PECULARITIES OF MHD FLOW SPIN-DOWN IN AN ANNULAR GAP

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Abstract: The behavior of azimuthal and radial velocity components of free decaying MHD flow in an annular gap with rectangular cross-section in an axial magnetic field has been studied. Experimental values of the velocity components of the flow were measured using a conductive anemometric system. Analysis of mean and oscillating characteristics has been carried out using a continuous wavelet transformation based on Morlet function. Signal scalograms were plotted and analyzed.

1. Introduction

Rotating magnetohydrodynamic (MHD) flows have been studied by various research teams for a number of years. Among them are flows in homopolar type facilities shown in Figure 1. These facilities have coaxial cylindrical electroconducting lateral walls and insulating end-faces with liquid metal in between [1-3].

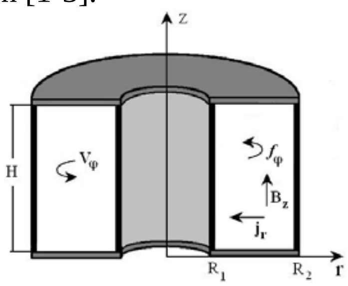

Figure1: Schematic view of experimental setup.

The device is located in a uniform axial magnetic field, and a rotating flow is generated by electromagnetic forces arising within the liquid metal volume at the passage of electric current between the cylindrical inner and outer walls-electrodes. The density of azimuthal electromagnetic body force $f_\varphi = j_r B_z$ is inversely proportional to the radius ($j_r = j_0 R_1 / r$, which leads to $f_\varphi = j_0 B_z R_1 / r$), and the flow becomes different from rotating flows generated by RMF [4,5], a rotating cylindrical container [6], cylindrical lateral walls (Couette-Taylor flow) or rotating end-faces [7].

The interest in said problem is connected with the study of the existence time for structures of various scales in a rotating flow after the electromagnetic body forcing is switched off and of the peculiarities of their decay. Such estimates are extremely useful for the analysis of characteristics of rotating liquid metal flows under the action of amplitude- and frequency-modulated rotating fields [8]. Their usage makes it possible to optimize the regime of electromagnetic stirring of melts and to improve the quality of the obtained products [5].

In the examined spin-down flow regime in an axial magnetic field, it is possible to measure the azimuthal and radial velocity components by the conductive method [8]. As known, his method is delayless (without any response time), does not require calibration and allows analyzing temporal evolution of mean and pulsational velocity values, their spectral properties and correlation characteristics.

2. Experimental setup

The experiments were performed on a facility described in [9]. A ternary eutectic Indium-Gallium-Tin alloy was used as the electroconducting liquid. The properties of the alloy are: $\rho = 6360\,kg/m^3$, $\sigma = 3.4\,S/m$, $\nu = 3.4\cdot10^{-7} m^2/s$ (density, electric conductivity and viscosity, respectively). Copper cylindrical vessel with the external radius R_2 = 35.25 mm and an internal copper electrode with the radius R_1 = 4 mm positioned along the vessel central axis form an annular cavity filled with the liquid metal. The end-faces of the vessel are electrically insulated and the volume is filled up to the level $H = 2(R_2 - R_1) = 2R_0$. The vessel is placed inside a solenoidal water-cooled electromagnet inducing an axial magnetic field. The interaction of the radial electric current j_r with the axial magnetic field B_z generates azimuthal electromagnetic Lorentz force f_φ which drives the liquid metal into rotation at the mean azimuthal velocity V_φ (Fig. 1). The electric current between coaxial electrodes, as well as the current in the electromagnet coil, are controlled by two autonomous Genesys programmable DC power supplies. The magnetic field is measured by FW Bell teslameter, model 6010; the magnetic field inhomogeneity in the volume occupied by the liquid metal does not exceed 8%. Three-electrode potential probe with the 1.5 mm distance between electrodes was used for measuring the azimuthal and radial components. The probe was connected to the Stanford Research Systems low-noise preamplifiers, model SR560, and programmable low-noise filters, model SR640. Analog signals were transformed into digital ones by the National Instruments DAQ card-6052E, and the data was processed and recorded with a 16-bit resolution at the rate of 1000 scans/s using the National Instruments LabVIEW-2012 software.

3. Main results

In the case under study, external boundaries of the flow region are motionless, and the flow structure is established under the action of azimuthal electromagnetic force. Here the radial distribution of the azimuthal velocity component $V_\varphi(r)$ points to the flow instability according to Rayleigh and to the possibility of the existence of the Taylor vortices in the stationary mode.

In this flow mode, the azimuthal component of the mean velocity exceeds the radial one. At that, turbulence level grows along the gap radius and is maximal near the external wall [9], [10]. The initial phase of spin-down mode is accompanied, side by side with a decrease in the velocity components, by a temporal change in the ratio between their amplitudes [9], which can be explained as follows. In a steady mode, the azimuthal velocity component is maximal, since the azimuthal electromagnetic force imposed a rotating motion on the liquid metal. An equilibrium between energy pumping (the work of azimuthal force) and losses for viscous and turbulent friction and Joule dissipation is established (lateral and end-face walls drag the flow whose kinetic energy is dissipated in boundary layers). After switching off the radial electric current (i.e. switching off the electromagnetic force generating the flow), the flow is rearranged – viscous boundary layers diffuse into the flow core and smear it after some time. At that, the ratio between the velocity components values of the decaying flow is also changed.

Such processes are observed in various rotating flows. For example, at the drag of a rotating cylinder with electroconducting liquid [6], the flow passes several stages including the generation of "solitary waves" propagating from the cylinder end-faces with a subsequent formation of a sequence of "internal waves", and then the stage of generation and development of the Taylor vortices near the lateral wall at the Reynolds number values exceeding the critical one. The determining role of azimuthal electromagnetic force in rotating flows is also observed at a combined impact of azimuthal and axial electromagnetic forces (RMF and TMF) [4, 11]. The flow structure is specified by the azimuthal component and is independent of the ratio between the electromagnetic force components. However, the problems of the existence of some regularity in the energy redistribution between the velocity components of a flow decaying in the magnetic field, their correlation, characteristic times of the process, etc., remain unsolved.

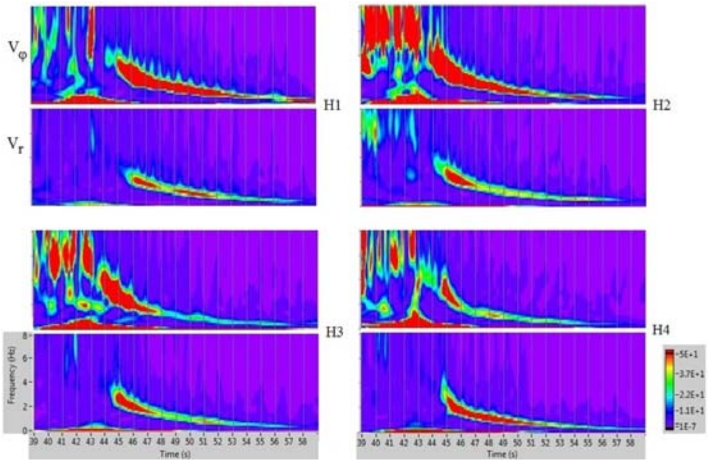

Figure 2: Scalograms of azimuthal and radial velocity components decay on different levels from a bottom (H_i = 38.5, 30, 20, 10 mm); R = 26 mm; B_z = 125 mT.

Switching-off the azimuthal electromagnetic force controlling the flow structure and the removal of energy "feeding" of the flow should lead to a rearrangement of its structure, including the smearing of the region with the Taylor vortices (if they are present) towards the internal wall of the annular channel. Besides, such rearrangement can be accompanied by the liquid circulation in the meridional plane [4] and, hence, by a respective additional decrease in the kinetic energy of both (radial and azimuthal) velocity components. Change in the ratio between the amplitudes of mean velocity components at the initial phase of spin-down regime is accompanied by a respective change in turbulence level. However, we should note that velocity components of transient spin-down flow were approximated by analytical functions, and velocity fluctuations were considered as deviations from them. At the same time, non stationary regime seems complex, and therefore, we consider the decay of low-frequency oscillations. Non-stationary nature of the spin-down regime is complicated to do the quantitative analysis using, e.g., fast Fourier transformation. We have examined several methods of data processing and used the wavelet analysis as the principal one [12, 13]. In our analysis, we have used signals of a conductive velocimeter normalized to the magnetic field value.

The presented scalograms of various spin-down modes are based on continuous wavelet transformation (CWT) using complex-valued Morlet wavelet. The respective program is a part of the Advanced Signal Processing Toolkit of LabVIEW 2012. They allow obtaining information on the frequencies pumped over from the azimuthal to the radial velocity component with a time shift. The wavelet analysis proves to be very efficient in the experimental data analysis of nonstationary turbulent flows [14]. The process is well illustrated in Figure 2, which shows the appearance of oscillations with the frequencies from 2 Hz to 4 Hz, which were previously absent, after switching-off the electromagnetic force in the radial velocity component. The results of flow characteristics analysis (continuous wavelet transformation based on Morlet function) are shown in Figures 3-5.

