Numerical Analysis of a Microfluidic Oscillator Flowmeter Operating with Gases or Liquids

Eliphas Wagner Simões [a b], Rogerio Furlan [c a], and Marcos Tadeu Pereira [b]
[a] Laboratório de Sistemas Integráveis - Escola Politécnica da Universidade de São Paulo
[b] Laboratório de Vazão - Instituto de Pesquisas Tecnológicas do Estado de São Paulo
[c] University of Puerto Rico at Humacao, Department of Physics and Electronics, CUH Station, Humacao, PR, 00791

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, r_furlan@cuhac.upr.clu.edu, and marcostp@ipt.br

ABSTRACT

We analyzed microfluidic oscillators operating with liquids (water, isopropilic alcohol, and acetone) or gases (nitrogen, argon, and carbon dioxide), using numerical simulation. The possible applications include rapid measurement and control of low fluid flows in areas as automatic control in industries, measurement in domestic gas storing, chemical or biological analysis, etc. In this case, the devices should possess easy maintenance and manipulation characteristics. And, the devices described in this work present potential to address satisfactorily all these requirements. For simulations, using the ANSYS 5.7 commercial package, the dimensions were derived from those of a typical wall attachment microfluidic amplifier. The results of these calculations indicate that conventional steady state and dynamic transient analysis are useful tools for evaluating fluidic oscillator in the micro dimension scale.

Keywords: fluidic oscillator, flowmeter, fluid mechanics, simulation, and micromachining

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][2]. The demand for reliable control in aerospace research stimulated progress of the technology of using the flow characteristics of fluids to operate a control system [1]. One of the newest means of measurement and control operations - microfluidics - has in recent years come to compete with mechanical and some electrical systems, because of microfabrication processes, that consist in the use of techniques from the microelectronics industry and from precision mechanics technology [3-5]. Furthermore, the scaling of nozzles, valves, and others fluidic devices are the subjects of several study and development in the last decade [6][7]. Fluidic sensors (transducers of ever increasing variety) and actuators, presently aim at a wide range of applications. The main applications in which microfluidic devices are needed are chemical analysis, drug research, chromatography, electronics chip cooling, and medical applications, like implantable drug dispensing or dialyze systems [7].

Many important contributions to fluidic technologies are associated with the fluid behavior that is known as the "Coanda effect" [1][2]. 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 [1]. 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 fluidic device based in this effect know as the wall-attachment fluidic amplifier [1][2][8].

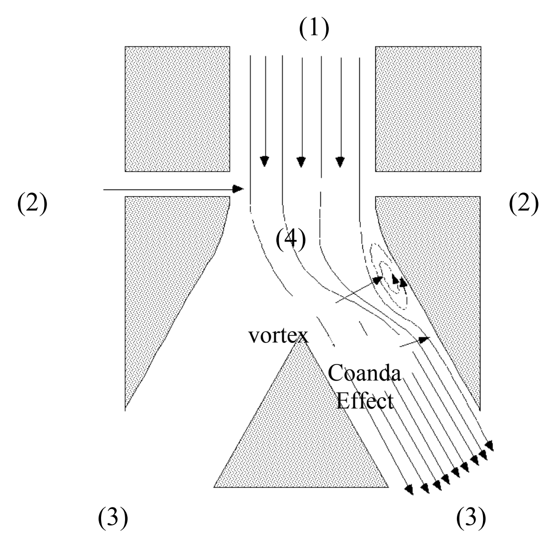


Figure 1: Functional parts of the bistable wall-attachment fluidic amplifier are illustrated: (1) a supply port, (2) control ports, (3) output ports, and (4) interaction region.

This type of device in general 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 (or 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][2].

The microfluidic oscillator proposed in this work consists of a bistable wall-attachment fluidic amplifier, which is made to oscillate connecting the output ports to the control ports, as shown schematically in Figure 2 [9-13]. This provides a feedback loop, from each output port to its corresponding control port.

Figure 2: Typical feedback oscillator configuration derived from wall attachment fluidic amplifier.

Thus, this type of device, usually known as "feedback fluidic oscillator", can be used for the direct flow measurement of Newtonian fluids [14]. The possible applications include automatic control in industries, measurement in domestic gas storing, medical diagnosis, chemical and biological analysis, mixers, among several other areas. However, as fluidic flowmeters are not as rapid as electronic ones, it is unlikely to compete in fields with high speed requirements, with operation involving response time between 0.01 to 100 milliseconds [12]. On the other hand, in many applications a fluidics flowmeter may be advantageous. For example, the elimination of electrical contacts prevents a possible fire hazard in several cases [14].

For subsonic or transonic flow, associated with quasi-laminar or turbulent regime [14], 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 [12]. In this case, the typical feedback oscillator can be designed to give a long linear range of frequency against velocity characteristics. The feedback oscillator tends to provide a cleaner signal at moderate velocities (Mach Number - ratio between local velocity and local speed of sound - between 0.3 to 0.7). The reason for the cleaner signal is that the feedback oscillator has fewer modes of oscillation competing at lower velocity [14]. The period of oscillation, T, is given in expression (1) as:

$$T = 2(\tau_t + \tau_S) = 2(\frac{l}{c} + \frac{\xi L}{u}) \qquad (1)$$

where: 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 (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, ξ is an empirical constant. A fast switching device has a value of ξ 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 [12][14]. 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.

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

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

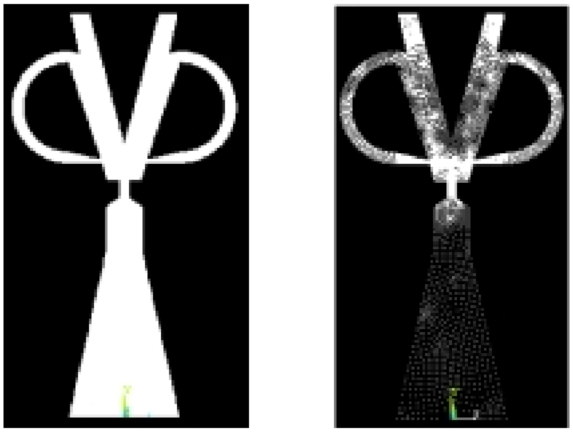
where a and b are constants and Q is the volume flow.

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 liquids or gases, a Computational Fluid Dynamics (CFD) [15][16] was undertaken according to the following topic.

2 SIMULATION PROCEDURES

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 [17]. The device geometry used in the analysis using the finite element ANSYS/FLOTRAN 5.7 package [18] are presented in Figure 3a. The basic oscillator is 5775 μm long and 3175 μm wide, and has a control nozzle width, which has a characteristic dimension of 50 μm. Its length of the feedback channels and width were 2515 μm and 150 μm, 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.



(a) ANSYS Model **(b) Mesh configuration**

Figure 3: Device geometry and mesh configuration adopted in the two-dimensional analysis of the feedback microfluidic oscillator.

We found out that the defined configuration (8123 nodes) was suitable in terms of our computational resources (PC platform with a Pentium III, 750 MHz, and 512 MB of RAM) and simulation time. We used standard two-equation κ–ε turbulent models and FLOTRAN 141 element [18]. 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 criteria.

The internal flow (velocity) behavior was analyzed as a function of the absolute supply pressure, considering values up 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 were assumed to be slightly higher than the reference pressure for all fluids analyzed. Typical physical parameters (density, viscosity, etc.) were employed for liquids (water (H_2O), isopropilic alcohol (C_3H_8O), or acetone (C_3H_6O)) or for gases nitrogen (N2), argon (Ar), or carbon dioxide (CO_2).

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.

3 RESULTS AND DISCUSSION

3.1 Steady State Analysis

Steady state analyses were used to determine the operation range of transient simulations and typical behavior inside the microfluidic oscillators.

For supply pressure higher than 125 kPa the Mach number becomes higher than 0.3 for gases, revealing that compressibility effects can influence the flow inside the microfluidic oscillators for the proposed design conditions. The flow in the interaction region, with the diverging shape, becomes supersonic for supply pressure higher than 250 kPa for Nitrogen, and supply pressure higher than 300 kPa for both Argon and Carbon Dioxide. Also, reaches Mach 1.5 for Nitrogen and Mach 1.1 for Argon and Carbon Dioxide in supply pressure around of 400 kPa. Thus, shock waves can be formed in the interaction region in this condition and that will have a significant influence on the oscillator flow behavior. Because the formation of shock waves results in higher density and pressure local gradients degenerate the principal flow jet and the control input feedback. These results are supported by previous work about microfluidic amplifier reported in the reference [17] 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. For liquids this phenomena is not observe in function of lower flow velocity (~0.1 m/s) and incompressible operation.

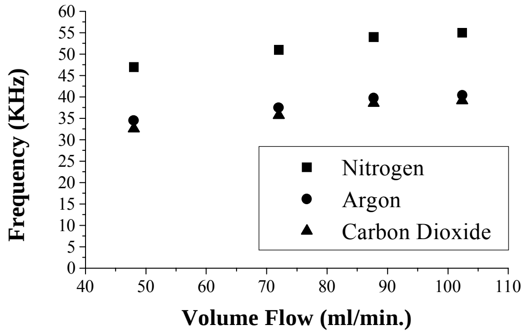
The maximum volume flow corresponds to nitrogen with supply pressure of 400 kPa. However, this conditions is associated with Reynolds Number higher than 4000, i.e. the fluid flow regime is turbulent, also the velocity in interaction region is supersonic and shock waves can be formed. For these effects, the best range for transient analysis to gases corresponds to pressures between 125 kPa to 250 kPa, for all supply gases simulated. The Reynolds Number for liquids are very low (close to 1 or 10) and turbulent effects or shock waves formations are negligible.

Thus, our results indicate that for supply pressures between 125 kPa to 250 kPa, for all different gases analyzed, 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. And by comparison, we used the same conditions to operation involving liquids.

