The Pressure Dependency of a Micro Coriolis Mass Flow Sensor

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***Abstract*— In this paper the influence of pressure and gas flow on a micro Coriolis mass flow sensor will be investigated. The cross sectional shape of this tube is not perfectly circular, which causes the tube to bend under pressure. How much this tube bends and in what direction will be investigated. This will be done by simulating, doing measurements with a white light interferometer and a laser Doppler vibrometer under different pressures and flows. It is found that the channel bends upward due to pressure with $0.55\mu m/bar$.**

I. INTRODUCTION

Precise measurement of micro mass flow, of one gram per hour or lower, can be of utmost importance. For example to measure certain medicine in an infusion pump. Or in the chemical industry, where an exact mixture of importance is to get a desired result[1]. To measure these small amounts of liquids or gas, a micro Coriolis mass flow sensor can be used.

A Coriolis mass flow sensor consists of a vibrating tube that is made in a rectangle shape as can be seen in figure 1a. When there is a fluid flow in the tube while the tube is in a vibrating mode the mass in the tube has to change velocity. This will result in a Coriolis force on the tube. This force will induce an out-of-plane vibration mode with an axis of rotation orthogonal to that of the actuation mode, with an amplitude proportional to the mass flow[4]. In figure 1a and b it can be seen that when the tube is vibrating in twist mode, the tube will vibrate in swing mode when mass flows through the tube.

The flow is measured using a capacitive readout method. Two pairs of comb structures are placed on the tube, those combs act as a pair of capacitors. When the tube is moving out of the plane the distance between the combs increases. Therefore, the capacitance between those combs decreases, when actuating the tube in twist mode, as seen in figure 1 a. Without fluid or gas flow the capacitor values are 180° out of phase to each other. When there is a flow, the capacitor values will have an additional phase difference proportional to the mass flow rate through the tube, as shown in figure 1 b. This is because the additional movement of the swing mode due to the Coriolis force is added to the movement of the twist mode. the result of this movement can be seen in the figure 2 [2].

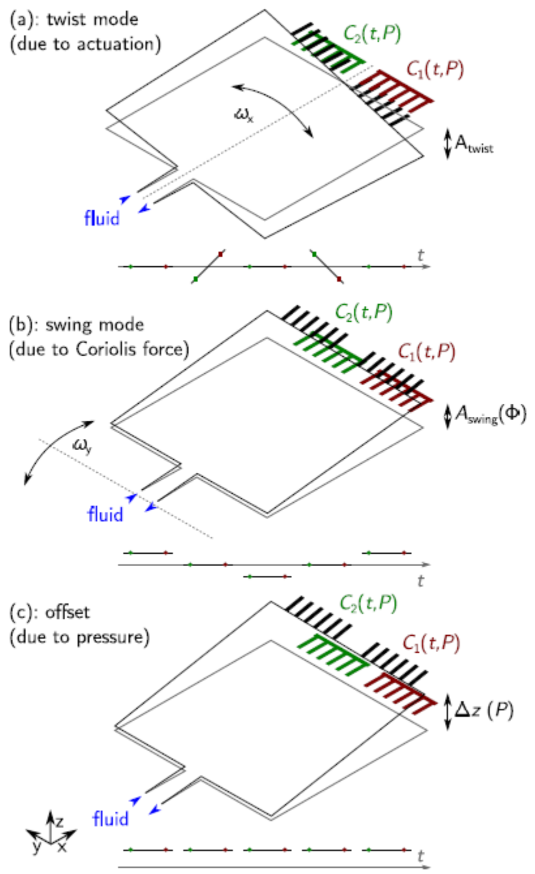

Fig. 1. Movement of a Coriolis mass flow sensor, with (a) the twist mode due to actuation, (b) the swing mode due to the Coriolis force and (c) the static offset due to the pressure[2].

