System Level Modeling of an Electrostatic Torsional Actuator

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Abstract

We present an efficient methodology for setting up MEMS macromodels which are based on a physical device description and lead to tractable mathematical relations for the device operation. Since design and technology parameters are input parameters of the resulting model, our approach is in particular suited for design studies. In addition to the reduction in degrees of freedom and, hence, the reduced simulation time, macromodels can easily be coupled with the electronic circuitry and the entire device can be simulated on system level. The methodology is demonstrated with reference to an electrostatic torsional actuator.

1. Introduction

A systematic methodology of formulating transparent compact models is, among others, provided by a thermodynamic system description in terms of driving forces and resulting flows of the relevant physical quantities [1]. This leads to a full system description as a "Generalized Kirchhoffian Network". This, in turn, is equivalent to a system of ordinary differential–algebraic equations for the node variables which can be solved using a standard analog network simulator. We demonstrate the practicality of the latter method by an exemplifying problem,

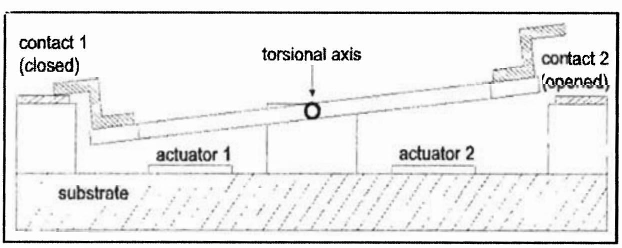

Fig. 1: Schematic cross section of a torsional actuator [2].

namely an electrostatic torsional actuator (fig. 1), which is a widely used basic structure employed in tiltable micromirrors [2] or microswitches [3]. Electrostatic actuation is especially favoured for switching applications in telecommunication because of its low power consumption.

2. Torsional Actuator

The torsional actuator is considered to be a tiltable, rigid body. Hence, the only degree of freedom is the angle of torsion φ. Neglecting fringing fields at the edges of the actuator, the total torque M acting on the upper electrode results in [5]:

$$M=\frac{1}{2}\epsilon\frac{U^2L^2}{D^2}w\frac{1}{\gamma^2}\left(\frac{\gamma}{1-\gamma}+\log(1-\gamma)\right) \qquad (1)$$

Here ε denotes the electric permittivity, U the applied voltage, L and w the length and the width of the actuation electrode, and D the gap between the electrodes. γ is the normalized angle of torsion.

The total torque is composed of the electrostatic torque (eq. 1), the mechanical torque exerted by the tethers by which the tiltable electrode is suspended, and the torque induced by the inertia and the damping of the actuator. In the notation of Kirchhoffian Network variables, the quantity conjugate to the generalized force (“across“) variable dφ/dt (angular velocity of torsion) is the torque M which plays the role of the generalized flow (“through“) quantity.

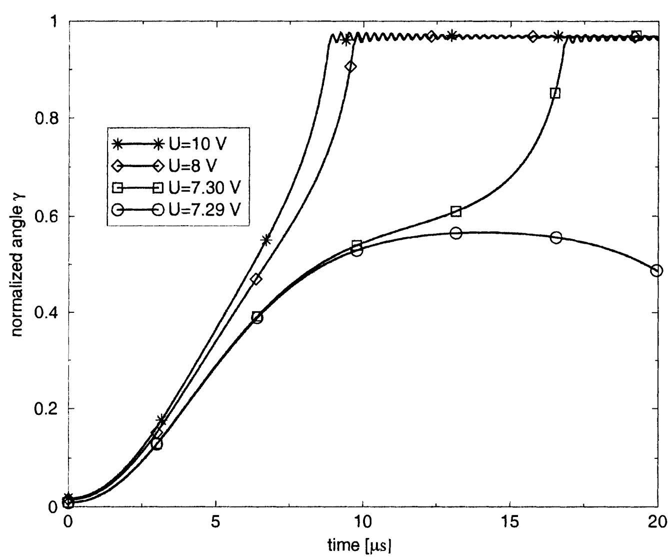

Fig. 2: Pull–in dynamics for various actuation voltages. The static pull–in voltage $U_{pi} = 8$ V.

2.1. Results

Performing a DC analysis allows to compute the pull–in hysteresis of the actuator. Below the static pull–in voltage V_{pi} exists an equilibrium between the nonlinear electrostatic torque and the restoring mechanical torque of the tethers. A compari–

son with experimental data is shown in [5] and shows good agreement.

Performing a transient analysis the snap down occurs at a dynamic pull–in voltage $U_{dpi} < U_{pi}$ due to the influence of the inertia (fig. 2).

