A THERMO-PNEUMATIC ACTUATION PRINCIPLE FOR A MICROMINIATURE PUMP AND OTHER MICROMECHANICAL DEVICES

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Abstract

A new type of actuator for a microminiature pump is presented. The pressure of air in a cavity, raised by resistive heating, deflects a thin silicon membrane. The dynamics of membrane deflection is studied experimentally, the results being in excellent agreement with simulation. We conclude that the device is suitable as an actuator in a micro-miniature pump.

Introduction

Since 1983, research on microminiature pumps has been carried out at the University of Twente. Several prototypes were realized in silicon, all piezoelectrically driven [1]. Major drawbacks of piezoelectric actuation are the necessity for high electrical voltages (100 V or more) and the unavailability of piezoelectric thin-film materials suitable for operation at low frequencies (10 Hz or less). Considering various actuation principles [2], it was concluded that thermo-pneumatic actuation, as we call it, might be a good alternative.

In general, we define a thermo-pneumatic actuator as a device consisting of a sealed cavity filled with a thermally expandable medium that can be heated or cooled down, resulting in a pressure change in the cavity. This induced pressure change is used to actuate a flexible or movable part, like a membrane or piston. Gas or a gas/liquid system can be used as the expanding medium. A temperature change in the cavity can be achieved by resistive heating, the use of a Peltier element or a laser. This actuation principle has been used in a microminiature valve, using a gas/liquid system and resistive heating [3]. This paper reports on the realization, behaviour and simulation of a thermo-pneumatic actuator designed to drive a microminiature pump.

Figure 1 shows a sketch of the actuator, comprising a cavity filled with air and a built-in aluminium meander that serves as a heater resistor. The resistor is supported by a thin silicon sheet suspended by four small silicon beams, which serve as a restriction to the heat flow. Aluminium current leads
connecting the meander to the bond flaps run through narrow channels, which form a restriction to the gas flow. This actuator is intended to be mounted on a pump, such that the flexible membrane can displace liquid present in a pump chamber.

Simulation model

Bond graph techniques [4] and TUTSIM [5] are used for physical modelling and simulation of the dynamic behaviour of the actuator. The model comprises the thermal behaviour of the actuator, the thermodynamics of the gas, the fluid dynamics of the channels and the mechanics of the flexible membrane. A detailed description of the simulation model will be reported elsewhere [2].

Experiments

Starting materials for the actuator are two silicon (100) 2 inch wafers, polished on both sides, and a Duran borosilicate glass wafer. The silicon wafers are shaped by wet chemical etching in a KOH water solution using standard photolithography for pattern definition. The glass wafer is cut out off a plate and polished (surface roughness <0.05 μm). The wafers are attached to one another by means of anodic bonding [6, 7]. To achieve a bond between the two silicon wafers, an intermediate layer of silicon oxide and sputtered borosilicate glass is required. A thermocouple is attached to the upper silicon wafer to monitor the temperature of the actuator as a whole.

Deflection of the flexible membrane as a function of power dissipated in the resistor is measured dynamically using a DEKTAK 3030 surface profiler scanning over 50 μm during 50 s with the scanning needle approx-
imately at the centre of the membrane. The scan length being small com-
pared with the membrane width, the needle remains virtually in the same
position. Thus, deflection at the centre of the membrane, \( w_0 \), versus time is
plotted directly.

**Results and discussion**

Figure 2 shows \( w_0 \) as a function of time, \( t \), for a number of d.c.
voltages, \( U \), applied to the resistor. The voltage is switched on at time \( t = 4 \) s.
A fast increase with a relaxation time \( \tau_t \) is followed by a slower decrease to
zero deflection, with a relaxation time \( \tau_p \). The first fast increase is caused by
a temperature rise in the cavity and a related pressure increase. The relaxa-
tion time for warming up the cavity is mainly determined by the thermal
conductance, \( G_{ta} \), of the air in the cavity, the thermal conductance, \( G_{th} \), of
the small suspending beams, and by the total heat capacity of the cavity.
Since the heat capacity of the air in the cavity is negligible, this total heat
capacity approximately equals the heat capacity, \( C_t \), of the suspended thin
silicon sheet supporting the resistor. Maximum temperature and pressure
build-up and related deflection \( w_0 \) are determined by input power and
thermal conductances \( G_{ta} \) and \( G_{th} \).

![Fig. 2. Deflection \( w_0 \) vs. time for a number of applied voltages.](image)

The subsequent slower decrease of \( w_0 \) is due to a flow of gas out of the
cavity and a related pressure decrease. \( \tau_p \) should be determined by the
volume of the cavity, \( V_p \), and the flow conductances, \( G_{pc} \), of the channels.
However, the calculated value of \( G_{pc} \) is much too low to account for \( \tau_p \).
Evidently there is some leak in our test device, with a flow conductance \( G_{pl} \),
which was confirmed by the observation of a partial failure during the
anodic bonding of the two silicon wafers.