To fabricate the sensors described in this paper, a standard silicon wafer can be used. This method uses different etching and pattering techniques as described in [3]. This technique is called Surface Channel Technology (SCT). The tube will be made out of silicon-rich silicon nitride which can be plated with metal tracks. These tracks can be used to conduct an alternating current over the tube, with a frequency equal to the resonance frequency of the tube. When the tube is placed in a magnetic field it will start resonating. When using SCT the tube that is produced will not be perfectly cylindrical.

The top of the tube will be flat. A cross sectional picture of the tube can be seen in figure 3.

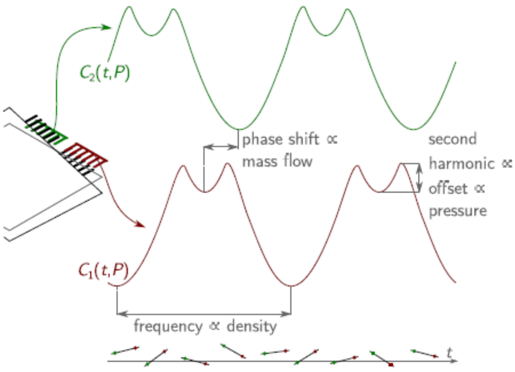

Fig. 2. The output signals of the Coriolis mass flow sensor: the phase shift is dependent on the mass flow, the frequency is dependent on the density and the ratio between the harmonics is dependent on the pressure.[2]

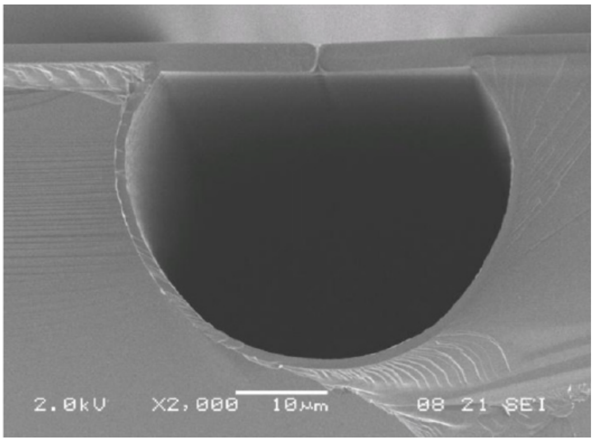

Fig. 3. A cross sectional view of the tube.[4]

II. THEORY

A. *Influence of pressure in a static tube*

When a tube is fabricated using SCT, the corners on the opposite site from where the tube is attached to rest of the chip will bend slightly upwards due to internal stresses[2]. When pressure is applied in the tube, it will bend even further upwards. The reason for this is that the tube is not perfectly circular[2]. Because the circular part of the tube is thinner, it will stretch out more than the plate on top. This will result in a longitudinal force at the bottom of the circular part. The top plate stretches less because it is thicker, therefore there is a longitude force at the bottom of the tube which results in an upward force in the corners of the tube. Therefore the corners of the tube will bend upwards at the opposite side from where it is attached to the chip. This can be seen in figure 1 c. The out of plane bending of the tube results in a lower initial capacitance of the comb structure because the fingers are further apart from each other. That the structure is bending upward under pressure is known, because the capacitor values can be measured[2]. However, the exact bending of the tube under a wide range of pressure has never be tested. When there is a flow in the tube there will be a pressure difference from the inlet to the outlet. This can cause the tube to bend more upward at the inlet side than at the outlet side.

B. *Influence of pressure when actuating a Coriolis mass flow sensor at its resonance frequency*

The static tube bends slightly upwards due to initial stresses. Therefore the initial value of the capacitance between the combs will not be at its maximum point. When the combs are moving down first the capacitance increases, after the combs have passed each other the capacitance will decrease. This will result in a second harmonic in the output signals of the capacitors when the tube is actuated in twist mode. This effect can be seen in figure 2. If the tube bends more due to pressure, the second harmonic will have a smaller amplitude and the first harmonic will have a greater amplitude. Therefore, the amplitude of the first and second harmonic is proportional to the pressure. When the initial distance is as great that the combs do not pass each other the second harmonic will disappear and the first harmonic will also decrease inversely proportional to the distance. Furthermore, the resonance frequency of the twist mode will be dependent on the pressure. This can be caused by an increased stiffness due to expanding of the tube[2].

