Lenterra's Drag Force Flow (DFF) Sensor: Description of the Technology

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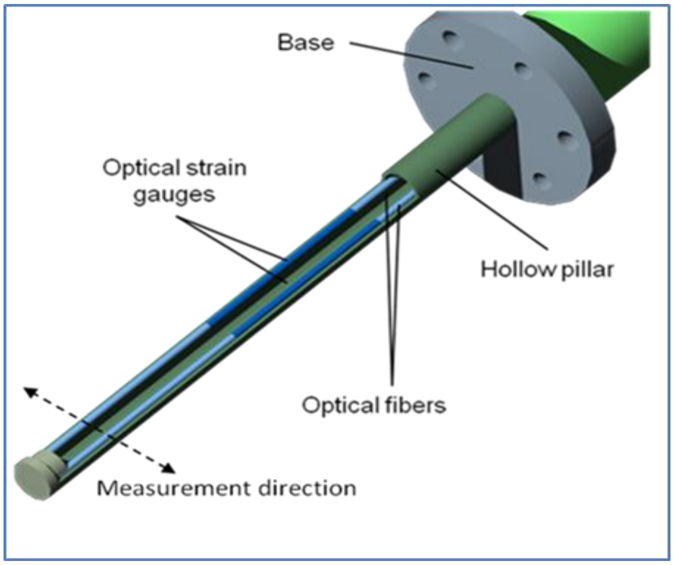
Most of industrial processes involve primary material particles that are being either reduced in size, or blended together into a uniform phase, or agglomerate into larger size particles known as granules. The resulting characteristics (particle density and size distribution) are typically monitored using an off-line rheometer. Drug Force Flow (DFF) sensor is an on-line measurement device that provide real-time monitoring of a magnitude and direction of flow force in a particular locality.

This note describes principles of the DFF sensor measurement in powder and fluid flows.



DFF Probe

In a course of industrial processing, local forces in the processed material vary strongly with time and position in space. For any given point within the mass, flow or shear forces change according to the velocity and mass of the particles passing the point at a given instant. Measuring instantaneous local forces in different positions within the flow may provide information about both the fluid, such as size and density of flow particles, and the system, by comparing the particle mass and velocity in various points within, as well as about process robustness and day-to-day and minute-to-minute uniformity of the operation by showing force-time dependence with good temporal resolution.

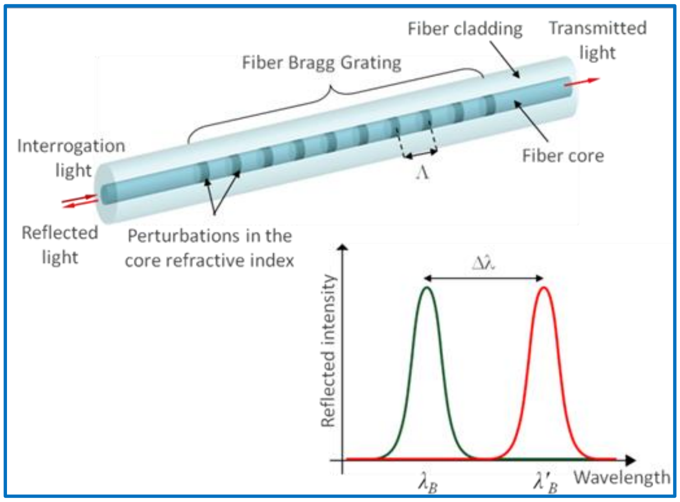
The DFF probe is a hollow cylindrical pin, whose deflection by the flow is sensitively measured by an assembly of optical strain gages, or Fiber Bragg Gratings (FBGs). The FBGs are affixed on the inner surface of the hollow pin and, therefore, not exposed to the flow. The measurement direction of the flow force is along the imaginary plane that is formed by the two optical strain gauges.

The pin is thin (~1-4 mm in diameter), rugged, and stiff. It, therefore, provides minimal intrusion to the flow, and its measurement sensitivity depends weakly on the amount of flow material that may stick to the sensor surface. In addition to force, the optical assembly of the DFF sensor measures the *temperature* of the pin. Information is collected via optical fibers that connect the FBGs to an optical interrogator.

