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Study of instabilities in a quasi-2D MHD duct flow with an inflectional velocity profile

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HIGHLIGHTS

- We investigate inflectional instabilities in quasi-2D MHD duct flows.
- A velocity profile is artificially induced in a channel through current injection.
- The Q2D velocity field is measured via the electric potential on a Hartmann wall.
- Results are compared to numerical simulations of the same geometry/conditions.
- Similar experimental and computed results suggest a Q2D approximation is valid.

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ABSTRACT

The mechanisms responsible for instabilities and a transition to turbulence in liquid metal duct flows of a fusion blanket are not understood very well, which limits predictive capabilities for heat and material transport in a blanket. In order to elucidate such mechanisms in quasi-two-dimensional (Q2D) magnetohydrodynamic flows with inflection points, an experimental and computational effort is underway to electromagnetically induce a Q2D turbulent flow through the injection of current at the Hartmann walls. In such a flow, inflectional instabilities arise at the two locations where current is supplied. In the experiments, Hartmann wall inductive velocimetry is employed as the main flow diagnostics. The electric potential field is measured using an array of small probes embedded in the wall material, and the fluctuating velocity field is reconstructed from the potential data using Ohm's law. First experimental data have been taken, which are in qualitative agreement with the pre-experimental analysis, where the flows are numerically simulated using a Q2D flow model.

1. Introduction

A thorough understanding of instabilities and transitions in liquid metal (LM) magnetohydrodynamic (MHD) flows in rectangular ducts is vitally important to the effective design and operation of breeder blankets such as the dual-coolant lead–lithium (DCLL) blanket [1]. Although MHD flows in LM blankets are often unstable [2], the instability mechanisms are not well understood. Up to now, much attention has been paid to the stability of the Hartmann layers and their role in the transition to turbulence [3–5], but the role of the Shercliff (side) layers has been less explored.

Smolentsev et al. [6,7] recently addressed instability in a particular quasi-two-dimensional (Q2D) velocity distribution with two inflection points, commonly found in MHD duct flows. The results of these theoretical studies [7] provide a good idea of how bulk vortices are generated and then interact with the side boundary layers to cause secondary instabilities in the flow. While some experimental work has been done to explore the stability of side layers (see, e.g. [8,9]), no dedicated experimental studies have been performed to our best knowledge to address vortex-wall interactions. This paper introduces an ongoing effort to study such interactions including an experimental approach, pre-experimental numerical analysis and first experimental data.

2. Experimental design and setup

The goal of the present so-called MHD instability experiment (see Figs. 1 and 2) is to induce a Q2D base velocity profile with inflection points in a closed insulated duct filled with mercury. The desired Q2D flow is electromagnetically forced using some combination of injected current and applied magnetic field, in such a way that instabilities first develop at the locations where

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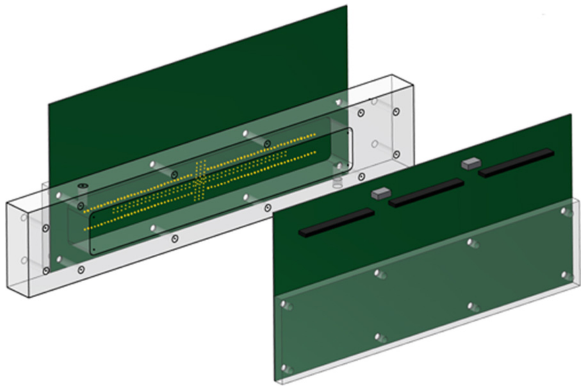

Fig. 1. Schematic of the MHD instability experiment test section showing the cavity and electrical contacts.

electric current is injected. The electric potential pulsations at the Hartmann wall are measured and recorded, and the fluctuating velocity field is reconstructed using Ohm's law.