III. SIMULATIONS

The bending of the tube is investigated using COMSOL Multiphysics 5.6 with 'solid mechanics' physics. First, the geometry is built. This is done by making a 2d image of the cross-sectional part of the tube similar to figure 3. Secondly, sweeping this cross-section over the path of the tube. The whole geometry can be seen in figure 4. The dimensions of the rectangular channel are $4mm$ by $2mm$, the wall thickness of the circular part of the tube is $1.2\mu m$ and the radius is $20\mu m$. The top plate is $3.3\mu m$ by $80\mu m$[4]. The material selected is silicon nitride, this has a similar Young's modulus as silicon-rich silicon nitride, the material used to fabricate the tube.

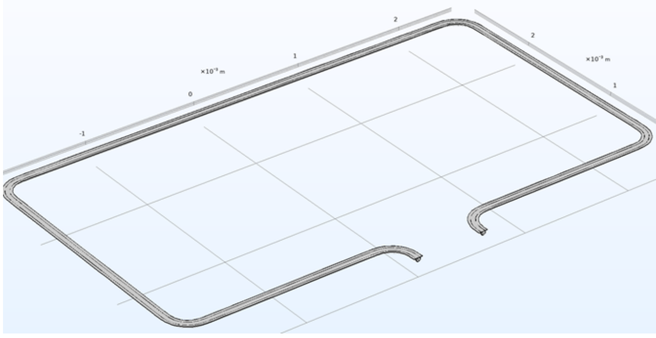

Fig. 4. The Geometry of the model.

A. *Stationary simulations*

A stationary study in COMSOL is used when a system does not change in time after some period of time. This is ideal to replicate what will happen to the sensor when pressure is applied without actuation of the tube. In figure 5 it can be seen that in the corners the tube bends upwards with $0.52\mu m$ at a pressure of 1 bar inside the channel and 0 bar outside the channel. In the real measurements this will be 2 bar inside the channel and 1 bar outside the channel. This simulation was done for pressures from 0 to 10 bar. The bending of the tube in the simulation is found to be exactly linear, the bending is $0.52\mu m/bar$. The linear deformation is expected because the deformations are small compared to the dimensions of the tube. With larger deformations, a non-linear effect is expected due to geometric deformations. In the simulations, the initial deformation of the tube is not taken into account. It is expected that the total deformation is equal to the initial deformation plus the deformation as a result of pressure. An advantage of using simulations is that you can easily change parameters. This will give you information about how the change in this parameter will influence the effect in the real world.

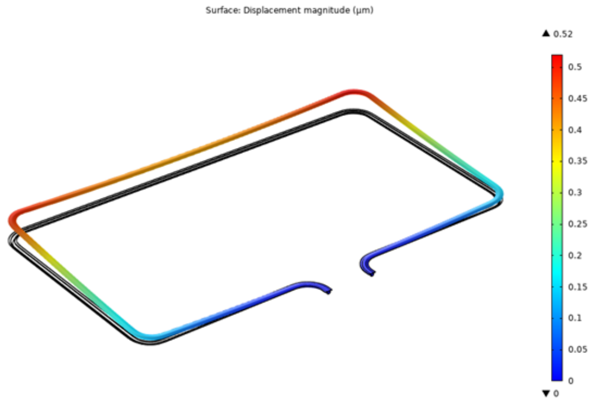

Fig. 5. Simulation result with 1 bar of pressure.

The wall thickness of the circular part was varied from $1\mu m$ to $1.9\mu m$. On every wall thickness different pressures where applied. It was found that the simulation result where linear for every wall thickness, those results can be found in figure 6. In this figure it can be seen that overall when the wall gets thicker the deformation per bar becomes less. This is conform expectations because the circular part of the channel will expand less, this will result in a smaller force that is forcing the channel upwards. The sudden decrease at $1.1\mu m$ and the small increase in at $1.4\mu m$ are standing out. An explanation why there is an sudden drop at $1.1\mu m$ and the small increase at $1.3\mu m$ has not been found.

