Micro fluidic Oscillator for Gas Flow Control and Measurement

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Abstract- Micro fluidic oscillators were obtained from wall attachment micro fluidic amplifiers using a feedback loop from the outputs to the control inputs. These devices can be used as actuators, as mixers, and also as flow meters, when the oscillation frequency is proportional to the volumetric flow in subsonic and moderately compressible conditions. The devices were then made in a SU-8 based epoxy photo resist using photolithography ultraviolet process. The article shows the results obtained in the experimental tests of the devices with gases (nitrogen, argon, and carbon dioxide). The dimensions are of the order of 280 μm. The typical variation of the frequency with volumetric flow presents a range close to thousands of Hz. The oscillation frequencies were obtained using hot wire filaments (in this case with 12 μm of diameter). The experimental results indicated which operation of the micro fluidic oscillator were direct function of the length of feedback loop and the velocity inside of the interaction region.

Keywords: fluidic, flow control, flow meter, micro fabrication, and fluidic oscillator

1. Introduction

In this research was developed a series of fluidic micro flow meters, at the University of São Paulo (Brazil) in collaboration with University of Puerto Rico at Humacao (UPRH), aiming at to investigate innovative and original processes and applications of these devices. Fluidic technology based on natural oscillation phenomena is a relevant topic in several strategic areas such as aerospace; automotive; military; drug research, drug dispensing, dialyze in medicine; analytical chemical instrumentation; automatic control in industries; electronics chip cooling; among many others [1-7]. In these cases, the oscillatory flowmeters utilize specially designed geometric configurations, identified by the absence of moving parts, to create an environment where self-induced, sustained oscillations will occur [6,8]. Oscillating flowmeters are inherently fluidic logic (digital) devices, and the basic measurement they read is frequency. In a properly made flowmeter, the frequency of its oscillations is proportional to the volumetric flow rate and using these devices in millimeter/micrometer scale, the operating speeds are increased in a higher rate when compared to those of their macroscopic counterparts due to the reduced inertia. Furthermore, several categories and subgroups of oscillatory flowmeters exist, each with a unique shape and particular approaches. This paper in particular analyze one *"feedback fluidic oscillator"* [6-8] obtained from wall attachment microfluidic amplifiers.

The technology of using the flow characteristics of liquid or gas to operate a control system are fairly old, it was not until about 1960's that researchers attempted to use fluidics [7,8]. The demand for reliable controls in space and marine environment researches stimulated these progresses.

Very important contributions from fluidic logic technologies are associated with the fluid behavior known as "*Coanda effect*"[6], discovery in the 1930's by Henri Coanda [7]. He observed that as a free jet emerges from a jet nozzle the stream would tend to follow a nearby curved or inclined surface. It also "attaches" itself to and flows along this surface if the curvature or angle of inclination is not too sharp. Coanda explained this tendency as being caused by the jet stream's entraining nearby fluid molecules. When the supply of these molecules is limited by an adjacent surface, a partial vacuum develops between the jet and the surface. If the pressure on the other side of the jet remains constant, the partial vacuum, which is a lower pressure region, will force the jet to bend and attach itself to the wall [7].

The microfluidic oscillator utilized in this work consists of a bistable wall-attachment fluidic amplifier [9], which is made to oscillate connecting the output ports to the control ports, as shown schematically in Figure 1. This provides a feedback loop, from each output port to its corresponding control port.

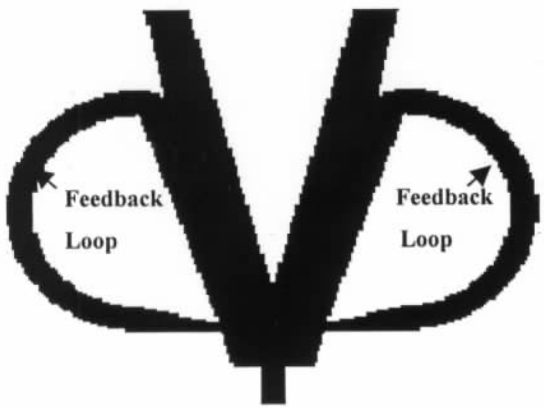


Fig 1 Typical feedback oscillator configuration derived from wall attachment fluidic amplifier.

The scope was to determine how this tiny (1.0 millimeter from inlet to outlet) oscillator flow circuit produces dual pulsating outflows from a single constant inflow, with no moving parts. In this application, a portion of each primary outflow is captured in a feedback channel, and then this captured fluid is used to redirect the primary outflow over to the opposite leg.

The feedback fluidic oscillator can be used in the direct flow metering of liquids, gases, and several other types of Newtonian fluids. However, because fluidics flowmeter is not as rapid as electronics, it is unlikely to compete in fields with ultrahigh speed requirements, the typical operation with pure fluidic devices involving response time between 0.01 to 100 milliseconds [6]. On the other hand, in many applications fluidics based flowmeter is advantageous. It is now possible to detect, interlock, and power complex operations by using gas throughout a system.. The elimination of in-situ electrical contacts prevents a possible fire hazard in several cases. Also, this type of flowmeters possesses easy maintenance and easy manipulation, and the advantage that the output of the flowmeter can be transformed into an electric signal to facilitate the reading process of the total flow rate.

With the device operating in incompressible (Mach Number less than 0.3) to moderate compressible regime (Mach Number between 0.3 to 0.7), the frequency of oscillation is determined by: the time of residence of the fluid in the control port interconnection (feedback loop), by the amplifier switching dynamics [8.9], and by the flow-rate if the Strouhal number (expression 1) and Reynolds Number (expression 2) are constants or linearly dependents. In these conditions, and only in these, the feedback oscillator can be designed to give a wide linear range of frequency - velocity and tends to provide a good signal at low velocities. The reason for the good signal is that feedback oscillator has few modes of oscillation competing for the energy at low velocities. The period of oscillation, T, is given in expression 3.

$$Str = \frac{n.D}{u} \quad (1)$$

$$Re = \frac{\rho.u.D}{\mu} \quad (2)$$

$$T = 2(\tau_t + \tau_S) = 2(\frac{l}{c} + \frac{\xi L}{u}) \quad (3)$$

Where: n is the number of vortices inside of interaction region; D is the hydraulic diameter; u is the jet velocity; ρ is fluid density; μ is the absolute viscosity; τ_t is the transmission time; τ_S is the switching time; l is the length of one loop; c is the speed of wave propagation (the speed of wave propagation tends to the speed of sound in this case);

L is the nozzle-to-splitter distance; and, finally, ξ is an empirical constant. A fast switching device has a value of ξ between one and two, but higher values can occur as a function of velocity and oscillation frequency unbalance.

For liquids, generally the frequency of oscillation, f in expression (4), is strongly dependent on the switching time, because the speed of wave propagation is much higher than the jet velocity in the nozzle-to-splitter path. Typically, the transmission time for operation with liquids is approximately two or four order smaller than the switching time. For gases, expression (5), the frequency of oscillation depends of both transmission time and switching time.

$$f = \frac{1}{2\tau_S} = a + bQ \quad \text{(for liquids)} \qquad (4)$$

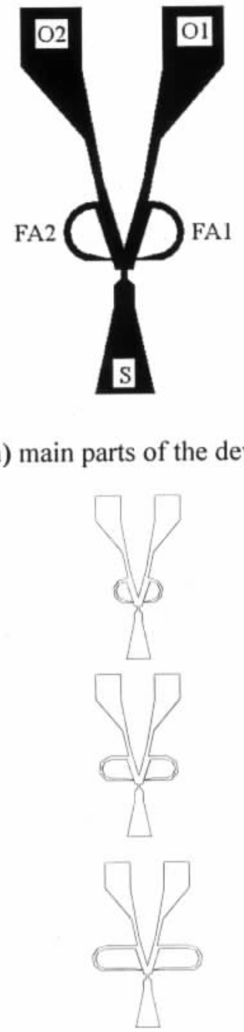
$$f = \frac{1}{2(\tau_t + \tau_S)} = a + bQ \quad \text{(for gases)} \qquad (5)$$

Where a and b are constants and Q the volume flow.

The oscillator frequency increases linearly with increasing volume flow and this behavior favors the feedback fluidic oscillator to be used in the flow measurement of Newtonian fluids. Furthermore, the linear regime between frequency and volume flow is due to a faster compensation of the low-pressure regime with a higher flow rate. In this case, the volume flow can be varied by changing the geometry of the supply nozzle, i.e., the flow resistance and the given supply pressure.

2. Geometrical Characteristics and Fabrication

Figure 2 presents the geometrical characteristics of the microfluidic oscillators used in this work.. Figure 2a shows the main parts of the device that include: supply input, interaction region, outputs, and feedback arms. Figure 2b illustrates the resulting configurations obtained with different feedback arms (6500 μm, 12500 μm and 18500 μm). Two microchannel depths were adopted, 100 μm and 175 μm, what led to hydraulic diameters of ~ 147 μm and ~ 215 μm at the output of the supply nozzle, and of ~ 100 μm and 127 μm at feedback arms.



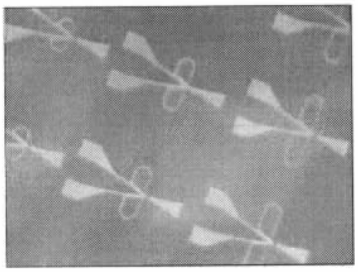
(a) main parts of the device

(b) configurations with different feedback arms (6500 μm, 12500 μm and 18500 μm)

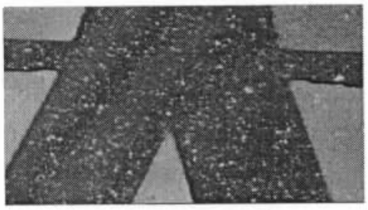
Fig. 2 Geometric configurations.

The devices were defined in epoxy based SU-8 photoresist spin cast (2,500 rpm, 60 s and 1,750 rpm, 60 s for thickness of 100 μm and 175 μm respectively), on alumina square wafers (5 cm x 5 cm) covered with a thin bilayer of Ti (~40 nm) on Au (~100 nm) as shown in the photos of Figure 3. Before SU-8 deposition, these samples were cleaned using standard RCA chemical solutions. After the spinning process, the photoresist passed by the following steps: pre-bake

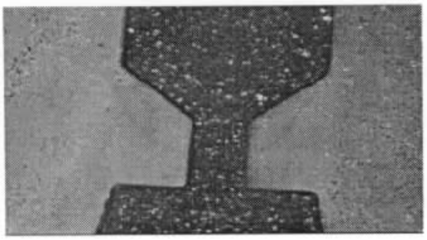
(95 °C/ 20 minutes), exposition (600 mJ/cm^2 at 365 nm), post-bake (95 °C/ 15 minutes) and development using the solvent PGMEA (propyleneglycol monomethylether acetate) (T = 60 °C, 6 h).



(a) Microfluidic oscillators



(b) Interaction region



(c) Supply port

Fig.3 Some photos of the implemented devices.

The devices were sealed using glass plates (Pyrex® 7740, 2.5 mm thick) with input/output holes (diameter of 2 mm) defined by drilling. A layer of PMMA (20 μm thick) was deposited on one side of the glass plate that was attached to the photoresist. The resulting structures were heated at 100 °C for 60 min, while submitted to a pressure of 10 MPa.

Tests with nitrogen were performed using the experimental setup presented in Figure 4, composed of a filter (FESTO, 5 μm, discharge coefficient of 95%), pressure sensor, flow sensors, and anemometers.

