Design, Fabrication, and Characterization of a Micro Coriolis Mass Flow Sensor Driven by PZT Thin Film Actuators

Yaxiang Zeng, Jarno Groenesteijn, Dennis Alveringh, Remco J. Wiegerink, and Joost C. Lötters

Abstract—A micro Coriolis flow sensor accurately measures small mass flows without being affected by properties of the fluid. This paper presents a micro Coriolis mass flow sensor driven by PZT thin film piezoelectric actuators, which allows a combination of large actuation force, low power dissipation and virtually no self-heating. The sensor was fabricated using surface channel technology, resulting in a tube diameter of 40 µm and a thin silicon-rich silicon nitride tube wall of 1.2 µm thick, with a few additional steps to form the integrated piezoelectric actuators. The integrated actuators can actuate the sensor into both swing mode and twist mode. Both actuation modes were evaluated for different fluids and the results are presented in this paper. In the case of swing mode actuation, an optical readout was used to detect the resulting Coriolis movement, resulting in a relatively low sensitivity. In the case of twist mode actuation, a capacitive readout was used and, in comparison to previously published devices, a high mass flow sensitivity was achieved thanks to an optimized readout design. The measurement results show the read-out noise has a standard deviation of 0.15% of the full scale of 1.8 g·h⁻¹ when actuated in the twist mode.

Index Terms—Coriolis mass flow sensor, piezoelectric actuator, PZT, capacitive readout, fluid-structure interaction, density compensation.

I. INTRODUCTION

Accurate flow measurement and control are critical for many applications such as green energy [1], petroleum industry [2], microreactors [3] and medical infusion systems [4]. In any application where flow of a fluid mixture of varying composition needs to be measured, flow sensors based on the Coriolis principle are the preferred choice because of their ability to measure true mass flow regardless of the properties of the fluid [5].

Several studies have reported on miniaturized Coriolis mass flow sensors and methods for improving their performance. Micro Coriolis mass flow sensors with electrostatic actuation [6], [7] and Lorentz force actuation [8], [9] have been reported. A mass flow resolution in the range of milligram per hour has been realized with the reported sensors. However, both electrostatic actuation and Lorentz force actuation have their respective limitations. Electrostatic actuation either requires a high quality factor [10] or high voltages to obtain sufficient actuation force [11]. Lorentz force actuation results in relatively large power dissipation in the order of 1 mW and causes Joule heating of the sensor tube [12]. Furthermore, it requires external magnets that can interfere with other devices nearby. Using piezoelectric actuation is an option to avoid these problems as it results in a large actuation force with low power dissipation of less than 1 µW. Recent developments in deposition technology allow integration of piezoelectric materials into MEMS devices. However, most of the reported devices have simple structures like cantilevers [13], [14] or membranes [15], [16]. The integration of piezoelectric materials on more complicated structures like a suspended microfluidic channel is still rare [17], [18]. We have reported preliminary measurements on a micro Coriolis mass flow sensor driven by integrated lead zirconate titanate (PZT) thin film actuators in [19], using swing mode actuation and an optical readout. In this paper we present a detailed analysis and characterization, including twist mode actuation and an on-chip optimized capacitive readout.

The paper is organized as follows. First, in Section II the operating principle of a Coriolis mass flow sensor is explained when actuated in either swing or twist mode. The sensor design is explained together with the design considerations. Next, in Section III, the fabrication process of the sensor is presented. After that, in Section IV, the different measurement setups that were used for swing mode and twist mode actuation are explained, followed by the presentation of the results in Section V. The sensor response for different fluids and different actuation modes is presented and discussed. The measurement results are compared with previously reported micro Coriolis mass flow sensors with electrostatic or Lorentz force actuation.
II. DESIGN AND OPERATION PRINCIPLE

A schematic drawing of the micro Coriolis mass flow sensor driven by PZT actuators is shown in Fig. 1a. A rectangular loop of the microfluidic channel is suspended from one side. A fluid mass flow $\phi_m$ flows inside the suspended channel as indicated by the arrows. Note that a Coriolis flow sensor can measure mass flow bidirectionally [20], thus the flow direction can also be opposite to the direction indicated by the arrows. Two sets of capacitive readout combs are placed near the mid-point of the channel as shown in Fig. 1b,c. The thin film PZT actuators are placed on the top surface of the channel close to the suspension points as shown in Fig. 1d. The combination of the PZT thin film and the channel underneath forms a unimorph actuator, resulting in out-of-plane bending of the channel when a voltage is applied. Note that the interdigitated electrode pattern results in a periodically alternating electric field direction, as indicated in Fig. 1d. The PZT thin film is polarized by a DC bias voltage between the interdigitated electrodes, so that the polarization direction of the PZT is also alternating [21], [22]. As a result the PZT material is actuated in the $d_{33}$ mode along the $y$ direction.