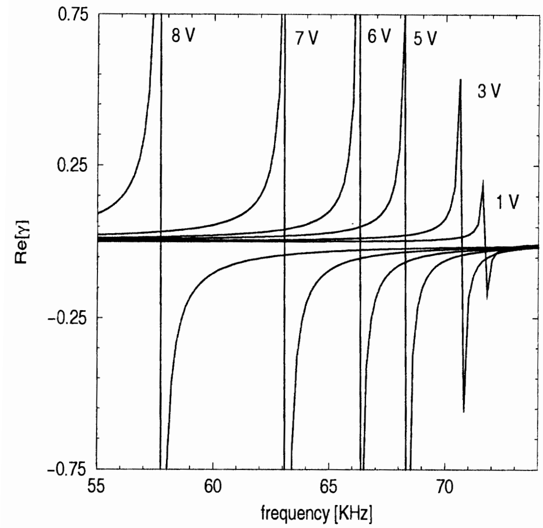

Fig. 3: Small signal analysis showing the shift of the resonance frequency caused by spring softening for various voltages.

For an electromechanical modal analysis and resonance measurements of electro–statically actuated devices, the effect of electrostatic spring softening has to be taken into account. Using our compact model the shift of the resonance frequency effected by the bias voltage can easily be analysed (fig. 3) and conforms well with the measured frequency of 72 kHz [3].

3. Charge pump

Due to technical constraints the available supply voltage is in many cases too low to operate the switch. This problem can be solved by means of a charge pump. A cascade of several capacitors and diodes is driven by an alternating voltage generated from the DC supply voltage. At each stage, the voltage is increased, but the available output current is limited by the corresponding demand of charge per cycle ($I_{max}=U_0C_1f$). Therefore, a charge pump can be described as a voltage source with a virtual source impedance, leading to a voltage drop but not associated with resistive loss. Also the ripple increases, if the load current is high compared to the available capacitors.

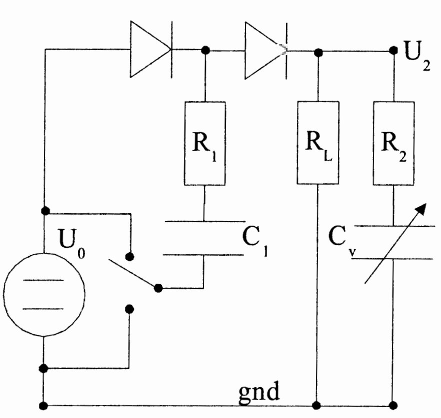

Fig. 4: Schematic of a simple charge pump.

4. System level simulation

Because charge pumps are sensitive to the behaviour of the load they drive, it is important for the circuit designer to have a reliable simulation model for the interaction of these two components. Hence a combination of a simple charge pump and the torsional actuator mentioned above was chosen as an example (fig. 4). The charge pump has only one stage, resistors (R1, R2, R_L) are included to represent the losses in a non-ideal circuit. The torsional actuator is displayed as a variable capacitance. As the actuator is coded in SpectreHDL[4] (analog hardware description language similar to the standard VHDL-AMS), it can easily be included in the circuitry of the charge pump. The influence of the pump frequency on the behaviour of the system is depicted in fig. 5.

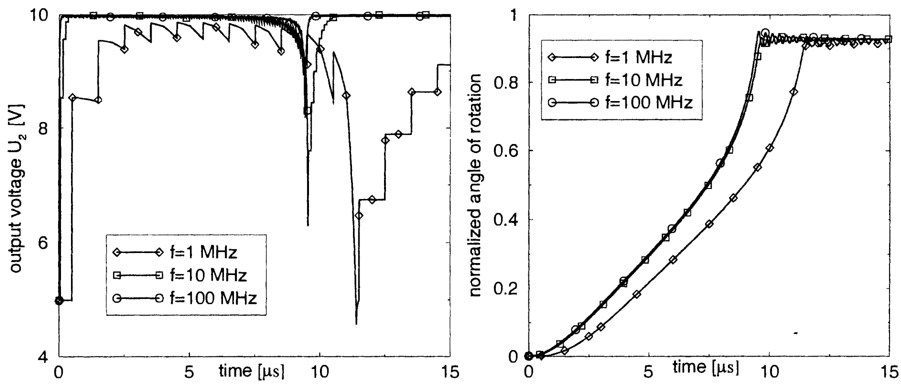

Fig. 5: Evolution of the output voltage U_2 of the charge pump and the pull-in characteristics for various pump frequencies.

5. Conclusion

System level modeling based on physical device description provides valuable insight and understanding of the dynamic behaviour of the device and allows one to perform parameter studies (geometry of the actuator and specifications of the components of the charge pump) in order to optimize the system with respect to performance, technological constraints and chip area.

References

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