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DESIGN, SIMULATION AND PROTOTYPING OF POLYMERIC ORTHO-PLANAR MICROVALVES

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Abstract. In this work, a passive ortho-planar microvalve design is investigated. The component is conceived to be integrated in micropumps and microfluidic systems. It is very compact and it can be realized through standard planar machining techniques, such as laser rapid prototyping or MEMS surface micromachining.
Analytical and Finite Element coupled approaches are used to describe the microvalve response to the fluid flow. A validation of the models is successfully carried out with respect to literature data for silicon microvalves. The proposed analytical model well describes the hydraulic resistance. Eventually, a calibration through a limited number of numerical simulations can be done. Subsequently, polymeric prototypes are realized and tested. The manufactured microvalves are effective in flow rectification and a power law $Q - \Delta p_V$ trend is evidenced. As expected, deviations are found with respect to the modeled ideal response. This seems to be due to tolerances in assembly and high structure compliance.

1 INTRODUCTION

Microvalves are fundamental components in microscale fluid manipulation systems. As an example, in reciprocating micropumps valves have to be used to convert the non-directional fluid motion in a directional flow [1].

In this research, a passive ortho-planar valve design is considered, suitable be used for flow rectification in micropumping devices [2; 3]. The device fully develops in plane, while it works outside the plane through an orthogonal motion [4]. A major advantage of this type of structures is that they are very compact and they can be easily manufactured with planar techniques, also at the microscale. Moreover, there is no need to actively drive valve action. This results in low complexity in both manufacturing and control.

Basically, the investigated microvalve consists of a central disk suspended by compliant elements over a circular inlet hole. The working principle is shown in Figure 1. If the pressure in the upper chamber is higher than the pressure in the lower one, the disk is pushed to close the hole. A higher pressure in the lower chamber will result in a lift of the boss, allowing the fluid to flow.

Fundamental requirements are a low leakage (especially in the reverse direction) and a low pressure drop in the flow direction. As a consequence, spring stiffness and geometry should be carefully selected [5]. The most elementary option to realize ortho-planar springs is represented by straight beams with an out-of-plane action; more convoluted spring geometries can be considered, such as folded beams [4–6]. Valve designs characterized by one or two suspension arms exhibit large leakage, caused by kipping motion of the disc [6]. A three beams design is then selected here.

A wide variety of shapes and materials can be envisaged, as well as different fabrication methods. A number of Authors proposed and successfully realized micro check valves exploiting the ortho-planar working principle. Recently, SU-8 microvalves at the millimeter scale have been studied by Nguyen *et al.* especially for implementation into micropumps and microfluidic devices [6]. Small *et al.* [5] manufactured and characterized analogous systems, with an in-plane characteristic size in the range of hundred of microns and a 100 μm layer thickness. Interestingly, micromachined in-silicon ortho-planar microvalves realized through conventional etching techniques were demonstrated too [7; 8]. The in-plane characteristic size was in the range of a hundred of microns; a thickness of tenth of microns was utilized to obtain structures with an adequate compliance. Oosterbroek and collaborators also reported a complete description of the proposed fabrication process, suitable to be embedded in a standard MEMS microfabrication workflow [7].

Although polymeric check valves have a much lower spring constant and a soft sealing surface that allows almost zero leakage [6], it has been shown that the micromachined in-silicon counterpart is characterized by a more predictable and reproducible behaviour (compare [5; 6], [7; 8]). Besides, the full compatibility with MEMS fabrication processes and the possibility to easily scale down the size of the device are important advantages.

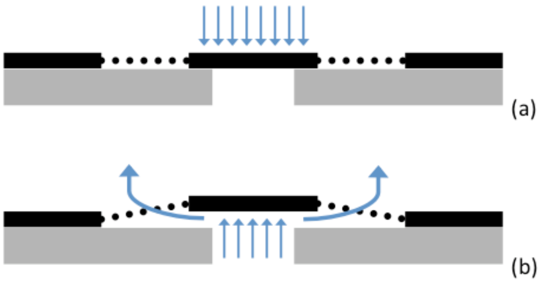


Figure 1: Schematic cross section of the microvalve in closed (a) and open state (b).