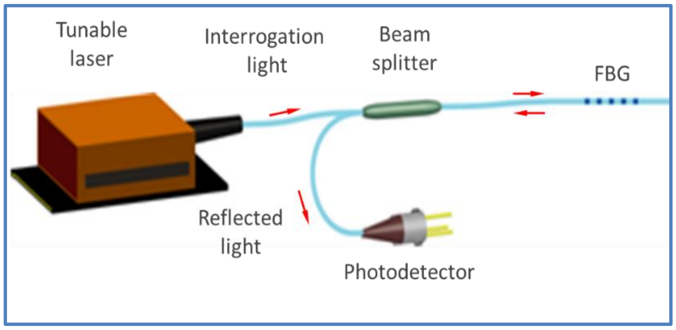
Employing optical sensing provides a number of advantages, such as the measurement is not affected by electromagnetic interference; the probe presents no ignition hazard, and the ability to withstand higher temperatures.

Fiber Bragg Gratings

FBGs are periodic structures of varying refractive index embedded in the core of optical fibers.



While being illuminated by broad-spectrum light, FBG reflects back only a portion of it that corresponds to a specific wavelength (green line spectrum). Bragg grating wavelength, λ_B, the center wavelength that is back-reflected from the FBG, is found as $\lambda_B = 2n\Lambda$, where n is the index of refraction of the fiber material and Λ is the refractive index modulation period. This equation implies that the reflected wavelength λ_B is affected by any variation in the physical or mechanical properties of the grating region. For example, strain on the fiber alters Λ and n, via the stress-optic effect. Similarly, changes in temperature lead to changes both in n via the thermo-optic effect, and in Λ because of thermal expansion or contraction of the grating material. As a result of either force or thermal action, the FBG wavelength λ_B shifts.



Measurement of shift in this wavelength, $\Delta\lambda$, is the core principle of DFF sensor's measurement of flow forces.

Typical interrogation scheme involves a narrow band tunable laser source. Light from the laser travels through the fiber and beam splitter to an FBG located on the inner surface of the pin of the sensor. Depending on the laser wavelength and FBG reflection spectrum, a part of the light is reflected from FBG and travels back through the same fiber and the beam splitter to a photodiode, where its intensity is measured. The reflection spectrum of FBG is recorded by scanning laser wavelength through a predetermined range.

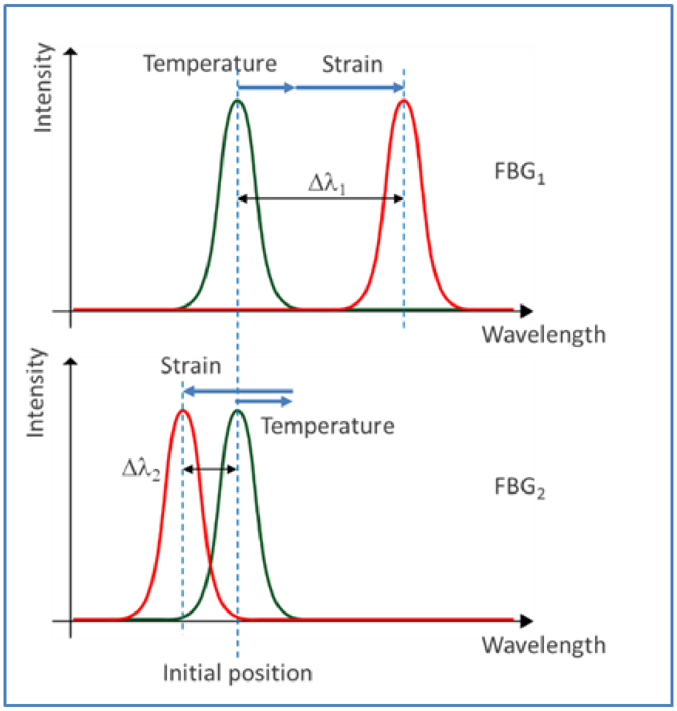
The device recording the FBG spectrum shift, the interrogator, is doing so in a continuous way for all FBGs of the sensor. The interrogator software determines relative spectra shifts and calculates force acting on the pillar as well as ambient temperature according to the following algorithms.

Force and Temperature Measurements

FBG spectrum shifts due to both physical stress and change of ambient temperature. Temperature-related spectrum shift can be calculated from

$$\Delta\lambda_{temperature} = \beta \Delta \mathrm{T} \qquad \text{Eq. 1}$$

where β is the FBG thermal response coefficient (typical value is 9.9 pm/°C). To separate force and temperature action, a pair of FBGs are embedded within the probe. When the pin is deflected, one of the FBGs is stretched and another compressed by a comparable length. Their spectra, therefore, shift in opposite directions. Assuming that temperature shifts are same for both FBGs, temperature and force actions are separated as follows:



$$\Delta\lambda_{force} = \frac{|\Delta\lambda_1 - \Delta\lambda_2|}{2} \qquad \text{Eq. 2}$$

$$\Delta\lambda_{temperature} = \frac{|\Delta\lambda_1 + \Delta\lambda_2|}{2} \qquad \text{Eq. 3}$$

The absolute value of **temperature** change is therefore

$$\Delta \mathrm{T} = \frac{1}{2\beta}(\Delta\lambda_1 + \Delta\lambda_2) \qquad \text{Eq. 4}$$

While the temperature shift occurs independently from motion of the pin, the force-induced shift $\Delta\lambda_{force}$ occurs only due to pin deflection.

A **point force**, F, acting on the tip of cylindrical hollow pin causes the elastic cylinder to bend, with the pin tip deflection calculated as

$$\delta = \frac{Fl^3}{2E\pi(r_o^4 - r_i^4)} \qquad \text{Eq. 5}$$

Here E is the Young's modulus of the material, r_o is the outer radius, r_i is the inner radius of the hollow pin, and l is its length.

Deflection of the probe tip causes each FBG attached to the inner surface of the hollow pin to change its length. Assuming that the force is acting along the measurement direction and that the deflection is small, the relative change of the FBG length, ε, is

$$\varepsilon = \frac{\Delta L}{L} = \frac{\delta(r_i - r_{FBG})}{l} \qquad \text{Eq. 6}$$

where r_{FBG} is the radius of the optical fiber (62.5 microns). Change in the FBG length results in a shift of the FBG spectrum of

$$\Delta\lambda = \alpha\varepsilon \qquad \text{Eq. 7}$$

where α is FBG strain sensitivity (typical value is 1.2 pm/$\mu\varepsilon$).

Equations 5-7 show that the force acting on the pin tip is proportional to the FBG spectrum shift:

$$F = \gamma\Delta\lambda \qquad \text{Eq. 8}$$

where γ can be either calculated or determined via calibration.

Force Measurement Sensitivity

The FBG probe provides an optical response based on the value of the pin tip deflection, δ. By selecting appropriate material, diameter and length, one can fabricate a DFF sensor with desired sensitivity to δ and, therefore, to applied force F.

Existing optical interrogators enable detection of wavelength shifts as small as 0.1 pm, at the measurement frequency of 500 FBG spectra per second. Assuming a stainless steel hollow pin with a length of l= 40 mm, diameter of r_o = 1 mm, and wall thickness of 0.2 mm, the minimal detectable force that is calculated from Eqs. 2 to 7 is 0.5 mN. The corresponding pin tip deflection is δ = 1.4 microns.

Conclusions

The DFF sensor detects drag force exerted by a flow of particles with high sensitivity and temporal resolution. This sensor detects not only the bulk flow properties but also individual force impacts on the sensor probe that provides information about particle mass and momentum. The DFF sensor is a robust and safe device that can be applied to any industrial process. For example, it can been used to fingerprint high shear wet granulation (HSWG) to aid in process monitoring, scale-up, and control. The sensing is based on FBG gratings that optically transmit information about a stainless steel hollow cylindrical probe bending with force impacts. Such a configuration allows electricity-free operations with minimal product contact surfaces and chances of fouling in the process, that are suitable for a highly regulated manufacturing environment that follows current good manufacturing practices (cGMP) for drug product manufacture. Future developments of this technology promise to provide directional resolution of particle flow that can fingerprint the process with greater precision.

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