DESIGN OF MICROFLUIDIC OSCILLATORS
Eliphas Wagner Simões, Rogério Furlan, and Marcos Tadeu Pereira*
Laboratório de Sistemas Integráveis (LSI)
* Laboratório de Vazão - Instituto de Pesquisas Tecnológicas do Estado de São Paulo
Escola Politécnica da Universidade de São Paulo (EPUSP)
São Paulo - SP, Brazil
C.E.P. 05508-900, Tel. 55 11 3818 5657, Fax. 55 11 3818 5665
E-mail: eliphas@lsi.usp.br, furlan@lsi.usp.br, and marcostp@ipt.br

Abstract
This paper reports the project of microfluidic oscillators, which can be used in the measurement and control of low fluid flows. The possible applications include automatic control in industries, measurement in domestic gas storing, and chemical as well as biological analysis. In this case, the devices should possess easy maintenance and manipulation characteristics, and rapid response time. Also, it can be advantageous if the output of the flowmeter can be transformed in an electric signal to facilitate the reading process. The devices described in this work present potential to address all these requirements. Thus, in this stage of the project, microfluidic oscillators were simulated using the ANSYS 5.4 simulation package and device dimensions derived from those of the typical wall attachment microfluidic amplifier (control nozzle width of 50 micrometers). The results of these calculations indicate that conventional steady state and dynamic transient analysis are useful tools for evaluating fluidic oscillator in micro dimension scale.

1. Introduction
Although the knowledge of fluidic principles is fairly old, it was not until about 1960 that fluidic devices, which are characterized by the absence of moving parts, started to be used commercially [1-4]. The demand for reliable control in aerospace research stimulated progress of the technology of using the flow characteristics of liquid or gas to operate a control system [3]. One of the newest of means measurement, control, and actuation technologies - microfluidics - has in recent years come to compete with mechanical and some electrical systems, because of microfabrication processes, that are the use of techniques from the microelectronics industry, and from precision mechanics technology [5–8]. Furthermore, the scaling of nozzles, valves, and others fluidic devices are the subjects of several study and development in the last decade [8]. Also, the operating speeds of the micro-devices are increased over those of their macroscopic counterparts due to the reduced inertia of their parts, often becoming less sensitive to external noise [9]. Fluidic sensors (transducers of ever increasing variety) and actuators, actually aimed at a wide range of applications [7][10-14].

One of the major contributions to fluidic technologies is associated with the behavior that is known as the “Coanda effect” [3][4]. It is observed that for a free jet emerging from a jet nozzle, the stream tends 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 [3]. The fluid molecules nearly the jet-entraining stream causes this tendency. When the supply of these molecules is limited by an adjacent surface, a partial vacuum develops between the free 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 [3]. Figure 1 shows a typical fluidic device based in the Coanda effect, know as the wall-attachment fluidic amplifier [3][15], which has four basic functional parts: (1) a supply port, (2) control ports, (3) output ports, and (4) an interaction region. A turbulent jet emerging from the supply port interacts with flows from the control ports in the interaction region, which can be see in Figure 1. As a result, the jet from the supply port is directed to one or another output, depending on the pressure (flow) of the control ports. In this way, the jet attaches itself to a wall, due to the Coanda effect, thereby causing the device to be bistable or digital [1-3].

Fig. 1: Functional parts of the bistable wall-attachment fluidic amplifier are illustrated: (1) a supply port, (2) control ports, (3) output ports, and (4) interaction region.

The microfluidic oscillator proposed in this project and presented schematically in Figure 2, consists of a bistable wall-attachment fluidic amplifier, which is made...
to oscillate connecting the output ports to the control ports as shown in the figure [16-20]. This provides a feedback loop, see Figure 2, from each output port to its corresponding control port. This type of device, usually known as feedback fluidic oscillator, can be used for the direct flow measurement of liquids, gases, and several other types of Newtonian fluids. The possible applications include automatic control in industries, measurement in domestic gas storing, medical diagnosis, chemical and biological analysis, among several other areas.

