APPLICATION NOTE 1

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

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Introduction

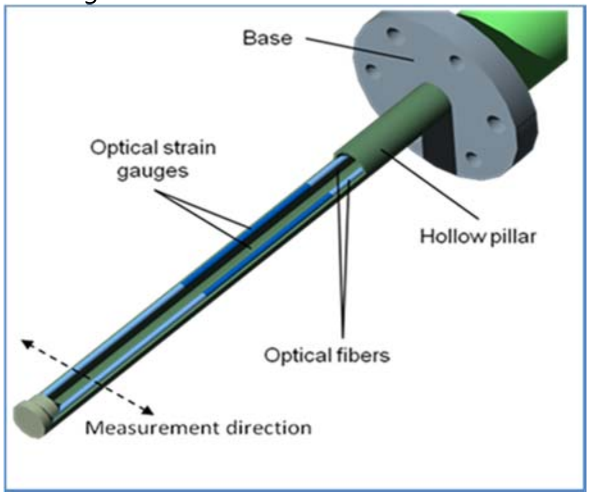
Most of industrial processes involve primary material particles that are either being reduced in size, or blended together into a uniform phase, or agglomerate into larger size particles known as granules. The resulting characteristics (particle density/porosity and size distribution) are typically monitored 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 a flow force in a particular locality.

This note describes principles of the DFF sensor force measurement in a powder and fluid flows. Measurements of single granule impacts are compared with the theoretically calculated forces.

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, force changes 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 would provide information about fluid parameters such as distribution of size and density of the particles, and about the system – by comparing the particle size, density and the velocity magnitude and direction 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 pin can be made thin (~1-4 mm in diameter), rugged (stainless steel), 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. DFF sensor responds to a force component along the measurement axis (indicated with an arrow in the figure), which is typically aligned with the direction of the flow. 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.



A schematic diagram of the drag force flow (DFF) sensor showing internal structure of the hollow pin design. The deflection of the Fiber Bragg Gratings (FBGs) affixed on the inner surface of the pin (labeled as optical strain gauges) sensitively measures the force impact on the pin. Notice that the measurement direction of the flow force is along the imaginary plane that is formed by the two optical strain gauges.

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

Force Measurement Technology

FBGs are periodic structures of varying refractive index embedded in the core of an optical fibers (top left). FBG reflects the propagating light from a broad-spectrum interrogation optical source at specific wavelengths (bottom right). 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 effective index of refraction of the light propagation 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

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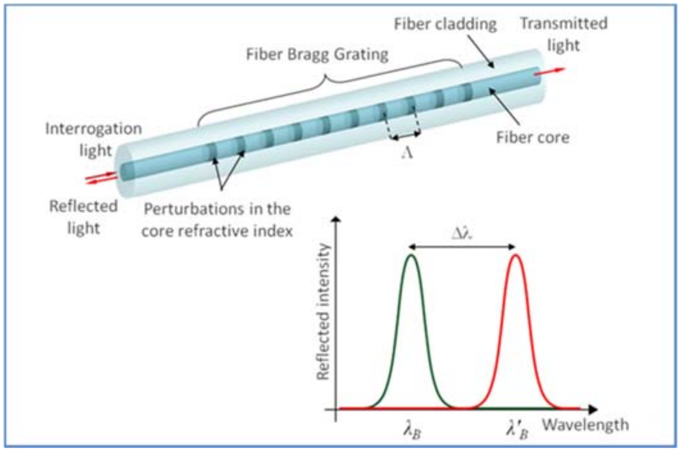
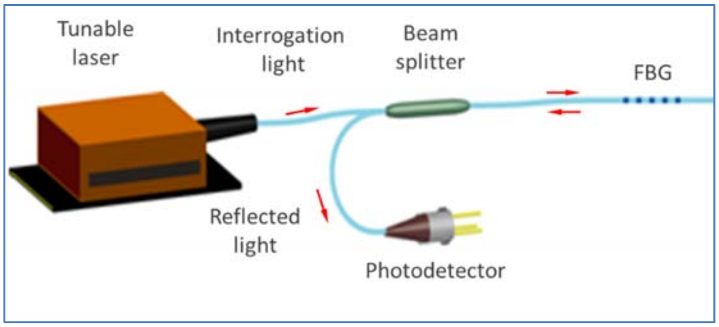


A detailed view of the fiber Bragg grating (FBG) as an optical strain gauge. Miniscule physical bending of the FBG leads to perturbations in the grating constant Λ that impacts the characteristic wavelength of the reflected laser light. Measurement of shift in this wavelength, $\Delta\lambda$, is the core principle of DFF sensor's measurement of flow forces.

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, the central wavelength λ_B shifts. By monitoring the FBG spectrum shift $\Delta\lambda$, therefore, it is possible to determine the force acting on FBG and/or FBG's temperature.