When the d.c. voltage is switched off at time \( t = 25 \) s, the opposite
behaviour is observed. The cavity cools down, causing a pressure drop in the
cavity and a related fast decrease of \( w_0 \), with a relaxation time \( \tau_t' \) approxi-
mately equalling \( \tau_t \). The following slower increase to zero deflection is due
to a flow of gas into the cavity, with a relaxation time \( \tau_p' \) determined by \( V_p \)
and \( G_{pl} \), and therefore approximately equalling \( \tau_p \). The dashed lines in Fig. 2
represent results of simulations. Table 1 summarizes some parameter values.
TABLE 1
Calculated and measured parameter values

| Parameter                      | Measured (plots) | Calculated (geometry) | Simulated | Units 
|-------------------------------|------------------|-----------------------|-----------|---------
| Volume cavity VP              |                  | $2.7 \times 10^{-8}$ | $2.7 \times 10^{-8}$ | m$^3$   
| Flow conduct. channels Gpc    |                  | $4.0 \times 10^{-16}$ | $8.0 \times 10^{-14}$ | m$^5$/N s 
| Flow conduct. leak Gpl        |                  | $10$                 | $9$       | s       
| Relaxation time $\tau_p$      | $10$             | $9$                  | $9$       | s       
| Relaxation time $\tau_p'$     | $11$             | $9$                  | $9$       | s       
| Relaxation time $\tau_p''$    |                  | $9$                  | $9$       | s       
| Heat capacity sheet $C_t$     | $4.4 \times 10^{-3}$ | $6.0 \times 10^{-3}$ | J/K      
| Heat conductivity, air $G_{ta}$| $1.2 \times 10^{-2}$ | $1.2 \times 10^{-2}$ | W/K   
| Heat conductivity, beams $G_{tb}$ | $1.5 \times 10^{-2}$ | $1.8 \times 10^{-2}$ | W/K      
| Response time $\tau_t$        | $0.25$           | $0.16$               | $0.20$    | s       
| Response time $\tau_t'$       | $0.25$           | $0.16$               | $0.20$    | s       

Figure 3 shows $w_0$ when a block voltage of 12.9 V is applied to the resistor at 0.1 Hz. The system moves towards a steady state with a relaxation time $\tau_p''$, which is also determined by the volume of the cavity, $V_p$, and the flow conductance of the leak, $G_{pl}$; therefore $\tau_p''$ approximately equals $\tau_p'$ and $\tau_p$. After 30 s this steady state is reached with an amplitude $A_m$ of 23 μm. The dashed line corresponds to a simulation.

At higher frequencies the actuator shows a similar behaviour. However, at frequencies exceeding 0.4 Hz, there is no time to reach maximum or minimum $w_0$, resulting in a decrease of $A_m$. Therefore, the maximum of $A_m$ is determined by input power, $G_{ta}$ and $G_{tb}$, and frequency. In Fig. 4 measured and simulated amplitudes are given as a function of frequency, for a block voltage of 12.9 V.

The temperature rise of the actuator as a whole, as determined by means of the attached thermocouple, appears to be slow and small. For instance, a maximum temperature rise of 10 K is reached after 5 min at an input power of 0.5 W.

In order to determine the influence of the presence of a liquid on the behaviour of the actuator, to check its suitability for application in a pump,

![Fig. 3. Deflection $w_0$ vs. time for a block voltage of 12.9 V and 0.1 Hz.](image1)

![Fig. 4. Measured and simulated amplitudes $A_m$ vs. frequency for a block voltage of 12.9 V.](image2)
the membrane was covered with a drop of water. The presence of this water has no measurable effect on $w_0$ or $A_m$.

A deflection of 23 $\mu$m corresponds to a pressure difference over the membrane of 0.02 atm and a volume stroke of 0.5 $\mu$l. Reduction of the thermal conductances $G_{ta}$ and $G_{th}$ will result in an increase in temperature and pressure build-up.

If the actuator is to operate at frequencies exceeding 0.4 Hz, the relaxation times $\tau$ and $\tau'$ have to be reduced. This can be achieved by reducing the heat capacity $C_t$ of the suspended thin silicon sheet.

Conclusion

The actuator behaves as expected: results of simulations and measurements coincide within 10%. Hence the simulation model can be used for optimizing the actuator for a required pressure build-up in the cavity and a specific related (free) volume stroke of the membrane.

Important parameters are the response time $\tau_t$ (determining maximum frequency $f_{\text{max}}$) and the maximum build-up pressure $\Delta p_{\text{max}}$. The heat capacity of the suspended thin silicon sheet supporting the aluminium resistor determines, to a great extent, $\tau_t$ and $f_{\text{max}}$, while $\Delta p_{\text{max}}$ is mainly determined by input power and thermal conductances. Both $\Delta p_{\text{max}}$ and the induced membrane deflection are sufficient to drive the microminiature pump we have in mind, and can be even further optimized.

The construction of the actuator is simple and it can be fabricated using IC-compatible materials.

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References

2. F. C. M. van de Pol et al., to be published.
5. TUTSIM, a commercially available simulation program, developed at the University of Twente.