

On the Interplay of Viscoelasticity and Air Permeation in Modelling the Dynamics of Embedded Tactile Sensors

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Summary: We investigate via experiments and finite element simulations the dynamic behavior of soft artificial fingertips. While viscoelasticity is a well-recognized dynamical mechanism, here we reveal air diffusion through silicone layers to be an equally important mechanism influencing dynamics. A series of experiments, performed in air and submerged in oil to reduce air diffusion, support unambiguously the participation of both dynamical mechanisms. A finite-element model further supports these findings, reproducing qualitatively the main dynamical features of the measurements.

Keywords: tactile artificial fingertip, soft materials, viscoelasticity, air diffusion through silicone

Background and Motivation

Tactile sensing is a key enabler for dexterous robotic manipulators [1]. Integration of tactile sensor arrays into soft materials will enable human-like fingertips suitable for delicate and precise object grasping. Such a technology, that we introduced in [2] is shown in Fig. 1. However, using soft materials such as silicones introduces several complexities stemming from hyper- and viscoelastic effects, entailing nonlinear deformations and dynamical effects.

In this work we draw attention to an additional effect, namely air diffusion, that may co-influence the dynamics of sensors integrated into soft materials. This is particularly important when the sensors incorporate an air-filled gap as the one illustrated in Fig. 1.

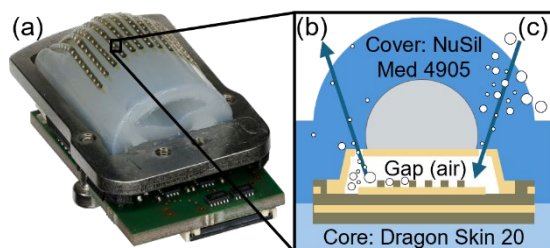


Fig. 1. **Technology overview.** (a) Artificial fingertip with embedded tactile array (12x12 taxels) [2]. (b, c) Cross-section of a taxel showing the air gap (cavity) and $\sim 400 \mu\text{m}$ cover layer, with pressure-difference driven air diffusion between cavity and ambient (schematic, not to scale).

Description of the New Method

Experiments were conducted with the artificial fingertip either placed directly in an air pressure chamber or partially submerged in oil to prevent air diffusion into the taxel air gap.

Finite-element simulations were performed with COMSOL Multiphysics, to get insight into the physics of the observed dynamical effects. The applied pressure P and number of molecules n were interconverted via the ideal gas law. A diffusion-based simulation, as illustrated in Fig. 2(b), was utilized to compute n (and corresponding pressure P) within the air gap of the taxel. The pressure difference ΔP was used subsequently in an electromechanical taxel model to predict capacitance changes ΔC .

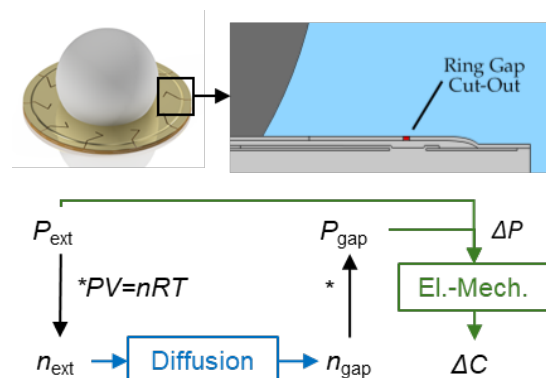


Fig. 2. **Finite-element simulation framework.** Detailed representation of 2D axisymmetric taxel with cover layer (top). Schematic representation of simulation flow with decoupled diffusion simulation to predict pressure in the air gap and electro-mechanical simulation to predict ΔC (bottom).

For computational efficiency, a 2D axisymmetric model was derived from the 3D geometry. The membrane spring cut-outs (Fig. 2) were simplified, replacing them with a single equivalent air opening. Material parameters and diffusion constants were taken from literature, experiments, and previously reported work, (see Table 1).

