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Towards Feasibility of an Inkjet-Printed Capacitive Sensor for Position Tracking of a MOEMS-Mirror in a Michelson Interferometer Setup

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Abstract

Mechanical micro-mirrors are, nowadays, employed in a variety of devices (measurement equipment as well as consumer goods). Drawbacks of the widely used optical position feedback are complexity and space requirements. We propose an inkjet-printed capacitive position sensor for a resonant MOEMS in a Fourier Transform InfraRed (FTIR) spectrometer as part of a smart packaging solution. Statistical models are adopted based on Finite Element Method (FEM) simulations for the dynamic system. A specifically designed hardware is considered to cope with the challenging requirements of a position accuracy of res_{pos} = 50 nm at a sample rate of B = 10 MS/s with an overall measurement range of r_m = 1000 µm to be reached with a sensor limited to d_s = 5 mm diameter at d_{min} = 500 µm minimum distance. A noise analysis is performed for direct and parametric measurement strategies, and the influence of uncertainties in the position measurement on resolution and bandwidth capabilities of the system are assessed.

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Keywords: MEMS; FT-IR; capacitive sensing; noise analysis; CRLB;

1. Introduction

Micro-optical devices have gained vastly in interest over the last decade, and are, by now, deployed in various fields. Applications range from FTIR spectroscopy [1] and multimedia optical devices [2] to light barriers [3]. Formerly, such optical arrangements used to consume a considerable amount of space. MicroOpticalElectroMechanical Systems (MOEMS) now offer the possibility of integrating complex setups into mobile applications, especially when combined with smart packaging solutions [4]. A common way to manufacture

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an FTIR spectrometer device is combining the light source with a Michelson interferometer setup [5]. To keep the measurement time low while still providing for a sufficient Signal-to-Noise-Ration (SNR) demands fast position tracking of the moving mirror while the necessity to add spectra congruently claims accuracy of the same. Existing devices are realized holding a reference interferometer to measure and control the mirror position [1], [6]-[7] or feature optical position sensing [8]. To enable further miniaturization of such devices, we propose a multilayer, inkjet-printed, capacitive position sensor. Considerations on the design of MicroElectroMechanical Systems (MEMS) subject to uncertainties [9], [10] as well as robust control of the electrostatic drive of MEMS [11] under parametric uncertainties have already been published. We extend this design methodologies by assessment of the possible lower bounds (Cramer Rao Lower Bound) on the measurement uncertainties. A stochastic system model based on FEM simulations is employed, reflecting the sinusoidal mirror movement. Based on these and characteristics of the specifically designed measurement hardware, a basic noise analysis is combined with the determination of the CRLB for a baseband (static) and carrier-frequency (dynamic) system to assess the sensor's suitability and limitations for position tracking.

2. Finite Element Method Simulation

A commercial multiphysics-capable software tool is used to draw the topology, assign materials and assemble and solve for the relevant physics and couplings. The capacitive sensing system is realized as conductive surface below the moving mirror plate. The conductivity σ_{ink} = 12.32 MS/m of the printed material is chosen based on worst case assumptions given in datasheets of the ink manufacturer [12]. In a time-dependent study, first the mirror motion is computed and then propagated to the electrostatics equations which are then solved based on the new geometric configuration. At its rest position, the corresponding capacitance C_b= 108.5 fF is found, further defined to be the base capacitance of the system.

3. Static System Analysis

In a first approach to a suitable surrogate model for the capacitive position sensor, a polynomial model is fitted to the data from FEM simulations (compare also [13]).
We presume the measured signal (capacitance) to be a function of the mirror position or distance, or equivalently, $C(d_m)$ with

$$d_m = \mathrm{d}_0 + \mathrm{A}_m \cos(2\pi \mathrm{f}_m \mathrm{t} + \varphi_m)$$

Here, d_0= 1 mm is the initial or rest position, A_m= 0.5 mm is the absolute maximal displacement (mirror amplitude) and f_m = 500 Hz is the mirror resonance frequency.
While the analytic description is a simplistic version of the true system behavior, simulation data, though still subject to allowed assumptions, provides an improved description by considering also disturbances (e.g. fringing fields). To incorporate this behavior, a meta-model is sought, based on which further resolution capability analyses of the considered system are possible. An estimator minimizing the Least Squares (LS) error, which consequently yields the Least Squares Estimate (LSE) can provide parameters A_1 to A_3 [14] to establish such a model based on a previously chosen structure (e.g. polynomial). Based on this model, it is then possible to quantify necessary conditions on the system bandwidth, noise and hardware parameters to provide for the necessary position resolution.
The LSE provides for a model linear in parameters, here

$$C_{LSE} = \frac{A_1}{d_m} + \mathrm{A}_2 d_m + A_3$$

To convey the known non-linear dependence to the semi-analytic description, a beforehand transformation of the data is applied. Afterwards, an estimator for the model parameters can be computed using Singular Value Decomposition (SVD).

4. CRLB Analysis for Direct Measurement Strategy

We perform a sensitivity analysis of the model to determine the bandwidth restrictions in the first place. From the analytic description model of the considered system it is possible to compute the partial derivative of the capacitance with respect to the distance $s = dC/dd$, i.e. its sensitivity and $|s|$ is its absolute value. Using the requirement for the standard deviation of the position σ_d = 50 nm, i.e. the necessary resolution, we find a necessary condition on standard deviation for the capacitance σ_c

$$\sigma_c < \sigma_d|s|$$

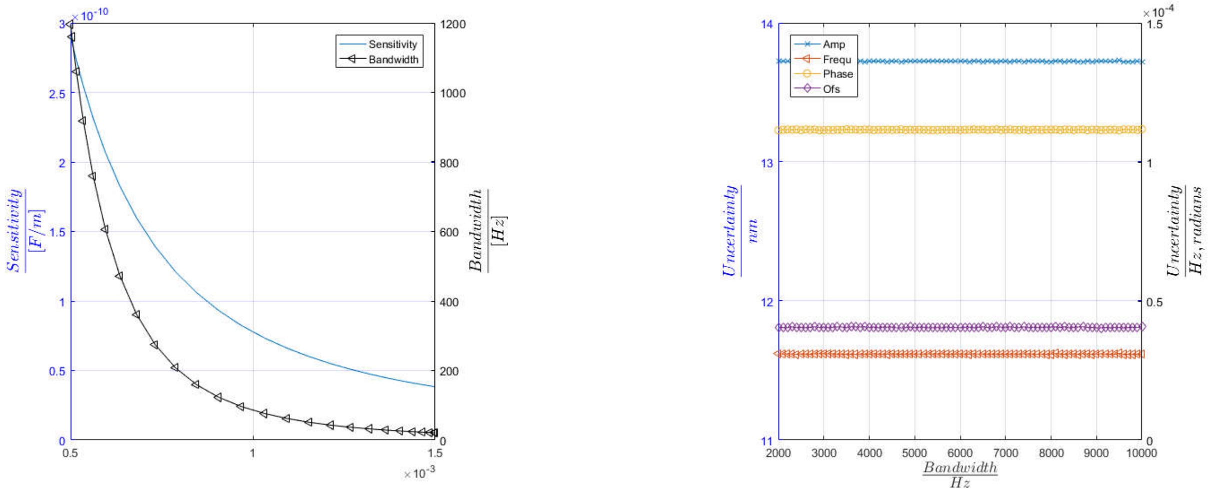
Then, with B the bandwidth in Hertz and c_n the capacitance equivalent spectral noise density as found from noise analysis of the considered hardware

$$\sigma_c = \sqrt{B}c_n$$

we have

$$B = \frac{{\sigma_c}^2}{{c_n}^2} = \frac{(\sigma_d|s|)^2}{{c_n}^2}$$

where we determine the bandwidth for an absolute value of the distance deviation. Since the sensitivity of the model varies over distance, so does the necessary bandwidth. The lower sensitivity at a distance d = 1.5 mm calls for a bandwidth as low as B ~ 16 Hz. This low bandwidth is obviously neither suitable to control the mirror device nor to satisfy spectrometer resolution demands. Besides this, digital filtering which fulfills timing requirements with respect to group delay is not easily implementable for the mirror resonance frequency of f_m = 500 Hz. Therefore, we suggest



(b) (a)

Fig. 1 (a): Sensitivity and bandwidth restrictions over distance for the direct measurement system. Fig. 1 (b): CRLB for the four model parameters. The CRLB is constant over bandwidth: although the measurement noise increases, more samples can be considered for the same observation period.

using a system model to estimate the parameters of the movement separately. Based on the LSE, we can calculate the CRLB for the parameters to be estimated, i.e. the mirror amplitude A_m, frequency f_m, phase φ_m and distance offset d_0 for the carrier frequency (i.e. the dynamic) system.

5. CRLB Analysis for Parametric Measurement Strategy

Three parameters, i.e. the mirror amplitude A_m frequency f_m, phase φ_m are supposed to be subject to environmental influences and thus time-varying. Although, these parameters vary with time, a major advantage is the low frequency of this change: the mirror position changes with the mirror frequency f_m = 500 Hz, the amplitude A_m is supposed to vary at a frequency of f_{amp}<< 1 Hz. Digital filtering fulfilling the timing requirements will thus be much better achievable. Under these assumptions, similar to the CRLB on the distance determined in terms of sensitivity, we can find the CRLB for the parameters with respect to a chosen carrier frequency and bandwidth. This can be calculated as the inverse of the so-called Fisher information matrix. Under the assumption of a signal in Additive White Gaussian Noise (AWGN) its elements can be computed as [14]

$$[I(\vec{\theta})]_{ij} = \left[\frac{\partial C(\vec{\theta})}{\partial \theta_i}\right]^T \frac{1}{\sigma^2} I \left[\frac{\partial C(\vec{\theta})}{\partial \theta_j}\right]$$

With $\vec{\theta}$ the vector of parameters of interest, $C(\vec{\theta})$ the measured signal (capacitance dependent on the parameters to be estimated), σ^2 the variance of the noise and I the identity matrix. Based on this equation, the bandwidth dependent uncertainties for the parameters of interest can be found. When analyzing the uncertainty evolution, (Fig. 1b), a restriction to B = 2000 Hz yields a theoretical lower bound for the uncertainty of the amplitude $CRLB_{A_m}$ < 14 nm. The direct measurement setup as considered previously demands for intractable restrictions on the bandwidth. The consequently suggested approach to employ a parameterized system model, exploiting prior knowledge about the system, now enables to adopt measurement strategies allowing for higher considered bandwidths.

6. Conclusion

In this work, resolution capabilities of a capacitive position sensor for MOEMS device as part of a Michelson interferometer setup has been investigated. The resolution capabilities have been evaluated based on a noise analysis for static and parametric measurement setups. To overcome the shown system limitations with respect to the lowest achievable resolution (CRLB), as a next step, the application of Extended Kalman Filtering, a Bayesian approach to statistical signal reconstruction, is suggested. With aid of this method to smart signal processing, the useable measurement bandwidth is to be increased and system specifications are assumed to be met.

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