23.4: Novel Sensor Technology for Shear and Normal Strain Detection with Generalized Electrostriction

Torrey R. Filanc-Bowen
Mechanical Engineering
University of Wisconsin - Madison
Madison, WI, USA
tfilancbowen@students.wisc.edu

Geun Hyung Kim
Mechanical Engineering
University of Wisconsin - Madison
Madison, WI, USA
gkim@cae.wisc.edu

Yuri M. Shkel*
Mechanical Engineering
University of Wisconsin - Madison
Madison, WI, USA
yshkel@engr.wisc.edu

Abstract

We present a novel technology for stress and strain sensing. As a fundamental property of any dielectric material, electrostriction determines the effect of elastic deformation on dielectric properties. An electrostriction sensor detects the dielectric changes due to deformation in the media with data acquisition approach, which resembles well-known capacitance sensing techniques. Electrostriction sensing technology does not rely on mechanical contact between the sensor electrodes and the sensing media, nor does it require physical displacement of the electrodes. Thus, detection of normal and shear loads can be implemented in a single plate configuration with no moving parts. Electrostriction sensor design is robust and has high tolerance to overloads—a critical issue for tactile sensing in robotic applications. With many materials available for sensing media, we discuss electrostriction phenomenon in isotropic and anisotropic polymer composites and provide guidance for selection of a material for a given application.

Keywords

Tactile, stress and strain sensors; capacitance sensing; electrostriction; solid-state sensor.

INTRODUCTION

Deformation and displacement measurements are required for stress, strain, pressure, and tactile sensing. Tactile sensors are widely used in manipulation tasks, automatic grasping, and compliance control (see [5] for a review). Many of the tactile sensors in existence use capacitance arrays [2, 5] of pressure-sensitive elements which, when in contact with an object, can provide information on the location of the contact and a distribution of normal stresses in the contact area. Traditional design of capacitance sensors with a vacuum or air-gap capacitor cannot withstand large loads. It is also a challenging task to design a simple and reliable capacitor sensor arrays for shear deformations.

An entirely new concept of capacitor sensors—single plate solid-state device is proposed. Single plate technology offers a simple and reliable way to manufacture sensor arrays for stress and strain mapping. In this article we discuss the design, modeling and testing of novel single-plate capacitance sensor that incorporates an elastic dielectric material on top of the electrodes. Electrostriction properties of the material are employed to detect deformations. Thus, the dynamic response of the sensor is determined by properties of the dielectric material rather than properties of the electrodes and no physical displacement of electrodes is needed. This technology overcomes shortcomings of air-gap or vacuum-gap capacitors such as lack of robustness, fragility, rigid backing, cost, manufacturability, but retains the benefits of a capacitor sensing solution. Proper selection of dielectric material and electrode configuration could make such a device capable to resolve normal or shear deformation.

To illustrate advantages of electrostriction sensing we briefly consider operation of a parallel plate capacitor sensor. Such systems have been traditionally employed in sensor applications and implemented with micromachining designs (see, for example, [7] and references within). Pressure or stress loads transmitted to the capacitor electrodes deform them and alter capacitance of the sensing element. The capacitance can be measured by a number of well established methods [1, 3].

A single-plate capacitor sensor for pressure, stress and strain measurements has no moving parts and detects deformations via change in properties of the dielectric material attached to the electrodes. An electrode pattern on the surface can be easily manufactured by photolithographic process. With proper selection of electrode orientations and dielectric material structure, an array of single-plate sensors is capable to resolve a distribution of normal and shear stress components over the surface. We deliberately do not limit the choice of materials attached to the sensor electrodes—any existing dielectric material can be utilized. For example, material used as a construction element of any design such as manipulator or transducer, can be a sensing media, thus, avoiding excessive "interface layers" between device and the sensing mechanism. Although not addressed in this paper, future investigations may be focused on the engineering materials tailored for specific sensor applications.

*Author to whom all correspondence should be addressed.