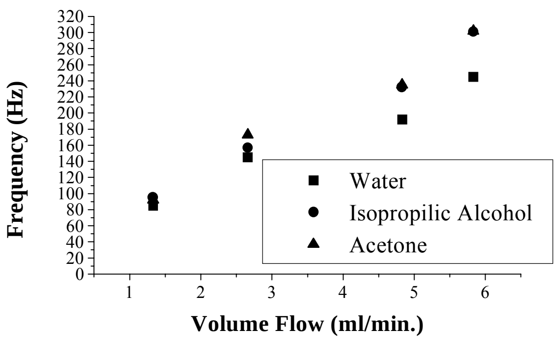
3.2 Transient Analysis

The transient analysis adopted the steady state simulation as initial step. In this case, we used a total number of 25000 iterations (250 iterations per step), the time step was defined in the range between 1 to 10 μs to gases and 100 μs to 1 ms to liquids. 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 compared with the frequency, which was calculated by analyzing the shape obtained by simulations of flow profile against time-dependence at device.

Figures 4a and 4b displays the variation of the frequency with volume flow for all supplies fluids simulated. The typical variation of the frequency with volume flow presents a range close to tens thousands of Hz for gases and two hundred of Hz for liquids. Furthermore, for gases the angular coefficient of straight line is strongly dependent of transmission time (proportional to feedback loop and local sound velocity).



(a) Gases



(b) Liquids

Figure 4: Frequency against volume flow for microfluidic oscillators simulated. In (a) Gases and (b) Liquids.

CONCLUSIONS

The performance of a microfluidic oscillator with dimensions derived from those of a typical wall attachment microfluidic amplifier was simulated using the commercial ANSYS 5.7. The results of these calculations, with a two-dimensional finite-element model, indicate that conventional steady state and dynamic transient analysis are useful tools for evaluating fluidic oscillator systems at rapid response time. Using steady state analysis, the internal flow behavior inside the microfluidic oscillators, operating with different supply fluids was calculated as a function of supply pressure. The simulations reveal that for supply pressures between 125 kPa to 250 kPa, for all different gases analyzed the device can operate with compressible and subsonic flow at the interaction region with a quasi-laminar regime. For liquids the typical operation involves low velocities (~0.1 m/s) and low Reynolds Number, between to 1 or 10. The typical variation of the frequency with volume flow presents a range close to tens thousands of Hz for gases and two hundred for liquids. Thus, the project of a microfluidic oscillator using simulations permits to find future and promising applications, involving the measurement of flows in the micro scale range.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support of FAPESP (P. N. 00/04218-0), PADCT, and CNPq.

REFERENCES

[1] J. M. Kirshner, editor, “Fluid Amplifiers”, *McGraw Hill Book Company*, 1966.

[2] J. M. Kirshner, “Introduction to Fluidics”; *Fluidics Quaterly*, v.1, n.2, 93 pp., 1968.

[3] D. Banks, “Microfluidic Systems - An Emerging Technology”, *University of Surrey*, UK., 1997.

[4] H. Fujita, “A decade of MEMS and its future”, 10 th annual International *IEEE Workshop on MEMS*, 1997.

[5] M. Madou, “Fundamentals of microfabrication”, *CRC Press*, 1997.

[6] J. N. Zemel, and R. Furlan, “Microfluidics, Handbook of chemical and biological sensors”, edited by Taylor, R. F. and Schultz, J.S., Bristol and Philadelphia, *Institute of Physics Publishing*, cap. 12, pp. 317 – 347, 1996.

[7] P. Gravesen, J. Branebjerg, and O. Jensen, *Journal of. Micromechanical and Microengineering*, v 3, pp. 168-82, 1993.

[8] J. Vollmer, H. Hein, W. Menz, and F. Walter, *Sensors and Actuators A*, v. 43, pp. 330 – 334, 1994.

[9] R. Deadwyler, *Harry Diamond Laboratories* - report HDL - TR-1422, 1969.

[10] W. Gaylord and V. Carter, *Harry Diamond Laboratories* - report HDL, TR-1428, 1969.

[11] H. Yasuda, K. Sakai, and M. Okabayashi, “Development of small-sized fluidic gas flowmeter” - *International gas research conference*, 1989.

[12] U. Gebhard, H. Hein, and U. Schmidt, *Journal of Micromechanical and Microengineering*, v. 6, pp. 115-117, 1996.

[13] L. Zipser, F. Wächter, and H. Franke, *Sensors and Actuators B*, v.68, pp. 162-167, 2000.

[14] J. R. Tippetts, H. K. Ng, and J. K. Royle, "An Oscillating Bistable Fluid Amplifier for Use as a Flowmeter", *Fluidics Quarterly*, v.5, n°1, 1973.

[15] J. N. Reddy, “An Introduction to the Finite Element Method”, *New York,MacGraw-Hill.*, 1993.

[16] C. J. Freitas, *Journal of Fluids Engineering*, vol.117, pp. 208 – 218, 1995.

[17] E. W. Simões, R. Furlan, and J. N. Zemel, *Proceedings of the International Conference on Modeling and Simulation of Mycrosystems Semiconductors*, pp. 480 – 485, 1998.

[18] ANSYS, Inc. Revision 5.7, Houston, SAS IP, 2000.