The two actuators can be driven independently from each other, which allows actuation of both swing mode and twist mode vibration of the tube. Fig. 2 shows a schematic illustration of each actuation mode and the corresponding vibration due to the Coriolis forces when a fluid flows through the channel. Fig. 2a depicts the situation in case of twist mode actuation. The thin black line indicates the tube position at rest. The orange arrows correspond to the direction of fluid flow. The actuation mode indicated by the grey tube shape corresponds to a rotation over angle $\phi_2$, which is also indicated in Fig. 1. At the position of the capacitive readout electrodes this results in an amplitude of displacement $A_{act}$. The small blue arrows represent the instantaneous velocity of...
Fig. 2. Illustration of the two possible actuation modes and their corresponding Coriolis mode. The thin black lines indicate the tube shape at rest. The orange arrows indicate the fluid flow direction. The actuation mode is generated by the piezoelectric actuators and the Coriolis mode is the result of the Coriolis forces due to the mass flow inside the tube. The swing and twist mode correspond to a rotation over angle $\phi_1$ and $\phi_2$, respectively, as also shown in Fig. 1a. The small blue and red arrows indicate the momentary channel velocity and Coriolis force distribution, respectively. The tube displacements due to the actuation $A_{\text{act}}$ and due to the Coriolis forces $A_{\text{cor}}$ are indicated at the positions where they are measured.

A. Twist Mode Actuation

Twist mode actuation was achieved by driving the two actuators in counterphase using actuation voltages $V_1$ and $V_2$ of the following form:

$$V_1 = V_0 + V_a \sin(\omega t)$$
$$V_2 = V_0 - V_a \sin(\omega t)$$

where $\omega$ represents the angular frequency of the actuation signal, which is equal to the resonance frequency of the twist mode. $V_a$ represents the amplitude of the AC part of the signal. $V_0$ is a bias voltage which is needed in thin film PZT layers to prevent changing the poling direction of the material. $V_0$ can be applied by either an offset on the driving signal or a bias voltage on the counter electrode of the actuator as will be explained in Section IV-A.

The momentary displacement of the center points of the two capacitive readouts can be decomposed into an actuated displacement $S_{\text{act}}$ and a displacement due to the Coriolis forces $S_{\text{cor}}$, where the latter is 90° out of phase as the Coriolis forces are proportional to the angular velocity of the tube, i.e., proportional to the time derivative of $S_{\text{act}}$. With $A_{\text{act}}$ representing the actuation mode amplitude and $A_{\text{cor}}$ representing the Coriolis mode amplitude, the displacements $S_{\text{act}}$ and $S_{\text{cor}}$ are expressed as:

$$S_{\text{act}} = A_{\text{act}} \cos(\omega t + \theta_0)$$

The channel at a specific time, which in combination with fluid flow results in Coriolis forces, indicated by the small red arrows, that actuate the Coriolis mode. At the position of the capacitive readout electrodes the latter results in a displacement amplitude $A_{\text{cor}}$. Fig. 2b depicts the situation in case of swing mode actuation. The grey tube shape indicating the actuation mode now corresponds to a rotation over angle $\phi_1$. Again, the instantaneous velocity of the channel and the resulting Coriolis forces are indicated by small blue and red arrows, respectively. In case of swing mode actuation an optical readout is used that measures the displacement amplitudes $A_{\text{act}}$ and $A_{\text{cor}}$ at the corners of the channel loop. Note that in Fig. 2b, the red Coriolis force arrows are pointing towards the channel while in Fig. 2a, the red arrows are pointing away from the channel. This is because in our design the resonance frequency of the twist mode is higher than that of the swing mode. In case of twist mode actuation this results in an additional phase shift of 180 degrees.
where \( \theta_0 \) represents an arbitrary phase shift. \( A_{\text{act}} \) and \( A_{\text{cor}} \) represent the displacement amplitude of actuation mode and Coriolis mode.

Note that everywhere on the tube the Coriolis displacement \( S_{\text{cor}} \) is much smaller than the actuated displacement \( S_{\text{act}} \), except for the region close to the midpoint in case of twist mode actuation. The fact that the magnitudes of \( S_{\text{cor}} \) and \( S_{\text{act}} \) are comparable near the midpoint allows the use of a capacitive readout as indicated in Fig. 1. As long as the changes in capacitance are relatively small, they will be proportional to the displacement of their center points which are at distance \( d_c \) from each other. A detailed analysis on the relation between the out-of-plane electrode distance \( g_e \) and the capacitance changes can be found in [23]. The displacement amplitudes \( A_{\text{act}} \) and \( A_{\text{cor}} \) at the center points of the two capacitor structures can be expressed in terms of the rotation angles \( \varphi_1 \) and \( \varphi_2 \) with small angle approximation:

\[
A_{\text{act}} = \frac{\varphi_2 d_c}{2}
\]

(5)

\[
A_{\text{cor}} = \varphi_1 L_1
\]

(6)

With that we can write the displacements \( S_1 \) and \( S_2 \) at the center of each capacitor as:

\[
S_1 = -S_{\text{act}} + S_{\text{cor}} = -A_{\text{act}} \cos(\omega t + \theta_0) + A_{\text{cor}} \sin(\omega t + \theta_0)
\]

(7)

\[
S_2 = S_{\text{act}} + S_{\text{cor}} = A_{\text{act}} \cos(\omega t + \theta_0) + A_{\text{cor}} \sin(\omega t + \theta_0)
\]

(8)

which can be rewritten as:

\[
S_1 = A \sin(\omega t + \theta + \theta_0 - \pi/2)
\]

(9)

\[
S_2 = A \sin(\omega t - \theta + \theta_0 + \pi/2)
\]

(10)

where

\[
A = \frac{1}{2} \sqrt{\left(\varphi_2 d_c\right)^2 + \left(2\varphi_1 L_1\right)^2}
\]

(11)

and, with small angle approximation:

\[
\theta = \arctan\left(2\varphi_1 L_1 / \varphi_2 d_c\right) \approx \frac{2\varphi_1 L_1}{\varphi_2 d_c}
\]

