TOWARDS A PRECESSION DRIVEN DYNAMO EXPERIMENT

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Abstract : The most ambitious project within the DREsden Sodium facility for DYNamo and thermohydraulic studies (DRESDYN) is the construction of a precession-driven dynamo experiment. After discussing the scientific background and some results of water pre-experiments and numerical predictions, we focus on the numerous structural and design problems of the machine. We also delineate the progress of the building construction, and the status of some other experiments that are planned in the framework of DRESDYN.

1. Introduction

Pioneered by the Riga [1] and Karlsruhe [2] liquid sodium experiments, the last fifteen years have seen significant progress in the experimental study of the dynamo effect and of related magnetic instabilities, such as the magnetorotational instability (MRI) [3,4] and the kink-type Tayler instability (TI) [5]. A milestone on this way was the observation of magnetic field reversals in the VKS experiment [6] which has spurred renewed interest in simple models to explain the corresponding geomagnetic phenomenon [7]. This is but one example for the fact that liquid metal experiments, though never representing perfect models of specific cosmic bodies, can indeed stimulate geophysical research.
One of the pressing questions of geo- and astrophysical magnetohydrodynamics concerns the energy source of different cosmic dynamos. While thermal and/or compositional buoyancy is considered the favourite candidate, precession has long been discussed as a complementary energy source of the geodynamo [8,9], in particular at an early evolutionary stage of the Earth, prior to the formation of the solid core. Some influence of orbital parameter variations can also be guessed from paleomagnetic measurements that show an impact of the 100 kyr Milankovic cycle of the Earth's orbit eccentricity on the reversal statistics of the geomagnetic field [10]. Recently, precession driving has also been discussed in connection with the generation of the lunar magnetic field [11], and with dynamos in asteroids [12].
Therefore, an experimental validation of precession driven dynamo action appears very attractive, yet the constructional effort and safety requirements for its realization are tremendous. In this paper, we delineate the present state of the preparations of such an experiment, along with giving an overview about the further liquid sodium experiments that are planned within the DRESDYN project at Helmholtz-Zentrum Dresden-Rossendorf.

2. To B or not to B

Compared to the flow structures underlying the Riga, Karlsruhe and VKS experiment, the dynamo action of precession driven flows is not well understood. Recent dynamo simulations in spheres [9], cubes [13], and cylinders [14] were typically carried out at Reynolds numbers Re of a few thousand, and with magnetic Prandtl numbers Pm not far from 1. Under these conditions, dynamo action in cubes and cylinders was obtained at magnetic Reynolds numbers $Rm:=\mu\sigma R^2\Omega_{rot}$ of around 700 (R is the radius, Ω is the cylinder rotation rate), which is indeed the value our experiment is aiming at. Yet, there are uncertainties about this value, which have much to do with the inaccessibility of realistic Reynolds numbers in numerical simulations. What has been achieved in this respect is some qualitative, though not quantitative, agreement of the dominant flow structures between experiment and numerics for precessing cylindrical flows. Basically, at low precession ratios $\eta:=\Omega_{prec}/\Omega_{rot}$ the flow is dominated by one or a few Kelvin modes. This more or less laminar regime breaks down suddenly at $\eta\sim0.1$ (details depend on the aspect ratio of the cylinder and the angle between rotation and precession axis). There are two global features by which this laminar-turbulent transition can be easily characterized. The first one is the energy dissipation, measurable by the motor power of the rotating cylinder. The second one is the maximum pressure difference between opposite points on the side wall of the cylinder. Figure 1a shows the maximum pressure p (numerically determined at Re=6680) and the maximum pressure difference Δp (numerically determined at Re=6680 and experimentally at Re=$1.6\mathrm{x}10^6$), with all values up-scaled to the dimensions of the large machine. The right end-point, at $\eta\sim0.07$, of the parabola-like experimental Δp curve marks the sudden transition between the laminar and turbulent regime. The corresponding numerical Δp curve is qualitatively similar, but shows significant quantitative deviations.

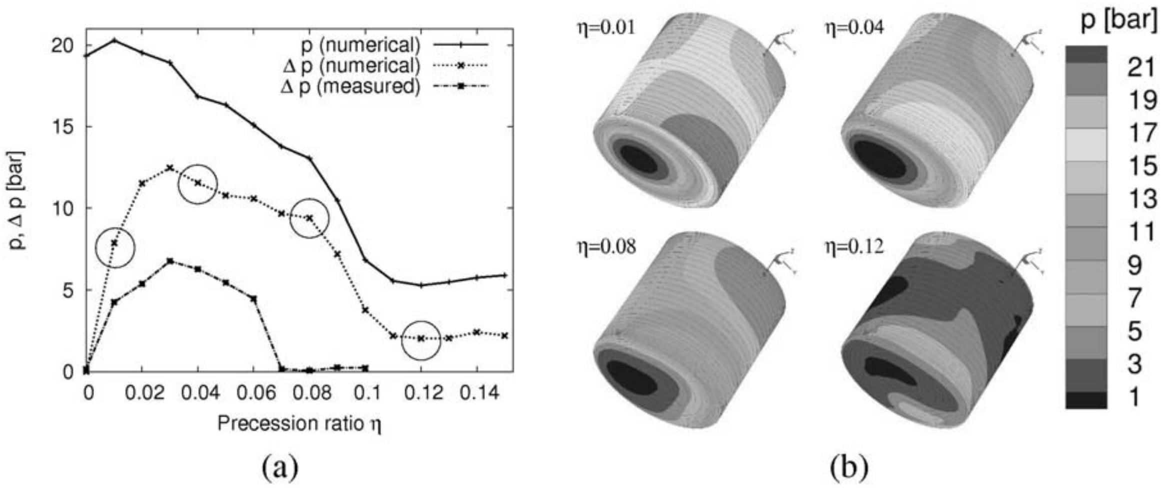

Figure 1: Pressure values for a precessing cylinder with 90° angle between rotation and precession axes, when scaled to the large device. (a) Maximum pressure p (numerically determined at Re=6680) and maximum pressure difference Δp (numerical and experimental). (b) Pressure distribution (numerical) for 4 specific precession ratios.

Up to present, dynamo action for precessing cylindrical flows has been confirmed numerically for the case Pm~1 and η=0.15 [14]. The critical Rm depends on the specific electrical boundary conditions, with a surprisingly low optimum value of 550 for the case of electrically conducting side layers and insulating lid layers (actually, this finding has led us to consider an inner copper layer attached to the outer stainless steel shell).

Encouraging as this low critical Rm may look, the question of self-excitation in a real precession experiment is far from being settled. Further simulations at lower Pm have led to an increase of the critical Rm, and for lower values of η dynamo action has not been shown yet.

Interestingly, an intermediate regime characterized by the occurrence of a few medium-sized cyclones has been observed at the ATER experiment in Paris-Meudon [15]. So far, these vortex-like structures could not be identified at our water experiment. Here, work is going on to utilize 3D particle image velocimetry to gather simultaneous information on the axial components of velocity and vorticity. The helicity distribution that can be computed from them could then serve as an input for dynamo simulations. In general, we expect more conclusive dynamo predictions, in particular for the cyclonic and the turbulent regime, from a close interplay of water test measurements and advanced numerical simulations.

3. Status of preparations

In comparison with previous dynamo experiments, the precession experiment has a higher degree of homogeneity since it contains neither impellers nor guiding blades. Its central module encases a sodium filled cylindrical volume of 2 m diameter and the same height (Figure 2). For this volume, we aim at reaching a rotation rate of 10 Hz (to obtain Rm~700), and a precession rate of 1 Hz (to cover the laminar, the cyclonic, and the turbulent flow regimes). With total gyroscopic torques of up to 8×10^6 Nm, we operate at the edge of technical feasibility, so that much optimization work is needed to make the machine safely operable.

The complicated simultaneous rotation around two axes poses several challenges: filling and emptying procedures, heating and cooling methods, and handling of thermal expansion. A decision was made in favor of a slightly enlarged vessel, comprising two conical end-pieces that serve, first, for a well-defined filling and emptying procedure at 43° vessel tilting, and, second, for hosting two bellows which compensate the thermal expansion of the liquid sodium.

Having defined this basic structure of the central vessel, much effort was, and is still, devoted to the optimization of the shell. A shell thickness of around 3 cm is needed anyway to withstand the centrifugal pressure of 20 bar in case of pure rotation. For increasing precession ratio, this total pressure decreases, but is complemented by a pressure pulsation due to the gyroscopic forces (Figure 1). In addition to those mechanical stresses, we have also to consider the thermal stresses that arise from the temperature difference over the shell when the dynamo is cooled by a strong flow of air.

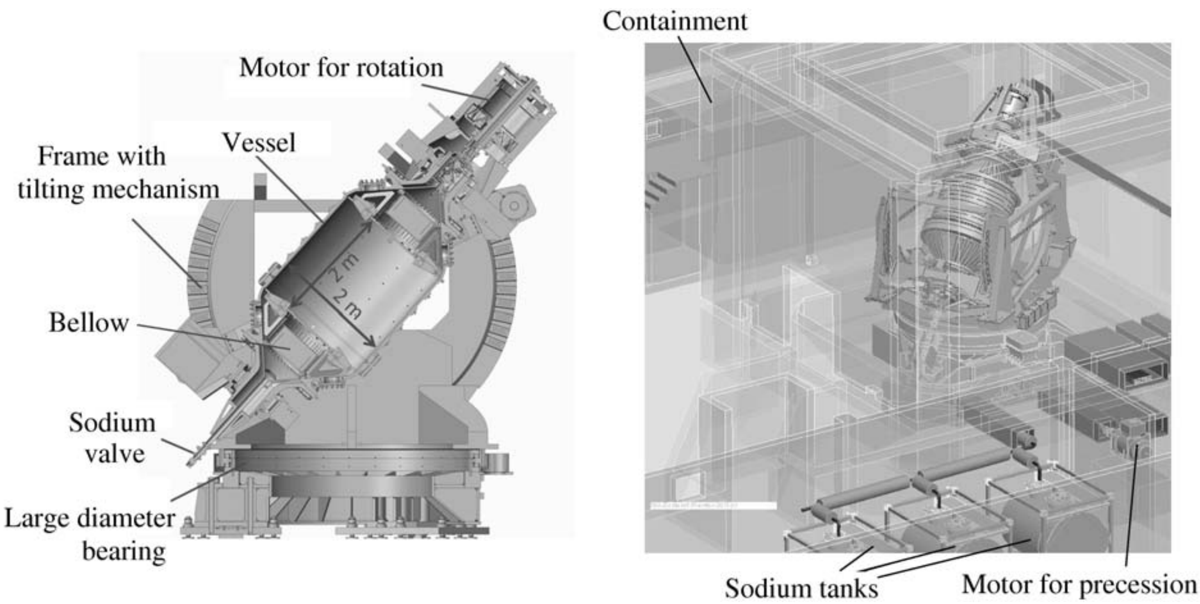

Figure 2: Present status of the design of the precession experiment

The next step is the design of the bearings and of a frame that allows to choose different angles between rotation and precession axis. Finding appropriate roller bearings for the vessel turned out to be extremely challenging, mainly because of the huge gyroscopic torque. It is the same gyroscopic torque that also requires a very stable basement (Figure 3a), standing on seven pillars, each reaching 22 m deep into the bedrock. The dynamo experiment itself is embedded in a containment (Figure 2, right), preventing the rest of the building from the consequences of possible sodium leaks. Since the double rotation cannot be stopped quickly in case of an accident, this containment is the only chance of preventing jets that would spill out of a potential leak from perfectly covering all surrounding areas with burning sodium. For such accidents, the containment can be flooded with argon, which is stored in liquid form.

(a) (b)

Figure 3: The DRESDYN building: (a) Construction of the three feet of the precession experiment. (b) Present status of the shell construction (as of April 7, 2014).

4. DRESDYN – What else is it good for?

Given the significant investment that is needed for the very precession experiment and the infrastructure to support it, we have combined this specific installation with creating a general platform for a variety of further liquid metal experiments. Another experiment with geo- and astrophysical relevance is devoted to the investigation of different combinations of the MRI and the current-driven TI. Basically, the set-up is a Taylor-Couette experiment with 2 m height and 20 cm gap width. With rotation rates of the inner cylinder of up to 20 Hz we plan to reach an Rm of around 40, while the axial magnetic field will lead to a Lundquist number of 8. Both values are about twice the respective critical values [16] for the standard version of MRI (with only an axial magnetic field applied). Still below those critical values we plan to investigate how the helical version of MRI approaches the limit of standard MRI. For this purpose, we will use a strong central current, as it was already done in the PROMISE experiment [3,4]. This insulated central current can be supplemented by another axial current, guided through the (rotating) liquid sodium, which will then allow to investigate arbitrary combinations of MRI and TI. A recent theoretical study [17] has shown that even a slight addition of current through the liquid would extend the range of application of the helical and azimuthal MRI to Keplerian flow profiles.

The TI will also play a central role in a third experiment in which different flow instabilities in liquid metal batteries (LMB) will be studied. LMB’s consist of three self-assembling liquid layers [18], an alkali or earth-alkali metal (Na, Mg), an electrolyte, and a metal or half-metal

(Bi,Sb). In order to be competitive, LMB's have to be constructed quite large, so that charging and discharging currents in the order of some kA are to be expected. Under those conditions, the occurrence of the TI and of interface instabilities must be carefully avoided [19,20].
The next installation is an In-Service-Inspection (ISI) experiment for various studies related to safety aspects of sodium fast reactors (SFR). Related to this, we also intend to investigate the impact of magnetic materials on the conditions of magnetic-field self-excitation in the helical core flows of SFR's.
The construction of the DRESDYN building is well advanced. Figure 3b illustrates the status of the shell construction as of April 2014. The interior construction is expected to be finalized in 2015. Thereafter, the installation of the various experiments can start. It goes without saying that both the precession and the MRI/TI experiment will first be tested with water, before we can dare to run them with liquid sodium.

Acknowledgment

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