In this work, analytical and Finite Element fluid-structure coupled approaches are adopted to describe microvalve response under the assumptions of rigid boss, linear elastic response of beam springs and zero leakage. A validation of the models is successfully carried out with respect to literature data for silicon microvalves [7]. Subsequently, polymeric prototypes are designed, realized through laser rapid prototyping, and tested.

2 ANALYTICAL MODEL

To perform the check valve design, a simple analytical model is defined first. The response of the structure under fluid load is described as follows. An ideally rigid disc with radius R_d is considered. Three equally spaced, straight radial beams with length L, width w and thickness t are designed. The fluid load is assumed to act on the boss only; the action of fluid flow on beams is neglected (Figure 2). This model exhibits radial symmetry.

A linear spring response of the beams is assumed. The force versus displacement relationship for the system is

$$F = k_V \, \delta \tag{1}$$

The total fluid load acting on the disc is assumed to be equally divided between each arm. Beams are clamped on the outer edge and subjected to a load $F_t = F/3$ at the tip, where orthogonal (out of plane) displacement only is allowed. For straight, slender beams ($L/t < 20$) in small deformations regime ($t/\delta < 10$), the displacement at the tip is

$$\delta = \frac{F_t L^3}{12EI} \tag{2}$$

where E is the Young's modulus of the material and $I = wh^3/12$. The equivalent spring constant become then

$$k_V = \frac{F}{\delta} = \frac{3Ewt^3}{L^3} \tag{3}$$

The expression of the force due to the fluid load, for a given pressure drop Δp_V, when

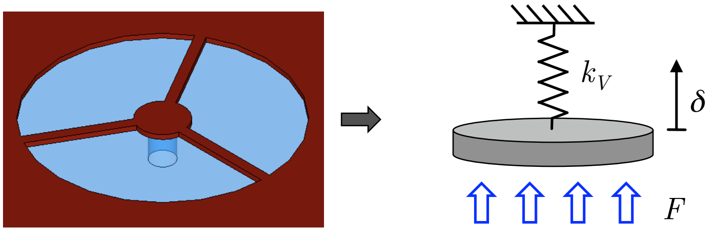


Figure 2: Representation of the model adopted to describe valve mechanical response: the displacement δ of the rigid boss under the fluid load F is described through an equivalent linear spring of constant k_V.

the internal radius is R_i and the external radius R_d, is [5]

$$\begin{aligned} F = \int_0^{2\pi}\int_0^{R_i} \Delta p_V\, r\, dr\, d\theta + \int_0^{2\pi}\int_{R_i}^{R_d} \frac{\Delta p_V}{R_d - R_1}\,(r - R_d)\, r\, dr\, d\theta = \\ = \frac{\pi}{3}\,\Delta p_V\,(R_d^2 + R_d R_i + R_i^2) \end{aligned} \tag{4}$$

Finally, disc displacement δ can be expressed with respect to pressure drop:

$$\delta = \frac{\pi}{9}\frac{L^3}{Ewh^3}\,\Delta p_V\,(R_d^2 + R_d R_i + R_i^2) \tag{5}$$

At this point, the fluid flow through the microsystem is treated. Fluid is assumed to be water. In small scale systems, the gravity effect exhibits a negligible effect; thus, the correspondent body force is coherently neglected. The flow of an incompressible fluid in stationary conditions can be described by the generalized Bernoulli equation [9].

The fluid path through the valve can be conveniently split into two contributions [10]: the vertical inlet channel and the meatus with variable thickness δ between the disc and the base layer. Radial symmetry is considered. Along the inlet channel, the flow profile is not strictly unidimensional, and a rigorously correction on the kinetic energy terms have to be considered [11]. However, since the most relevant contribution to the overall pressure drop is expected in the meatus, the contribution of this part will be neglected.