![Fig. 2: typical feedback oscillator configuration derived from wall attachment fluidic amplifier.](image)

However, as fluidic flowmeters are not as rapid as electronic ones, it is unlikely to compete in fields with ultrahigh speed requirements, typical operation with pure fluidic devices involving response time between 0.01 to 100 milliseconds [18-20]. On the other hand, in many applications fluidics based flowmeter is advantageous. The elimination of electrical contacts prevents a possible fire hazard in several cases. Also, this type of flowmeter possesses easy maintenance and easy manipulation [16]. With the device operating in incompressible (Mach Number - ratio between local velocity and speed of sound - less than 0.3) to moderate compressible regime (Mach Number between 0.3 and 0.7) [3], the frequency of oscillation is determined by: the time of inertance of the fluid in the control port interconnection (feedback loop), by the amplifier switching dynamics, and by the flow-rate [21]. Also, the feedback oscillator can be designed to give a long linear range of frequency - velocity characteristics. The feedback oscillator tends to provide a cleaner signal at lower velocities. The reason for the cleaner signal is that the feedback oscillator has fewer modes of oscillation competing for the energy at lower velocity [21]. The period of oscillation, $T$, is given in expression (1) as:

$$T = 2(\tau_t + \tau_s) = 2\left(\frac{1}{c} + \frac{\xi L}{u}\right)$$  \hspace{1cm} (1)

where: $\tau_t$ is the transmission time; $\tau_s$ is the switching time; $L$ is the length of one loop; $c$ is the speed of wave propagation (if the duct is not small, the speed of wave propagation tends to the speed of sound); $L$ is the nozzle-to-splitter distance; $u$ is the jet velocity; and, finally, $\xi$ is an empirical constant. A fast switching device has a value of $\xi$ between one and two.

For liquids, generally, the frequency of oscillation, $f$, as given in expression (2), 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 [16][21]. Typically, the transmission time for operation with liquids is two to four orders of magnitude lower than the switching time. For gases, expression (3), the frequency of oscillation depends on both, transmission time and switching time.

$$f = \frac{1}{2\tau_s} = a + bQ \quad \text{(for liquids)}$$  \hspace{1cm} (2)

$$f = \frac{1}{2(\tau_t + \tau_s)} = a + bQ \quad \text{(for gases)}$$  \hspace{1cm} (3)

where $a$ and $b$ are constants and $Q$ is the volume flow. The oscillator frequency increases linearly with increasing volume flow and this behavior favors the feedback fluidic oscillator to be used for the flow measurement of Newtonian fluids.

In order to obtain an understanding of the flow features inside this type of microfluidic oscillators, operating with gas (Nitrogen), a Computational Fluid Dynamics (CFD) [1][22-25], using the ANSYS/FLOTRAN package, was undertaken according to the following topic.

### 2. Simulation Procedures

Many of the simulations presented in the literature [26] use the ANSYS finite-element program - which presents a specific module (or library) for dynamic simulations in fluids, denominated FLOTRAN. We wish to emphasize that in order to simplify the computational process, we assumed that a two-dimensional analysis would be adequate to test the oscillator operation. This is valid because of the probable experimental aspect ratio (width to height) of the implemented devices [27][28]. The device geometry used in the analysis using the finite element ANSYS/FLOTRAN 5.4 package [29] are presented in Figure 3a. The basic oscillator is 5775 $\mu$m long and 3175 $\mu$m wide, and has a control nozzle width, which has a characteristic dimension of 50 $\mu$m. Its length of the feedback channels and width were 2515 $\mu$m and 150 $\mu$m, respectively. In this case, we manually defined the mesh configuration, the number and the aspect ratio of the nodes for each region, as shown in Figure 3b.

We found out that the defined configuration (with 62 keypoints, 69 lines, 18 areas, and 8123 nodes) was suitable in terms of computational resources (PC platform with a Pentium III, 450 MHz, and 256 MB of RAM) and simulation time. We used standard two-
equation κ-ε turbulent models and FLUID141 elements (rectangular form, 4 nodes, and 2D space) [29].

\[
P_{01} \quad \text{P} \quad \text{P}_{02}
\]

\[\text{(a) ANSYS/FLOTRAN Model}\]

\[\text{P}_{S}\]

\[\text{(b) Mesh configuration}\]

Fig. 3: Device geometry and mesh configuration adopted in the two-dimensional analysis of the feedback microfluidic oscillator: (a) ANSYS/FLOTRAN model and (b) mesh configuration.