In the experiment, the rectangular liquid-filled enclosure composed of an insulating acrylic body is closed by two-layer printed circuit boards (PCBs) at the Hartmann walls (see Fig. 1). The walls have small electrical contacts embedded on their inner surfaces (see Fig. 2) for current injection (1-mm diameter) and electric potential measurement (0.25-mm diameter). Due to the small size of the electrodes, they cause no significant hydrodynamic or electromagnetic disturbance of the flow, and the duct walls retain their insulating quality since currents induced in the contacts are so limited in extent.

The LM working fluid, ultra-pure mercury, sits inside a horizontal rectangular closed cavity with dimensions 30 cm × 4 cm × 3 cm, subject to a uniform transverse magnetic field of the lab electromagnet (1.8 T maximum) aligned with its shortest dimension. A flow-forcing technique to generate a rotating flow [10].

The current is driven between the electrodes. Together with the applied magnetic field, this current produces a Lorentz force in the middle section of the duct directed along the long axis of the test section. It is well known that MHD duct flows tend to rapidly become Q2D under a sufficiently strong transverse magnetic field [11]. For the conditions employed in this experiment, the net flow through any cross-section of the enclosure is zero, so

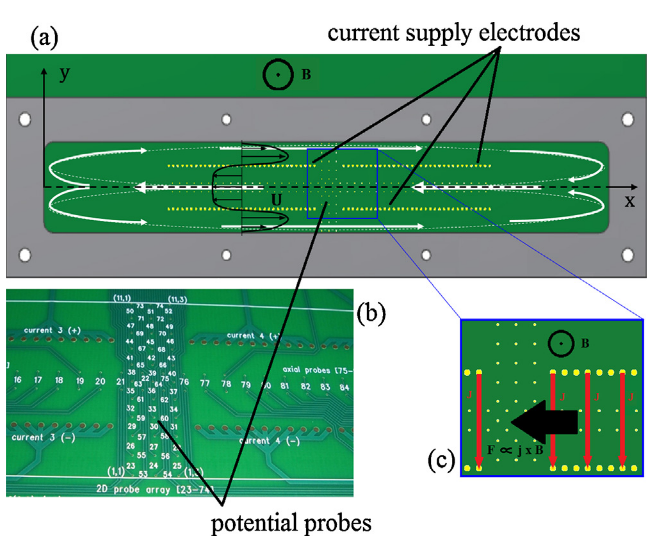

Fig. 2. Schematic of test section cavity showing direction of unperturbed fluid flow and velocity profile (a). The figure also shows the locations of the current supply electrodes and electric potential probes (b and c).