B. *Eigenfrequency simulations*

Another option to simulate the system in COMSOL is to select the study Eigenfrequency prestressed. This study should be able to calculate the different Eigenfrequencies under different pressures. The second Eigenfrequency is corresponding to the resonance frequency of the twist mode. In figure 7 the simulated resonance frequencies over different pressure can be seen. From literature it is known that the resonance frequency over pressure varies with a few Hertz[2]. Therefore it is concluded that this simulation is not in accordance with reality.

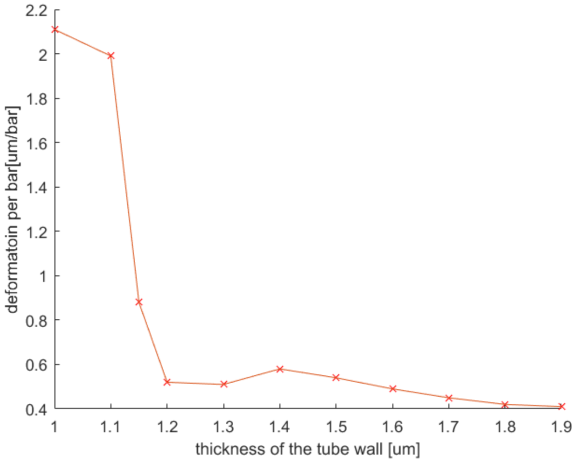

Fig. 6. Deformation per bar with different wall thicknesses.

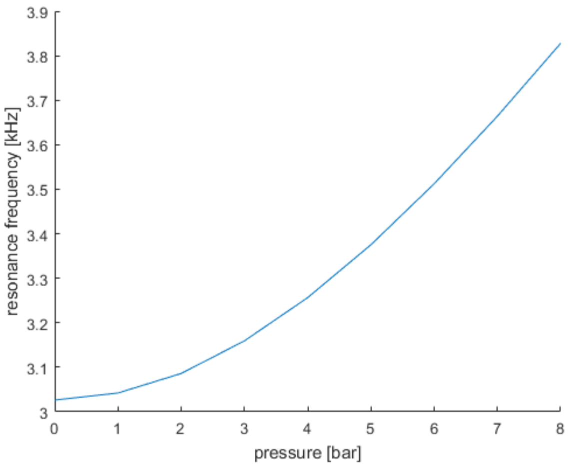

Fig. 7. The resonance frequency of the twist mode simulated under different pressures.

IV. MEASUREMENT SETUP

A variety of experiments will be done to investigate the influence of pressure and flow on the sensor.

1) a static experiments when the sensor is not actuated
    - with a gas flow
    - without a gas flow
2) a dynamic experiment where the sensor is actuated
    - with a gas flow
    - without a gas flow

In all experiments, the pressure is varied from 1 to 9 bar in absolute pressure at the inlet of the sensor, with steps of

1 bar. Then the air pressure is measured and subtracted from measurements in order to get a pressure inside the channel relative to the pressure outside the channel. In the cases without flow the upward bending due to the pressure will be measured. In the experiments with flow, the difference in deformation of the tube his corners due to pressure difference will be measured. This will also be measured in the experiment without flow to see if there is a deformation difference without flow.

A. Sensor setup

Nitrogen pressure is applied to a flow sensor(Bronkhorst EL press5D), this flow sensor is attached to a pressure controller (Bronkhorst mini CORI-FLOW) and this pressure controller is attached to the test device. The setup can be seen in figure 8. At the outlet of the test device, a plug can be placed to stop the flow. When a flow is needed this plug can be removed. In this manner, the flow is controlled with the pressure controller. To do the dynamic measurements the tube is actuated by placing an alternating current at the metal track on top of the tube, because the tube is in a magnetic field it will start vibrating with the frequency of the current if this current is the same as the resonance frequency of the twist mode it will have the largest amplitude.

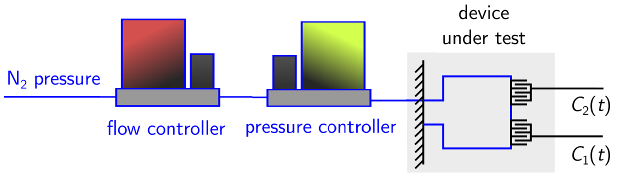

Fig. 8. Measurement setup.

B. White-light interferometer

To measure the static influence of pressure and flow, on the deformation of the tube a White-light interferometer will be used. This device can make a height map of a surface[7]. The white-light interferometer integrated into the MSA 400 from Polytec will be used. The interferometer can measure which places of the test device has a certain distance to the scanner. When sweeping over different distances it can make a height map of the area. This sweep has a step size of $130nm$[6].

C. Laser Doppler vibrometer

White-light interferometry cannot be used in the dynamic experiment, because it cannot measure moving objects. In the dynamic experiment, a laser Doppler vibrometer is used. This device can measure the velocity of a surface using the laser Doppler effect[5]. By integrating the velocity the deformation can be displaced. However initial displacement will not be visible. Additionally, this device has a function generator that can sweep over an range of frequencies. In this manner the resonance frequency of the channel can easily be found.

V. MEASUREMENTS

For this experiment two micro Coriolis mass flow sensors produced by Bronkhorst were used. The chips where tested on any leakages or blockages of the flow. The complete static measurements were performed on both chips. Due to time limitation the dynamic experiment was only conducted on one chip.

A. Static measurements

Unfortunately, the entire tube did not fit under the scanning area of the white-light interferometer. Therefore two different scans had to be made. To measure the deformation due to pressure without flow, a scan of at least one half of the chip is made. The height of the place where the tube is attached to the chip is subtracted from the height of the place of inquiry, the right top corner from figure 9. This scan is made for an inlet pressure of 0 to 8 bar relative to the air pressure. The average height of the little dark blue squares is measured to filter out small local height differences. This experiment was done on two different devices. The result of this experiment can be seen in figure 10, in this figure the simulation results are also added, in this simulation the circular part of the tube has a wall thickness $1.2\mu m$ because the measured tube had this wall thickness as well.

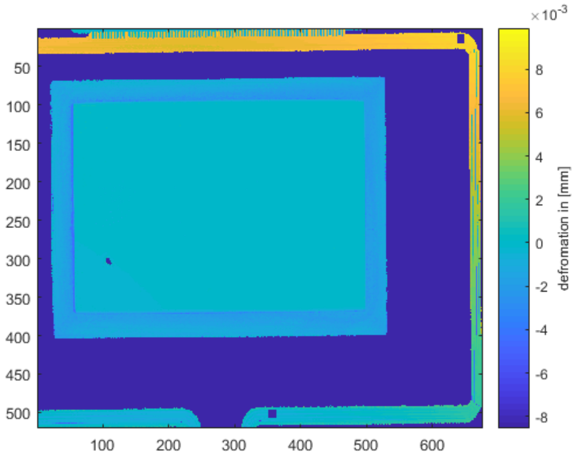

Fig. 9. With-light interfernometer height map of the outlet site at 0 bar pressure relative to air pressure. The dark blue squares indicate the places where the height is averaged in order to get an accurate readout of the deformation at that place.

To determine if there is deformation difference due to flow, the test device has to be placed diagonally under the scanner head, this scan can be seen in figure 11. In order to test if the difference in deformation is because of the flow, first the deformation is measured when there is no flow. This difference is measured from 0 to 8 bar. Then the difference in deformation of the two corners is measured from 0 to 8 bar with flow through the tube, this is done by removing the plug. Those tests are done on two different devices. These results can be seen in figure 12. The difference in deformation of the corners of the channel with no flow are $53nm/bar$ for

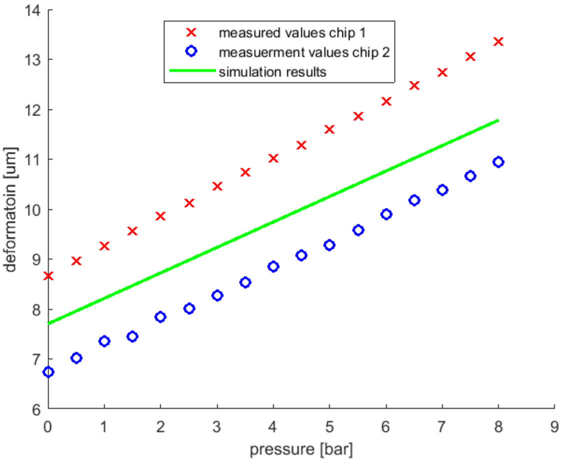

Fig. 10. Simulations and measurements result of the deformation of the upper corner seen in figure 9 from 0 to 8 bar relative to the air pressure. In the simulation a wall thickness of $1.2\mu m$ was used, the average initial deformation due to stress of the two devices are added to the simulation results. The red cross and blue circles are the measurements of two different devices.

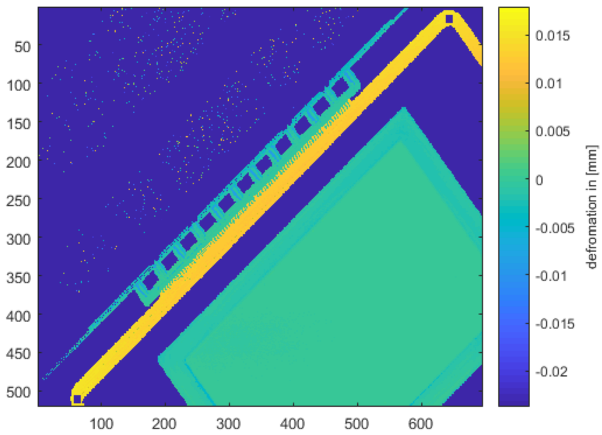

Fig. 11. With-light interfernometer height map of the two corners of the tube at 0 bar pressure relative to air pressure. The dark blue squares indicate the places where the height is averaged in order to get an accurate readout of the deformation at that place

chip 1 and $67nm$ for chip 2. When there was a flow through the tube this was $129nm/bar$ for chip 1 and $159nm$ for chip 2.

B. Dynamic measurements

The laser Doppler vibrometer was used to measure the resonance frequency of the channels with and without flow. Due to time limitations only 1 chip was measured. The result measured resonance frequencies can be seen in figure 13. In both experiments, with and without flow, it can be seen that the resonance frequency is slightly higher when the pressure increases. The resonance frequency increases even more when there is no flow. This could be explained by the fact that when there is pressure in the tube it will be stiffer. Hence a higher resonance frequency. When there is a flow the overall pressure in the tube is lower, this will result in a lower resonance frequency. No insightful information about the deformation due to pressure was measured with the vibrometer. Deformation due to pressure when the pressure is not fluctuating is static. Therefore the vibrometer filters out the most relevant information.

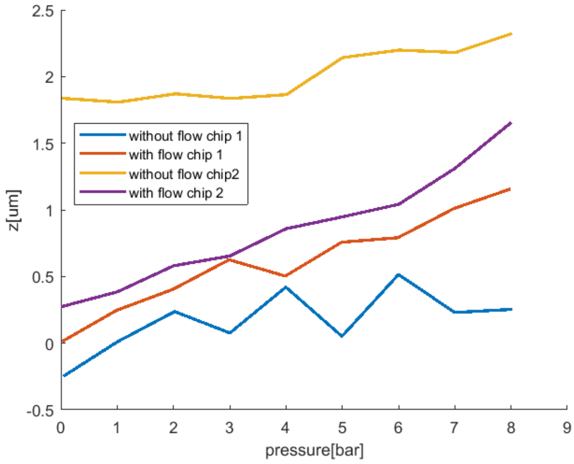

Fig. 12. Deformation of the upper right corner subtracted from the upper left corner under pressures from 0 to 8 bar, with flow and without flow in the tube.

