Available online at www.sciencedirect.com
ScienceDirect
Sensors and Actuators A 143 (2008) 399–408
SENSORS AND ACTUATORS A PHYSICAL
www.elsevier.com/locate/sna

Simulated and experimental dynamic response characterization of an electromagnetic microvalve

Rajesh Luharuka, Saniya LeBlanc, Jemmy S. Bintoro, Yves H. Berthelot, Peter J. Hesketh*

George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

Received 27 January 2005; received in revised form 14 August 2007; accepted 29 October 2007
Available online 13 November 2007

Abstract

The dynamic response of two electromagnetically actuated microvalves operating in open-air conditions are measured experimentally and simulated using a three-dimensional fluid–structural finite element model. Open-air conditions mean that the fluid inlet and outlet are not pressurized. The dynamic response of the membrane is obtained experimentally by exciting the valve with a step voltage signal of 1 kHz and measuring the membrane vertical displacement using a Polytec Laser Doppler Vibrometer (LDV) system. Vibration analysis of the experimental data provides dynamic parameters such as natural frequency, air damping coefficient, spring constant, and settling time of the membrane. An electromagnetic force model based on the reluctance method is constructed and validated from the experimental data. The validated electromagnetic force model and corrected material properties are then used in a three-dimensional, fluid–structural finite element model to simulate membrane dynamics. Pertinent dynamic parameters such as resonance frequency, spring constant, microvalve closing time, settling time of the membrane, and actuation energy of the microvalve are finally compared with the simulated results. The comparison of experimental and simulation results shows that the finite element model accurately reproduces the dynamics of the membrane in the slip-flow region. A valid simulation method can then be used to simulate microvalve dynamic response in pressurized flow conditions and evaluate new designs. Valve closing time of less than 150 μs is demonstrated in one valve design. The energy required to close the microvalve is in the range of 300–678 μJ.

Keywords: Microvalve; Electromagnetic actuator; Reluctance model; Finite element analysis; Vibration analysis; Membrane dynamics

1. Introduction

Microvalves are essential components of miniaturized fluidic systems. Valves provide control of fluid flow in a variety of applications as diverse as chemical analysis systems, microfuel cells, and integrated fluidic channel arrangements. Using microvalves, these systems offer important advantages: they can operate using small sample volumes, provide rapid response time, and function with low power consumption [1–3]. One particular interest is to develop a low power, latching valve suitable for use in a micro gas chromatography system [4–6]. The growing interest in recent years to miniaturize gas chromatography systems has created a need for microvalves that can operate at flow rate of few hundred sccm at differential pressure of 2–7 psig, have low energy consumption, and have quick response time.

In order to predict and control the behavior of a microvalve, its dynamic response must be characterized. The dynamic response of a microvalve is its movement as it opens and closes. Ultimately, it is necessary to control the microvalve movement and to simultaneously optimize its performance under specified operating conditions. Specifically, the dynamic response will indicate the mechanical model characteristics, optimal energy, and time required to actuate the valve. The ability to optimize design based on simulation of dynamic response has been demonstrated by Gong et al. [7] through the simulation of pulse response of a microelectromagnetic pump. It is valuable to compare theoretical model with experimental dynamic response results in order to validate and improve the model of a device. A Laser Doppler Vibrometer (LDV) is a high-resolution, non-contacting instrument with which experimental dynamic response is measured, and the results can be used to modify a model [8]. It has been used in numerous MEMS applications such as to measure resonance frequency of a microvalve actuator [9], determine piezoelectric coefficient of a PZT film [10], and study squeeze film damping in a microsystem [11].

* Corresponding author. Tel.: +1 404 385 1358; fax: +1 404 894 8496.
E-mail address: peter.hesketh@me.gatech.edu (P.J. Hesketh).

0924-4247/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2007.10.084

In this paper, experimental dynamic response of two microvalves are obtained using a LDV. The experimental data is compared to a simulated response model to estimate material properties of Orthonol membrane and validate a reluctance-based electromagnetic force model. These are then used in a multiphysics finite element model of the microvalve to reproduce the membrane dynamic response measured in the two microvalves. The dynamic parameters of concern for the microvalve presented herein are its mechanical spring constant, natural frequency, damping coefficient, closing time, settling time, and actuation energy. The experimental and simulation methods used to obtain the dynamic parameters are presented. Comparisons of simulated and measured microvalve dynamic characteristics are provided. The simulation method is validated, and operating features of two microvalves are established.