(12)

The minus sign in (7) indicates the phase relationship between \( S_1 \) and \( V_1 \) from (1). The capacitive readout will result in output signals proportional to (9) and (10). The phase shift of \( 2\theta \) between these signals is proportional to the mass flow and independent of the actuation amplitude \( \varphi_2 \), because \( \varphi_1 \) is proportional to the product of mass flow and \( \varphi_2 \). From (12) we can conclude that the phase shift versus mass flow sensitivity can be improved by increasing the ratio \( L_1/d_c \), which is the reason for placing the capacitive readout combs close to the twist mode rotation axis. Note that the exact value of the distance \( g_e \) is defined by stresses in the microfluidic channel and will be dependent on temperature. This will affect the signal magnitudes in the capacitive readout, however, as this affects both displacements \( S_{\text{act}} \) and \( S_{\text{cor}} \) in the same way, the net effect on the measured phase shift is very small.

B. Swing Mode Actuation

Swing mode actuation was achieved by driving the two actuators with the same voltages, that is:

\[
V_1 = V_2 = V_0 + V_a \sin(\omega t)
\]

(13)

In this case the capacitive readout cannot be used, as the capacitance changes due to the actuated swing mode will be much larger than the changes due to Coriolis forces. Therefore, an optical readout is used instead, which measures the tube displacement near the corners of the tube, at distance \( L_2/2 \) from the twist mode rotation axis.

Using a similar derivation as above, we can write the displacements \( S_1 \) and \( S_2 \) at these corners as:

\[
S_1 = -\varphi_1 L_1 \cos(\omega t + \theta_0) - \frac{\varphi_2 L_2}{2} \sin(\omega t + \theta_0)
\]

(14)

\[
S_2 = -\varphi_1 L_1 \cos(\omega t + \theta_0) + \frac{\varphi_2 L_2}{2} \sin(\omega t + \theta_0)
\]

(15)

Which we can rewrite as:

\[
S_1 = A \sin(\omega t + \theta_0 - \theta - \pi/2)
\]

(16)

\[
S_2 = A \sin(\omega t + \theta_0 + \theta - \pi/2)
\]

(17)

with

\[
A = \frac{1}{2} \sqrt{\left(\varphi_2 L_2\right)^2 + \left(2\varphi_1 L_1\right)^2}
\]

(18)

and, with small angle approximation:

\[
\theta = \arctan\left(\frac{\varphi_2 L_2}{2\varphi_1 L_1}\right) \approx \frac{\varphi_2 L_2}{2\varphi_1 L_1}
\]

(19)

Again, the measured phase shift \( 2\theta \) between the output signals represented by (16) and (17) is proportional to the mass flow.

C. Actuation Frequency Dependence of Phase Shift Versus Mass Flow Sensitivity

The Coriolis force due to a mass flow inside the tube is proportional to the product of mass flow and angular velocity of the tube. The latter is proportional to the actuation amplitude, but also to the actuation frequency. Therefore, if the tube is actuated at its resonance frequency a shift in resonance frequency will change the phase shift versus mass flow sensitivity of the sensor. Haneveld et al. [24] derived expressions for the ratio between the actuation mode amplitude and the Coriolis mode amplitude. When the sensor is actuated in twist mode, \( \varphi_1/\varphi_2 \) is expressed as:

\[
\frac{\varphi_1}{\varphi_2} = \frac{2L_2 L_3}{K_{\text{sw}} K_{\text{tw}} \omega_{\text{sw}} \omega_{\text{tw}} \phi_m}
\]

(20)

where \( L_2 \) and \( L_3 \) are the dimensions of the channel loop as shown in Fig. 1. \( K_{\text{sw}} \) represents the modal spring constant of the swing mode. \( \omega_{\text{sw}} \) and \( \omega_{\text{tw}} \) represent the resonance angular frequency of the swing and twist mode respectively. \( \phi_m \) is the fluid mass flow through the channel.
When the sensor is actuated in the swing mode, \( \varphi_2/\varphi_1 \) is expressed as:

\[
\frac{\varphi_2}{\varphi_1} = \frac{2L_2L_3}{K_{twist} \omega_{swing} \phi_m} \tag{22}
\]

where \( K_{twist} \) represents the modal spring constant of the twist mode.

We can rewrite (12) and (19) to find the phase shift as a function of mass flow \( \phi_m \) for twist mode actuation

\[
\frac{\theta}{\phi_m} = \frac{4L_2L_3}{K_{swing} \omega_{twist} \phi_m} L_1 \frac{L_1}{d_c} \tag{23}
\]

and for swing mode actuation:

\[
\frac{\theta}{\phi_m} = \frac{L_2L_3}{K_{twist} \omega_{swing} \phi_m} L_1 \frac{L_1}{L_2} \tag{24}
\]

Thus, when comparing measurement results of fluids with different densities, a correction is needed according to (23) or (24) to correct for the changes in resonance frequencies \( \omega_{twist} \) and \( \omega_{swing} \).

Another method of comparing results from fluids with different density is to use the time delay instead of phase shift [25]. (23) can be rewritten as follows to give the time delay \( \Delta t \):

\[
\frac{\Delta t}{\phi_m} = \frac{\theta}{\omega_{twist}} \frac{L_1}{\phi_m} \frac{L_1}{d_c} K_{twist} \frac{4L_2L_3}{L_1} \tag{25}
\]

\[
\frac{\Delta t}{\phi_m} = \frac{4L_2L_3}{K_{swing}} \frac{L_1}{L_1} K_{twist} \frac{L_1}{d_c} \tag{26}
\]

The right hand side of (26) is independent of fluid properties. \( \Delta t/K^2 \) can be used as a parameter to determine the mass flow.