A minimum of 1500 iterations to steady state analysis and 25000 iterations to transient analysis were necessary to obtain the desired convergence for the results. A value lower than 10\(^{-6}\) was adopted for the convergence monitors, calculated as E, in expression 4:

\[
E = \sum_{i=1}^{N} \frac{\phi_i^{k} - \phi_i^{k-1}}{\phi_i^{k}}
\]

where \(\phi\) is a degree of freedom (pressure, velocity, temperature, etc.), \(N\) is the total number of nodes, \(i\) is the iteration number and \(k\) is the number of iterations.

The internal flow (velocity) behavior was analyzed as a function of the absolute supply pressure, \(P_S\), considering values between 125 kPa to 400 kPa, which lead to reasonable velocity and associated oscillation frequencies. The reference pressure was assumed to be 101.35 kPa. The output pressures (\(P_{01}\) and \(P_{02}\) in Figure 3a) were assumed to be slightly higher than the reference pressure. The physical gas parameters (density (\(\rho\)), viscosity (\(\mu\), etc.) employed to Nitrogen (\(N_2\)) were those indicated in Table 1 [30].

<table>
<thead>
<tr>
<th>Gas</th>
<th>Nitrogen ((N_2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference pressure (kPa)</td>
<td>101.35</td>
</tr>
<tr>
<td>Reference temperature (K)</td>
<td>298.15</td>
</tr>
<tr>
<td>Density in reference condition (Kg/m(^3))</td>
<td>1.15</td>
</tr>
<tr>
<td>Viscosity in reference condition ((\mu)Pa s)</td>
<td>17.8</td>
</tr>
<tr>
<td>Sound velocity in reference condition (m/s)</td>
<td>351.9</td>
</tr>
<tr>
<td>R - Gas constant (J/Kg.K)</td>
<td>296.8</td>
</tr>
<tr>
<td>(\gamma) ((C_P/C_V))</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Tab. 1 - Physical fluid parameter employed in simulations.

Where:

- \(C_P\) is the specific heat at a constant pressure
- \(C_V\) is the specific heat at a constant volume
- \(\gamma\) is the ratio between \(C_P\) and \(C_V\)

Finally the sound velocity, \(C\), is defined in expression 5 as [3][30-31]:

\[
C = \sqrt{\gamma RT}
\]

We should keep the fact that the speed of sound, depends on the temperature and therefore on the local pressure and density [3].

The goal of the study was to determine how microfluidic oscillators would operate in different pressure regimes and oscillation frequencies. The following topics indicate the results obtained by steady state analysis and transient analysis based in the simulation procedure described above.

### 2.1 Steady State Analysis

Steady state analyses were used to determine the operation range of transient simulations and typical behavior inside the microfluidic oscillators.
The behavior of the Mach number [3][30], at the interaction region as a function of supply pressure is presented in Figure 4. For $P_s > 125$ kPa the Mach number are higher than 0.3, revealing that compressibility effects can influence the flow inside the microfluidic oscillators for the proposed design conditions. The flow in the interaction region becomes supersonic for $P_s > 250$ kPa, as can be seen in Figure 4. Thus shock waves can be formed in the interaction region for $P_s > 250$ kPa, having a significant influence on the oscillator flow behavior. Because the formation of shock waves results in higher local density and pressure gradients, it can degrade the principal flow jet and the control feedback. These results are supported by previous work about microfluidic amplifier reported by Simões-Furlan [28] where can be seen that a choked flow condition can be reached at the output of the supply nozzle of microfluidic devices. Thus, after reaching this condition, further increases in the supply pressure only increase the density in the supply nozzle, as is well known.

The Reynolds numbers at the output of the supply nozzle of the microfluidic oscillators, calculated as function of supply pressure and hydraulic diameter, according to the expression 6 and 7, are presented in Figure 5.

$$\text{Re} = \frac{\rho D_h u}{\mu} \quad (6)$$

$p$ is the density; $\mu$ is the absolute viscosity; $u$ is the cross-sectional average velocity; and $D_h$ is the hydraulic diameter, described in expression (7):

$$D_h = \frac{4A}{P} \quad (7)$$

where $A$ is the cross-sectional area and $P$ is the wetted perimeter.