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



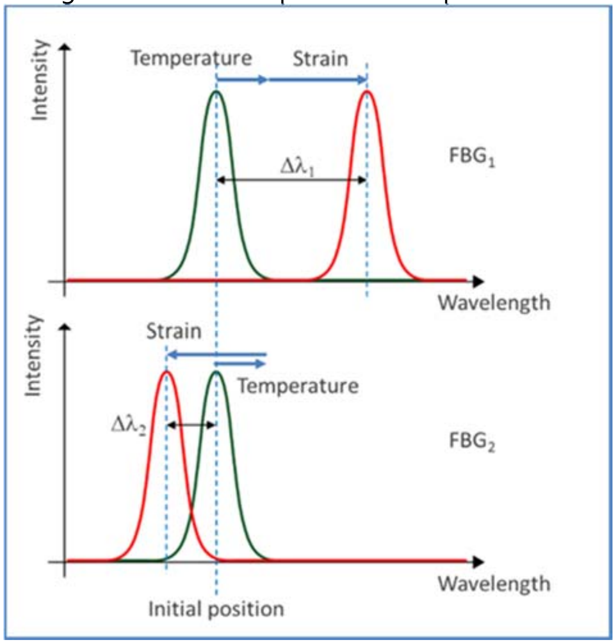
Instrumentation of the DFF sensor demonstrating the principle of the interrogation: a tunable laser that passes light into the fiber Bragg grating (FBG) through an optical circuit, which also detects the wavelength of the light reflected back by FBG.

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 of wavelengths.

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



FBG spectrum shift due to physical stress and ambient temperature.

spectrum shift can be calculated from $\Delta\lambda = \beta\Delta T$, 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 employed with 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, and the shift due to strain for FBG_1 is of the same magnitude as that for stress for FBG$_2$, temperature and force actions are separated as follows:

$$\Delta\lambda_{force} = \frac{|\Delta\lambda_1 - \Delta\lambda_2|}{2} \quad \text{Eq. 4}$$

$$\Delta\lambda_{temperature} = \frac{|\Delta\lambda_1 + \Delta\lambda_2|}{2} \quad \text{Eq. 5}$$

The absolute value of **temperature** change can therefore be calculated from

$$\Delta T = \frac{1}{2\beta}(\Delta\lambda_1 + \Delta\lambda_2). \quad \text{Eq. 6}$$

Consider, for example, a **point force**, *F*, acting on the tip of cylindrical hollow pin. This force causes the elastic cylinder to bend, with pin tip deflection calculated as

$$\delta_{\max} = \frac{Fl^3}{2E\pi(r_o^4 - r_i^4)} \quad \text{Eq. 7}$$

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. The FBG probe provides an optical response based on the value of the pin tip deflection, $\delta_{\max}$. By choosing sensor's pin material and dimensions, it is possible to fabricate flow force sensor with desired sensitivity to $\delta_{\max}$ and, therefore, to an applied force *F*.

Sensitivity

Deflection of the pin tip causes an FBG attached to the inner surface of the hollow pin to change its length. Assuming that the force is acting along the sensor measurement direction and that the deflection is small, the relative change of the FBG length, *ΔL/L* is

$$\frac{\Delta L}{L} = \frac{\delta_{\max}(r_i - r_{FBG})}{l} \quad \text{Eq. 8}$$

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

$$\Delta\lambda = \alpha\frac{\Delta L}{L} = \alpha\varepsilon \quad \text{Eq. 9}$$

where α is FBG strain sensitivity (typical value is 1.2 pm/με). The existing optical interrogator enables detection of wavelength shifts as small as 0.1 pm, at the measurement frequency of 500 spectra per second. Assuming the stainless steel hollow pin length is *l*= 40 mm, its diameter is r_o = 1 mm, and wall thickness is 0.2 mm, the minimal detectable force that is calculated from Eqs. 1, 2 and 3 is 0.5 mN. The corresponding pin tip deflection found from Eqs. 7-98 is $\delta_{\max}$ = 1.4 microns.

Equations 7-9 show that the force acting on the pin tip is proportional to the FBG spectrum shift; or $F = \gamma\Delta\lambda$, where γ can be either calculated or determined via calibration.

Conclusions

The DFF sensor detects the drag force exerted by a flow of particles with tunable and very 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, size, density, and momentum. The DFF sensor is a robust and safe device that can be applied to any industrial process. It has been used to fingerprint HSWG processes to aid in process monitoring, scale-up, and control. This sensing is based on FBG gratings that optically transmit information of 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. The following notes (02 and 03) connect the sensor output to the particle impacts and provide the algorithm for the industrial process monitoring using the DFF technology.