Optical measurement of a Micro Coriolis mass flow sensor

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Abstract

Haneveld [1,2] demonstrated a micro Coriolis mass flow sensor, operating in the measurement range of 0 to 1 g/hr achieving a resolution in the order of 10 mg/hr using a laser vibrometer. Equipped with an integrated capacitive [3] readout the measurement uncertainty amounted to 2% of the full scale range. We demonstrate a down-scaleable and low-cost optical sensor system that measures the movement of the micro Coriolis mass flow tube with a high resolution. The noise level is measured to be 6 mg/hr at a 3σ confidence interval.

1 Coriolis based mass flow measurement

The Coriolis type MEMS-based flow sensor (figure 1) consists of a vibrating tube being driven by Lorentz actuation at the torsion resonance frequency in the order of 3 kHz, depending on the measured medium. A mass flow inside the tube results in

Figure 1: Micro Coriolis mass flow meter chip, with the electrical connections, fluidic connections (on the chip bottom) and the magnets for Lorentz actuation visible on the sides. The chip is designed and fabricated by Haneveld [1,2,3]
Coriolis forces that excite a secondary deflection mode, as shown schematically in figure 2. The tube deformation due to actuation and Coriolis forces is approximately 5 mrad and 35 µrad respectively, at full scale mass flow. Mass flow rate may be inferred by sensing these two components of the deflection. As the Coriolis force is proportional only to the angular velocity and the mass flow, the Coriolis sensor is insensitive to flow profile, pressure, temperature and properties of the fluid (density, viscosity, etc.).

Figure 2: Working principle of the micro Coriolis mass flow meter. An actuation rotational velocity $\omega_{\text{act}}$, in combination with a mass flow $\Phi_m$ yields a Coriolis force $F_{\text{cor}}$.

2 Tube sensing using 2D optical beam deflection

The tested optical measurement principle (figure 3) relies on Optical Beam Deflection, which is often used in atomic force microscopes. A metal plate of 80 x 80 x 0.2 µm on the resonant tube, at the reflection location indicated in figure 3, is used as a mirror-surface to reflect the diode laser beam. The reflection angle of the incident laser beam changes in two DOFs. Over a distance, the angular beam deflection translates into a displacement of beam intensity distribution of the reflected beam, which is sensed by a quad cell photo sensor. The quad cell enables 2-DOFs spot displacement measurement, distinguishing between angular deflections caused by actuation forces and by Coriolis forces.

Sensitivity and range of spot displacement on the detector are tunable for each DOF by dimensioning of the spot radii on the detector. The optimal detector distance is equal to the Rayleigh range of the Gaussian laser beam, and therefore defined by the
waist radius (limited by reflector dimensions) and the laser wavelength. The latter is chosen 650 nm because of the reflectivity spectrum of the gold reflector on the tube and the quad cell sensitivity which are both high for $\lambda > 650$ nm.

A phase locked loop is used to actuate the tube at its instantaneous resonance frequency, together with feedback control to maintain a constant oscillation amplitude. Frequency mixing with two orthogonal reference sinusoids removes out-of-band noise and resolves the phase relations of the measurements, as done in lock-in amplifiers.

Figure 3: Working principle of the optical beam deflection using a laser source and a quadrant cell which resolves the spot displacement due to rotational tube deflections. The shown location of reflection shows little translation and is therefore optimal.

Figure 4: Experimental setup. Components are annotated. Also, three cylindrical lenses can be seen, which are used to shape the spot independently in two directions.
3 Experimental results

In experiments performed using the laboratory setup shown in figure 4 the noise level is found to be in the order of 1 mg/hr. As shown in figure 5, above a certain hydrostatic pressure the measured mass flow is an almost perfectly linear function of the fluid pressure, resulting in a $\pm 3\sigma$ confidence interval of 6 mg/h for a response time to reach 67% of a step in 0.1 s. Integrated design study revealed that an improvement of at least a factor 10 is possible by increasing both the actuation measurement range and the Coriolis measurement sensitivity, while reducing the outer dimensions to 50 x 35 x 12 mm.

Figure 5: Pressure versus (laminar) mass flow as measured by the measurement system. The full flow in this case equals 0.4 g/h. An offset due to a hydrostatic pressure is visible.

References:

