A Control System for Piezoelectric Micro-Pumps

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Introduction

In the field of microfluidics, many devices such as microscale total analysis systems (µTAS)[1,2] and other specialized systems are being developed presently for genetic analysis[3] or clinical diagnosis.[4] A key component in such a system is the micro-pump which may be fabricated following different techniques.[5,6] Former to the new applications described above, piezoelectric micro-pumps have always been one of the main components in ink-jet printing systems.[7]

Results reported in the literature indicate that there may be a large discrepancy between required and actual ejection velocities and what is even worse differences in characteristics may occur from one drop to another leading to a loss of quality of printed patterns.

To remedy to the above cited problems we propose in this paper, a tool which should help to analyze and control the flow for drop on demand applications. More precisely the tool, in its present implementation, enables to calculate the velocity and to detect the eventual variations due to external perturbations. This may be used in the future for diagnostics and control of large systems.

Description of the Control System

For the control of large systems, we need to know the behavior of individual piezoelectric micro-pumps which should help us to discriminate the main parameters. This in turn should help us to choose the adequate strategy for the control of the full process.

Theoretical Background

In general, the geometrical configurations of industrial systems may be quite complicated to model or even not fully known. For this purpose, we propose an equivalent mechanical system, presented on figure 1, comprising an axisymmetric chamber fitted with a piezoelectric transducer and for which the unknowns are the length and radius of the chamber and the piezoelectric characteristics of the transducer.

In this case, we have to consider the transient flow in the pipe created by the pressure using the piezoelectric transducer. The ejection process can be described by the following steps:

- Displacement of the transducer and consequent transient start-up of the fluid (Step one).
- Backward movement of the transducer when the voltage step is finished (i.e. U = 0V). In this work, we do not consider negative voltages (Step two).
- Drop formation (Step three).
- Drop ejection (Step four).

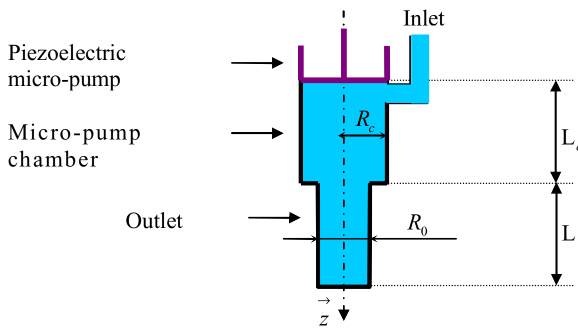

Figure 1. Equivalent mechanical system

In order to find the adequate control strategy, it is necessary to take into account all the parameters of the system and the links which may exist. For this purpose, we need to determine the flow model which is schematically showed in figure 2 below:

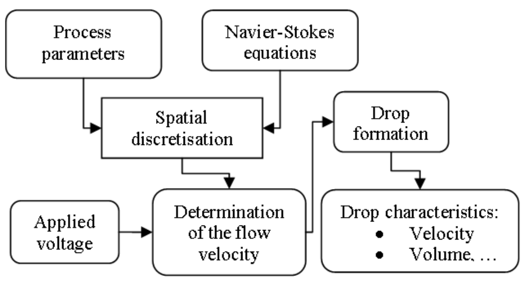

Figure 2. Establishment of the model

Obviously, the only parameter of action is the flow velocity, so we detail below the two first phases.

The fluid is taken to be viscous and Newtonian, and considering the geometry of the system (refer to Fig. 1) as well as the fluid flow equations,[8] we can write:

$$\begin{cases} \text{For } U \neq 0: \\ \dfrac{\partial V_z(t,r)}{\partial t} = \dfrac{P_{pzt} - \dfrac{2\gamma}{R_0}}{\rho L} + \dfrac{\mu}{\rho}\left(\dfrac{1}{r}\dfrac{\partial}{\partial r}\left(r \cdot \dfrac{\partial V_z(t,r)}{\partial r}\right)\right) \\ \text{For } U=0: \\ \dfrac{\partial V_z(t,r)}{\partial t} = -\left(\dfrac{\dfrac{2\gamma}{R_0} + P_{atm}}{\rho \cdot L_c}\right) - \left(\dfrac{2\gamma R_c}{\rho \cdot \pi \cdot R_0^2 L_c}\right) + \dfrac{\mu}{\rho}\left(\dfrac{1}{r}\dfrac{\partial}{\partial r}\left(r \cdot \dfrac{\partial V_z(t,r)}{\partial r}\right)\right) \end{cases} \quad (0.1)$$

with

$$\begin{cases} P_{pzt}(t,z) = 0 \quad , \text{if } \Delta e(t) = \Delta e_{\max}. \\ P_{pzt}(t,z) = 0 \quad , \text{if } U(t) = 0. \\ P_{pzt}(t,z) = E\left[\dfrac{d_{33}U(t)}{e} - \dfrac{R_0^2}{e \cdot R_c^2} \cdot \displaystyle\int_0^t V_z(t')\,dt'\right], \text{if } \Delta e(t) < \Delta e_{\max}. \end{cases}$$

and the following initial and boundary conditions

$$\begin{cases} V_z|_{t=0} = 0 \ \forall r \in [-R_0 \quad R_0] \\ V_z(R,t) = 0 \ \forall t \end{cases} ,$$

where $\vec{\mathbf{V}}$ is the fluid velocity, P the pressure, ρ the fluid density and μ the viscosity, γ the superficial tension of the fluid, L is the pipe length, $P_{pzt}(t,z)$ the pressure created by the transducer, $P_{cap}(t) = 2\gamma/R_0$ the capillarity back pressure, R_0 the outlet radius, R_c the chamber radius, E is the Young's modulus of the transducer, d_{33} the piezoelectric characteristic, e the transducer thickness, and U the applied voltage.

