Nonlinear large-scale flow transition in a precessing cylinder and its potential for hydromagnetic dynamo action

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In this paper, we present an experimental investigation that centers on exploring the fluid dynamics within a precessing cylinder. Our research is part of the DRESDYN project at Helmholtz-Zentrum Dresden-Rossendorf, specifically focusing on the precession dynamo experiment. The primary objective of our study is to examine how different rotation configurations influence the dominant flow modes inside the precessing cylinder, specifically considering the prograde and retrograde rotations. Our main focus lies on two significant flow modes: the directly forced mode (m1, k1) and the non-geostrophic axisymmetric mode (m0, k2). These modes hold substantial potential for precession-driven dynamo action. By analyzing the outcomes between the prograde and retrograde configurations, we gain valuable insights into the prevailing flow patterns within the precessing cylinder.

Keywords: Precession, DRESDYN, modes, dynamo

1. Introduction

Rotational flows are present in diverse environments, including the rotation of fuel payloads in spacecraft, atmospheric phenomena like tornadoes and hurricanes, bodies of water such as oceans and lakes, as well as in astrophysical and numerous technical applications. The presence of rotation in a system allows for the existence of inertial waves, which arise due to the restorative influence of the Coriolis force. One method of exciting inertial waves is through a phenomenon known as precession, which involves simultaneous rotation around two axes, as depicted in Figure 1. Previous studies have demonstrated that precession can efficiently drive flow in a rotating container without the need for a propeller or pump [1]. In this context, there has been some debate [2] regarding whether the Earth's magnetic field was generated primarily through precession-driven flow rather than, or in addition to, convection. Several numerical studies have shown that precession-driven flows can indeed generate magnetic fields [3, 4, 5].

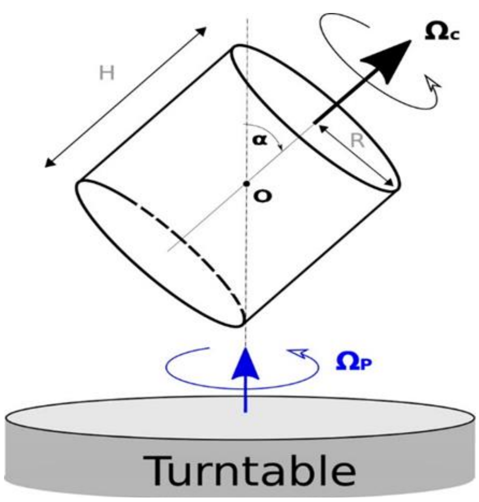


Fig. 1. Schematic representation of precessional motion. [6]

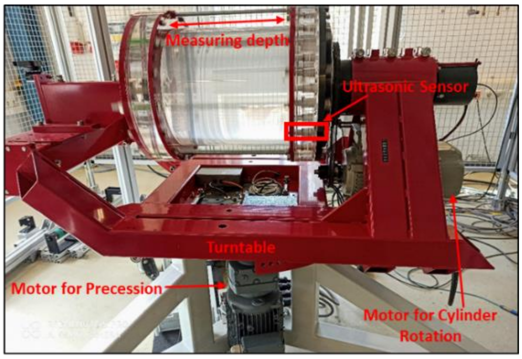
In 1971, Gans conducted a precession-driven liquid metal experiment, achieving a three-fold amplification of the magnetic field [7]. This experiment served as the basis for the development of a larger precession dynamo experiment as part of the DRESDYN project, currently being constructed at Helmholtz-Zentrum Dresden-Rossendorf (HZDR). The experiment involves a cylinder with a radius of R = 1 m and a height of H = 2 m. The cylinder rotates around its symmetry axis at frequencies up to f_c = 10 Hz and precesses around another axis at frequencies up to f_p = 1 Hz. Liquid sodium will be used as the working fluid in this experiment to induce dynamo action [8].

In order to gain a better understanding of the flow dynamics in the large-scale precession dynamo experiment planned within the DRESDYN project, a downscaled 1:6 water mock-up experiment with identical aspect ratio and rotation rates has been constructed. By conducting this downscaled experiment, valuable insights can be obtained regarding the flow behavior and the most influential factors in preparation for the forthcoming large-scale precession dynamo experiment. The primary objective of this water experiment is to identify the optimal operating parameters in the context of the future large-scale experiment. There are many parameters influencing the flow inside the precessing cylinder [9]. These include four key parameters: (i) geometric aspect ratio – height (H) to radius (R) ratio of the container; (ii) precession ratio (Po) - precession frequency (f_p) to rotation frequency (f_c) ratio; (iii) nutation angle - angle between precession and rotation axis and; (iv) Reynolds number ($Re = \Omega_c R^2/\nu$) - Coriolis force to viscosity ratio, where ν is the kinematic viscosity. This study expands the work of Kumar et al. [10] where the influence of nutation angle with different configuration of cylinder rotation is presented (i.e. prograde or retrograde). Prograde precession takes place when the projection of the turntable rotation on the cylinder rotation is positive, while retrograde precession occurs when the projection is negative. In this paper we present the preliminary experimental results at nutation angle, α = 80°.

