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MRI investigation of granular interface rheology using a new cylinder shear apparatus

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Abstract

The rheology of granular materials near an interface is investigated through proton magnetic resonance imaging. A new cylinder shear apparatus has been inserted in the magnetic resonance imaging device, which allows the control of the radial confining pressure exerted by the outer wall on the grains and the measurement of the torque on the inner shearing cylinder. A multi-layer velocimetry sequence has been developed for the simultaneous measurement of velocity profiles in different sample zones, while the measurement of the solid fraction profile is based on static imaging of the sample. This study describes the influence of the roughness of the shearing interface and of the transverse confining walls on the granular interface rheology.

Keywords: Velocimetry; Granular material; Annular shear; Interface; Roughness

1. Introduction

The interaction of a granular material with a solid interface is of interest in various engineering problems, such as industrial conducts [1], geotechnics [2,3] and in geophysical situations, such as tectonophysics [4] or gravity flows [5].

At the immediate vicinity of the shearing interface, a thin granular layer, where the shear and dilation is localized, plays a significant role in the stress transmission between the solid interface and the bulk granular material. This rheology is influenced by the roughness of the shearing surface [6–12].

In this article, we focus our attention on the annular (*Couette*) shear geometry, where the material is confined between two cylinders and sheared by the rotation of the inner rough one (see [13] for a recent review). This geometry has been used to measure the rheological properties of granular materials, both in two [14–17] and three dimensions [18–28]. However, the visualization of the granular interface is usually limited to the upper (free surface) or bottom layers (through a transparent glass window) [7,19,29]. Following previous magnetic resonance imaging investigation of granular rheology [30–33]: flows in rotating drum [34–37], vertical chute [38], annular shear cell [20,25,39], segregation and convection under vibration [40–47], we have used magnetic resonance imaging (MRI) to measure the granular rheology (velocity and solid fraction profiles) well inside the sample.

Sec. 2 is devoted to the description of a new annular shear cell, specially designed to be inserted in a MRI device. Based on a geotechnical cylinder shear apparatus [7,19,29,48–51], its originality relies on the control of the radial confining pressure exerted by the outer wall on the grains and on the measurement of the torque on the inner shearing cylinder.

Sec. 3 explains the multi-layer MRI velocimetry. MRI velocity measurements were performed using a spin-warp / phase encoding technique previously adapted from [52] and used for routine liquid rheology in annular Couette cells (see for instance [53–57]). It was here further modified on purpose of quasi-simultaneous assessment of different regions in the sample.

Sec. 4 describes the measurement of the velocity and solid fraction profiles, as well as the shear stress on the shearing

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wall, from which we deduce the influence of the roughness of the shearing interface and of the transverse confining walls on the granular interface rheology. Our study is restricted to the quasi-static regime (small shear velocity and/or high confining pressure).

Preliminary and complementary results are presented in Ref. [7].

2. Annular shear cell

The annular shear cell is inserted in the MRI device through an external support. Fig. 1 shows a schematic cut view of the cell, which components are made of Polymethyl Methacrylate (PMMA).

The sample has a hollow cylinder shape. The granular material is confined between two fixed horizontal (bottom and upper) plates (height H=10 cm), an internal rotating cylinder (radius R_i=3 cm) and an external latex homemade dip molded membrane (radius R_e=6 cm) backfilled with water. A pressure-volume controller (GDS) applies a radial confining pressure P to the sample, in the range 0–15 kPa. An optical fiber sensor (FOP MEMS 1000 kPa; Fiso Technologies) accurately monitors this pressure close to the membrane.

The internal rotating cylinder is guided by two journal bearings set in the external support, while the main cell (membrane, bottom and upper plates) is only connected to the external support through the torque sensor, which measures the whole torsion effort.

An aluminum-alloy torque sensor was specially designed, based on resistive strain gages, in the range ±10 Nm. This measurement was not possible during MRI experiment, but when displacing the cell bellow the MRI device. This prototype is a first step toward the realization of a torque sensor working inside the MRI device.

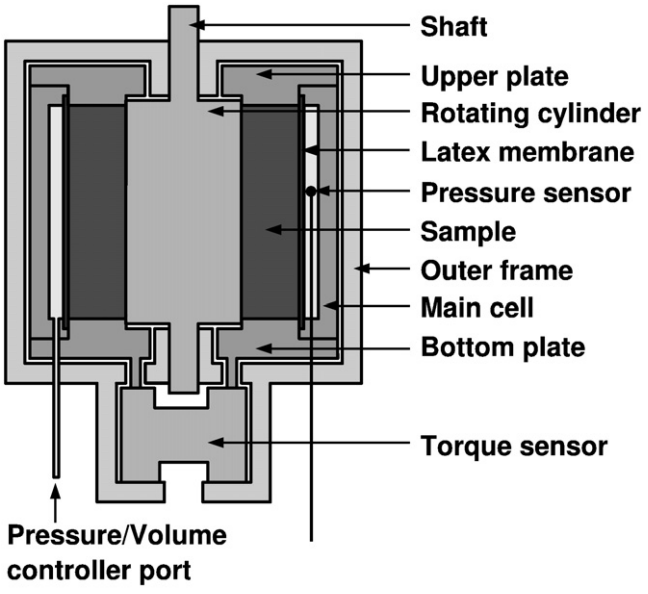

Fig. 1. Schematic cut view of the shear cell.

Depending on the way upper and bottom plates are mounted, it is possible to measure the whole torsion effort or only the fraction transmitted to the lateral membrane (the difference between those two measurements provides the torque transmitted by the horizontal walls).

The cell is connected to the transmission axis of a rheometer previously designed to be inserted within the MRI facility [56,58–60], through a gearbox. This two-stage timing-belt and pulley system is placed close to the cell and far from the motor. Its reduction factor of 10 provides a rotation range $0.1 \leq \Omega \leq 10$ RPM (rotations per minute).

This configuration allows to place down the cell (out of the MRI tunnel) during the sample preparation and torque measurement and then move it up to the observation position.

The complete cell has a total diameter of ≈19.5 cm and a total height, without gearbox, of 28 cm, which fits inside the radiofrequency (RF) coil.

3. Multi-layer MRI velocimetry

MRI experiments were carried out on a Bruker Biospec 24/80 MRI facility operating at 0.5 T (21-MHz proton frequency). The MRI magnet is a vertical superconducting prototype (Magnex Scientific, Oxford, UK), with a 40-cm bore. These characteristics are particularly suited for the study of large and inhomogeneous samples, exhibiting strong internal susceptibility contrasts. The magnet is equipped with a birdcage RF coil (height: 20 cm, inner diameter: 20 cm, hard $\pi/2$ pulse duration: 100 μs), and a BGA26 shielded gradient system (Bruker), delivering a 0.05-T/m gradient strength with a rising time of 500 μs.

MRI methodology for radial velocimetry inside the cell was that of [52] as further modified by [59] and [60]. It is based on a two-pulse spin echo sequence (Fig. 2A), in which the two pulses are made space-selective in z and y direction, respectively, so as to virtually cut a beam along one cell diameter (Fig. 2B). A read-out gradient in x direction permits to get after Fourier transform of the signal a 1D magnetization profile along the beam. An additional pair of gradient pulses in y direction (in black) induces on the magnetization profile an x dependent phase shift reading:

$$\varphi(x) = \gamma G \delta \Delta v_y(x), \tag{1}$$

where γ is the gyromagnetic ratio of proton, G the strength of these "velocity" pulses, δ and Δ are timing components of the sequence as described in Fig. 2 and $v_y(x)$ is the y velocity component along the selected diameter. In order to get a velocity profile, one performs two MRI measurements with respectively positive and negative velocity gradients, and then compares in each pixel the phase of the two magnetization profiles. When the thickness of the beam in y direction is small enough as compared with the cell diameter, such measurement may be regarded as a direct