In the meatus, laminar flow loss is considered, by applying a derivation of the Navier-Stokes formula [12]. For microchannels with a width d such that $d/\delta > 4.5$:

$$\Delta p = \frac{12\mu_w L Q}{d\,\delta^3} \tag{6}$$

where μ_w is water viscosity. The section is an annulus. Thus, the equivalent width can be evaluated by performing an integration as follows:

$$\Delta p = \int_{R_i}^{R_d} \frac{12\mu_w Q}{2\pi\, r\,\delta^3}\, dr = \frac{6\mu_w Q}{\pi\,\delta^3}\ln\left(\frac{R_d}{R_i}\right) \tag{7}$$

Now, by combining Equations 3, 5 and 7, the flow through the valve can be computed:

$$\begin{cases} \Delta p_V(\delta) = \dfrac{6\mu_w Q}{\pi\,\delta^3}\ln\left(\dfrac{R_d}{R_i}\right) \\ \delta\,(\Delta p_V) = \dfrac{\pi}{3}\,k_V\,\Delta p_V\,(R_d^2 + R_d R_i + R_i^2) \end{cases} \tag{8}$$

It is worth emphasizing that the solution above effectively considers the coupling between the solid domain and the fluid domain. The relation between pressure drop Δp_V and flow rate Q in Equation 8a depends on device geometry and valve opening $\delta(\Delta p_V)$, thus inherently on the structural response of the equivalent spring that represents the beams. The deformation of the system computed in Equation 8b is determined by the fluid load, here explicitly represented in terms of the pressure drop Δp_V.

To summarize, the fluid flow Q can be expressed as

$$Q \propto k_V^{-3} \cdot \Delta p_V^4 \cdot \Gamma(R_i, R_d) \tag{9}$$

where $\Gamma(R_i, R_d)$ is a geometrical function. From Equation 9, it can be seen that the microvalve fluidic component is expected to be characterized by a fourth order power law $Q - \Delta p_V$ relationship. The effect of valve spring constant is relevant, since a third order relation with respect to k_V is found. Oosterbroek [7] developed an analogous analytical model and proposed an interesting adimensionalization of the full problem. Differently, the flow through valve gap was considered as a Poiseuille flow, but the same fourth order power law $Q - \Delta p_V$ and third order dependence on valve stiffness k_V were identified. The design of the compliant structure is a crucial aspect in ortho-planar microvalve development.

3 FINITE ELEMENT MODEL

With COMSOL Multiphysics 3.5a (COMSOL AB), a fully-coupled Fluid-Structure Interaction (FSI) Finite Element model is developed. A 2D model is defined (Figure 3), since a 3D model would be very expensive from a computational standpoint. Rigid boss assumption is in fact relieved, but the motion of the disc is constrained due to imposed radial symmetry.

A preliminary study with structural 3D models showed indeed that, for the proposed geometry, the assumption of radial symmetry during valve opening due to a uniform fluid load is not always respected. In particular, when the valve is realized with a material with $E \simeq 1 - 10$ GPa (here, $E = 3.5$ GPa), the boss deformation is relevant, leading to a wavy profile and a non-uniform meatus thickness. Thus, higher flow rate can be expected. When $E \simeq 100$ GPa or higher (e.g. for polysilicon, $E = 160$ GPa), the radial symmetry assumption is reasonably fulfilled. The 2D model here introduced do not aim therefore to provide a precise representation of polymeric valve response, but to give interesting information on valve functioning and to provide a comparison with the analytical approach above expounded.

In the FSI axisymmetric model, at inlet and outlet of the fluid domain a pressure boundary condition is imposed. Concerning the fluid-structure interaction, at the fluid/solid interface boundary velocity and fluid load are exchanged. The disc can move along the axial direction according to the response of the compliant elements. The elastic response of beams is assumed to be concentrated on a linear spring of constant k_V. For implementation purposes, spring action is distributed and applied as a pressure over the upper disc surface. In the present model, complete valve closure cannot be achieved. This would require the fluid domain in the gap to collapse on a line. This is not allowed in a standard Finite Element formulation. Thus, a manual remeshing is performed, when mesh deformation in the domain degenerates in element inversion.

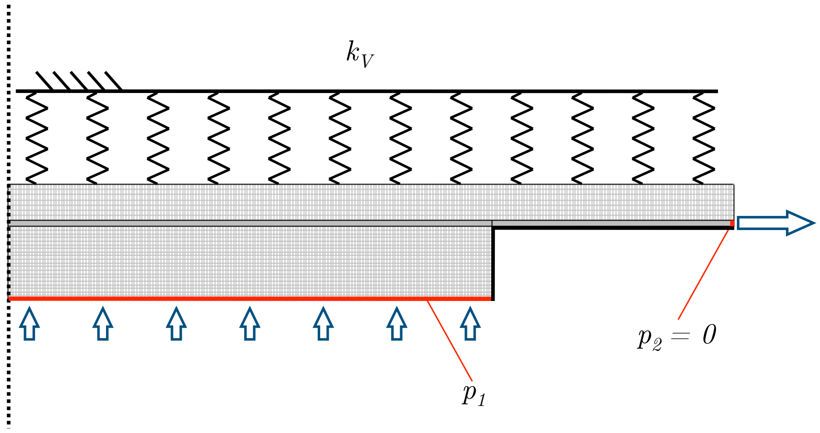


Figure 3: Axisymmetric Fluid-Structure Interaction Finite Element model of the microvalve.

Simulations are performed starting from an open valve configuration. The nodal force acting on the upper surface is evaluate as $\tilde{F}_{n,z} = k_v\,(w + \delta_0)$, where δ_0 is the valve gap at the beginning of the simulation, and w is the displacement. First, the system is initialized by means of the analytical model. Then, a portion of the $Q - \Delta p_V$ is swept. The solution scheme can be summarized as follows:

1. Initialization:
    - For a trial pressure drop across the valve Δp_V^* (ideally, the upper or lower limit of the interval of interest), a guess for boss equilibrium position δ_0^* is obtained from Equation 5.
    - The model geometry is drawn. Inlet pressure $p_1 = \Delta p_V^*$ is imposed.
    - A value of the flow Q^* for the given configuration is obtained, for the fluid domain only (fixed disc). Field solution over the fluid domain is stored.
    - The value of the flow Q is computed again, for full model, starting from stored solution for fluid domain. Field solution over whole model is stored.
2. Curve sweep:
    - A small variation in the inlet pressure p_1 is imposed, and the new value of Q is computed. At each step, the field solution over whole model is stored.
    - The procedure is repeated until excessive mesh deformation is found. Then, manual remeshing is performed, and the solution is restarted from the last step.

In this solution scheme, the field solution over a domain or the whole model is stored at each step. The solution is then used as initial condition for the further step of the analysis. This originates a relevant decrease of the computational cost of each iteration, since a guess, very close to the solution, is used.

4 PROTOTYPING

With the aim to realize a prototype of planar microvalves, laser rapid prototyping has been considered. This process can be adopted to easily manufacture a variety of planar valve designs, on various materials. The valves here reported are realized on Polyimide/Kapton film (DuPont). Machining is realized with a TruMark Series 6000 laser (Trumpf). Nominal dimensions $w = 125$ μm, $R_i = 250$ μm, $R_d = 1000$ μm, $L_i = 1500$ μm are defined for all the valves, while different beam widths $w = 300$ μm, 400 μm, 500 μm are selected.

After the valve layer is realized, PMMA top and bottom layers containing inlet and outlet channels are realized. Layers are finally stacked to obtain a sandwich – with the valve layer in the middle – by using a double-sided high performance acrylic adhesive tape (3M 467MP with 200MP adhesive). Assembly is done by means of alignment screws. Process is shown in Figure 4.

