Spatial Force Correlations in 3D Granular Flow

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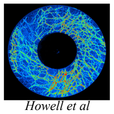
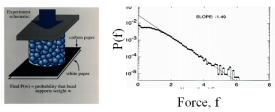
Background: Force fluctuations in static sand

Forces are spatially inhomogeneous

Stress mainly along linear structures – ‘force chains’



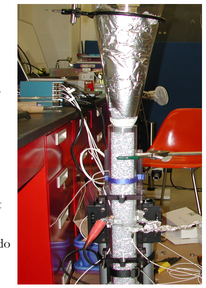
Howell et al



$P(f) \sim \exp(-f/f_o)$

Force distribution is exponential, not Gaussian

Major Questions

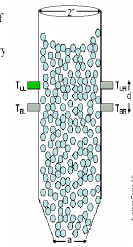


- **Are there force chains in flow?**
- There has been indirect evidence of dynamic force chains, can we look for them through direct force measurements at the boundary?
- Are the forces at the boundary correlated, i.e. when the force is high on one side is it high on the other?
- Once a force is high, how long does it stay high?
- Once forces are correlated how long do they remain that way?
- How does flow velocity affect force correlations and durations?

Experimental Setup

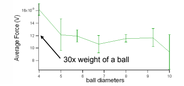
- Spherical glass beads of diameter, d=4mm
- Opening size a, can vary from 4d to 10d
- Flow velocity ranging from 1.4 cm/s to 30 cm/s

Openin g a(d)	Flow (cm/s)
5.00	3.1
5.75	5.3
6.75	8.1
8.00	14.0
9.25	23.0
10.00	30.0



- Diameter of transducer head is comparable to the ball diameter
- Transducer scan rate: 3.2×10^5 Hz
- Normal forces

Average Force at the Transducer



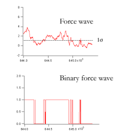
Opening size in ball diameters

Some Terminology

High Forces are those higher than one standard deviation above the average force value.

$$f_{high} > f_{ave} + \sigma$$

Force data is scaled and converted to binary. High forces get a value of 1, low forces 0.



Transducer Pairs:

Directly/Diametrically Opposite

Diagonally Opposite

Partial Diagonal

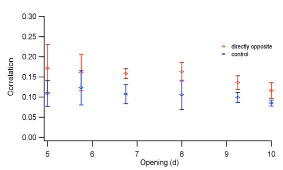
Same Side

The “**control**” data is created by calculating the correlation between two sets of force data from unrelated runs. This gives the smallest correlation value that can be expected while still taking into account the fact that high forces cluster.

Force correlations at the boundary as flow moves toward jamming

Forces correlation calculated between diametrically opposite transducers for different flow rates.

Force Correlation vs. Opening size



Openin g a(d)	Flow (cm/s)
5.00	3.1
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9.25	23.0
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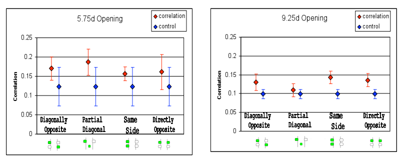
Weak correlations insensitive to flow rate

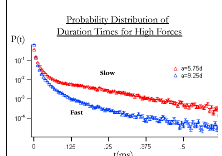
No apparent directionality



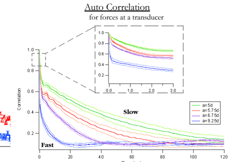
No significant difference between transducer pairs. If there are force chains forming, they do not prefer any one direction over another.

Durations of high forces

Probability Distribution of Duration Times for High Forces



Auto Correlation
for forces at a transducer

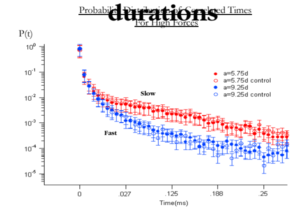


High forces are more frequent in slower flows.

Longer time scale shows that high forces also cluster more frequently in slower flows.

Correlated durations

Probability Distribution of Correlated Times For High Forces



Forces stay correlated longer in slower flows. However, actual correlation (solid circles) **is not distinguishable from control correlation** (open circles)**.** Consistent with small correlated values shown on slide 5

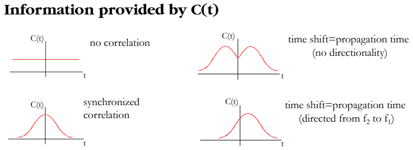
Time shifted correlations

What is it: Force f_1 at one transducer is correlated with the force f_2 at the other transducer at a later time. **$f_1(t_0)$ is correlated with $f_2(t_0+t)$** to produce the…

The Correlation Function C(t)

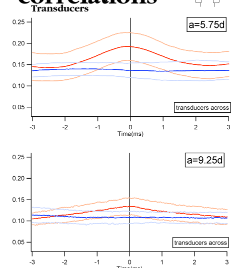
$$C(t) = \langle f_1(t_0) * f_2(t_0+t) \rangle_{t_0}$$

Information provided by C(t)



Time shifted correlations

Diametrically Opposite Transducers



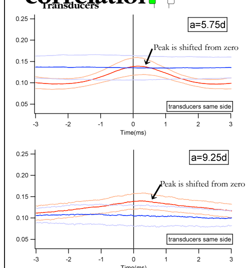
Diametrically opposite forces (red lines) **are correlated with no time shift or directionality**

Control data (blue lines) **show no correlation**

(correlation values at 0 are consistent with values on slides 5 and 6)

Time shifted correlations

Same Side Transducers



Peak *is not* centered at zero.
Forces are more highly correlated with a time shift.

Right shift indicates **force information is traveling upward** (opposite direction of flow) at a calculated speed v.

Flow (cm/s)	Shift (ms)	v (m/s)
5.3	0.1625	151.23
23.0	0.265	92.45

v is over 400 times the flow velocity for a= 9.25d and almost 3000 times the flow velocity for a=5.75d

collisional transfer of information?

Conclusions

- Forces are weakly correlated at the boundaries
- High forces are more frequent and live longer in slower flows
- Force information travels up the flow

So are there force chains?

It’s a resounding maybe.

Forces are correlated at the boundaries, but it is a very weak effect. It is possible that the force chains exist but that their effect is watered down when looking at the flow as a whole. Short lifetimes or infrequent occurrences could account for the weak correlation

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