DFF Sensor Model: Measurements of Fluids, Bulk Powder and Single Granules

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The DFF sensor works by quantifying the force exerted by the flow against the pin. Depending on the nature of the flow, the sensor either measures a continuous drag force exerted by fluid or a momentum of a particulate component of the flow. Multicomponent flows such as those realized in an industrial processing can be modeled as combination of a uniform fluid flow and a flow of particles. Connection between Lenterra's DFF sensor output and flow characteristics in such "elementary" flows may be established as follows:

DFF Probe in a Uniform Fluid Flow

The force acting on the cylindrical hollow pillar in uniform flow is:

$$F = \frac{1}{2} C_d A \rho_{fl} v^2 \qquad \text{Eq. 1}$$

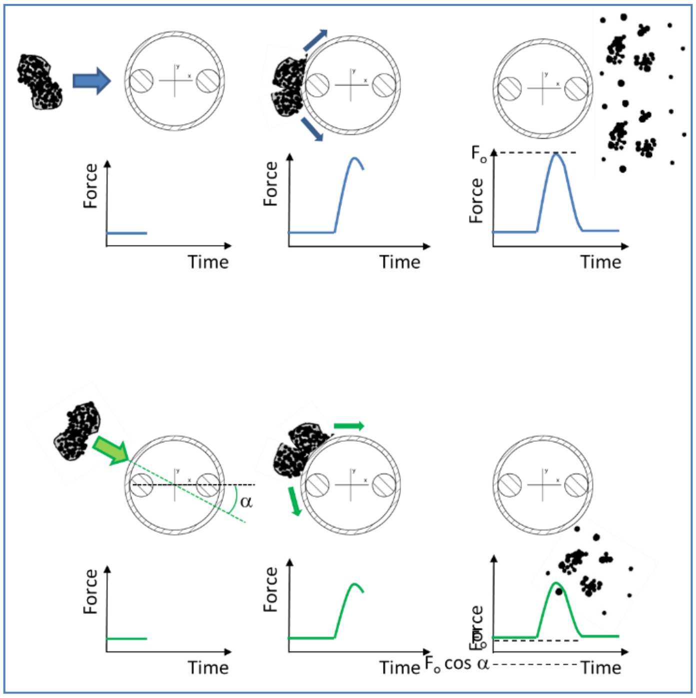
where C_d is the drag coefficient of a cylinder, $A=2r_o l$ is cross section of the cylinder exposed to a flow (r_o is the radius and l is the length of the cylinder), ρ_{fl} is the fluid density, and v is flow velocity. C_d is a function of the Reynolds number, $Re_d = \frac{2r_o v \rho_{fl}}{\mu}$ where μ is the kinematic viscosity. Thus, if the flow velocity is known, the DFF sensor output is related to the density and viscosity of the fluid.

Probe in Powder Flow

Another measurement occurs when a continuous one-dimensional uniform flow of identical small particles of mass m and density ρ interacts with the probe. Assuming that the particle diameter d is smaller than the diameter of the probe, the equivalent (integrated over pin length) force on the tip of the probe can be evaluated as follows (Gere & Goodno, 2013).

$$F_0 = \frac{3}{8} mv \frac{dN}{dt} = \frac{3}{8} mv \cdot nAv = \frac{3}{8} A(mn)v^2 = \frac{3}{8} A\hat{\rho} v^2 \qquad \text{Eq. 2}$$

Here, N is the total number and n is the concentration of the particles, A is the cross-sectional area of interaction (length times diameter of the probe), and v is the velocity of the flow. Here $\hat{\rho} = mn$ is powder bulk



density. $\hat{\rho}$ can be measured, for example, by weighing the powder in a calibrated volumetric flask.

Assuming the minimal detectable force of 0.5 mN, for a powder velocity of 2 m/s, the lowest density detectable by DFF sensor is estimated using Eq. 2 as $\hat{\rho}$ = 0.01 g/cm^3.

Single Particle Impact

An elementary interaction between a particle and the cylindrical probe manifests itself as a pulse in the force vs. time measurement. An impact of a particle colliding head-on with the DFF probe tip would cause the tip to deflect from its equilibrium position. The magnitude of the tip deviation δ is determined by the relation between mass of the particle and the effective mass of the pin, $M_{eff} = \frac{1}{4\pi^2}\frac{k}{f^2}$, where k is the stiffness of the pin and f is its mechanical resonance frequency.

For a stainless steel pin of 40 mm in length and 1 mm in diameter with 0.2 mm walls, $k \cong 360$ Nm^{-1}, $f \cong 460$ Hz, and $M_{eff} \cong 0.04$ g.

Assuming a **perfectly inelastic** collision, the momentum conservation yields $mv = (m + M_{eff})V$ and for $m \ll$

M_{eff} leads to $V = \frac{m}{M_{eff}} v$. Here m is the particle mass, v is its velocity before impact and V is the velocity of the particle and probe tip after impact. The energy of the impact is transferred to the energy of the tip motion of the pin, which is related to the measured force pulse magnitude F_0 as $\frac{M_{eff} V^2}{2} = \frac{k\delta_0^2}{2} = \frac{F_0^2}{2k}$. Thus,

$$F_0 = mv\sqrt{\frac{k}{M_{eff}}} = \frac{\pi^2}{6} f v \rho d^3 \qquad \text{Eq. 3}$$

The force pulse magnitude due to interaction of a single particle is therefore proportional to the first power of particle density ρ and third power of its diameter *d*. Using this equation, one can estimate the smallest particle impact that will be detected by the sensor. For example, the sensor with pin parameters described above will measure force down to 0.5 mN. Such a force is realized, for example, during an impact of a 0.7 mm diameter water droplet moving with at 2 m/s.

In the above analysis, it is assumed that the impact is along the measurement direction of the sensor. If a particle collides with the probe tip at an angle α to the measurement axis, the sensor generates a smaller signal:

$$F_\alpha = \frac{\pi^2}{6} f v \rho d^3 cos\alpha \qquad \text{Eq. 3a}$$

Conclusion

Rheologically complex flows can be generally characterized by a combination of a fluid, bulk powder and large granules. Due to extremely high measurement frequency, DFF sensor detects not only the bulk flow properties but also individual force impacts on the sensor probe and is capable to provide information about particle mass, size, density, and momentum. The sensor can be designed to measure flow forces in a wide range of sensitivities, and detect single particle impact as small as that formed by a 0.7 mm water droplet moving at speed of 2 m/s, or powder flow of particles of bulk density 0.01 g/cm^3.

References

Gere, J.M. & Goodno, B.J. (2013). *Mechanics of Materials.* (8th ed.). Stanford: Cengage Learning.

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