Finally, connection of microvalves to the external fluidic circuit is achieved by using a NanoPort connector (Upchurch Scientific) at the inlet. At the outlet a Polyimide conical connector is used; it is kept in place by a mechanical contrast, while an optimal sealing is achieved by realizing PDMS seals. The $Q - \Delta p_V$ characterization is performed in flow control. A flow rate is imposed by means of a syringe pump (Harvard PHD2000), and pressure drop across the valve is measured with a differential pressure transducer (Honeywell 142PC05D) read by a function implemented through LabView (National Instruments). To finally obtain the characteristic $Q - \Delta p_V$, a series of static measurements is performed varying the imposed flow rate.

5 RESULTS

5.1 Modelling

To perform a consistent validation of the proposed models, experimental data for silicon micromachined microvalve are considered [7]. This choice is made since this component during functioning fulfills the hypotheses of rigid boss and linear elastic response of beam springs. Comparison with experimental data is satisfactory (Figure 5).

The analytical formulation overestimates the flow. The valve characteristic obtained by the Fluid-Structure Interaction fully-coupled model very well represents the system response in the considered range. Interestingly, the discrepancy between the two proposed approaches is constant, and can be compensated by a correction factor on the flow rate. In this case, the ortho-planar circular microvalve response can be represented by an expression in the form

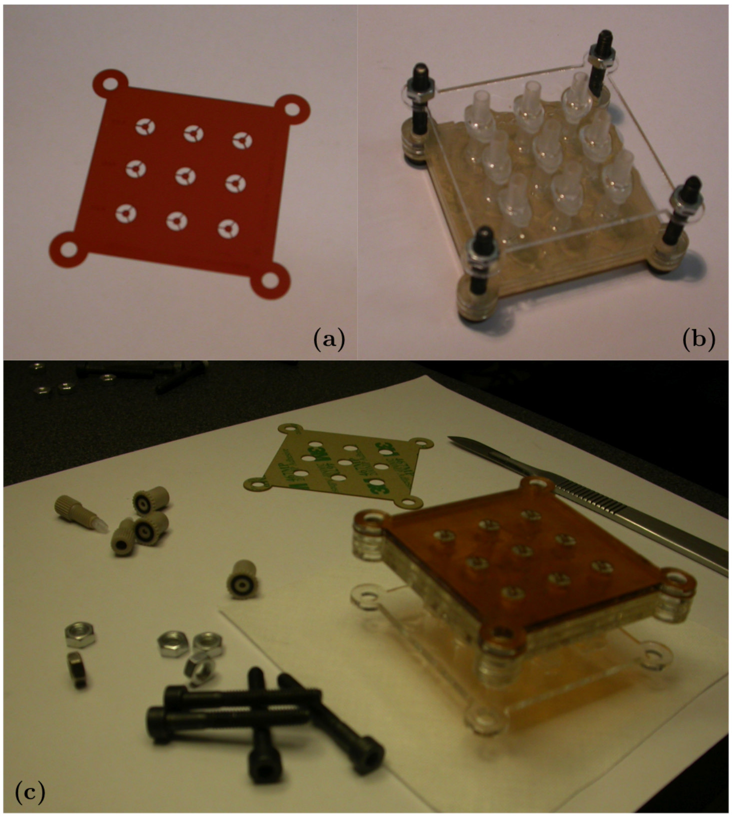


Figure 4: Microvalves prototypes: (a) Kapton valve layer; (b) outlet part, with conical connectors and contrast; (c) application of valve layer on the outlet part.

$$Q \simeq k_Q \cdot \frac{\pi^4}{162} \cdot \frac{\Delta p_V^4}{\mu_w \, k_V^3} \cdot \frac{(R_d^2 + R_d R_i + R_i^2)^3}{\ln\left(\frac{R_d}{R_i}\right)} \tag{10}$$

where $k_Q \simeq 0.765$ is a correction factor, which can be extracted by means of a small number of FSI simulations.

5.2 Prototype testing

In Figure 6a, results of microvalve characterization is reported. The tests evidenced the possibility to successfully obtain flow rectification. The three different geometries here proposed differ by spring stiffness: the measured flow rates coherently reflect this. While for a given pressure drop across the valve the flow rate is proportional to spring stiffness, the response cannot be in general identified as a power law as expected from models. Indeed, the more compliant valves (w = 300 μm and w = 400 μm) exhibit a response which is somehow linear, similarly to polymeric microvalves reported by Small and co-workers [5].

