocity field in a 1:6 downscaled water mock-up.

Keywords: Ultrasound Doppler Velocimetry, Precession, Dynamo

1 INTRODUCTION

Although most theories of the geodynamo rely basically on a flow driven by thermal and/or compositional buoyant force [1], precession has been discussed since long as a complementary energy source [2,3,4]. This idea seems to be supported by paleomagnetic measurements that have revealed a modulation of the geomagnetic field intensity by the 100 kyr Milankovic cycle of the Earth's orbit eccentricity and by the corresponding 41 kyr cycle of the Earth's axis obliquity [4]. Although the observed 100 kyr signal might be biased by climate-driven lithological variations, it reappears in the more robust reversal statistics of the geomagnetic field [5]. Most interesting in this respect is the correlation of geomagnetic field variations with climate changes, as hypothesized for the sequence of ice ages [6], demonstrated for variations during the last 5000 years [7], and perhaps also existing for the recently discovered 60 years cycle of the climate [8,9]. Yet, it is still a puzzling question how exactly the variation of orbital parameters affects both the climate and the geomagnetic field. In the standard scenario, pioneered by Doake [10], growing or melting ice sheets are thought to change the moment of the inertia of the Earth, thereby influencing the geodynamo by a modified rotation period. However, the recently revealed role of the solar and geomagnetic field as possible climate drivers due to their varying shielding effect on galactic cosmic ray particles [11] makes it worthwhile to consider also the reversed causal direction: What if the changing orbital parameters would *first* influence the geodynamo and *then and thereby* the climate by preventing cosmic rays from triggering cloud formation?

Aside from those questions of general geophysical interest, precession driven dynamo action is also interesting from the narrower magnetohydrodynamic point of view. For more than a decade now, the experimental study of dynamo action in the liquid metal laboratory has made great progress [12]. In a sequence with the previous experiments in Riga [13], Karlsruhe [14] and Cadarache [15], a precession driven dynamo experiment would represent a logical next step towards a real homogeneous dynamo. With just a fluid rotating around two axes, it would neither contain any propeller, as in Riga, nor any assembly of guiding tubes, as in Karlsruhe, nor any soft-iron material (which is crucial for the low critical magnetic Reynolds number and the close to axisymmetric eigenmode) as in the Cadarache experiment [16].

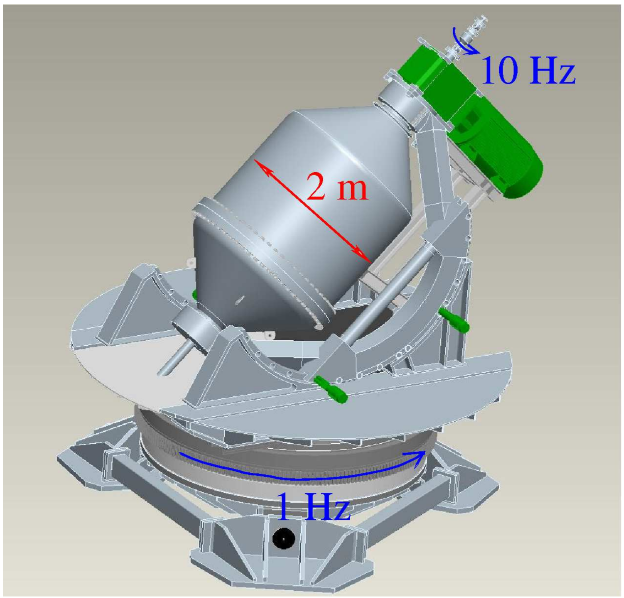

Figure 1: Preliminary draft of the planned large scale precession driven dynamo experiment. The angle between rotation and precession axes can be varied between 90° and 45°.

The precession driven dynamo experiment that is planned to be set-up in the framework of the DREsden Sodium facility for DYNamo and thermohydraulic studies (DRESDYN) will be a cylindrical vessel of approximately 2 m diameter and length, rotating with up to 10 Hz around its symmetry axis, and with up to 1 Hz around the precession axis whose angle to the symmetry axis can be varied between 90° and 45° (see Fig. 1 for a preliminary draft). An inner cylindrical copper shell is immersed into a slightly larger cylindrical stainless container with conical end parts. With the indicated rotation and precession rates, this precessing vessel would exert a huge gyroscopic moment of around $5\text{x}10^6$ Nm on the ground which requires the construction of a very solid basement.

2 THE WATER MOCKUP AND THE ULTRASONIC DOPPLER SYSTEM

Despite some numerical evidence for the possibility of dynamo action in a precessing cylinder [17], many aspects are still in need of further investigation. In order to figure out optimal design and process parameters for the later large-scale liquid sodium experiment, we have started a series of experiments at a smaller, 1:6 down-scaled, water precession experiment that is shown in Fig. 2.