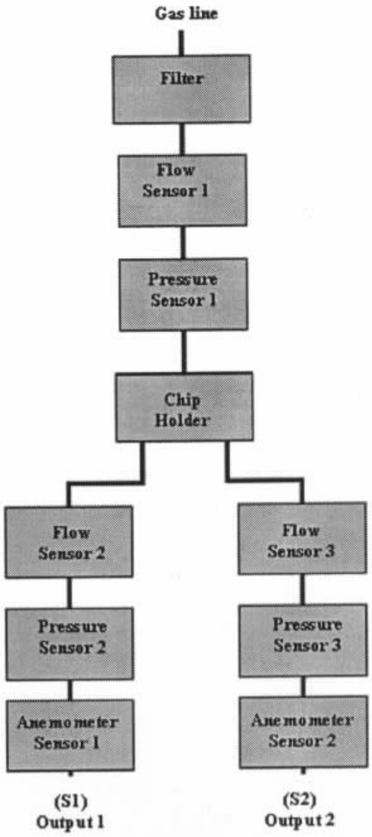


Fig. 4 Experimental setup.

In these case, thermal mass flow meters (MKS-500 and MKS-100 model 1179A and 2179A) monitored the mass flow rates at supply, control and output stations. Pressure sensors (SDE - 16-5 V/20 mA) were also used to monitor the pressures at the supply and control connections. Cut-off and needle-type valves were used to control the flows going into the device. The anemometers (Dantec CTA 12 μm) were used to determine the oscillation frequency of these devices.

The devices thus fabricated were mounted on a chip holder plate establishing the connection to gas supply lines and exits to atmosphere as illustrated in Figure 5. A stereoscope was used to align the access ports with chromatographic tubes and the grooves (in which Viton elastomers were positioned).

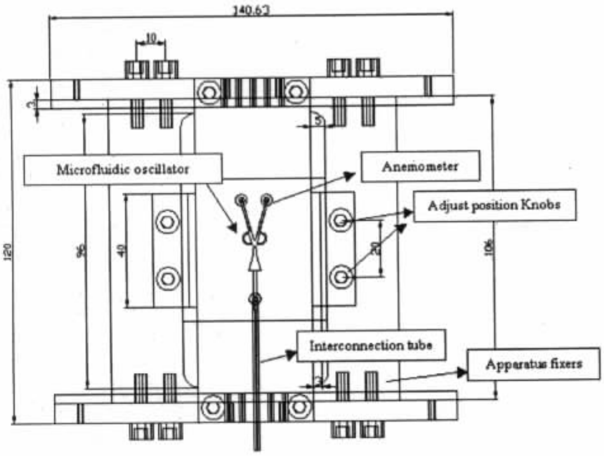


Fig. 5 Chip holder (dimensions in mm).

3. Results and Discussion

Figure 6 shows experimental results of the variation of the oscillation frequency as a function of the volumetric gas flow (Nitrogen, Argon and Carbon Dioxide) and of the length of the feedback arms. It can be seen that the oscillator operates with frequencies in the range of kHz, confirming a fast performance expected for miniaturized devices.

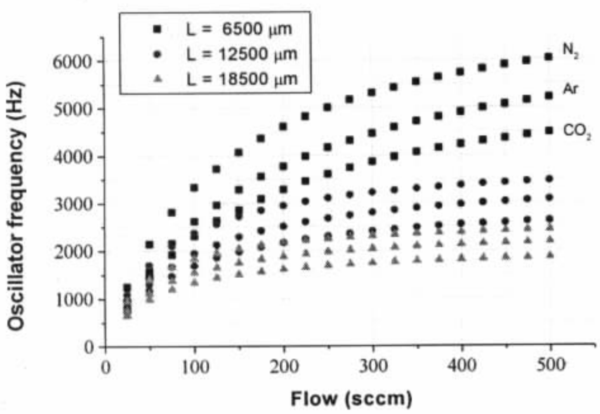


Fig. 6 Oscillation frequencies output as a function of feedback loop length (L), input gas and flow (in standard centimeter cubic per minute). Microchannels 100 μm deep.

The theoretical behavior predicted from expression (3) is observed, as the curves present a linear part for low volumetric flows, for which the dependence with the switching time (τ_s) is more pronounced. As the volumetric flow increases the behavior is controlled by the transmission time (τ_t), and frequency tends to a constant value that decreases with the length of the feedback arm (3).

Figure 7 illustrates the behavior observed at the output of the anemometers for different frequencies, showing regular oscillation with nearly constant amplitude for each case. It has to be stressed that the maximum frequency measured is much lower than that of the limit of operation of the anemometers, of 16.7 kHz. Thus, the saturation in frequency observed with higher volume flows is a characteristic of the devices and not of the anemometers.

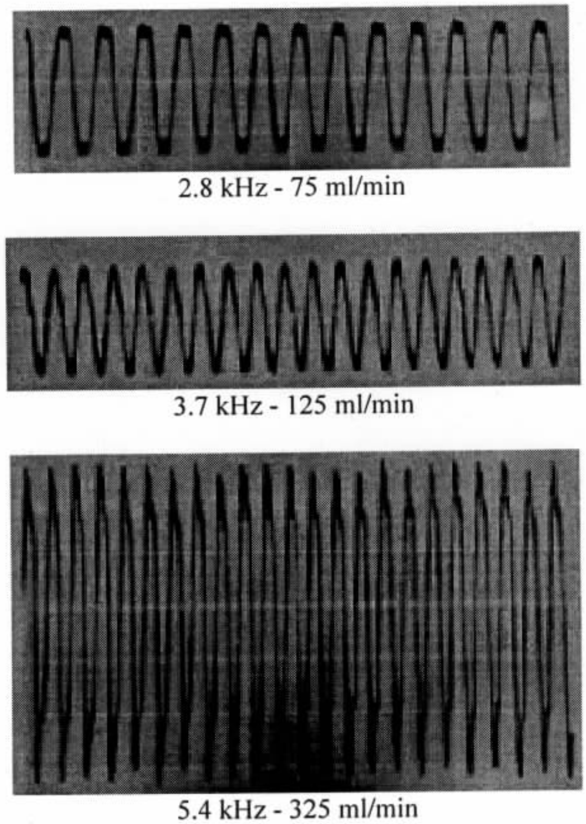


Fig. 7 – Behavior observed at the output of the anemometers for different frequencies for a device with l = 6500 μm and microchannels 100 μm deep.

Figure 8 compares experimental curves with theoretical ones obtained with expression (3) to nitrogen, the others gases presented a similar behavior. For a qualitative analysis of the behavior of the device, we assumed for the theoretical calculation that the velocity of propagation was the sound velocity for nitrogen and the empirical constant was $\xi = 2$. Each curve was normalized with respect to its maximum frequency (obtained for a volumetric flow of 500 ml/min), as the theoretical frequency values ever resulted larger than the experimental ones. A very good agreement can be observed between the experimental curves, indicating that the same type of behavior was observed for the different devices. A reasonable agreement is also observed with respect to the theoretical values, which improves with the decrease of the feedback arm length.

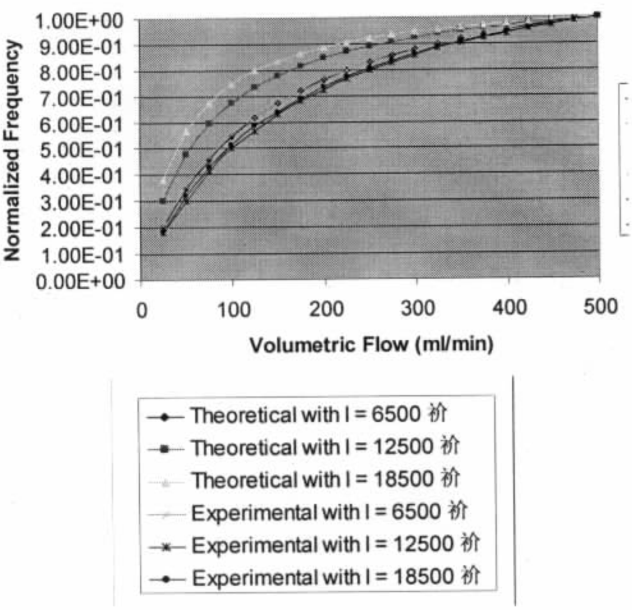


Fig. 8 Comparison of experimental curves with theoretical ones obtained with expression (1). For the theoretical calculation the velocity of propagation was assumed to be the sound velocity for nitrogen and the empirical constant was ξ = 2. Each curve was normalized with respect to its maximum frequency (obtained for a volumetric flow of 500 ml/min).

Figure 9 shows the Mach Numbers as a function of the volumetric flow, estimated at the output of the supply nozzle considering a steady flow. One can notice that the device operates in the incompressible flow regime for volumetric flows of up to 400 ml/min, avoiding undesirable effects as shock waves, which can affect its linear response observed in the range of up to 200 ml/min.

Figure 10 gives the Reynolds Number at the output of the supply nozzle as a function of the volumetric flow. Observe that for supply flows lower than 275 ml/min the device operates in the laminar regime (considering a transition occurring for Re = 2300). Although this condition does not favor the Coandas' effect, there is evidence of wall attachment for microdevices, as demonstrated experimentally by Volmer[15]. Also, this condition may favor the suppression of microvortices and surface effects (related with channel roughness) that may difficult the occurrence of the feedback cycles.

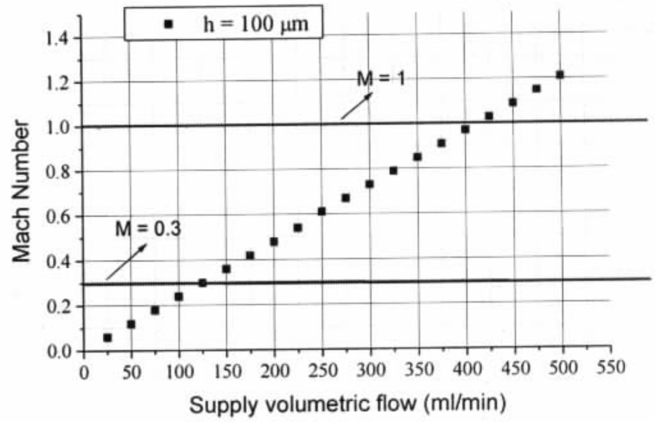


Fig. 9 Mach Numbers estimated at the output of the supply nozzle.

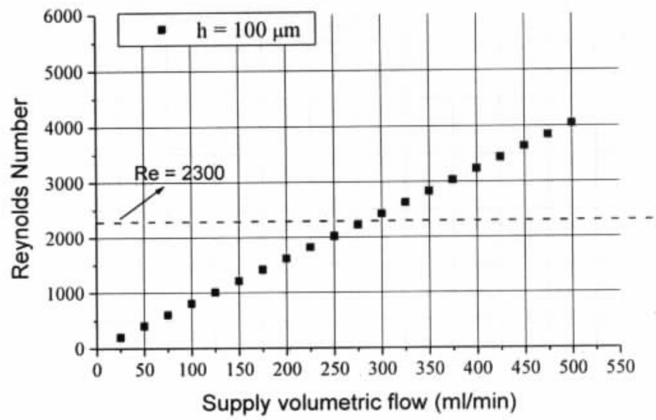


Fig. 10 Reynolds Number at the output of the supply nozzle.

Thus, the results demonstrate the occurrence of natural oscillation phenomena in microfluidic devices for operation with gas, with the possibility of operation with a linear variation of frequency with volumetric flow, which is suitable for the implementation of flow sensors.

4. Conclusions

It was successfully demonstrated the possibility of fabrication of the micro fluidic oscillators using a feedback loop from the outputs to the control inputs. These devices can be used as flow meters, when the oscillation frequency is proportional to the volumetric flow in moderately compressible conditions. The devices were made in a SU-8 based epoxy photo resist using photolithography ultraviolet process. The output of the supply nozzle is of the order of 280 μm. The experimental tests of the devices were performed using nitrogen, argon, and carbon dioxide. The typical variation of the frequency with volumetric flow presents a range close to thousands of Hz. The oscillation frequencies were obtained using hot wire filaments (in this case with 12 μm of diameter). And the experimental results indicated which operation of the devices were directly dependents of the length of feedback loop and velocity in the interaction region, which is suitable for the implementation of sensors with different flows ranges.

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