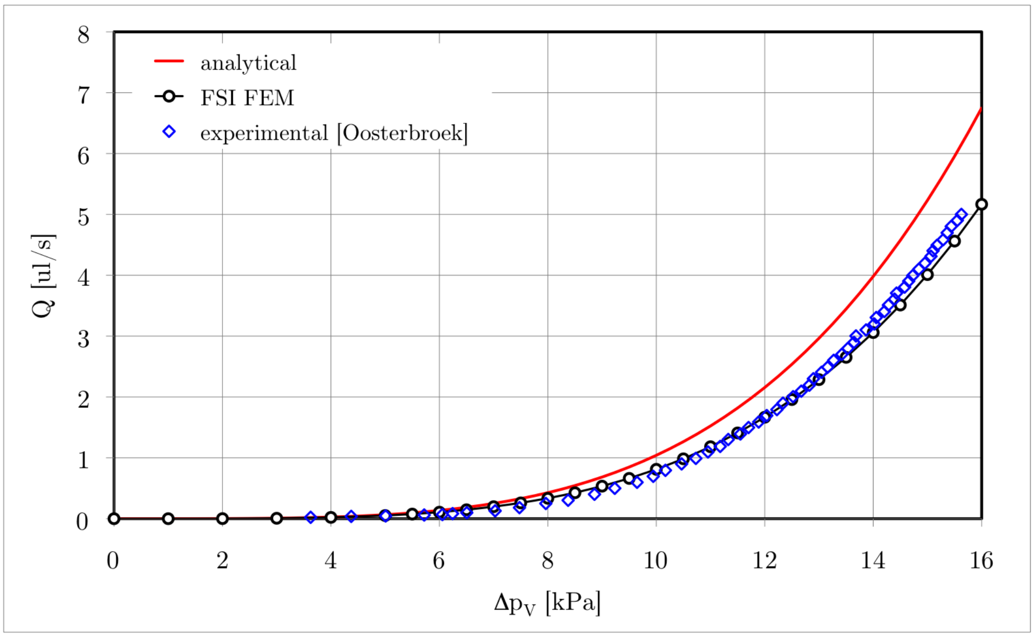


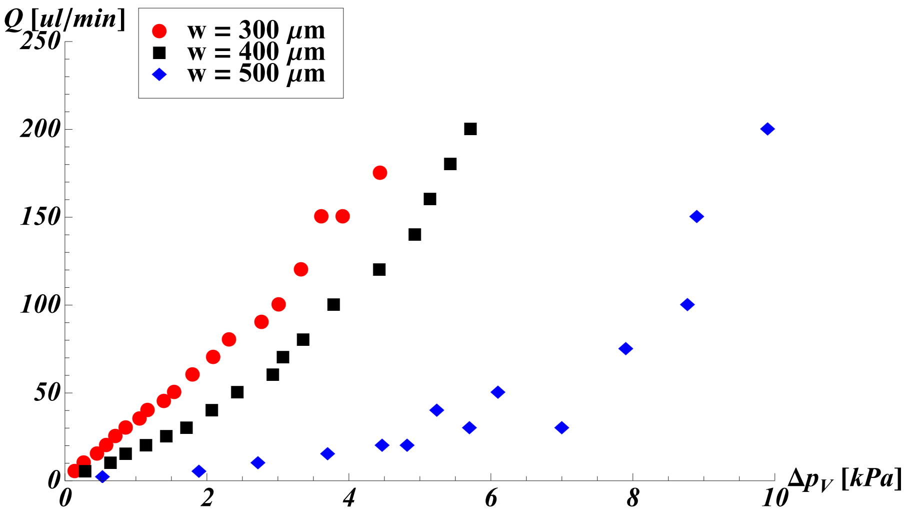
Figure 5: Microvalve flow curve: comparison of the proposed models with literature experimental data.