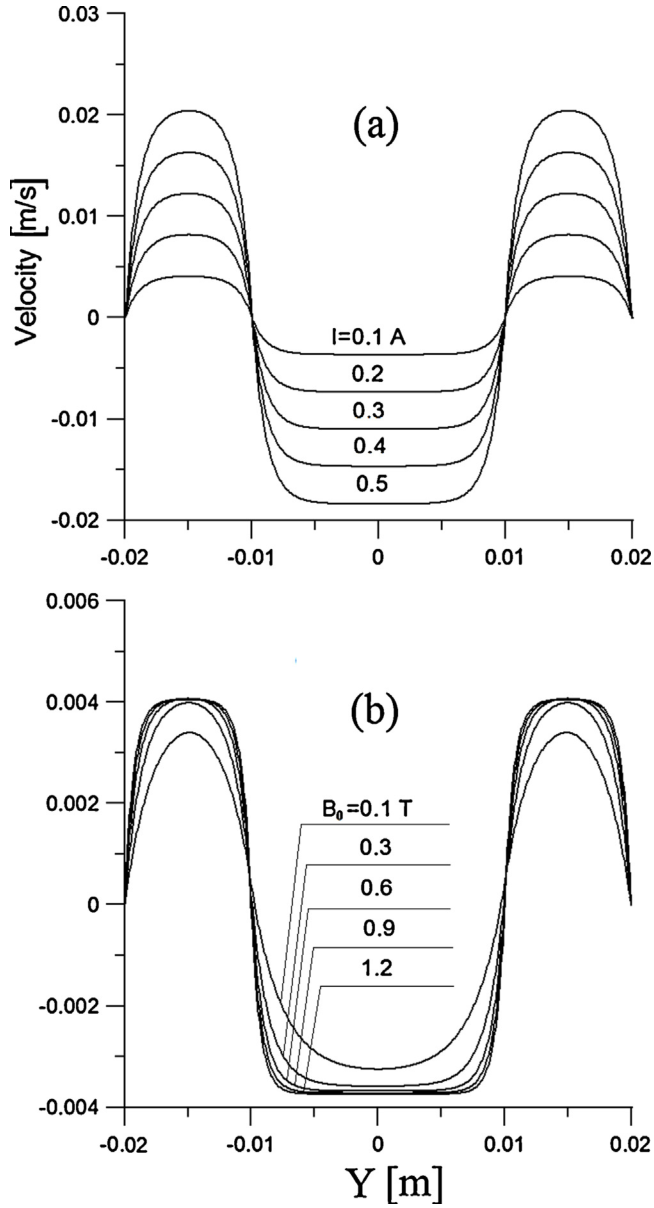

Fig. 3. Computed base (undisturbed) velocity profiles showing: (a) effect of the applied current at $B_0 = 0.5$ T and (b) effect of the magnetic field at $I = 0.1$ A.

by mass conservation, near the side walls the liquid is forced to flow in the opposite direction compared to the middle portion of the flow (see, for example, computed velocity profiles in Fig. 3). The two parameters used in the experiment to control the flow are the applied magnetic field ($0.5\,\mathrm{T} < B_0 < 1.5\,\mathrm{T}$) and the applied current ($I < 500$ mA).

Inflection points in the velocity profile are then formed at the electrodes, where instabilities tend to initially appear. By placing the electrodes closer to the side walls or closer to the center, different interactions between bulk inflectional instabilities and boundary layers may be observed, as predicted numerically in [7]. Each row of 66 current supply electrodes is 1 cm from a side wall, and the separation between them on each Hartmann wall is 2 cm. They extend over less than 60% of the channel length, leaving over 20% of the total length at each end unforced, which allows for a smooth turning of the flow without influence from the end walls. Each row is broken into six sections of 11 electrodes, so that the current distribution may be applied to all or a subset of the instrumented cavity.

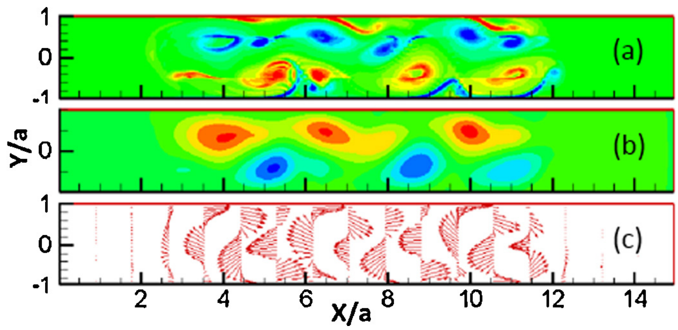

Fig. 4. Numerical results for $B_0 = 1.0\,T$, $I = 0.5$ A: (a) vorticity, (b) streamfunction, and (c) velocity vector field. Duct half-width $a = 2$ cm is used as a length scale.

To control the applied current in the experiment a feedback constant-current circuit is used. This circuit allows for uniform current distribution among all current supply electrodes. In addition it provides constant current conditions regardless of any changes in the flow. The embedded velocity probes are arranged in overlapping square grids with 4-mm spacing. Aligned symmetrically about the long axis of each Hartmann wall is a 2×44 array of probes, and in the center of the wall, where there is an 8-mm gap in the current supply electrodes, is an 11×3 array of probes that spans the entire Hartmann wall vertically. This arrangement provides the 2D velocity distribution along the axis and a rectangular grid of 2D velocity vectors near the center of the duct. The potentials, which are on the order of microvolts, are passed through a pre-amplifier to a National Instruments multiplexer and analog-to-digital converter connected to a PC with LabView software. They are sampled at a rate between 20 and 500 s^{-1}, and data is typically taken for 10 to 60 s. These data are used to reconstruct the velocity field at each time step, which can then be organized into a movie or analyzed statistically.