![Fig. 4: Maximum Mach number at the interaction region as a function of supply pressure for nitrogen, with $P_{O1} = P_{O2} = 101.85$ kPa.](image)

The values of density and viscosity were obtained by simulation. For a hydraulic diameter of $\sim 90$ $\mu$m, considering a width of output supply nozzle of 130 $\mu$m and a depth of 67 $\mu$m, a transition to turbulent regime can occur at high supply pressures. This probable depth was established assuming a high-density plasma etching process, according to experimental results indicated in Simões et al. [27]. It is important to notice that for a supply pressure less than 175 kPa the devices can operate with compressible flow with an essentially laminar regime.

Figure 6 displays the volume flow as a function of the supply pressure. Where the volume flow was determined using the velocity profiles of the simulations. The cross sectional area was obtained considering the hydraulic diameter, using expression 7.

![Fig. 5: Reynolds number at the output of the supply nozzle of the microfluidic oscillator as function of the supply pressure, with $P_{O1} = P_{O2} = 101.85$ kPa.](image)

![Fig. 6: Volume flow as a function of supply pressure, with $P_{O1} = P_{O2} = 101.85$ kPa.](image)

The maximum volume flow ($\sim 3 \times 10^{-6}$ m$^3$/s) corresponds to Nitrogen with $P_s = 400$ kPa. However, this condition is associated with Reynolds Number higher than 4000, i.e. the fluid flow regime is turbulent. The velocity in interaction region is supersonic and shock waves can be formed. Comparing Figure 4 to Figure 6 the best range for transient analysis corresponds to pressures between 125 kPa and 250 kPa.
Thus, our results indicate that for supply pressures less than 175 kPa, the microfluidic oscillator can operate with compressible and subsonic flow at the interaction region with a laminar regime. This condition is usually the range of operation used in the transient analysis, as shows the following topic.

2.2 Transient Analysis

The transient analysis adopted the steady state simulation as the initial step. In this case, we used a total number of 25,000 iterations (250 iterations per step), the time step was defined in the range between 1 and 10 µs. With a given difference between the input supply and output ports pressures, a transient calculation was performed to determine the pressure and velocity distribution inside the microfluidic oscillator. The probable switching and transmission times were obtained using the expression (1) and were compared with the frequency, which was calculated by analyzing the volume flow time-dependence at the output ports.

Figure 7 displays the variation of the frequency with volume flow. For comparison we included an approximately linear fit expected for a correlation between frequency and volume flow for this oscillator operation range. The typical variation of the frequency with volume flow presents a range close to tens of thousands of Hz. Furthermore, the angular coefficient of the straight line is strongly dependent on transmission time (proportional to feedback loop and local sound velocity).

\[ \text{Frequency (kHz)} = 38.57 + 0.01 \times Q \]

Fig. 7: Variation of the frequency with volume flow for the simulated microfluidic oscillators.

Thus, the initial design and development of a microfluidic oscillator by using simulations, permits to foresee promising applications, involving the measurement of gases flows in the micro scale range.

3. Conclusions

The performance of the microfluidic oscillator with dimensions derived from a typical wall attachment microfluidic amplifier (characteristic nozzle width of 50 micrometers) was simulated using the commercial ANSYS (FLOTRAN) 5.4 package. The results of these simulations, with a two-dimensional finite-element model, indicate that conventional steady state and dynamic transient analysis are useful tools for evaluating fluidic oscillators operating with gas (Nitrogen). Using steady state analysis, the internal flow behavior inside the microfluidic oscillators, was calculated as a function of supply pressure. The simulations reveal that for supply pressures less than 175 kPa, the microfluidic oscillator can operate with compressible and subsonic flow at the interaction region with a laminar regime. This range of operation used in the transient analysis corresponds to a linear dependence between the frequency of oscillation and volume flow. Also, the typical variation of the frequency with volume flow presents a range close to tens of thousands of Hz. Thus, the design and development of a microfluidic oscillator by using simulations, permits to foresee promising applications, involving the measurement of low gas flows in the micro scale range.

4. Acknowledgements

The authors would like to acknowledge the financial support of FAPESP (Proc. Number 00/04218-0), PADCT, and CNPq. The authors thank the discussions with Mauricio Massazumi Oka.

References: