SINGLE-CHIP MASS FLOW CONTROLLER WITH INTEGRATED CORIOLIS FLOW SENSOR AND PROPORTIONAL CONTROL VALVE

Jarno Groenesteijn1, Dennis Alveringh1, Maarten S. Groen1, Remco J. Wiegerink1 and Joost C. Lötters1,2

1MESA+ Institute for Nanotechnology, University of Twente, Enschede, THE NETHERLANDS
2Bronkhorst High-Tech BV, Ruurlo, THE NETHERLANDS

ABSTRACT

We have designed, fabricated and tested the, to our knowledge, first ever single-chip mass flow controller with an integrated Coriolis mass flow sensor and a proportional control valve. A minimum internal volume is obtained, because the complete fluid path is integrated in a single chip. We demonstrated that the system can control mass flow up to 70 mg h⁻¹ nitrogen gas at an applied pressure of 500 mbar.

INTRODUCTION

Accurate flow control is essential in e.g. gas chromatography, where the analytical result is amongst others depending on the stability of the carrier gas flow. Since the flow rates involved could be extremely small, in the range of 75 mg h⁻¹ (1 mL/min N₂) or less, it is important to have a very compact integrated system with a very low internal volume. Other applications are flow chemistry for the production of specialty drugs, and infusion systems to administer drugs to newborn babies, both requiring accurate control of a very low flowrate. Many microvalves have been presented in literature in the past, but the number of proportional control valves is significantly lower [1, 2, 3]. In most cases, the focus of the publications lies on the microvalve itself and not on combining these valves with flow sensors to make a flow controller. Some combinations have been proposed using either thermal flow sensors [4, 5, 6] or (differential) pressure based flow sensors [7, 8]. However, these solutions have very limited sensing resolution on the order of a few percent of their full range and their sensing principle, and thus their ability to control the flow, is dependent on the type of fluid flowing through the flow controller.

OPERATION PRINCIPLE AND DESIGN

The integrated mass flow controller presented here consists of an in-plane proportional control valve integrated on the same chip with a micro Coriolis mass flow sensor which can sense the mass flow through the sensor independent of the fluid and with high accuracy. Below the separate parts are introduced and the work performed to integrate them on the same chip is described.

Micro Coriolis mass flow sensor

A Coriolis mass flow sensor consist of a vibrating channel through which a fluid flows. Figure 1 shows the rectangular channel window, vibrating around the twist axis. Due to the mass flow $\Phi_m$, a Coriolis force $F_C$ perpendicular to the rotational axis $\omega_y$ develops exciting a second motion according to:

$$F_C = -2L_x(\omega_{act} \times \Phi_m), \quad (1)$$

where $L_x$ is the length of the channel perpendicular to the rotational axis (the width of the channel window) as shown in Figure 2. Unlike other types of sensors, the Coriolis measurement principle is independent of fluid properties, allowing for measurement of both liquids and gases without any need for recalibration or conversions.

Previously, we presented micro Coriolis mass flow sensors [9, 10] with a freely suspended, semi-circular channels located right underneath the surface of the chip. The channel width was 40 µm and the rectangular channel window had a width and height of 4 mm and 2.5 mm respectively. The channel’s movement is measured using two capacitive read-out structures located at both sides of the twist rotational axis. The Coriolis-induced movement will cause a phase-shift between the outputs of these two structures proportional to the amplitude of the Coriolis movement and inversely proportional to the amplitude of the measured actuation movement. These sensors are capable of measuring with an accuracy of 0.5 % reading and a zero stability of 2 mg h⁻¹. The pressure drop over the sensor was approximately 1 bar at 100 mg h⁻¹ of nitrogen flow. This design was adapted for higher sensitivity and lower pressure drop as explained below.
In-line proportional valve

In [11], we presented a proportional valve that could control the mass flow between two surface channels which was fabricated in a process similar to that of [9]. Figure 3 shows the operating principle of this valve. The incoming flow through a surface channel is shown with a blue line. A vertically translating valve plate controls the flow from the outer cavity, through the radial flow channel between the valve plate and valve seat, to the inner cavity (blue arrow). It then flows through outflow channels to other surface channels on the chip (yellow arrows). Since both incoming and outgoing flow are connected with surface channels, the valve can be used to control the flow between different devices on the same chip. The separation between valve plate and valve seat is controlled by an external piezo-electric actuator. The in-line proportional control valve presented in [11] was capable of operating up to an applied pressure of 200 mbar. When the valve was fully open, this resulted in a flow of 75 mg h\(^{-1}\).

![Figure 3: Artist impression of the proportional control valve showing the ring-shaped valve plate that controls the hydraulic resistance between the inner and outer cavity.](image)

Integrated micro Coriolis mass flow controller

To be able to combine the micro Coriolis mass flow sensor and the in-line proportional valve in an integrated mass flow controller, they must both operate in the same flow and pressure ranges. To increase the maximum supported pressure of the valve, the design has been changed to reduce the mechanical bending stress at the places where it was most highly concentrated (e.g. by the sharp edges in the membrane). To achieve a lower pressure drop over the sensor, the width of the channels has been increased from 40 µm to 56 µm. A larger channel diameter will result in a stiffer channel while the mass of the channel and fluid will increase. Both these effects result in a lower sensitivity to the Coriolis force [12]. The capacitive read-out structures have therefore been placed closer together to decrease the sensitivity to actuation movement, resulting in an increased sensitivity to mass flow (in \(^{\circ}/(g/h))\).

Using the phase shift signal of the micro Coriolis mass flow sensor, a proportional controller can be used to control the separation of the valve using a piezo actuator. This is shown schematically in Figure 4.

![Figure 4: Schematic overview of the system showing the proportional controller and the integrated flow controller chip with the micro Coriolis mass flow sensor and the valve.](image)

**FABRICATION**

The fabrication process used to fabricate the integrated Coriolis mass flow controller has been described in [11]. An overview is shown in Figure 5. A thin silicon-rich nitride (SiRN) layer is deposited on a silicon-on-insulator (SOI) wafer with a device layer of 50 µm, a buried oxide (BOX) layer of 5 µm and a handle layer of 400 µm. The fluidic inlets and outlets are etched from the backside of the wafer using deep reactive ion etching (DRIE) (Figure 5a). Rectangular slits, 5 µm long and 1.2 µm wide, are etched in the SiRN layer at the top to define the outline and size of the channels and cavities. Using a semi-isotropic SF\(_6\) plasma etch, the surface channels and cavities are etched through these slits (Figure 5b). The BOX layer in the in-and outlets and underneath the valve seat are removed using HF etching. To prevent valve stiction, this is done with a combination of fast liquid phase HF etching and slower vapour phase HF etching (Figure 5c). A thick (2 µm) layer
of SiRN is then deposited to form the channel/cavity wall and seal the etch slits (Figure 5d). A 10/200 nm thick layer of chromium and gold is sputtered and patterned on top of the SiRN to form the electrodes for actuation and read-out of the Coriolis mass flow sensor. The silicon surrounding the outflow channels is removed using an isotropic plasma etch to reduce their bending stiffness when the valve is closing (Figure 5e). The finished chip is shown in Figure 6. The rectangular tube window of the Coriolis mass flow sensor is shown to the left and the proportional control valve to the right. The pressure sensors at the bottom have not yet been characterized. The channels that connect the different parts of the chip are indicated with a red dashed line.

The chip is mounted on a printed circuit board (pcb) to make electrical connections to the chip. Two permanent magnets are glued to the pcb on each side of the chip to provide the magnetic field for the used Lorentz force actuation. The valve is actuated using an external piezoelectric actuator that applies a controlled displacement to the valve plate by means of a glass stylus. This is shown in Figure 7.

Figure 7: Photograph of the chip mounted on a printed circuit board with the two permanent magnets to either side of the chip. A glass stylus is used to transfer the displacement from the piezoelectric actuator to the valve plate.

EXPERIMENTAL

Measurement Setup

To characterize the integrated mass flow controller, three different measurements had to be performed: (i) characterisation of the micro Coriolis mass flow sensor to calibrate the sensitivity of the sensor, (ii) characterisation of the mass flow controller while using a proportional control loop to control the valve opening and (iii) zero-flow stability of the sensor.

The measurement setup for the first two measurements is shown schematically in Figure 8. A Bronkhorst P-602CV pressure controller is connected to the inlet of the chip. On the chip, the fluid then first flows through the micro Coriolis mass flow sensor and then through the proportional valve. The outlet of the chip is connected to a Bronkhorst F-111B EFlow flowsensor to measure the actual flow through the chip. The zero flow stability is measured by filling the channels with nitrogen and closing both the in- and outlets of the chip. The output of the micro Coriolis mass flow sensor is measured over a period of one hour while the valve is not actuated.

Figure 8: Schematic overview of the measurement setup used to characterise the single-chip micro Coriolis mass flow controller.

Measurement Results

Figure 9 shows the measurement result when the mass flow controller is actuated to control mass flows between 0 and 70 mg h$^{-1}$. The phase shift measured by the micro Coriolis sensor shows a linear behaviour over the whole range up to 70 mg h$^{-1}$, with a sensitivity of 6.5$^\circ$/g/h). The zero flow stability measurement showed a standard deviation of 0.1 mg h$^{-1}$.

Figure 10 shows the results when the setpoint of the proportional controller is varied while the pressure controller was set to 1.3 bar(a). The setpoint is varied between 27 mg h$^{-1}$, 38 mg h$^{-1}$ and 33 mg h$^{-1}$.

DISCUSSION

Measurements show that when the valve is closed, a leakage flow of approximately 15–20 % of its full scale can be measured by the reference sensor. It has been shown by Groen et al. [11] that this is equivalent to a minimum separation of approximately 1 µm for such valves. This min-
is presented. The micro Coriolis mass flow sensor consists of a freely suspended channel window of 4 mm x 2.5 mm. The channel has a width of 56 µm and a wall thickness of 1.5 µm. The mass flow controller can control the flow up to 70 mg h\(^{-1}\) at an applied pressure of 500 mbar. Future work will focus on reducing the leakage through the valve when it is fully closed, increasing the maximum flowrate and miniaturization of the complete system by mounting the piezoelectric actuator directly on the chip.

**ACKNOWLEDGEMENTS**

The authors would like to thank Remco Sanders for his work on the measurement setup. This work is carried out within the Coriolis-based SAS project of NanoNextNL.

**REFERENCES**


**CONTACT**

J. Groenesteijn, +31 53 489 4992, j.groenesteijn@utwente.nl

**CONCLUSIONS**

A single-chip mass flow controller with integrated micro Coriolis mass flow sensor and proportional control valve minimum separation can be caused by several factors, e.g. a particle stuck underneath the valve plate or non-symmetric actuation of the valve plate, causing it to tilt when closing. The latter can be solved by creating a single point of contact at the centre of the valve plate between the piezo actuator and the valve.

**Figure 9:** Measured dry nitrogen gas flow through the chip measured by the integrated Coriolis mass flow sensor versus measurement with an external reference sensor. The dashed line is a linear regression of the measurement values.

**Figure 10:** Measured dry nitrogen gas flow through the in-plane valve measured by the integrated Coriolis mass flow sensor (blue) and an external flow sensor (green) when the valve is controlled by a proportional controller. The red line is the setpoint for the control loop and the output voltage to the piezo controller is shown in magenta.