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Drag and Lift forces in granular media

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Abstract

Forces exerted on obstacles moving in granular media are studied. The experiment consists in a horizontal cylinder rotating around the vertical axis in a granular medium. Both drag forces and lift forces experienced by the cylinder are measured. The first striking result is obtained during the first half rotation, before the cylinder crosses its wake. Despite the symmetry of the object, a strong lift force is measured, about 20 times the buoyancy. The scaling of this force is studied experimentally. The second remarkable observation is made after several rotations. The drag force dramatically drops and becomes independent of depth, showing that it no longer scales with the hydrostatic pressure. The rotation of the cylinder induces a structure in the packing, which screens the weight of the grains above.

1. Introduction

The problem of forces experienced by an object in a granular flow is of particular interest in many fields, like industrial processes or geophysics. It might be also of importance for the design of rovers moving on granular soils. If several studies focused on drag forces [1, 2], lift forces have received less attention [4]. In this paper we discuss the properties of drag and lift forces on a rotating horizontal cylinder.

2. Experimental device

The experiment is sketched in figure 1. It consists in a horizontal cylinder immersed in a bucket full of glass beads of diameter $d = 500\,\mu$m and density $\rho_g = 2500\,\text{kg.m}^{-3}$. The tank rotates at a constant angular velocity of 2 rpm around its vertical axis. The cylinder of diameter D and length L is maintained horizontally in the granular bed at a controlled depth h by a thin rigid vertical rod 3 mm in diameter, whose axis coincides with the rotation axis. The cylinder is kept static by the vertical rod and experiences a torque and a lift, which are measured at the top using respectively a torque meter and a precision scale.

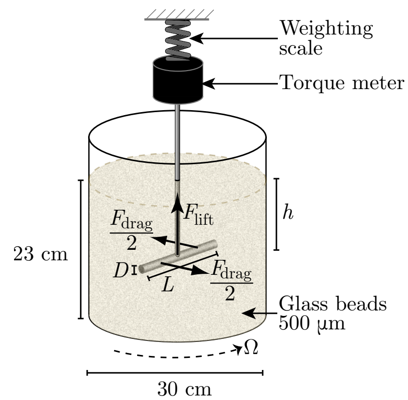

Figure 1: Sketch of the experiment

The experimental procedure is the following. The grains are first poured in the tank and the packing is slightly compacted by tapping on the bottom. The cylinder is then plunged at the desired depth into the granular medium and the tank is put in rotation while recording the forces. All the experiments have been carried out in the quasi-static regime when the measured torque is independent of the angular velocity [1].

3. Forces during the first half-turn

We first study the drag $F^{\text{half}}_{\text{drag}}$ and lift $F^{\text{half}}_{\text{lift}}$ forces experienced by the cylinder during the first half turn, before it goes through its own wake. The drag force is found to be proportional to the depth of the object (red curve in figure 3) and scales with its surface, as previously found in other studies [1, 2]. This observation can be explained by the fact that the interaction between the grains and the object is mainly controlled by friction, which implies that the stresses on the cylinder are proportional to the mean pressure i.e. the hydrostatic pressure P of the grains. Far from the walls of the tank, $P = \rho g h$ with $\rho = \rho_g \phi \sim 1500\,\text{kg.m}^{-3}$ the density of the medium, $\phi = 0.62$ being the volume fraction of the packing. The experiments give:

$$F^{\text{half}}_{\text{drag}} \simeq 13 \cdot P \cdot DL = 13 \cdot \rho g h \cdot \, DL \qquad (1)$$

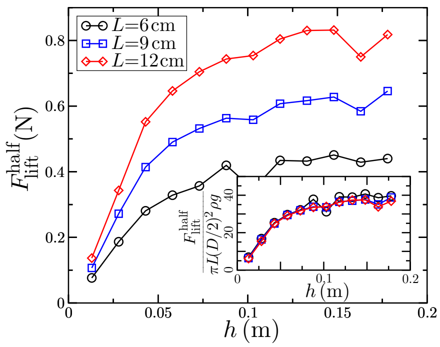

Figure 2: $F_{\text{lift}}^{\text{half}}$ versus h for cylinders $D = 4\,\text{mm}$ and various lengths. Inset : $F_{\text{lift}}^{\text{half}}$ scaled by buoyancy for the same cylinders.

Beside the drag force, the striking result obtained in the experiment is the existence of a strong lift force, about 20 times the lift expected from Archimede's force, despite the up-down symmetry of our object. The depth dependence of the lift force $F_{\text{lift}}^{\text{half}}$ is shown in figure 2 and differs from the drag force : close to the free surface the lift is proportional to the depth but it saturates at higher depth. This saturation never observed before ([4]), can be understood by the fact that the origin of the lift force is the pressure gradient and not the pressure as for the drag force. The systematic experiments carried out with cylinders of various lengths (figure 2 inset) and diameters show the following scaling for the lift force when the cylinder is far enough from the free surface ($h \gg D$) and when the diameter is large compared to the grains ($D \gg d$):

$$F_{\text{lift}}^{\text{half}} \simeq 20 \cdot \rho g \cdot \pi (D/2)^2 L \qquad (2)$$

4. Forces in the steady state

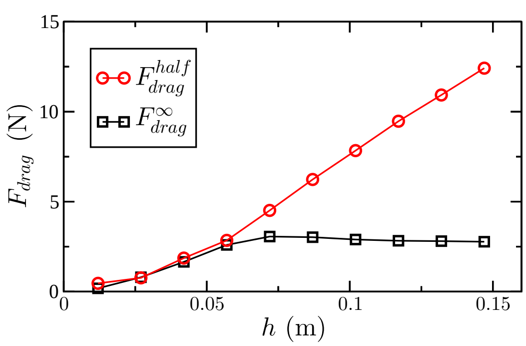

Figure 3: $F_{\text{drag}}^{\text{half}}$ and F_{drag}^{∞} at various depth for a cylinder $D = 6\,\text{mm}$, $L = 60\,\text{mm}$.

In the previous section, the forces were measured during the first half rotation, before the cylinder goes through its own wake, because the behavior of the drag force dramatically changes after half a rotation. In figure 3 we have plotted both the drag measured during the first half turn $F_{\text{drag}}^{\text{half}}$ and the one measured after several turns, in the steady state F_{drag}^{∞}. The remarkable result is that, whereas the drag force during the first half rotation increases with depth h, the stationary value after long time is roughly the same for all runs, independent of h. Passing over and over in its own wake seems to create a structure within the packing, which is able to screen the mass of grains above and to dramatically lower the force needed to move. The steady drag force being independent of depth, another scaling than eq. 1 has to be found. From systematic measurement on different cylinders, we find that the relevant pressure scale controlling the drag is no longer $\rho g h$ but $\rho g L$ leading to the following scaling when the cylinder is far enough from the free surface ($h \gg L$), and when the aspect ratio is large ($L \gg D$):

$$F_{drag}^{\infty} \simeq 7 \cdot \rho g L \cdot DL \qquad (3)$$

5. Summary and Conclusions

We have shown that the motion of a symmetrical object in a granular bed leads to the apparition of a strong lift force, which scales like the Archimede's force but is 20 times stronger. This is due to the peculiar rheology of granular media, which is basically controlled by frictional properties. We have also shown that the successive motion of the object within its own wake creates a structures in the packing, which have strong consequences in terms of drag force, screening the hydrostatics pressure of the above grains. Understanding these new phenomena, and being able to model them within continuum description of granular flows remains a challenge.

References

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