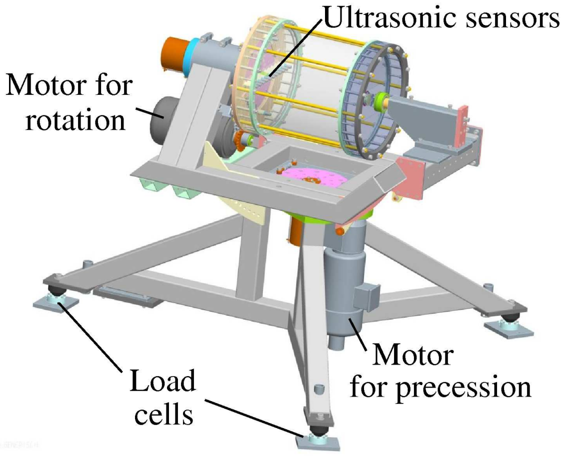

Figure 2: Drawing of the 1:6 downscaled water precession experiment for the determination of velocity fields, motor powers, and torques on the basement for various driving conditions.

This small water experiment is quite similar to the ATER experiment guided by J. Léorat [18], but allows for choosing different angles between the rotation and the precession axes. The installed measurement equipment enables the determination of the torques and motor powers needed to drive the rotation of the cylinder and the turntable, and of the gyroscopic torques acting on the basement.

Concerning the flow field determination, we have installed a number of ultrasonic sensors for the determination of the axial velocity component (Fig. 3 and 4). While the facility can run with rotation rates of 10 Hz and precession rates of 1 Hz, the well-known relation d $v_{max}=c^2/(8\ f)$ between signal depth d and maximal velocity v_{max}, for given sound velocity c and frequency f, restricts the UDV measurements to rather low rotation rates.

Figure 3: Photograph of the rotating cylinder and of the UDV sensors for the measurement of the axial velocity.

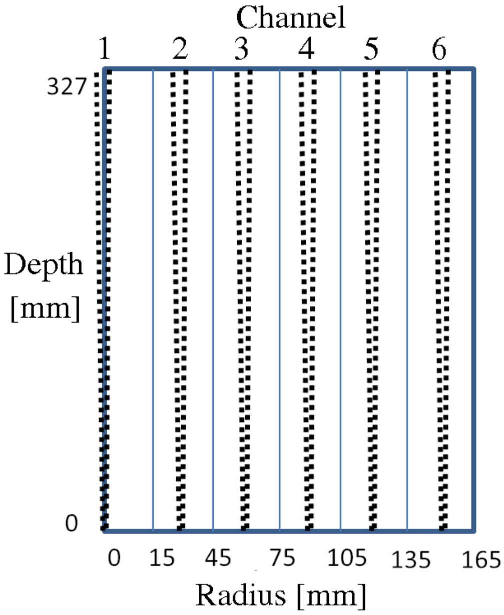

Figure 4: Sketch of the UDV sensor configuration and of the covering of the volume by the ultrasound beams.

3 FIRST RESULTS

For a rather low rotation rate of 0.2 Hz and a precession rate of 0.01 Hz, Fig. 5 shows the results of the axial velocity measured by UDV for an angle between the two axes of 90°. Hereby, the upper panel shows the raw data, and the lower panel shows the low-pass filtered data. The oscillatory sequence of positive and negative values is a typical indication for the first non-axisymmetric Kelvin mode with an azimuthal wave number m=1. The observed frequency of ~0.2 Hz indicates also that this mode is essentially fixed in the frame of the turntable, so that the UDV sensor rotating with the cylinder at 0.2 Hz experiences a changing v_z component of the precession mode along the azimuthal angle of the cylinder.

When scaled to the planned 10 Hz rotation rate, and to the 6 times larger sodium facility, the observed velocity of 40 mm/s would correspond to a value of around 12 m/s.

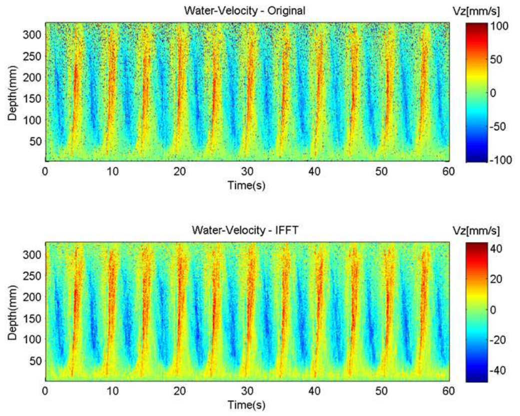

Figure 5: Axial velocity component at sensor 6 for a rotation rate of 0.2 Hz and a precession rate of 0.01 Hz. The m=1 Kelvin mode is fixed to the turntable frame.