The term \( K^2 \) remains almost constant when the fluid density changes [26]. Thus the time delay can also be used as a parameter to determine the mass flow.

Similarly, the ratio between the time delay and mass flow for swing mode actuation can be written as:

\[
\frac{\Delta t}{\phi_m} = \frac{\theta}{\omega_{swing} \phi_m} \frac{L_2L_3}{L_1} \frac{L_2}{L_1} \tag{27}
\]

which is also independent of the fluid density.

III. FABRICATION PROCESS

The fabrication process of the device is based on [27], [28], with some additional steps to include the PZT thin film actuators. Fig. 3 briefly describes the fabrication process. Firstly, a 500 nm thick silicon rich silicon nitride (SiRN) layer was deposited on the wafer by low pressure chemical vapor deposition (LPCVD). A 50 nm thick chromium layer was deposited on top of the SiRN layer by sputtering. Then, small slits were etched in the chromium layer with ion milling. Using the chromium layer as hard mask, the small slits were etched into the SiRN layer with reactive ion etching (RIE) and, subsequently, the channels were etched through those slits by isotropic SF6 plasma etching (Fig. 3a). The chromium layer was removed by wet etching. Then, a silicon dioxide layer was deposited by using LPCVD of TEOS (tetraethoxysilane) (Fig. 3b). The holes for fluidic inlets and outlets were etched from the back side of the wafer by DRIE, using the silicon dioxide layer inside the channels as etch stop. Next, the silicon dioxide was removed by 50% HF wet etching (Fig. 3c). Then another layer of SiRN was deposited by LPCVD. This second SiRN layer should be thick enough to close the slits etched in Fig. 3a to form channels with a SiRN wall. After this, a 10 nm LaNiO3 and 1 μm PZT stack was deposited on the top side of the wafer through pulsed laser deposition (PLD) as shown in Fig. 3d. The PLD process has been described in [29]. A titanium/platinum electrode layer with thickness of 10 nm/100 nm was deposited on top of the PZT layer by sputtering. Then the titanium/platinum layer and the PZT layer were patterned by ion milling to form interdigitated electrodes on top of PZT thin film actuators (Fig. 3e). The photoresist development process is a wet process. In order to keep the fluidic channels dry, dicing foil was applied on the back side of the wafer. Then a chromium / gold layer with thickness of 10 nm/200 nm was deposited and patterned to form conductive tracks and the capacitive readout combs. The last step of the process was to release the silicon nitride channel by etching the silicon around it. This was done by first patterning the
SiRN layer by RIE and then etching the silicon substrate by isotropic SF6 plasma etching. The schematic cross section after the release step is shown in Fig. 3f.

The finished chip as shown in Fig. 4 was glued on a printed circuit board (PCB). Through holes in the PCB are aligned to the fluidic inlet and outlet at the back side of the chip. Then the PCB is clamped onto a 3D printed holder and connected to the external flow control system. Details on the PCB, the 3D printed holder and the fluidic setup can be found in [30]. To make a good ground connection between the silicon substrate and the PCB, two corners of the chip were cut and covered with silver paint. A photograph of the finished chip bonded on the PCB is shown in Fig. 5.

Fig. 6 shows a photograph of the capacitive readout structures. The gold electrode layer is on top of a silicon nitride support structure. The latter is fully symmetrical with respect to the twist mode vibration axis. The gold layer covers only part of the support structures so that the two capacitive readout structures have a different center position.

Fig. 7 shows a cross sectional SEM image of the microfluidic channel. The channel consists of silicon rich silicon nitride. The ridges in the channel wall are the result of the isotropic etching through small slits.

Fig. 8 shows a SEM photograph of the PZT actuators. The platinum interdigitated electrodes are deposited on top of the PZT layer. The fingers are 5 \( \mu \text{m} \) wide with 5 \( \mu \text{m} \) spacing between adjacent fingers. Interdigitated electrodes were used instead of parallel plate electrodes because this does not require a bottom electrode and simplifies the fabrication process. Parallel to the channel with actuators thin silicon nitride bridges support additional wiring for the capacitive readout. The additional wiring can also be used for Lorentz force actuation. Fig. 7 and Fig. 8 show that there are four wires on the channel. The two wires at the sides are connected to the two capacitive readout structures. The two wires in the middle can be used for Lorentz force actuation. In this paper, Lorentz force actuation was used to actuate the sensor in twist mode to compare the performance with piezoelectric actuation.

### IV. Measurement Setup

Two measurement setups were used to characterize the sensor with twist mode and swing mode actuation. The most important difference is in the readout of the sensor. In the case of twist mode actuation the on-chip capacitive readout was used. In the case of swing mode actuation an external optical readout had to be used.
A. Twist Mode Actuation

Fig. 9 shows a schematic drawing of the fluidic and electronic setup to measure the response of the sensor to mass flow using the capacitive read-out electrodes. Nitrogen, argon and water were used as the measurement media. When measuring with water, a pressure container filled with water was connected to a compressed nitrogen source as indicated in the figure. When measuring with nitrogen and argon, the pressurized gas source was directly connected to the flow controller. The water flow was controlled by a Bronkhorst μ-FLow flow controller. The nitrogen and argon flows were controlled by a Bronkhorst EL-Flow controller. The actuation frequencies were 1551 Hz, 2793 Hz and 2799 Hz when measuring with water, argon and nitrogen, respectively. Two sinusoidal actuation signals with an amplitude of 1 V but with opposite phase were applied to one electrode of each of the piezo actuators. A constant 7 V bias voltage was applied to the other electrodes to avoid switching the poling direction of the PZT thin film. A carrier signal of 1.4 MHz was applied to the two capacitive readout combs on the microfluidic channel. The currents into the counter electrodes were converted into voltages using two charge amplifiers, resulting in two amplitude modulated signals with amplitudes proportional to the sensor capacitances. After demodulation and low-pass filtering, two Stanford SR830 lock-in amplifiers were used to obtain the phase shifts between the actuation signal and the output signals. The time constant of the lock-in amplifiers was set to 300 ms for flow measurements and 1 s for the long term stability measurement. The measured phase shifts are denoted as $\theta'_1$ and $\theta'_2$. From (7) and (8), we know that the measured phase shifts $\theta'_1$ and $\theta'_2$ relate to $\theta$ as follows:

$$\theta'_1 - \theta'_2 = \theta$$

(28)

The phase shift data was recorded every 1 s. After stabilization of the flow rate at a desired value 300 samples were taken before selecting the next flow rate.

For comparison, a mass flow measurement with nitrogen was also performed using Lorentz force actuation as described in [24]. An external magnetic field was applied as described in [31]. An actuation signal with an amplitude of 0.07 V, which corresponds to a current amplitude of approximately 0.2 mA, was used in this measurement, resulting in a power dissipation of approximately 0.14 mW.

B. Swing Mode Actuation

In the case of swing mode actuation it is not possible to use a capacitive readout, because the actuation motion is much larger than the Coriolis motion everywhere on the channel. Therefore, a Polytec MSA-400 laser Doppler vibrometer was used to measure the displacements near the corners of the channel [19], as indicated in Fig. 10 by point 1 and point 2. At these points the Coriolis motion has a maximum. The reference beam of the vibrometer was placed on the silicon substrate inside the channel loop. The displacements at point 1 and point 2 are measured alternatingly with a period of approximately 3 minutes as the measurement beam of the vibrometer is continuously switched between these points. The same Bronkhorst flow controllers were used to provide mass flows of nitrogen and water. The resonance frequencies for the swing mode were measured to be 957 Hz and 1704 Hz with water and nitrogen, respectively. For swing mode actuation both piezo actuators were driven with a sinusoidal actuation voltage with an amplitude of 2 V and an offset of 7 V. A Stanford SR830 lock-In amplifier was used to measure the phase shift between the actuation signal and the output signals of the laser Doppler vibrometer. For each flow rate, the phase shift was recorded 10 times. From (14) and (15), we know that:

$$\theta'_1 - \theta'_2 = 2\theta$$

(29)

In order to obtain an estimate for the power consumption of the piezoelectric actuators the impedance of the two actuators in parallel was measured with a HP4194A Impedance/Gain-Phase Analyzer while the channel was filled with nitrogen. At the actuation frequency of 1704 Hz the measured impedance was 0.58 MΩ with a phase angle of $-79.6^\circ$, giving a power consumption of 0.6 µW.

V. RESULTS AND DISCUSSION

A. Twist Mode Actuation

Fig. 11 shows the measured sensor phase shift output $2\theta$ as a function of mass flow of water when actuated in twist mode. The mass flow was changed in steps of 0.1 g h$^{-1}$, from 0.1 g h$^{-1}$ to 1.6 g h$^{-1}$ and then back to 0.1 g h$^{-1}$. At each mass flow rate 300 samples were recorded as described above. All samples are plotted in the figure along with a linear fit, indicating good linearity and no visible hysteresis. The linear fit residual error of all samples is within 3% of the full scale of 1.6 g h$^{-1}$.

Further measurements were performed with nitrogen and argon to determine the influence of the fluid density on the mass flow measurement. Fig. 12 shows the measured sensor phase shift as a function of the volumetric flow of argon and
Fig. 9. Schematic drawing showing the fluid path (indicated in blue) and the electronic interfacing of the sensor in case of twist mode actuation.

Fig. 10. Schematic drawing showing the fluid path, the actuation circuit, and the optical readout in the case of swing mode actuation. A laser Doppler vibrometer is used to measure the displacements of point 1 and point 2 close to the two corners as indicated by the blue dots in the photograph. The distance between the points is approximately 1.8 mm. \( R_1, \theta_1 \) and \( R_2, \theta_2 \) represent the amplitude and phase shift of the motion of the two points, which are measured alternatingly as the vibrometer continuously switches between the two points. The white spot inside the red circle in the photograph is the reference laser beam. In case of flow measurements with water the nitrogen source was connected to a pressure vessel filled with water, as shown in Fig. 9.

Fig. 11. Measured phase shift versus mass flow of water in case of twist mode actuation along with a linear fit. The mass flow is increased from 0.1 gh\(^{-1}\) to 1.6 gh\(^{-1}\) and then decreased again to 0.1 gh\(^{-1}\).