3. Pre-experimental analysis

In an effort to determine if current supplied through electrodes embedded in Hartmann walls can be used to induce a desired flow configuration, computations were performed using two computer codes. The first one solves the fully developed flow equations in the cross-sectional area of the duct [7]. With this code, it has been clearly demonstrated that the experimental flow becomes Q2D for magnetic fields stronger than about 0.25 T. In the second code, a Q2D flow model as described in [7] is employed. This numerical code, based on a spectral method with periodic boundary conditions at the inlet and outlet and seeded by random noise at the initial moment of time, is used to solve the Q2D vorticity-stream function flow equations. With this code, the base velocity profiles were first computed under the experimental conditions (Fig. 3). As expected, the base flow consists of the near uniform stream in the middle portion of the duct (where current is applied) and two symmetric flows at the side walls of opposite direction. Applied electric current seems to have a stronger effect on the velocity profile compared to that of the magnetic field. In fact, the base velocity is linearly proportional to the applied current. Second, the fluctuating flow was computed by imposing small disturbances and letting them develop in time. Fig. 4 contains contour plots of streamfunction and vorticity, as well as a vector plot of the velocity field. Important features of these results include bulk vortices at the location of current supply electrodes and secondary vortices, which result from the interaction of the bulk vortices with the side boundary layer.

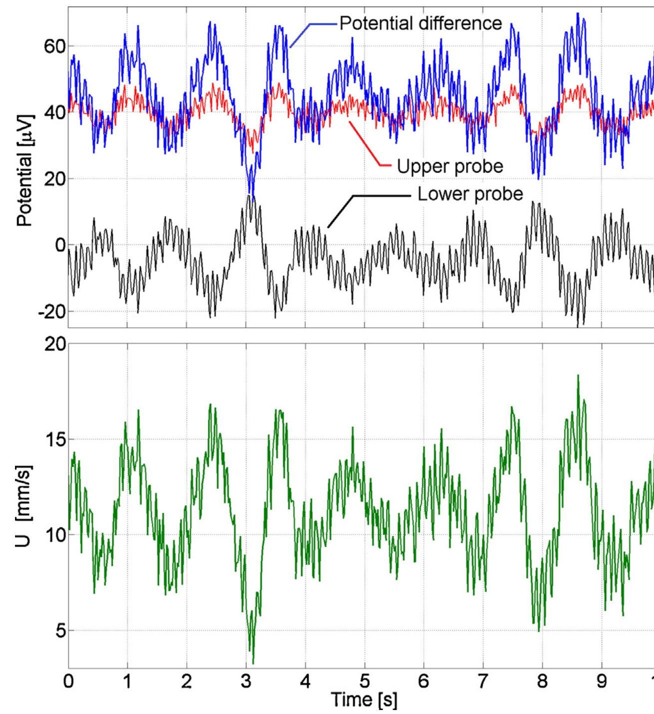

Fig. 5. Top: electric potentials recorded by a pair of probes, with the potential difference between them, for $B_0 = 1.0$ T and $I = 300$ mA. Bottom: velocity calculated from potential difference above.

Black dots represent electric potential probe locations. Velocity oscillations suggest the presence of one or more vortices, similar to those in the simulation results in Fig. 5.

4. Experimental results

4.1. Hartmann wall inductive velocimetry

The potentials measured at each moment of time at the probe locations on the Hartmann walls are used to calculate snapshots of the 2D velocity field in a plane perpendicular to the applied magnetic field. Once the flow is in a Q2D state, the velocity measured at the Hartmann wall is almost the same as in the core flow, allowing for the use of high-precision, low-disturbance embedded wall probes to measure bulk fluid motion rather than inserting a probe into the flow. Measurements in opaque fluids that do not disturb the observed flow are normally quite difficult, but since the fluid is conductive and the magnetic field is orthogonal to the Hartmann walls, an array of four probes arranged in a square is sufficient to measure the local 2D velocity vector.

