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Interactive comment on "Inertial drag and lift forces for coarse grains on rough alluvial beds" *by* Georgios Maniatis et al.

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Comment: The manuscript by Maniatis is based on a study that uses two custom-built smart particles (one spherical and one elliptical in shape) that contain an accelerometer and gyroscope. The manuscript focuses on (1) presenting a method for putting the accelerations extracted in the particle's frame of reference to one from the perspective of a fixed observer and (2) presenting the lift and drag forces measured while the particle was in motion in a laboratory and field experiment. The paper's strengths are the presentation of the mapping method between the two frames of reference and the introduction of the idea of inertial drag and lift impulses. The inertial drag and lift impulse are similar to the impulse idea put forward by Diplas et al. 2008 (Impulse = integral of force with respect to time applied to a particle) but is based on particle

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Discussion paper

forces inferred from particle motion rather than particle forces inferred from fluid measurements. I believe the paper presents (1) useful methodology information for those using accelerometer data in particles, and (2) useful data pertaining to particle motion. At the same time, I have a few questions for the authors and some suggestions on the presentation of the work that I think should be addressed.

Reply: We sincerely thank the Reviewer for the thorough review and the positive comments.

Comment: 1. My primary suggestion, or concern, is that the authors make it explicitly clear that all of their force measurements (and impulse calculations) require that the particle be moving (if I am understanding things correctly). It would also be helpful if they expanded their discussion on the benefits and limitations of such measurements. Many of my presentation suggestions below reflect this desire for it to be clear that the forces measured are only those extracted from the particle accelerations.

Reply: We realise that this is a point we need to highlight in the Introduction, Discussion and the section we introduce the Newton – Euler model. It is crucial for the understanding of the measurements to clarify that they only concern a state where the resultant forces on and/or the torques around the centre of mass of the particle exceed zero. We will refer to that explicitly in a revised section 3 of the paper where we will: a) slightly revise the notation in order to make sure that it is completely clear what we measure and what we don't (e.g. FLr is the hydraulic lift force, which is analysed in the r frame, but we cannot decouple it from the FL signal) and b) introduce the rotation threshold (which also refers to a subsequent comment from the Reviewer here). In the discussion we will also summarise the pros and cons of such a method. The main advantage is that the sensor "solves" a very complicated force balance for us, hence the threshold of motion is explicit (sum of torques and forces exceeding 0). The main disadvantage is that in order to predict the motion, complimentary measurements may be required (e.g. detailed flow measurements). However, it is worth noting that the pre-entrainment vibrations of the particle (where the particle moves without being completely dislodged) are captured by the sensor which can be informative (depending on the size of the particle).

Comment: 2. It seems that you have the highest number of entrainment events for an inertial impulse of zero. Is this because the primary motivating impulse came at a time before that which could be measured by the particle?

Reply: This is difficult to answer with certainty. The zero impulses are generated from forces that reached the threshold value and did not exceed it for more than 1/50th of a second (the sensor's sampling frequency). Also, not every exceedance dislodges the particle and we define the entrainment point at the start of continuous 1 particle of motion. Particle dislodgement is still stochastic for the inertial measurements (Figure 4). There is a very high chance that the motivating hydraulic impulse that begins the mobilisation of the particle comes before the particle starts to vibrate but we have no way to verify that with the existing dataset.

Comment: 3. Along these lines, do the potential travel paths of the particle dictate the forces measured? That is, are the FL and FD measurements sort of pre-determined by the orientation of the particle relative to others in the bed?

Reply: FL and FD would be different in a different bed topography. We are going to highlight this even further in the revised manuscript because we need to clarify that, although the method we present is general, the results are highly dependent on the experimental settings. At the same time, it is difficult to distinguish the most dominant control on the resistance of the particle (the orientation of the particle, the surrounding particle forces or the inertia of the particle). The orientation of the particle and the pivoting angle will dictate the mode of entrainment because the boundary condition will be different. At the same time, it is fair to assume that the trajectory of large particles will depend a lot on their moment of inertia (Icm in the paper) which describes the distribution of mass within the body frame of the particle and affects the direction of the resultant force. This is an exceptionally interesting question that will require a different data set in order to be answered.

Comment: 4. In equation 5, where is the contact force with the bed? Is it tied into the gravitational force terms? The critical drag and lift forces will depend on the submerged weight of the particle and the orientation of the grain within a pocket through the contact reaction force. The orientation of this force will also influence where it is more likely to have lift or drag dominate. How does it factor into equations 9 and 10? It should, shouldn't it? And 5. Along with the preceding question, how is this contact force for accounted for throughout the range of a particle's motion as it moves and interacts with the bed?

Reply: We want to thank the Reviewer for those observations, we realise that this needs further explanation. The short answer is that the threshold that will depend on the orientation of the particle is the rolling threshold of motion and we explicitly discuss the linear threshold of motion (Reviewer 3 refers to that as the threshold of tractive motion along the downstream and upward directions). In this context gravity keeps the particle on the bed and (since it is significantly exposed to the flow) it defines the threshold of the linear motion because of the opposite an equal reaction of the bed to the particle. We will provide a more directional description of the force balance (with signs) explaining this point.

Also, in the more general Newton Euler model (presented in the current section 3), the surface resistance forces (such as friction) are "hidden" in the FR term of equation 6. Because we resolve the force and torque balance on the centre of the mass of the particle (the sensor does it), all the forces applied on the surface of the particle have to be accounted for as torques. And, strictly speaking, they will only alter the direction of the motion through a rotational component (generating an angular acceleration and a torque that is normal to the direction of rotation). The integral of that angular acceleration is the angular velocity measured by the gyroscope in the body frame.

This rotational component is a spinning component (defined around the centre of the mass of the particle) and not an orbital component (defined around the centre of mass of a supporting particle as it is common in the literature of sediment hydraulics). It is also negligible when a particle is exposed (in terms of the magnitude of the turning moment applied around the centre of mass of the particle) because it depends on the moment of inertia which is generally a very small number even for relatively large particle diameters (for our spherical particle it is uniform and equal to 0.00085 kg. m2).

Overall, particle orientation will control the mode of entrainment, but we see here that for complete dislodgment (of a quite coarse exposed particle) the gravitational forces need to be exceeded. And that generally depends on the mean orientation of the bed. To address comments (4) and (5) of the Reviewer, we will:

a) Revise sections 3 and 4 in order to include a formula for the rotation threshold (also suggested by Reviewer 3 and described in previous comments here) and explain how it relates with the rolling mode of entrainment.

b) Demonstrate how much smaller the rotational component is compared to the linear component by adding the norm of torques in Figure 1 (for both the sphere and the ellipsoid) and

c) Add an appendix showing the same time series (derived from the norm of angular velocities) at a scale that is more visible.

Comment: 6. Please provide a figure showing the experimental setup with flow depth and bed arrangement. I would think that τB has little meaning in terms of mobilization with your particular laboratory setup.

Reply: We are going to revise extensively Figure 1 to address that and will describe the flume setup specifically. We will also remove τb based calculations completely; they are not directly relevant, and they complicate any possible comparisons between the flume and the field experiments.

Comment: 7. Terminology in Figure 2 and elsewhere. When do vibrations turn into motion? Does entrainment start when the particle reaches a distanced travelled of 1 diameter, or does entrainment start when the particle starts to move and then continues on a path that leads to it moving 1 particle diameter? Also, what is a non-entrainment event with a measured inertial impulse? Does that correspond to a case where the particle started to move out of the pocket but then fell back down before reaching the apex?

Reply: We define entrainment at the beginning of a vibration leading 1 particle diameter motion. A non-entrainment event with a measured inertial impulse corresponds to a case where the particle vibrates within the pocket (either parallel to the x or the y direction of the flow) but it is not fully entrained (dislodged into a trajectory of a minimum of one diameter). This explanation will be part of a revised section 5.0.1.

Comment: 8. In the discussion, I'd suggest non-dimensionalizing the force (maybe using sub- merged specific weight) when making the comparisons to other work. Also, how do your inertial forces compare to standard drag estimates using velocity, particle size, and a drag coefficient? What types of relative fluid/particle velocities are needed?

Reply: We are happy to non-dimensionalise the force with the submerged weight of the particle and we agree that it will enhance the comparisons significantly. The comparison of inertial forces with standard drag estimates is more difficult because most of the literature is devoted to fully developed flow which is not the case for our experimental setting (small bed of hemispheres and grain diameter/ depth ratios close to 1). We will refer however specifically to that difference in the discussion.

Presentation questions/concerns/suggestions Comment: The paper is reasonably well written, but I do have some suggestions below that I think would help to improve the presentation of the work. Abstract: L.1 Delete "been" L.4 Replace "on sediment" with "on a particle during" L.5-7 The sentence "Today, twenty years.... for the issue" is not needed in an abstract. Suggest deleting it L.9 Change "grains on" to "grain moving on" L.11 Change "resulting to the" to "resulting in a"

Reply: We accept of all those comments and will revise accordingly.

Comment: Introduction: overall I think you can shorten down the introduction L.38-41 I think you can remove the sentence that starts with "The term Lagrangian..." Most people know the difference between a Lagrangian and an Eulerian frame of reference

Reply: There is a quite delicate balance in terms of what type of terminology is required for such a paper (in this journal). We are in principle happy to make the introduction more concise, but don't want to alienate a broader audience (see comments from Reviewer 1).

Comment: L.44 Delete "(the exact definition of turbulence impulse)" L.72 Change opening sentence to: MEMS-IMU sensors ideally measure forces at the center of mass.... L.74 change to "acting on the grain as it moves" L.83 suggest changing to, "...and electrical engineering. Modeling of IMU error..." L.91&92 suggest changing resolve and resolution to "map" and "mapping" or "rotate" and "rotation" Frames of ref L.123 Suggest, "... frames is non-trivial. A widely-used method..." L.124 Suggest changing "to apply" to "the application of"

Reply: We accept those comments and revise accordingly

Comment: L.129-end of the section. I'm torn here. I could see all of this being better suited for the appendix if the focus of the paper is on the data from the particles. However, if you want the paper to be about the mapping between the frames of reference then you should keep it here.

Reply: We mainly focus on the method; however, we will probably need to move this to an appendix as we need to make room for an expanded explanation on the Newton Euler model.

Comment: L.157-158 Delete the beginning of the sentence that spans the text "As sediment" to "linear acceleration". Just start with ar.

Inertial measurements L.211 change to Ti L.216 suggest changing "that mobilizes

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Interactive comment

the particle" to "acting on the particle once it starts to move" Lab and field experiments L.238 0.028 l/s is a discharge, not a rate of increase in discharge L.240 change "recorded" to "video of" Figure 4. If I'm correct, I think you reference figure 4 before referencing figure 3. It should be the other way around L.254 suggesting changing to, "...inertial impulses for cases were the grain started to move." Discussion L. 360 - I'd suggest making the extended analysis part of the discussion. Use subsection for the different components of the discussion such as comparison with other work and L.368 - delete one of the "of"s

We accept all those comments and will revise accordingly.

References Maniatis, G.: Eulerian-Lagrangian definition of coarse bed-load transport: theory and verification with low-cost inertial measurement units, Ph.D. thesis, University of Glasgow, 2016.

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