Control System

The model as given above remains quite complicated essentially in the view of the establishment of the simplest control strategy. We thus choose to simplify eq. 1.1 considering the velocity on the axis of the flow (i.e., r = 0) which then leads to:

$$(1.1) \Leftrightarrow \begin{cases} \dfrac{d\mathbf{V}}{dt} = \dfrac{P_{pzt} - \dfrac{2\gamma}{R_0}}{\rho L} + f_v \cdot V \\ \dfrac{d\mathbf{V}}{dt} = -\dfrac{\dfrac{2\gamma}{R_0} + P_{atm}}{\rho \cdot L_c} - \dfrac{2\gamma R_c}{\rho \cdot \pi \cdot R_0^2 L_c} + f_v \cdot V \end{cases} \quad (0.2)$$

where V is the velocity in the axe of the flow, $P_{pzt}(t,z)$ the pressure due to the transducer and f_v an parameter representing the viscous stresses.

We want to control and reject external perturbation like the clogging of the nozzle which is one of the main deficiencies affecting drop on demand printing. This effect can be written as a specific pressure fall in the pipe. The pressure equation becomes:

$$\frac{\partial P(t,z)}{\partial z} = -\frac{P_{pzt}(t,z) - P_{cap}(t) - P_{c\log}(t)}{L} \quad (0.3)$$

where $P_{c\log}(t) = 0.5 \cdot \rho \cdot k_{c\log} \cdot V_z(t)^2$, a singular head loss, and $k_{c\log} \in \mathbb{R}$. This equation is similar in form to the pressure terms in eq. 1.1 and 1.2 with the account of the clogging effect.

We can only have access to the measurement of the ejection velocity (i.e. the velocity of the flying drop). Using that data, it is possible to simulate under the SIMULINK® environment the control process where the applied voltage is adjusted accorded to the difference between required and actual velocities. A schematic of the control system is provided below:

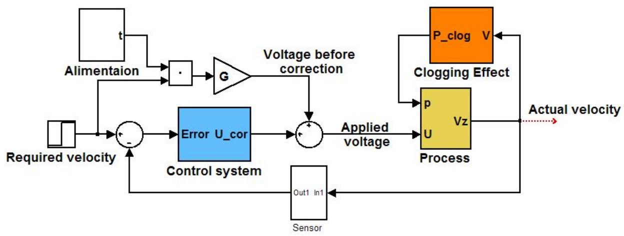

Figure 3. Control system with clogging effect

Results and Discussion

We show below how our system based on the simplified equations and taking into account an integrator (I) type regulator is able to reject the perturbations induced by the clogging. This simple regulator has the advantage of being linear and is very easily implemented. The clogging effect taken in our example is quite important since the initial velocity is divided by two but it evolves very slowly. Figure 4 gives the difference between required and actual velocities as a function of time. The control system is able to correct the process within about 25 measurement steps. But it is important to mention here that within 5 measurement steps the discrepancy between required and actual velocities (Error) is similar in variation to that found on a commercial print head for one ejection to another and working without any perturbation. Different other possibilities both in terms of regulators and transient perturbations are being tested and will be reported.

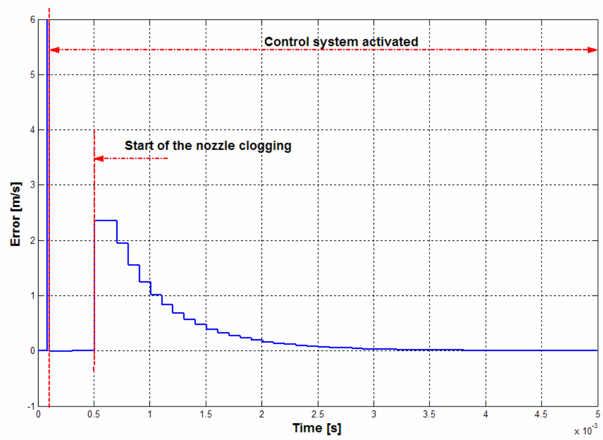

Figure 4. Correction of the clogging effect

Conclusions

In this paper, we have provided an elaborate model which is able to represent correctly the transient flow profile occurring in a printhead before ejection of a drop. We have also given simplified model based on the maximum velocity and which can be used for control process with different types of regulators. Future work will be focused on the detection of malfunctioning, the estimation of perturbations and their correction using optimized control strategy systems.

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Biography

Cittadino JM, 26 years old, is an engineer specialized in automatic control graduating from the National Polytechnic Institute of Grenoble (INPG). He is presently a final year doctoral student whose emphasis is on the design, modeling and optimization of the control of microfluidic actuators.