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Optimized design of micromachined electric field mills to maximize electrostatic field sensitivity

Yu Zhou, Cyrus Shafai *

Department of Electrical and Computer Engineering, University of Manitoba, Winnipeg, Canada R3T 5V6

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ABSTRACT

This paper describes the design optimization of a micromachined electric field mill, in relation to maximizing its output signal. The cases studied are for a perforated electrically grounded shutter vibrating laterally over sensing electrodes. It is shown that when modeling the output signal of the sensor, the differential charge on the sense electrodes when exposed to vs. visibly shielded from the incident electric field must be considered. Parametric studies of device dimensions show that the shutter thickness and its spacing from the underlying electrodes should be minimized as these parameters very strongly affect the MEFM signal. Exploration of the shutter perforation size and sense electrode width indicate that the best MEFM design is one where shutter perforation widths are a few times larger than the sense electrode widths.

1. Introduction

Many industries employ electric field measurement for various applications such as power system monitoring [1–5], electrostatic detection [6–8], and atmospheric science [9–11]. DC electric field measurement is known to be comparatively more complicated than ac field measurement due to the lack of cyclic variation with respect to time. Field mill devices are often employed for dc field measurement. These devices convert the dc field into an alternating field by employing an electrically grounded shutter to periodically shield sense electrodes from the incident dc field.

A few micromachined electric field mill (MEFM) designs have been investigated and fabricated based on the concept of the macroscopic field mill [12–17]. Most of the designs apply a vibrating perforated grounded shutter to periodically shield underlying sense electrodes from the incident dc field (see Fig. 1). As interference from the drive voltage can limit resolution, low voltage drives are more preferable for increased sensitivity. In some cases, resonant motion of shutter is used to further reduce the driving voltage. This was demonstrated by Wijeweera et al. [17], where a resonant shutter driven by low voltage thermal actuators was implemented. The sensor demonstrated a minimum detectable field strength at 42 V/m, which outperformed most of the other MEFM reported [12–16]. While performance was excellent, the sensor's structural parameters were not fully optimized, limiting is potential sensitivity.

A study on MEFM design optimization was undertaken by Gong et al. [18] for two different designs of MEFM, perpendicular-vibration MEFM and parallel-vibration MEFM. The structure parameters, including width of perforations (slits in the shutter), shutter thickness, and gap between the shutter and underlying electrodes, were optimized to achieve a maximum amount of induced charge on the exposed electrodes. These studies were based on the assumption that there would be no induced charge on the electrodes when visibly shielded by the shutter. However, this is not the case, as shielded electrodes are charged by the incident field due to fringing under the shutter. Therefore, a study of the operational performance of an MEFM must consider the differential charge between visibly shielded and exposed electrodes under the vibrating shutter.

In this paper, a study of the differential charge (shielded vs. exposed) on the sense electrodes as a function of MEFM geometry is presented using finite element analysis method (FEM). Comparing to the conformal mapping analysis that is commonly used in this area, FEM can more easily deal with a much more complicated structure, such as the structure considered in this paper. Furthermore, FEM readily includes the effect of the fringing electric field through the shutter perforations and incident on the lower electrodes. Accurate consideration of the fringing field is critical to determining the differential charging between shielded and exposed sensor electrodes. With the FEM, the optimization of structural parameters to maximize differential charge signal is studied. In addition, the effect of non-vertical shutter perforation geometry is studied, in order to explore the effect of non-ideal anisotropic etch of shutter perforations. All studies are undertaken for the case of an electrically grounded shutter, and the shutter defined to be metal

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* Corresponding author.
E-mail address: Cyrus.Shafai@umanitoba.ca (C. Shafai).

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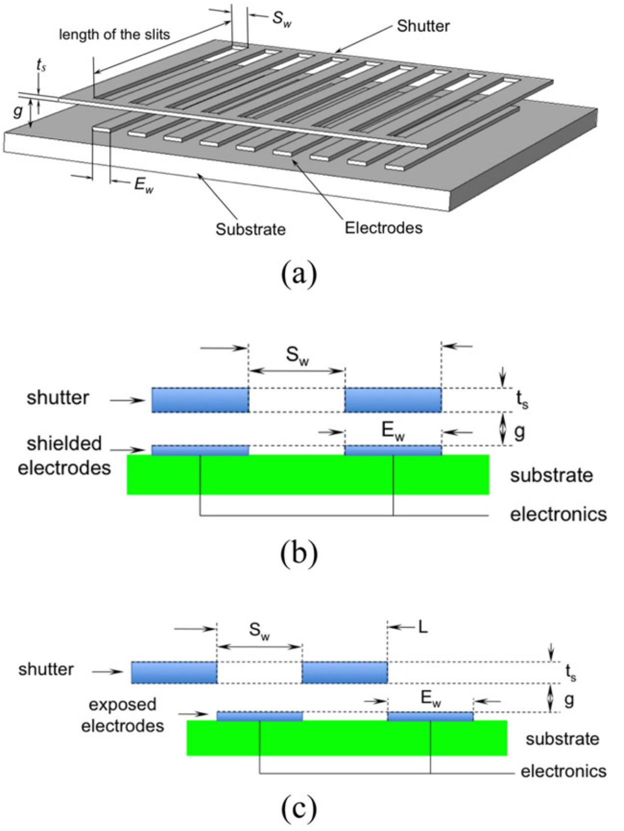

Fig. 1. (a) Schematic of a typical MEFM concept. (b) Illustration showing when the electrodes are visibly shielded by the shutter and (c) when the electrodes are exposed to the incident field.

conductor (gold). Earlier, the case of a silicon dielectric shutter was investigated in [19].

2. Simulation parameters

The parametric study of MEFM design in this paper focuses on the parameters in Fig. 1 of shielding shutter perforation width S_w, shutter thickness t_s, sense electrode width E_w, and shutter to electrode gap g, in order to determine their effects on the MEFM signal. In all studies, the thickness of the sense electrodes was 0.5 μm. All these four parameters are fully investigated using FEM simulations. The definitions of the different MEFM design parameters are given in Table 1.

If we were to neglect fringing under the shutter, the amount of the induced charge on the surface of the electrodes exposed to the electric field would follow:

$$I = \frac{dQ}{dt} = \varepsilon_0 \varepsilon_r E_i \frac{dA}{dt} \tag{1}$$

where Q is the amount of the induced charge on the surface of the electrodes, ε_0 is the permittivity of free space, ε_r is the relative permittivity of the medium, E_i is the incident electric field strength orthogonal to the surface of the sensing electrodes, and A is the area of the electrodes. According to this equation, the induced current is proportional to the incident field strength, and the rate of change of the surface area of the electrodes, as they are covered by the moving shutter.

Table 1
Definition of the MEFM design parameters and the expected range of each parameter.

Parameter	Definition
L	Shutter perforation repetition period
S_L	Length of perforation in the shutter
S_w	Width of perforation in the shutter
E_w	Width of the electrodes
t_s	Thickness of the shutter
g	Gap between the shutter and electrodes

However, in a real MEFM, fringing electric field under the shutter can induce charge on visibly shielded electrodes. The proportion of the dc field, which reaches the sensing electrodes, can depend greatly on S_w, t_s, and g. Therefore, to account for the fringing electric field, FEM was used to model the MEFM in operation. The FEM simulation settings are discussed in detail below.

3. Simulation settings

Finite element simulations were done with COMSOL Multi-physics. The electrostatic interface of the AC/DC module was used. Both 3-D simulations and 2-D simulations were carried out. The 3-D simulation was done first, with the shutter and electrodes electrically grounded and the electric field vertically incident from above the shutter. Since the results of the simulations for electrode charging are simply proportional to incident electric field strength, a field of 0.1 V/m was applied. The induced charge on the sense electrodes when fully exposed to the incident field was compared to the result from the similar simulations done by Gong et al. [18], and a strong agreement was found. With the simulation model verified, subsequent analysis was undertaken using 2-D simulations due to the lower computation time. The simulations were done along a line bisecting the MEFM shutter following the x-axis for symmetry. The 2-D simulations are valid as long as S_L is much larger than the other dimensions. The setup of 2-D simulations is shown in Fig. 2. The substrate used in the simulation is not shown in Fig. 2, in order to give a simpler picture which better illustrates the gold electrodes. In the simulation, the substrate lies directly under the electrodes, and was set to be intrinsic silicon. The far side of the substrate opposite to the electrodes was electrically grounded as it would be in a packaged device.

Fig. 3 compares the simulated charge on the exposed electrodes results for the 2-D and 3-D simulations, to verify that the 2-D model can be used in place of the more computationally intensive 3-D model. We can see that both results show a strong similarity, with the difference within a few percent. This indicates that usage of the 2-D model is appropriate for this study.

4. Results and analysis

4.1. Shutter with rectangular cross-sectional holes

The various parametric dimensions of the MEFM are studied in this section to determine their effect on the sense signal, for the case of a shutter with rectangular cross-sectional perforation holes (as shown in Fig. 1).

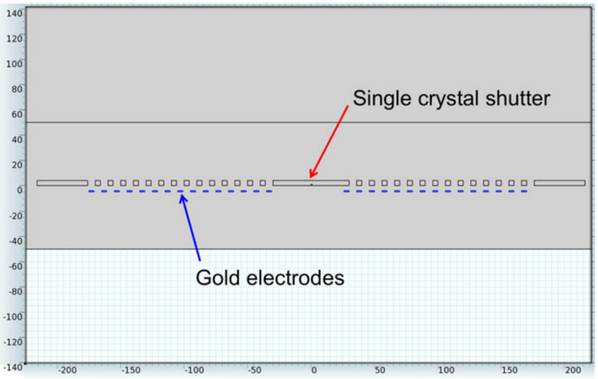

Fig. 2. Schematic of 2-D simulations.