In an insulated-duct MHD flow, the induced currents are small. When we apply this observation to Ohm's law

$$\vec{j} = \sigma(-\nabla\varphi + \vec{V} \times \vec{B}_0) \approx 0, \tag{1}$$

where φ is the electric potential, $\vec{V}$ is the velocity and $\vec{B}_0$ is the applied magnetic field. Based on the balance between the two terms on the right hand side of Eq. (1), for electrodes separated by a distance ℓ,

$$|\nabla\varphi| = \frac{\Delta\varphi}{\ell} = V_{\perp}B_o = |\vec{V} \times \vec{B}_o| \tag{2}$$

where $\Delta\varphi$ is the potential difference between the electrode pair, and $V_{\perp}$ is the component of velocity perpendicular to the magnetic

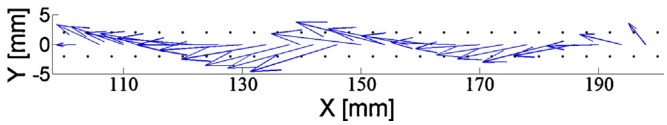

Fig. 6. The time-averaged velocity field at the axis of the duct for the same conditions shown in Fig. 4.

field. Thus, the measured velocity component (in the plane perpendicular to the magnetic field) is

$$V_{\perp} = \frac{\Delta\varphi}{B_0 \ell}. \quad (3)$$

Eq. (3) is used to calculate the Q2D velocity distribution using the electric potential measurements on the Hartmann wall. An example of reconstruction of the pulsating velocity from the electric potential measurements taken from neighboring probes is shown in Fig. 5. Another example is shown in Fig. 6 for the time-averaged velocity fluctuations at the axis of the duct. The flow demonstrates spatially periodic, sinusoidal-like behavior. These experimental observations are consistent with basic flow features obtained in computations as seen in Fig. 4.

After averaging the fluctuating velocity in time, the mean velocities can be obtained. An example of the averaged velocity at the duct axis is shown in Fig. 7. The experimental mean velocities are close in magnitude to those calculated and also demonstrate the same tendencies. Namely, the velocity seems to increase linearly with the applied current while the effect of the magnetic field becomes small for $B_0 \gtrsim 0.5$ T.

In spite of the qualitative agreement between experimental and numerical data, direct comparisons at this moment are not all satisfactory. The main reason for that is the extremely small potentials associated with our measurements (μV-range) and electrical noise from the electronics (primarily from the magnet). Since the test article and entire data acquisition system are electrically shielded, noise is introduced to the liquid metal mainly inductively through slight variations of the magnetic field in time. As a result, the noise is about 20% of the signal or even higher depending on the flow conditions. To improve the measurements, we are upgrading our equipment to handle very low input voltages. We are also in the process of upgrading the magnet power supply to improve the steadiness of the magnetic field in order to reduce the noise.

4.2. Spectral analysis

Based on simulations and previous experimental studies [12], we expect bulk inflectional vortices to exhibit periodic behavior with low characteristic frequencies not exceeding 30–40 Hz. To determine what frequencies dominate the velocity field we use the

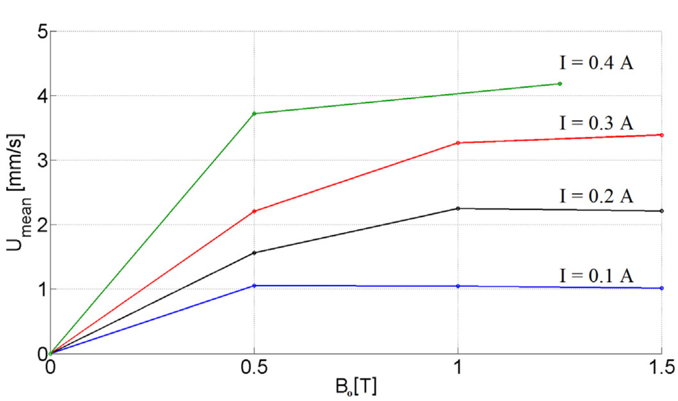

Fig. 7. Mean axial velocity vs. magnetic field for four different applied currents.

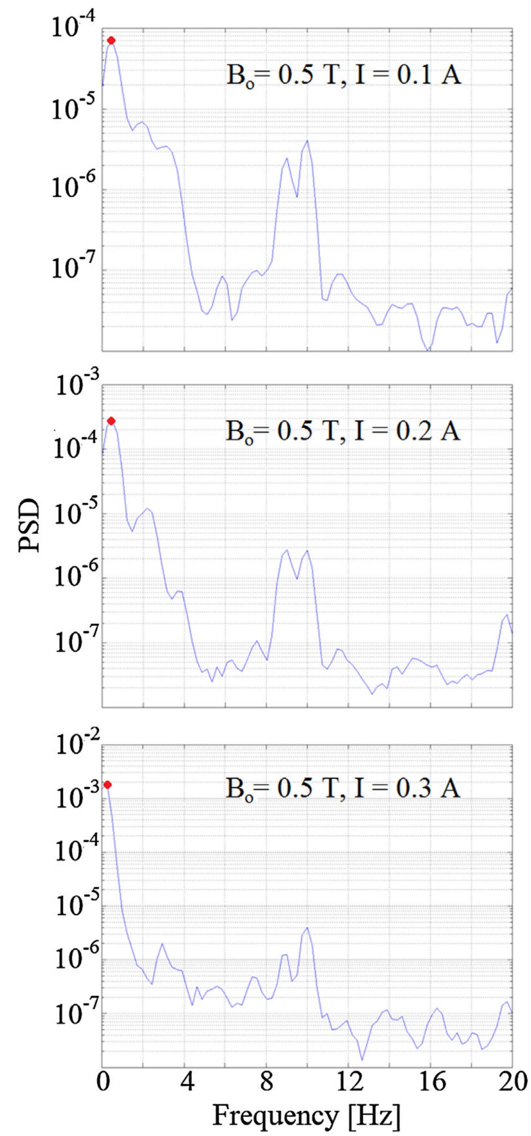

Fig. 8. Power spectral densities of experimental data for $B_0 = 0.5$ T and $I = 0.1$–0.3 A. The height of the lowest-frequency peak (<1 Hz) grows with increasing applied current.

Welch method to produce the periodograms in Fig. 8. The power spectrum density (PSD) has its largest peak at a very low frequency between 0 and 1 Hz, as well as several smaller peaks between about 3 and 22 Hz. It is interesting that the numerical data also show the highest peak at about 0.5 Hz. The spectrum shown for the experimental data has had the ambient noise spectrum subtracted, so though the facility noise shares some characteristic frequencies with the experiment, the dominant frequencies seen in the PSD plot in Fig. 8 are clearly related to the fluid motion.

5. Conclusion and future work

We have introduced an experimental and numerical effort to characterize instabilities in a Q2D MHD duct flow of LM, and to determine their role in the transition from laminar flow to Q2D turbulence. In the current phase of this effort, the main purpose is to ensure that the technique of simultaneously driving flow and measuring the velocity field on the Hartmann walls is viable, and to test the facility, identifying any weak points. First results suggest the current-injection system is indeed driving the flow along the axis, and an unstable and eventually turbulent flow is formed. Moreover, simulations of the experimental flows performed in parallel, which assume Q2D behavior, produce flow features qualitatively similar to those seen in the experiment, suggesting the Q2D model is a reasonable approximation for these types of flows. These preliminary results are encouraging and pave the way for more detailed, more accurate measurements to better match experimental conditions to those assumed in the numerical work. In order to obtain such improvements in accuracy, the facility is being updated both to improve the sensitivity of the data acquisition system and to reduce the electrical noise in the facility, especially that from the magnet.

Much better results are expected for the next version of the test section, which will be constructed with no gap in the current supply electrodes, better uniformity in the current distribution, and more probes with shorter connections to the data acquisition system. The updated test section will also have probes embedded in the side walls to detect the degree of three-dimensionality in the flow.

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