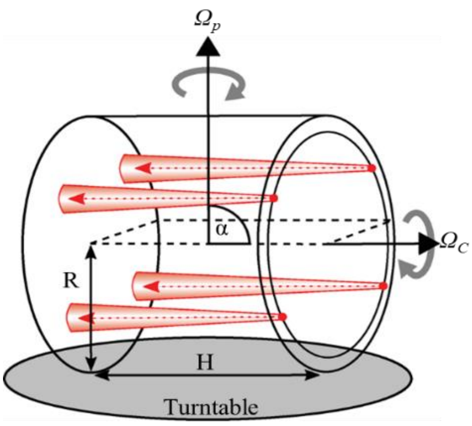
2. Downscaled water precession experiment

2.1 Setup

Figure 2(a) presents the downscaled water precession experiment, scaled at a ratio of 1:6. The experimental setup consists of a cylindrical vessel with a radius of 163 mm (R) and a height of 326 mm (H). The vessel is filled with water and undergoes rotation around its symmetry axis utilizing an asynchronous 3 kW motor connected via a transmission chain. This entire structure is mounted on a turntable, which is driven by a second asynchronous 2.2 kW motor. The maximum rotation rate achievable for the cylinder is f_{cmax} = 10 Hz, while the maximum rotation rate for the turntable is f_{pmax} = 1 Hz. The rotation rates of both the cylinder and the turntable are continuously monitored using two tachometers and recorded by a data acquisition system. For the purpose of analyzing the flow patterns within the cylinder, Ultrasonic Doppler Velocimetry (UDV) sensors are positioned at one end cap, as depicted in Figure 2(b). These sensors are oriented parallel to the central axis and capture the instantaneous axial velocity distribution between the two end caps of the cylinder.



(a)



(b)

Figure 2: (a) Setup of 1:6 downscaled water precession experiment. (b) Sketch of the water experiment with four ultrasound probes mounted at one end cap of the cylinder.[8]

2.2 Flow measurement procedure

In order to determine the flow characteristics inside the cylinder, ultrasonic transducers are positioned at one end cap of the cylinder, as shown in Figure 2(a). These transducers are connected to an ultrasound Doppler velocimeter (UDV), which measures the velocity with a temporal resolution of 0.47 Hz.

Before commencing the experimental run, the water undergoes vigorous mixing at a high rotation rate to ensure uniform distribution of tracer particles throughout the cylindrical vessel. Once achieved, the vessel is set into rotation at a frequency of f_c until the fluid co-rotates with the vessel. This co-rotation is indicated by a negligible velocity reading on the UDV channel. Subsequently, the turntable is set in motion at a frequency of f_p after a certain waiting period, and data recording is initiated. After approx. every 45 rotations of the cylinder, the rotational rate of the turntable is increased. The Poincaré number is varied within the range of 0.028 (i.e., f_p = 0.0021 Hz) and 0.19 (f_p = 0.011 Hz). Furthermore, the precession angle, which is the angle between Ω_p and Ω_c, is maintained at a constant value of 80°. Note that the considered rotation rate of cylinder (i.e. f_c = 0.06 Hz) corresponds to Re = 10^4.

3. Results

In this section, we present the outcomes of the water precession experiment and the flow pattern derived from the measurement of Ultrasonic Doppler Velocimetry (UDV). The contour plot in Fig. 3 displays the obtained flow structures. The plot demonstrates the temporal and spatial evolution of the axial velocity profile u_z, as it varies with time t and depth z (indicating the distance along the axis of the transducer). The prevailing oscillatory pattern of the velocity profile, characterized by the rotational frequency of the cylinder, represents the standing inertial mode with (m1, k1), as recorded by the UDV sensor attached to the rotating vessel wall.

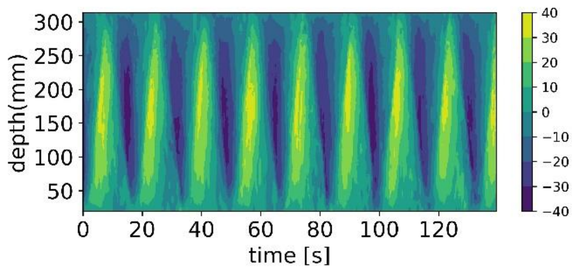


Figure 3: Axial velocity component at sensor 9 (located 150 mm from the centre of cylinder) for a rotation rate of 0.06 Hz and Po = 0.093. The m=1 Kelvin mode is fixed to the turntable frame.