In fact, this behaviour can be explained by the limitations concerning the manufacturing process and the assembly. In particular, surface finish could be too rough and some asymmetry in the assembly could be present [5]. Moreover, melting due to laser cutting originates irregular edges and features size slightly differs from the nominal ones, as evidenced by optical microscope observations. These aspect, combined with a low spring stiffness, can generate a relevant leakage. In practice, the flow through the valve is basically determined by this leakage.

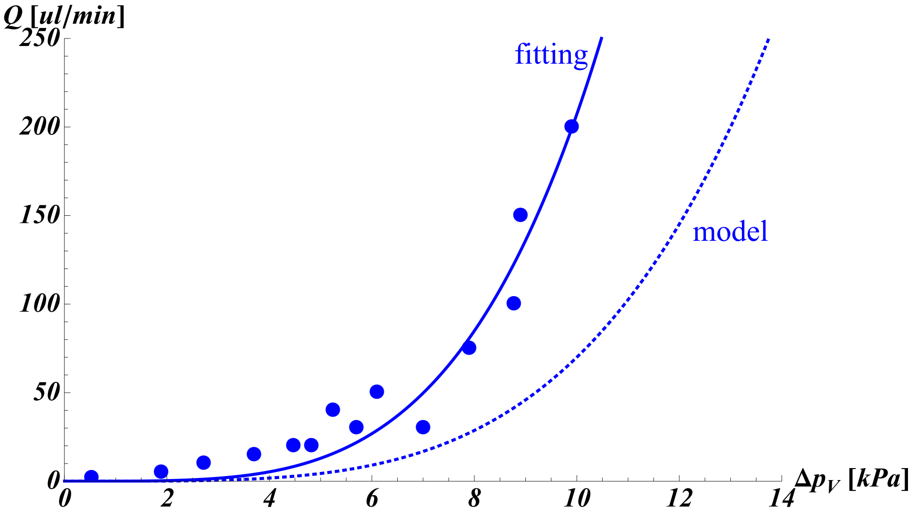
Concerning the stiffer valve ($w = 500\ \mu$m), a fourth order power law response can be reasonably identified. However, as evidence in Figure 6b, from the analytical model a stiffer response was expected. From a qualitative point of view, it can be argued that the higher spring stiffness of this valve design is capable to partially overcome the leakage due to manufacturing issues. Besides, the non-uniform meatus thickness that comes from the high compliance of the boss – which could be appreciated through a 3D modelling of the device – can explain the higher measured flows.

6 CONCLUSIONS

In this work, the design of valves to be implemented in microsystems for microscale fluid transport is illustrated. The proposed planar shape is compact and valves are suitable to be realized by means of standard standard planar machining techniques, such as laser rapid prototyping or MEMS surface micromachining.



(a)



(b)

Figure 6: Characteristic flow rate versus pressure drop curve for the polymeric microvalves: (a) Comparison of experimental results for different valve geometry; (b) Fourth order power law data fitting of experimental results on $w = 500$ μm microvalve, and prediction from the analytical model.

Analytical and Finite Element coupled approaches are defined to study the microvalve response to fluid flow, under the assumptions of rigid boss, linear elastic response of beam springs and zero leakage. A successful validation of both modelling strategies is achieved by comparison with experimental data available in the literature. It has been found that the proposed analytical model well describes the hydraulic resistance. Eventually, a calibration through a limited number of numerical simulations can be done.

Subsequently, polymeric prototypes are designed and realized through laser rapid prototyping. The manufactured microvalves are effective in flow rectification, while deviations are found with respect to the expected ideal response which are not captured by the proposed flow models. The deviations can be explained by limitations concerning the manufacturing process and the assembly, but also by considering that the proposed models are not suitable to describe in details the response of highly deformable microvalves. Indeed, a satisfactory agreement is found, while for a precise modeling 3D models able to capture structure non-symmetric deformation should be envisaged. It is worth noting that the modelling and simulation of polymeric microvalves is a challenging task. It is meaningful that, up to now, no effective simulation has been reported for this class of microvalves.

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