MODELING OF SERIAL PARALLEL ASSEMBLY OF VALVELESS MICROPUMP USING BOND GRAPHS APPROACH

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ABSTRACT
The bond graph methodology is used, in this work to model and study the working principle of valveless micropumps. Two kinds of architecture are considered. Their design is achieved by combining two single chamber valveless micropumps in serial and in parallel manner. Both architecture use a pair of pumping chambers provided with a pair of asymmetrical set of nozzle-diffuser. The working principle of the different parts used to create the liquid flow is analyzed. For each of these microfluidics systems, a global bond graph model is proposed to represent their dynamic behavior. From the analysis of the graphical representation, the corresponding mathematical models in state space representation are given in terms of dimensions. Considered as outputs of the two valveless micropumps models, the flow rate equations are proposed.

KEY WORDS
Bond graph, valveless micropumps, lab-on-a-chip, microfluidics, state space models.

1 Introduction
Micromechanics and microfluidics represent important areas of study and development. Since the 1990s micromachining domain, and particularly the Lab-on-a-chip concept have been developed. They present the advantages of small volume, high precision, fast reaction time and cheap cost. Particularly most applications in chemical analysis, medical testing, medicine delivery or chip cooling microsystems, require the use of micropumps as essential actuators to cause fluid flow. The design and manufacturing of reliable, robust and accurate micropumps is a real challenge. Various principles are used to conceive these micro actuators. They are divided into two categories, mechanical and non-mechanical [1-2]. Most micro-devices use rotation, peristaltic or oscillatory movement of mobile part to drive the fluid flow, some include intake and exhaust valves as shown in Figure 1. However the presence of the moving parts leads to construction difficulties and presents the risk of mechanical wear and fatigue. There is also a risk of valves clogging if particles are present in the fluids. To avoid these drawbacks, a solution is to replace the moving valves by static valves formed by a pair of nozzle/diffuser elements used as fluidic diodes. This structure provides a lower flow but sufficient for many applications. The device presented is based on the working principle, demonstrated in papers treating of microfluidics applications [2-3-4].

![Pump mode](image1)

Figure 1. Serial and parallel valveless micropumps

A bond graph model of a valveless nozzle/diffuser micropump controlled by an electric actuator and a deforming membrane has been proposed in [5]. To improve the efficiency this simple structure can be combined in serial and parallel manner as shown Figure 1. We propose to model and study the functioning of these serial and parallel valveless pumps. In the following, we assume that reader has some knowledge on the bond graph modeling. Therefore
the readers, non-familiar with this graphic method, can find more information referring to [6-7-8]. The rest of this paper is organized as follows. Section 2 details the actions that implicate the volume flow rate in the micropump. Section 3 presents the bond graph modeling of the serial and parallel structure. Section 4 gives elements on the equivalent state space models. Discussion and remarks on the work in progress are given in the last section.

2 Functioning Principle

The design of a single-chamber valveless pump during supply and pumping modes is illustrated in Figure 2. The pumping action uses the pressure drop characteristics of the flow through the asymmetrical pair of nozzle/diffuser. A vibrating membrane creates a volume variation in a pumping chamber. It is actuated electromagnetically or piezoelectrically in amplitude and frequency. The volume flow rate of the device depends on the ratio of the fluid volume entering to and leaving from the pump chamber.

![Figure 2. Single-chamber nozzle/diffuser pump during supply and pump modes](image)

Each cycle, the increasing volume maximizes the flow rate entering through the nozzle and minimizes the flow rate entering through the diffuser. The decreasing volume creates the opposite action, as depicted in the Figure. Globally, the pumping actions convey the fluid from the nozzle pipe to the diffuser one, through the micropump chamber. The volume flow rate of the device depends on the ratio of the fluid volume entering to and leaving from the pump chamber. Many models have been developed to study the nozzle/diffuser valveless micropump. Those studies use mathematical formulation of the hydraulic domain. They lead to some nonlinear equations combined with experimental parametric formulations. Theoretical approaches can be found in [9-10].

3 Bond Graph Models

If properly applied, the bond graph methodology allows to build a graphical model that is consistent with the first principle of energy conservation. Since the bond graph is considered to be an object oriented modelling tool [11], the subsystems’ bond graph models will be connected to build a global model respecting the energy flow. The modeling work starts considering the main parts of the valveless micropump represented in Figure 3. From the functioning analysis, five constitutive parts are identified. Step by step the bond graph modeling of the micropump dynamics during its activation cycles is established.