Fig. 12. Measured phase shift as a function of volumetric flow of argon and nitrogen in case of twist mode actuation. The measurement with nitrogen flow is also performed using Lorenz force actuation. The sensitivities obtained from the slope of the responses are \(3.92^\circ/\text{mL}_n/\text{min}\) and \(2.74^\circ/\text{mL}_n/\text{min}\) for nitrogen, \(3.92^\circ/\text{g/h}\) and \(3.92^\circ/\text{mL}_n/\text{min}\), for nitrogen, nitrogen with Lorenz force actuation and argon flow, respectively.

Nitrogen. The slopes of the linear fits are \(3.92^\circ/\text{mL}_n/\text{min}\) and \(2.74^\circ/\text{mL}_n/\text{min}\) for argon and nitrogen, respectively, which corresponds to mass flow sensitivities of \(36.5^\circ/\text{g/h}\) and \(36.7^\circ/\text{g/h}\).

Fig. 12 also shows the measured phase shift versus the applied nitrogen flow in the case of Lorentz force actuation. The results correspond very well to piezoelectric actuation, indicating that the sensitivity of the sensor is independent of the actuation method. The small difference can easily be explained by the Joule heating associated with Lorentz force actuation.
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corrections.

B. Swing Mode Actuation

Fig. 13 shows the measured phase shift as a function of mass flow rate of nitrogen and water in case of swing mode actuation. The phase shift is measured using a Polytec MSA-400 laser Doppler vibrometer. The sensitivities for nitrogen and water mass flow are 0.93° (g/h) and 0.57° (g/h), respectively, which are significantly lower than in the case of twist mode actuation.

The result shows a very good linearity. However, compared to twist mode actuation, the phase shift versus mass flow sensitivity is a lot smaller. The spread in the measurement points is also significantly larger, which is probably due to the fact that the displacements at point 1 and point 2 on the channel are not measured simultaneously but alternatingly. The lower sensitivity is obvious from equations (12) and (19). In case of twist mode actuation, the sensitivity can be increased by reducing the distance $d_c$ in the capacitive readout. In case of swing mode actuation, it is not possible to extend the distance between the measurement points of the vibrometer beyond the length $L_2$ of the sensor channel.

C. Density Independent Mass Flow Sensing

As explained in Section II.C, one can correct for the influence of the actuation frequency on the sensitivity by converting the phase shift into a time delay using equation (25). Fig. 14 shows the measured time delay versus applied mass flow rate for nitrogen, argon, and water in case of twist mode actuation. The zero flow calibration time delay is subtracted from all data points. The mass flow sensitivities for water, argon, and nitrogen are 37.5 μs/(g/h), 36.3 μs/(g/h), and 36.4 μs/(g/h), respectively.

In case of swing mode actuation, converting the phase shift in Fig. 13 into a time delay gives time delay sensitivities $\Delta t/\varphi_m$ of 1.52 μs/(g/h) and 1.66 μs/(g/h) for nitrogen and water, respectively. In this case there is still a significant difference in sensitivity between nitrogen and water. The reason is that the setup has to be adapted to change from gas to liquid measurements. As a result, the measurement spots of the laser vibrometer (see Fig. 10) have to be realigned to the sensor tube and a slight change in the distance between the two spots is inevitable.

A summary of the measured resonance frequencies and the measured mass flow sensitivities is given in Table II.

D. Sensor Stability

Fig. 15 shows the result of a long-term stability measurement. Mass flow of water is cycled between 0.6 g/h, 1.2 g/h, and 1.8 g/h, kept constant at each level for 10,000 s. The standard deviation of the samples within each interval of 10,000 s of continuous measurements is less than 0.06°, which corresponds to 2.7 mg/h or 0.15% of the full scale of 1.8 g/h. In most intervals, the measured standard deviation is below 0.03°. The drift in the average phase shift over each interval is within 0.05°, which corresponds to 2.25 mg/h.

A stability measurement was not performed for the sensor actuated in swing mode as the result would be limited by the use of the external laser Doppler vibrometer and the continuous switching between the two measurement points. The advantage of the laser Doppler measurement method is...
the flexibility in choosing the measurement spots and the possibility to fully characterize the vibration modes. However, in a practical application the two measurement points have to be measured simultaneously as is the case for the integrated capacitive readout.

E. Comparison With Previously Reported Sensors

All previously reported micro Coriolis mass flow sensors are driven by either piezoelectric, electrostatic or Lorentz force actuation. The Coriolis motions were detected by either optical methods or by an integrated capacitive readout. Different device designs and detection methods provide different output values for the same flow rate. For example, devices with the same fluidic channel design but having the capacitive readout electrodes at different positions give a different phase shift sensitivity [32]. However, for devices with similar mechanical properties, the ratio between the actuation amplitude and the Coriolis mode amplitude is also similar. In order to compare the performance of different devices this ratio is an important parameter. In the case of twist mode actuation this ratio is given by the amplitude ratio \( \phi_1/\phi_2 \), and in case of swing mode actuation it is given by \( \phi_2/\phi_1 \).

Table III gives a comparison between previously published sensors and the sensor reported in this paper in terms of sensor design, phase shift output and displacement derived from phase shift. The table reveals that for most designs the ratio between the actuation mode and Coriolis mode is in the same order of magnitude, even if the geometry of the channel is different. The devices from Enoksson et al. [6] show different ratios because those devices have completely different designs and stiffer and heavier channels. When comparing the devices that are actuated in the twist mode, the phase shift versus mass flow sensitivity is mainly defined by the distance \( d_c \) between the capacitive readout electrodes. The device reported in this paper has a very high phase shift sensitivity because \( d_c \) is the smallest among all devices shown in the table. The devices that are actuated in the swing mode all have a much lower phase shift sensitivity.

VI. Conclusion and Outlook

We have designed, fabricated and tested a micro Coriolis mass flow sensor that is driven by PZT thin film actuators. Compared to the previously used Lorentz force actuation, this results in a reduction of power consumption by a factor of 1000 to less than 1 \( \mu \)W, solving the problem of self-heating. The device was operated in air at a low AC actuation voltage with an amplitude of 1 V and a DC bias of 7 V. Electrostatic actuation would have required much higher voltages. The sensor was fabricated based on the surface channel technology.

The sensor was characterized using both twist mode and swing mode actuation. Both actuation modes can be excited using the same piezoelectric actuators. In the case of twist mode actuation an integrated capacitive readout is used, which results in a high phase sensitivity because \( d_c \) is the smallest among all devices shown in the table. For swing mode actuation an external laser Doppler vibrometer had to be used, resulting in a much lower phase sensitivity.

Characterization was done with water and different gases to investigate the influence of fluid density on the sensitivity of the sensor. When actuated in twist mode, the sensor shows a phase shift sensitivity of 36.6°/(g/h) and 21.6°/(g/h) for gas and water, respectively. Swing mode actuation results in a phase shift sensitivity of 0.93°/(g/h) and 0.57°/(g/h) for nitrogen and water. In comparison to previously reported

### Table II

**Summary of Resonance Frequencies and Mass Flow Sensitivities in Relation to Different Fluids by Different Actuation Modes**

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Twist</th>
<th>Swing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actuation frequency (Hz)</td>
<td>2799</td>
<td>2793</td>
</tr>
<tr>
<td>Phase shift mass flow sensitivity ( \theta/\phi_m ) (°/(g/h))</td>
<td>36.69</td>
<td>36.49</td>
</tr>
<tr>
<td>Time delay mass flow sensitivity ( \Delta t/\phi_m ) (s/(g/h))</td>
<td>3.64-5</td>
<td>3.63e-5</td>
</tr>
<tr>
<td>( K_2^m )</td>
<td>0.371</td>
<td>0.372</td>
</tr>
<tr>
<td>( \Delta t/(\phi_m K_2^m) ) (°/(g/h))</td>
<td>9.81e-5</td>
<td>9.75e-5</td>
</tr>
</tbody>
</table>

### Table III

**Comparison of Sensor Designs and Measured Phase Shift**

<table>
<thead>
<tr>
<th>Device</th>
<th>( L_1 ) (mm)</th>
<th>( L_2 ) (mm)</th>
<th>( d_c ) (mm)</th>
<th>Actuation mode</th>
<th>Measured fluid</th>
<th>Phase shift (deg/(g/h))</th>
<th>( \phi_1/\phi_2 ) (( \phi_2/\phi_1 )) at 1 g h(^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haneyveld et al. [24]</td>
<td>2.8</td>
<td>4</td>
<td>1.1</td>
<td>Twist</td>
<td>Water, ethanol and white gas</td>
<td>2.4 (estimated)</td>
<td>0.0082</td>
</tr>
<tr>
<td>Groenesteijn et al. [33]</td>
<td>2.7</td>
<td>4</td>
<td>1.1</td>
<td>Twist</td>
<td>Water</td>
<td>2.97 (estimated)</td>
<td>0.010</td>
</tr>
<tr>
<td>Ibid.</td>
<td>1.9</td>
<td>2.3</td>
<td>1.036</td>
<td>Twist</td>
<td>Water</td>
<td>1.57</td>
<td>0.0074</td>
</tr>
<tr>
<td>Groenesteijn et al. [34]</td>
<td>2.45</td>
<td>4.26</td>
<td>1.076</td>
<td>Twist</td>
<td>Water</td>
<td>3.47</td>
<td>0.0133</td>
</tr>
<tr>
<td>Groenesteijn et al. [32]</td>
<td>3.25</td>
<td>4</td>
<td>0.47</td>
<td>Twist</td>
<td>Nitrogen</td>
<td>6.5</td>
<td>0.0082</td>
</tr>
<tr>
<td>Enoksson et al. [6]</td>
<td>2.9</td>
<td>4</td>
<td>0.25</td>
<td>Twist</td>
<td>Water</td>
<td>21.6</td>
<td>0.0162</td>
</tr>
<tr>
<td>Ibid.</td>
<td>6</td>
<td>9</td>
<td>N/A</td>
<td>Twist</td>
<td>Water and methanol</td>
<td>N/A</td>
<td>( 1.21 \times 10^{-3} )</td>
</tr>
<tr>
<td>Zeng et al. [19]</td>
<td>2.75</td>
<td>4</td>
<td>N/A</td>
<td>Swing</td>
<td>Nitrogen</td>
<td>1.78</td>
<td>0.0203</td>
</tr>
<tr>
<td>Current paper</td>
<td>3.5</td>
<td>4</td>
<td>N/A</td>
<td>Swing</td>
<td>Nitrogen</td>
<td>0.93</td>
<td>0.0084</td>
</tr>
<tr>
<td>Current paper</td>
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<td>4</td>
<td>N/A</td>
<td>Swing</td>
<td>Water</td>
<td>0.57</td>
<td>0.0043</td>
</tr>
<tr>
<td>Current paper</td>
<td>3.5</td>
<td>4</td>
<td>0.18</td>
<td>Twist</td>
<td>Nitrogen</td>
<td>36.69</td>
<td>0.0165</td>
</tr>
<tr>
<td>Current paper</td>
<td>3.5</td>
<td>4</td>
<td>0.18</td>
<td>Twist</td>
<td>Argon</td>
<td>36.49</td>
<td>0.0164</td>
</tr>
<tr>
<td>Current paper</td>
<td>3.5</td>
<td>4</td>
<td>0.18</td>
<td>Twist</td>
<td>Water</td>
<td>20.92</td>
<td>0.0094</td>
</tr>
</tbody>
</table>
devices, the sensor showed very high phase shift sensitivity for twist mode actuation thanks to the optimized capacitive read-out design.

The time delays calculated from the phase shifts and actuation frequency give a sensor output that is almost independent of the fluid density. The theoretically calculated relation between the fluid density and the time delay matches very well with the measurement results. The standard deviation of the sensor output was within 0.15% of the full scale with full scale of 1.8 g h⁻¹.

For comparison the sensor was also operated with Lorentz force actuation using external magnets. The resulting sensitivity was almost identical, demonstrating that the actuation method has no influence on the Coriolis mass flow sensing.

Future research may focus on using piezoelectric transducers for both actuation and readout of the sensor [18], development of an integrated readout method with higher phase sensitivity in case of swing mode actuation, and optimization of the piezoelectric actuators for larger actuation amplitudes.

REFERENCES
Jarno Groenesteijn received the M.Sc. degree in electrical engineering from the University of Twente, Enschede, The Netherlands, in 2010, on the subject of a MEMS step-up voltage converter, and the Ph.D. degree in 2016. After his M.Sc. degree, he worked on his Ph.D. research on a platform for micro Coriolis mass flow sensors and other microfluidic sensors at the Micro Sensors and Systems (MSS) Group, MESA Institute for Nanotechnology, University of Twente. After his Ph.D. degree, he joined Bronkhorst High-Tech B.V., Ruurlo, The Netherlands, where his research is focused on design, fabrication, and characterization of MEMS-based fluidic sensors.

Dennis Alveringh received the M.Sc. degree in electrical engineering from the University of Twente, Enschede, The Netherlands, in 2013, on the subject of a microfabricated capacitive force sensor. He then joined the Micro Sensors and Systems (MSS) Group, MESA Institute for Nanotechnology, University of Twente, where he worked on his Ph.D. research on physical microfluidic sensors. After finishing his Ph.D. research in 2018, he joined Salland Engineering (Europe) B.V., where he focused on automated testing of semiconductors and MEMS devices. At the time of writing, he is a part-time Research and Development Scientist at Salland Engineering (Europe) B.V. (for 10%) and is an Assistant Professor with the Integrated Devices and Systems (IDS) Group, University of Twente, in the field of CMOS-sensor integration.

Yaxiang Zeng was born in 1992. He received the B.S. degree in material physics from Northeastern University, Shenyang, China, in 2014, and the M.S. degree in nanoscale engineering from INSA Lyon, Lyon, France, in 2016. He is currently pursuing the Ph.D. degree with the University of Twente, Enschede, The Netherlands. His work focuses on MEMS devices driven by piezoelectric actuators.

Joost C. Lötters received the M.Sc. and Ph.D. degrees in electrical engineering from the University of Twente, Enschede, The Netherlands, in 1993 and 1997, respectively. In 1997, he joined Bronkhorst High-Tech B.V., Ruurlo, The Netherlands, where his research focused on flow measurement and control in the field of thermal, Coriolis, and ultrasonic flow sensing. In 2010, he joined the Transducer Science and Technology Group. Since then, his research has focused on microfluidic handling systems, i.e., integrated systems for the accurate measurement, control, dosage, and analysis of (micro) flows. Highlights include a micro Coriolis flow sensor, a micro proportional control valve, a micro Wobbe index meter, and a single chip multiparameter flow measurement system comprising a thermal and Coriolis flow sensor, pressure sensor, thermal conductivity sensor, and dielectric constant sensor (e.g., to determine composition or energy content of gas or liquid mixtures). In 2015, he was appointed as a part-time Professor of microfluidic handling systems at the University of Twente. He is an inventor or co-inventor of more than 30 patents and an author or coauthor of more than 120 journals and conference papers.

Remco J. Wegerink received the M.Sc. degree in electrical engineering, on the subject of a fully integrated ultra-low frequency low pass filter for offset canceling in integrated audio amplifiers, and the Ph.D. degree in electrical engineering, on the subject of MOS translinear circuits, from the University of Twente, Enschede, The Netherlands, in 1988 and 1992, respectively. Between 1992 and 1995, he was with the Applied Physics Department, University of Twente, where he was engaged in the design of a superconducting flash analog-to-digital converter with GHz sampling frequency. In 1995, he joined the Transducer Science and Technology Group. Since then, his research has focused on mechanical microsensors, electronic interfacing of sensors, and packaging. Highlights include a silicon load cell with distributed capacitive readout, distributed thermal flow sensors using resistor arrays, an RF power sensor based on sensing the electrical force between the signal line and a suspended electrode, flow sensors based on the flow sensing hairs of crickets, and a micro Coriolis flow sensor. He is currently an Associate Professor with the Integrated Devices and Systems Group, MESA Institute for Nanotechnology. He is a (co)author of two books, several book chapters, and more than 250 journals and conference papers.