2. Electromagnetic microvalve description

The microvalve comprises of a membrane suspended over the valve seat (see Fig. 1). The membrane is normally held in the open position by multiple support beams that are fixed at ends. The valve seat is formed by a current carrying Au-coil on the outside of an orifice. The complete microvalve structure is fabricated on a single silicon substrate. Full details of the fabrication process are given by Bintoro et al. [12,13]. The membrane is made of a soft magnetic material—Orthonol (50% Ni, 50% Fe) [14]. Therefore, when the coil is excited with a current, the membrane is pulled to the closed position by a magnetic force.

The micrographs of the two microvalves chosen for characterization study are shown in Fig. 1. The overall dimension of Microvalve I is 1 mm (see Table 1) and has a 400 μm diameter membrane supported by four beams with fixed ends. The inlet orifice diameter is 45 μm, and the orifice is aligned with the center of the membrane. The gap between the membrane and valve seat is measured at 12 μm. Due to its straight beam design, the membrane has high mechanical stiffness and is expected to produce small displacement dynamics under the influence of a magnetic force generated by the coil. Membrane dynamics are then studied to investigate the actual material property (density and elastic modulus) and electromagnetic force generated. The corrected material properties and validated electromagnetic force model are then used to simulate membrane dynamics of Microvalve II, which has a larger overall size of 1700 μm. The membrane diameter is increased to 700 μm to provide better fluid seal in the closed state, and there is more turns in the coil. Microvalve II has three legs; these legs have folded spring ends that drastically reduce the membrane stiffness and allow it to close across a gap size of 34 μm under the influence of the magnetic force generated by the coil current.

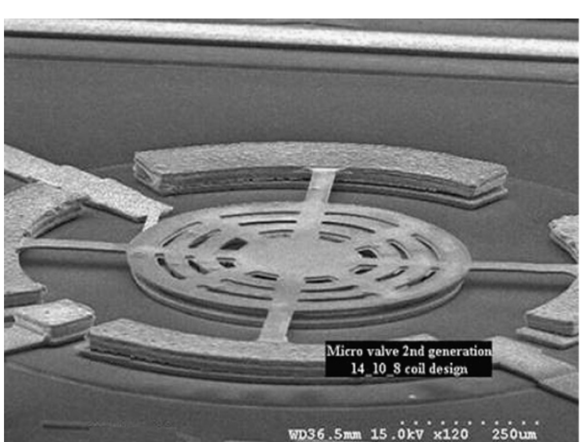
Table 1
Measured dimensions of the microvalves

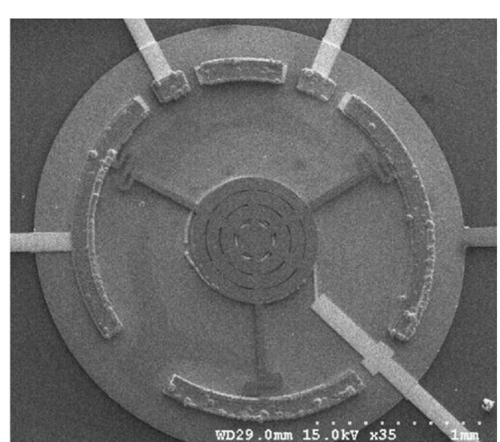
Geometrical parameters[a]	Microvalve I	Microvalve II
Inlet hole diameter	45	60
Actual gap size	12	34
Diaphragm diameter	400	700
# of legs	4	3
Legs length	300	400
Legs width	40	40
Legs thickness	3.5	3
Legs support type	Fixed	Folded spring
# of turns in coil	5	15
Coil resistance (Ω)	3.2	4.9

[a] All dimensions in microns.

3. Experimental approach

The microvalve dynamic response is obtained by measuring the displacement of the membrane with time. There are three primary methods used to assess membrane movement; they are capacitive and laser interferometric measurements. The preferred practice is to monitor membrane movement with a laser vibrometer rather than to measure capacitance changes [15]. The laser vibrometer uses an optical technique, so no physical contact is made with the valve membrane. Hence, there is no load applied to the valve that would alter its dynamic response, and spurious electrical effects from measurement wiring or circuitry are avoided. Additionally, the laser vibrometer is a high-resolution measurement tool [16]. A Polytec Laser Doppler Vibrometer





Microvalve I: four-legged **Microvalve II: three-legged**

Fig. 1. SEM pictures of the two microvalves tested for dynamic response in air.