![Figure 3. Parts of the nozzle/ diffuser pump to build Bond graph sub-models](image)

The bond graph model of the the micropump in serial configuration is shown Figure 4. It reproduces the scheme of two micropumps marked A and B. Each part materializes a bond graph subsystem. Considering the common flow powers, these models are connected to form a whole graphical representation. The two micropumps are linked by a common nozzle/diffuser. For each one, on the top the actuator part transforms (TF:m1) a source of periodic excitation (Se:U0) into a vibration of the membrane. The electric part is modeled by a resistive element (R1), a resistive and capacitive block could be considered but it would introduce a supplementary order in state space model. This input source may represent at first approach for a simplified and linearized model of a piezoelectric, electromagnetic, variable capacity motor, or for an actuator based on alternating air pressure source. The second block focuses on the membrane role. Its mechanical characteristics in terms of elasticity, inertia and friction, are materialized in a simple way by a second order dynamics using the capacitive (C1), Inertial (I1), and resistive (R2) elements. Its oscillating movement is transformed (TF:m2) to a volume variation into the pumping chamber.

This part of the model and the following may be improved and refined increasingly, taking into account neglected leaks, elasticity and non-linearity of the membrane, as allowed by the bond graph methodology. The part dedicated to the pumping chamber is composed with a capacity...
Figure 4. A bond graph representation of the serial valveless micropump

(CT) related to its volume. The set of elements, capacitive (C2), inertial (I2) and Resistive (R3) materializes the volume variation due to the membrane’s vibration. The varying pressure in the chamber is the same at each entry of the channels (nozzle/diffuser). At each entry of a pumping chamber, two conduits with a varying geometric profile are connected. In supply mode, the membrane is in high position, the incoming flow is important in the expanded input and weak in the narrow one. In pumping mode, the membrane compresses the chamber volume and the process is reversed. A microfluidic volume flow is driven from the left to the right side as shown in the scheme on Figure 2. The bond graph models of the nozzle/diffuser elements take into account their varying profile. We assume that fluid dynamics in these conduits complies with a distributed physical system. The bond graph model is built using a set of lumped parameters formed by sets of (R I C) elements whose values vary and take into account the increasing or decreasing geometry. The optimal number of these elements has to be determined experimentally. As a first approach, the model contains two elements for each conduit. Intrinsically, the bond graph models can be modified and augmented easily. At the two extremity of the global model two effort sources materialize the reservoirs at atmospheric pressure P0. The letters l and r subscript the nozzle/diffuser bonds located respectively on the left and right side of each pumping chamber. Figure 5 shows the bond graph model in parallel configuration. The valveless micropumps rated A and B, are linked by a pair of inlet/outlet tanks. The same bond graph models of subsystems are used. The operating principle creates a flow from the input to the output through the two micropumps. As mentioned above, this model could be improved and refined increasingly as allowed by the bond graph methodology and simulations.

4 State Space Equations

In the bond graph modeling, hydraulic volume flows and pressure efforts are dependent on the inertial (I) and the
capacitive (C) elements. In Figure 4 we can number 18 inertial (I) and capacitive (C) multi-domains elements in integral causality and 4 inputs. This gives 18 state variables and leads to a state model presented in terms of dimension by equation (1).

\[
\dot{X}_{18 \times 1} = [A_{18 \times 18}] X_{18 \times 1} + [B_{18 \times 4}] U_{4 \times 1} \quad (1)
\]

The volume flow rate in each side as well as the pressures for each chamber A and B represent the most useful elements to study the serial configuration. They are highlighted in Figure 4. These outputs are expressed in equation (2). They are directly extracted from the bond graph and rated \( f_i \) for volume flows and \( e_j \) for pressures. The state variables \( p_i \) and \( q_j \) are obtained by solving equation (1).

\[
Y = [C] X \quad (2)
\]

The bond graph model of the parallel structure is shown Figure 5. This model contains 26 inertial (I) and capacitance (C) elements in integral causality. The equivalent state space model contains 26 state variables.

Equation (3) shows this model in terms of dimension.

\[
\dot{X}_{26 \times 1} = [A_{26 \times 26}] X_{26 \times 1} + [B_{26 \times 4}] U_{4 \times 1} \quad (3)
\]

In the same manner the useful elements to study the parallel configuration, are highlighted in Figure 5. These outputs can be expressed by an equation equivalent to equation (4).
5 Conclusion and Future Work

This paper illustrates the bond graph ability to achieve a dynamic model, decomposing a complex multi-domains structure into several constituents. The subsystems can be modeled using a unique graphical representation. Each part can be simulated independently. Using this approach, the bond graph methodology is used as a powerful alternative to model the dynamics of the elementary functioning parts of serial and parallel nozzle/diffuser micropumps. A bond graph modeling and simulation of a single chamber valveless micropump are presented in [5]. The simulations can be performed by tools using directly the graphical bond graph models [12]. The State space Equations can also be extracted and solved. The future work concerns a campaign of simulations for the two bond graph models presented above. We use a method that converts the bond graph into block diagrams representation. This method is used regularly in our bond graph teaching. It allows to build the block diagram model from a direct reading of the bond graph, without writing beforehand all the equations of junctions. One can thus benefit from all the potentiality of a numerical computational tool supplied with a Block diagram graphical interface like Matlab/Simulink. More details can be found in the mentioned paper dedicated to this method [13]. Further developments beyond this stage of the modeling work are to collect set of dimensions and parameter’s values to perform a realistic simulation.

References