It is a typical feature of precessing flows in cylinders that they show quiet different flow patterns in dependence on the precession ratio ε, i.e. the ratio of the precession frequency to the rotation frequency. With the details depending slightly on the aspect ratio of height to diameter of the cylinder, we first observe a laminar flow with only a few non-axisymmetric modes which changes suddenly, at a critical value ε^*, to a turbulent flow. It is at this point, that the torque necessary for driving the rotation, and therefore the motor power, jumps significantly.

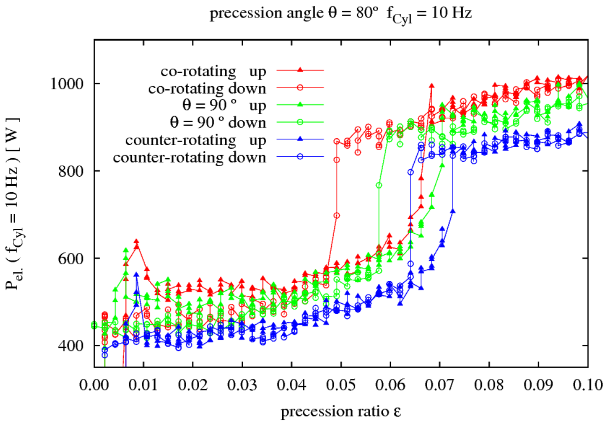

Figure 6: Motor power in dependence on the precession ratio for three different configurations between the axes.

This behaviour is illustrated in Fig. 6 which shows, now for a cylinder rotation rate of 10 Hz and for three different configurations, sudden jumps of the electrical motor power. The green lines are for the case of angle of 90°. Interestingly, we observe a slight hysteresis, i.e. for increasing precession ratio the upward jump occurs approximately at ε~0.07, while for decreasing precession ratio the downward jump occurs at ε~0.06.

The critical precession ratio changes slightly when we modify the angle between the axes to 80°. Then we have to distinguish between the co-rotating case (red lines) and the counter-rotating case (blue lines). It seems that the hysteresis becomes broader for the co-rotating case, and narrower for the counter-rotating case, although this needs further confirmation.

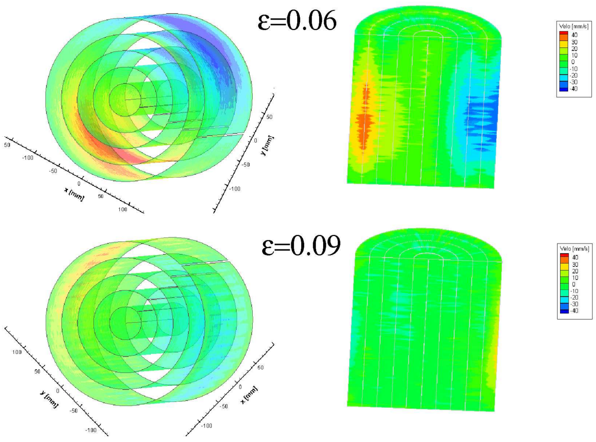

Figure 7: Axial velocity component measured by the 6 sensors for two different precession ratios in the laminar case (ε=0.06) and in the turbulent case (ε=0.09).

Figure 7 illustrates the physical mechanism that leads to the transition from a laminar to a turbulent flow. For a rotation rate of 0.2 Hz and an angle of 80° it shows the different flow structure for $\varepsilon=0.06<\varepsilon^*$, and for $\varepsilon=0.09>\varepsilon^*$. The left panel in either case shows the axial velocity as measured by the 6 UDV sensors in dependence on the azimuthal position and the depth, the right panel shows a cut in the meridional plane with the highest velocity contrast. Evidently, the clear m=1 mode that is dominating in the laminar case (ε=0.06), is significantly weakened in the turbulent case (ε=0.09).

6 SUMMARY AND OUTLOOK

In this paper, we have motivated the set-up of a large-scale liquid sodium dynamo experiment that is exclusively driven by precession. For the detailed characterization of the fluid flow in a precessing cylinder at different precession ratios, we have carried out a variety of experiments at an 1:6 downscaled water mock-up. The power measurements have confirmed the existence of a critical value of the precession ratio at which a transition between a laminar and a turbulent flow occurs. The UDV flow measurements were up to present restricted to rather small rotation rates, partly due to the well known maximum product of depth and velocity, but partly also by the disturbing effect of sound reflections at the opposite cylinder wall. By using sound absorbing material at this wall we hope to overcome this problem and to extend the flow measurement to up to 1 Hz rotation rate. A further goal for the future UDV measurements concerns the identification of the few large–scale helical eddies as they were identified by Particle Image Velcometry (PIV) at the ATER experiment in Meudon [19].

A major step will then be to assemble the acquired information about the stationary and fluctuating parts of the velocity field into an appropriate form that can then be utillized in dynamo codes to determine in detail the conditions and optimal parameters for magnetic field self-excitations in the precession driven dynamo.

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