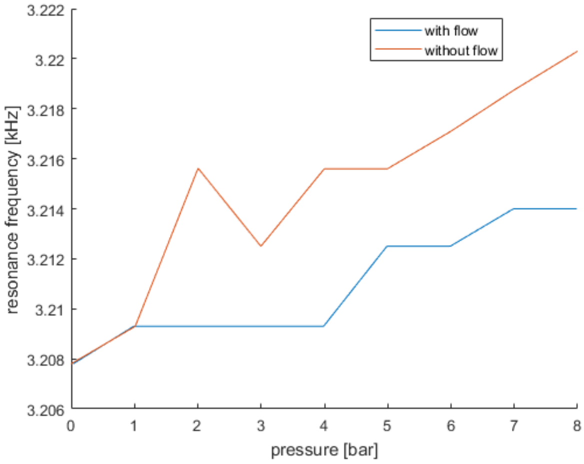

Fig. 13. Resonance frequencies of the sensor over pressure with and without a gas flow

VI. DISCUSSION

In figure 10 the measured result and the predicted results from the simulations are plotted in one figure. In the simulations the deformation per bar is $0.52\mu m/bar$ in the measurement this was on average $0.58\mu m/bar$ for chip 1 and $0.52\mu m/bar$ for chip 2. In both cases, the simulation is giving a decent prediction for a static deformation of the tube under pressure. It has to be investigated if varying the wall thickness of a channel will have the same result as it has in the simulations. In further studies it will also be useful to test if other changes in the geometry can predict what will happen to a real device. Simulations were not suitable to predict the resonance frequency of the sensor. On average the channel bends upward with $0.55\mu m/bar$, this could be used to measure the pressure in the tube statically by measuring the total capacitance of the comb pairs or dynamically by comparing the first and second harmonic of the output signal.

From figure 12 it can be concluded that when there is a flow, the upper corner at the inlet side of the tube bends up more than the upper corner at the outlet with $0.144\mu m/bar$ on average. The reason for this is that there is a pressure difference on both sides of the tube. Pressure causes the tube to bend upwards. Therefore when the pressure at one side of the tube is higher this part will bend upwards further.

With no flow, there is also a deformation difference measured of $53nm/bar$ for chip 1 and $67nm$ for chip 2. However the step size of the interferometer is $130nm$. Consequently, the assumption that the difference in deformation on average is $60nm/bar$ is not reliable.

The difference in deformation of the tube could be used to measure pressure drops over the tube. If the tube is static you could measure the differences in capacitance, this would be proportional to the pressure drop over the tube. Whether the difference in deformation is big enough to produce a measurable capacitance difference is not clear. Further studies will have to be dedicated to this topic. If the capacitance difference turns out to be to low, the chip could be redesigned. If the capacitor pairs are placed closer to the corner of the channels the difference in capacitance would be greater. Whether the same difference in deformation would occur with different outlet pressures and the same pressure drop should be investigated.

The tube bent upward under pressure and when there is a pressure difference from the inlet to the outlet there is a difference in deformation of the upper left and right corner. This information could be used to design an chip that can statically measure the pressure and pressure drop. The same chip could be used to dynamically measure flow and pressure. Whether this chip would be able to dynamically measure the pressure drop is not clear. It is also recommended to investigate the temperature dependency of the device.

VII. CONCLUSION

In the simulations the corners of the micro Coriolis mass flow sensor are bending upward with $0.52\mu m/bar$. When measuring the deformation of the chip it was found that on average the corners are bending upwards with $0.52\mu m/bar$. The static simulations correspond reasonably with the measurements. Thus this can be a reliable method to find the pressure behavior of the tube. When there is a pressure difference between the inlet and the outlet, there will be a deformation difference in the upper corners of the channel of on average $0.144\mu m/bar$. This information could be used to design an chip that can statically measure the pressure in the tube and measure the pressure difference over the tube. This same chip could dynamical measure the flow and pressure at the same time. Although it is not clear if this can be measured with the capacitors in their current place or that they need to be placed somewhere else.

ACKNOWLEDGEMENT

The Author thankfully acknowledge ING.R. G. P. Sanders and DR.IR. D. ALVERINGH For technical help.

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