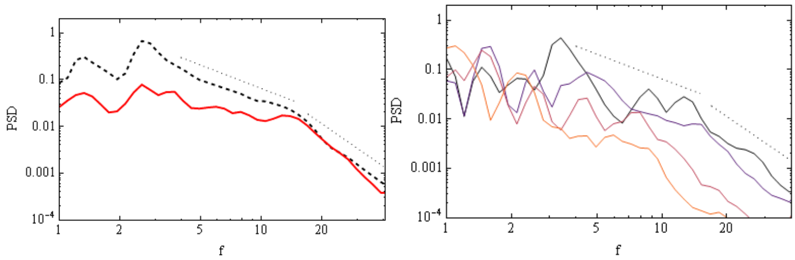

Figure 3: Wavelet power spectral density: left panel - azimuthal (black) and radial (red) velocity components in the stationary regime; right panel - total fluctuations energy in the decay regime for the different average intervals: 0-1 sec, 2-3 sec, 4-5 sec and 7-8 sec, downwards. Dotted lines show “-5/3” and “-3” power laws; B_z = 63 and 94 mT, R = 26 mm, H = 20 mm.

There are two energy spectrum intervals in the stationary regime corresponding to “-5/3” and “-3” power laws (fig.3). The second interval is characterized by energy equipartition for the fluctuations of azimuthal and radial velocity components. These two intervals remain likewise in decay regime, but amplitudes rapidly decrease and the frequency separation region changes from 15 Hz to approximately 6 Hz. Unlike this, lower frequency fluctuations are evaluated differently. The magnetic field impact on the decay process is illustrated in Figure 4 with temporal decreasing of dominant frequency fluctuations. As might be expected, the rate of fluctuations synchronization is determined by magnetic field value. It takes shorter time to get the same frequency of two velocity components with magnetic field increasing. It is also related to evolution of fluctuations amplitudes where the azimuthal energy is transferred to radial one.

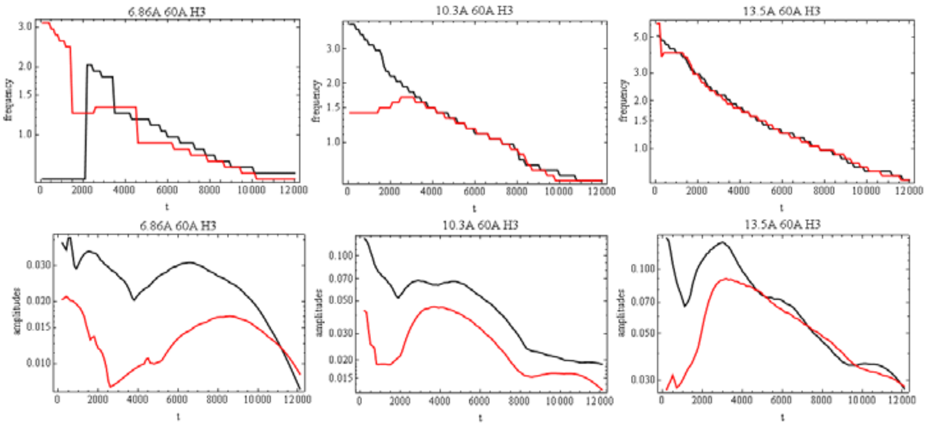

Figure 4: frequency (top panels) and amplitude (bottom panels) of dominating oscillations of azimuthal (black) and radial (red) velocity components in the decay regime for different magnetic field values (B_z = 63, 94, 125 mT from left to right, accordingly); R = 26 mm, H = 20 mm.

Components correlation is represented by the evolution of the phase shift between azimuthal and radial velocity components (fig.5). For stronger magnetic field, phase shift remains about 45 degrees while for the weaker magnetic field it vanishes with time (full correlation state).

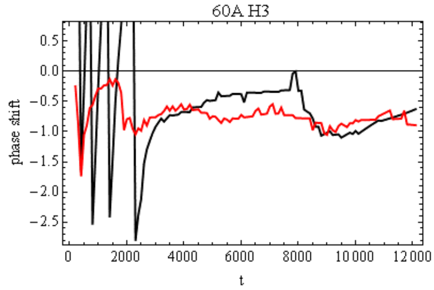

Figure 5: Phase shift between azimuthal and radial velocity components for different magnetic fields: B_z = 63 mT (black), B_z = 125 mT (red).

4. Conclusion

The obtained results allow to get an additional information on the peculiarities of the decay of a rotating MHD flows in an annular gap in the presence of axial magnetic field. It was established that in examined conditions the flow transformation is accompanied by energy exchange between velocity components. At that temporal evolution of fluctuations, the degree of their synchronization and correlations are determined by magnetic field value. We find that the energy of fluctuations at higher frequencies is similar to the energy at the steady regime. Lower frequency fluctuations become synchronized at the decay regime only. We demonstrated these peculiarities using the continuous wavelet transform because the standard cross correlation does not distinguish any particular relations for such phase and frequency modulated signals.

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