Tab. 1: Material parameters of silicone rubber and diffusivity constants for Nitrogen used in simulation

Neo-Hookean Lamé μ	82'124 N m ⁻²
Generalized Maxwell model parameters	Rt = 0.35 s Ef = 10
Pressure reduction factor	4.5
N ₂ self-diffusion [cm ² s ⁻¹]	0.209 [3]
N ₂ in silicone rubber [cm ² s ⁻¹]	1.5*10 ⁻⁵ [4]

Results and Discussion

For linear pressure ramps up to 3000 mbar in oil viscoelastic effects of the silicone layer dominate (Fig. 3). Slower ramps result in higher ΔC values, particularly during loading, as silicone has more time to undergo creep. During unloading, the responses are more similar, indicating partial compensation of these effects. Hysteresis decreases with increasing ramp time.

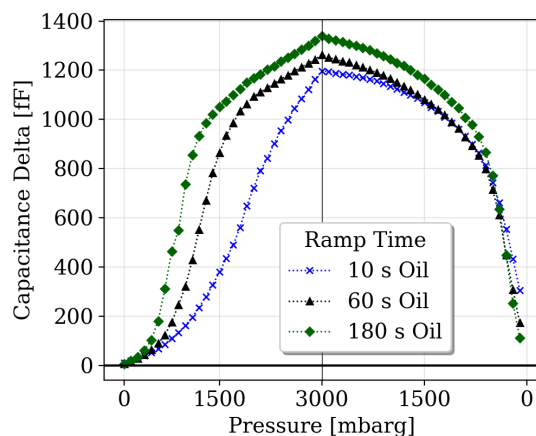


Fig. 3. **Viscoelastic dynamic effects** for linear pressure ramps up to 3000 mbar for different ramp times with artificial finger submerged in oil. Slower ramps show higher response but lower hysteresis.

Fig. 4 compares the capacitance response (ΔC) in air and oil environments after switching the pressure up to 500 mbar holding it for 90 s and then releasing it back to ambient pressure. Comparing air and oil measurements, supported by simulation, reveals the influence of diffusion. During the first 10 s, similar behavior is observed across all cases. Past the 15 s mark, the behavior starts to differ, with ΔC starting to decrease for air (w/ diffusion) as opposed to oil (w/o diffusion). This behavior is attributed to air diffusing through the silicone cover layer into the membrane cavity, which reduces the effective pressure difference ΔP and restores the initial membrane configuration. The effect becomes significant after 20 s, with approximately 10% of the applied pressure establishing within the taxel gap. No such relaxation is observed in oil

measurements or simulations with disabled diffusion, confirming this effect.

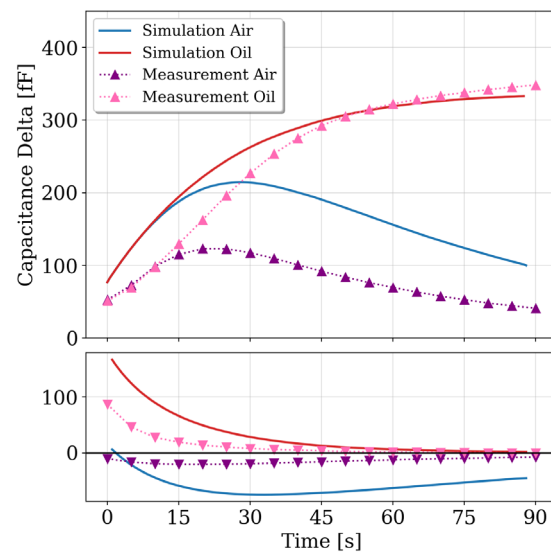


Fig. 3. **Impact of air diffusion.** Comparison of simulations with and without diffusion to experiments in air and oil (no diffusion). (top) Taxel response in simulation and taxel array average of experimental data after switching the chamber pressure up to 500 mbar and holding it for 90 s and (bottom) after returning to ambient pressure. Fast transients (<2s) not shown.

In addition to well-known viscoelastic effects, air diffusion should be considered when analyzing the dynamics of sensors that contain soft and permeable silicone covers. In our case, for artificial fingertips, a linear ramp duration of 30 s or a pressure hold duration of up to 15 s provides a suitable balance between reduced viscoelastic effects and limited diffusion. Furthermore, intentionally varying ramp speed can provide additional insight into the electromechanical behavior of the taxels, enabling more advanced model-based normalization strategies.

References

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