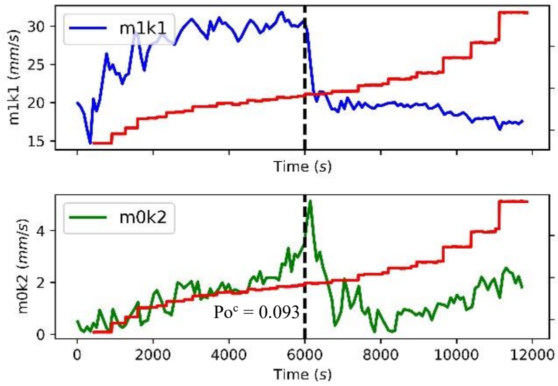
In a quantitative analysis, the mode amplitudes are determined through the decomposition of the axial velocity field u_z into (m, k) modes. To achieve this, a discrete sine transformation (DST) is initially applied to the axial velocity at each time step during the experiments. A more detailed explanation of the calculation of inertial mode amplitudes can be found in Ref. 10. In our analysis, we focused on specific modes, namely (m1, k1) and (m0, k2), which exhibit significant amplitudes and hold particular relevance for dynamo action.

Figure 4 depicts the temporal changes in the amplitudes of the dominant modes as the Poincare number (Po) increases for both prograde and retrograde cases. The analysis was conducted at a precession angle of 80° and a Reynolds number (Re) of 10^4. For prograde case, we observe an increase in the amplitude of (m1, k1) mode up to a Po of approximately 0.093. However, beyond this threshold value, there is an abrupt shift (within some revolutions) in the flow state caused by the breakdown of the (m1, k1) mode. This breakdown marks the transition from a laminar to a turbulent state. Concurrently, within a narrow range of Po, an emergence of the axially symmetric mode (m0, k2) has been seen (cf. Fig. 4 (a)). This mode corresponds to a double-roll structure, which has previously been identified as highly relevant for dynamo action [11]. On the other hand, the data obtained for the retrograde case do not exhibit a distinct breakdown of the directly forced mode, i.e. (m1, k1), the amplitude of this mode gradually decreases. However, a smoother behaviour of the amplitude of the axially symmetric mode (m0, k2) within the range of considered Po has been noticed (see Fig. 4 (b)). The potential of retrograde precession to generate a more robust large-scale flow amplitude without causing a sharp breakdown of the directly forced mode (m1, k1) is intriguing for dynamo applications. This characteristic could be significant for dynamo applications since it permits the injection of more energy into the flow without disrupting the base flow. In comparison to the prograde case, the critical values of Poincare number (Po^c) are shifted towards larger values for the retrograde case. Power measurements of the cylinder manifest the same tendence [12] and will be analysed for present measurements in the near future.

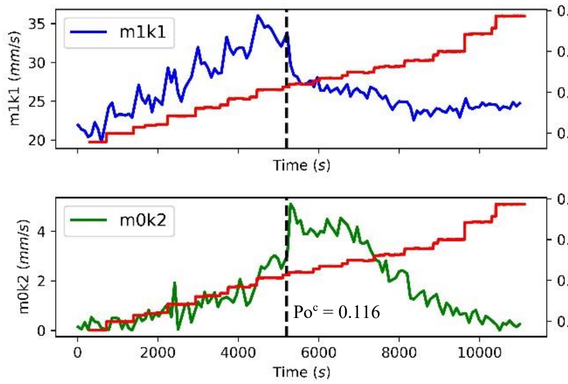
5. Summary

This study focuses on examining the impact of 80° nutation angle on a precession-driven flow in a cylindrical geometry, considering both prograde and retrograde rotation directions. Experimental measurements using the UDV sensor mounted on the cylinder's end cap were conducted, and these measurements were then analyzed by decomposing the axial velocity fields into various (m, k) modes. Specifically, we considered the (m1, k1) and (m0, k2) modes due to their significant amplitudes and relevance to dynamo studies.

For the prograde cases, a transition from a laminar to a turbulent regime was observed. In contrast, the retrograde motion did not show a clear breakdown of the directly forced mode (m1, k1), but instead exhibited a smoother behaviour of the non-geostrophic axisymmetric mode (m0, k2). Notably, the retrograde cases are of particular interest for dynamo studies as the absence of a breakdown in the directly forced mode allows for increased energy injection into the flow without disrupting the base flow. In future investigations, we plan to extend this experimental work to higher Reynolds numbers.



(a) Prograde



(b) Retrograde

Figure 4: Amplitudes of the directly forced mode (m1,k1) and the axisymmetric mode (m0,k2) for the precession angle of 80˚ at Re = 10^4. The red lines show the Poincaré number.

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