0-7803-7454-1/02/$17.00

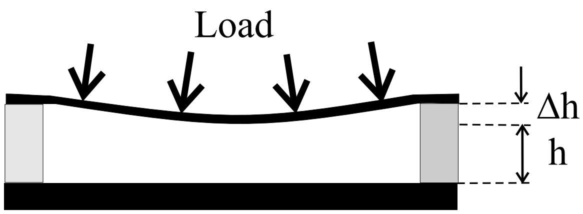

Figure 1. Capacitance of the system varies due to deformation of the flexible electrodes. The system is very sensitive to overloads—large forces can damage the electrodes or cause the electronics to short.

TRADITIONAL CAPACITANCE SENSOR

A parallel plate capacitor with vacuum or air between the electrodes represents a basic design element of many capacitance sensors (see Figure 1). This element is typical for most micro-machined pressure and tactile capacitor sensors and can be easily analyzed. The capacitance, C, of a parallel plate capacitor with area, A, and gap, $h \ll \sqrt{A}$, between the plates is

$$C = \frac{\epsilon_0 \epsilon A}{h}[1 + O(\log \frac{\sqrt{A}/h)}{2\sqrt{A}/h})], \tag{1}$$

where $\epsilon_0 = 8.85 \times 10^{-12} F/m$ is the permittivity of free space and ϵ is the relative dielectric constant of the material between the plates. The contribution of the fringe effect is estimated by the second term in the brackets and will be ignored in the following analysis. Traditional capacitance sensing detects the variation in the capacitance with deformation or displacement of the sensor electrodes. The relative change in capacitance, $\Delta C/C$, caused by variation in the gap thickness, h, between rigid electrodes is given by

$$\frac{\Delta C}{C} = \frac{\Delta\epsilon}{\epsilon} - \frac{\Delta h}{h}. \tag{2}$$

This expression assumes that the electrodes are not deformed (the term $\Delta A/A$ is absent). In most capacitance sensor designs the dielectric constant does not change (dielectric between the electrodes can escape without deformation). The change in capacitance can be measured by a variety of well-established methods [1, 3].

Sensing response of parallel plate vacuum-gap or air-gap sensors is defined by the elastic properties of the electrodes (membrane). The system is very sensitive to overloads—unexpected large deformation can damage the membrane or electrically short the electrodes. Micro-machining of the capacitance sensor arrays with a large-area and small-gap parallel plate design is a challenging manufacturing task. As it has been discussed in Ref. [9], reliability of the parallel plate capacitor sensor can be improved by introducing an elastic dielectric material between the plates. The sensor becomes more robust, because its dynamic response is determined by elastic properties of the material between the plates. In addition, dielectric material between the electrodes increases the sensor sensitivity due to electrostriction effect. It is also much easier to manufacture a device with a dielectric film between the plates given a wide selection of technologies for producing uniform films of dielectric materials.

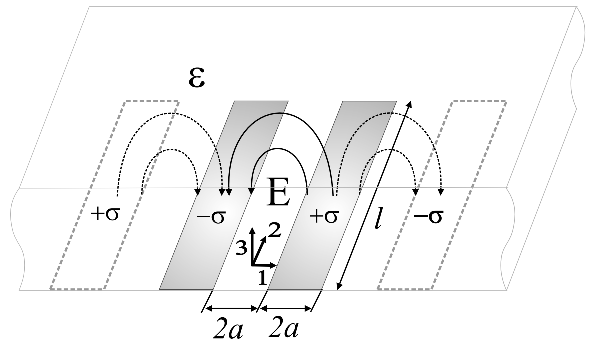

Figure 2. Electrodes of equal width are spaced equally apart. The dielectric layer has length, ℓ, and separation between lines $2a$, where ($h/a, \ell/a \ll 1$). Deformation of the dielectric layer affects the dielectric constant of the material and, therefore, the sensor capacitance.

SINGLE-PLATE CAPACITANCE SENSOR

An entirely new concept of capacitor sensors—single plate solid-state device is proposed. This sensor has no moving parts and detects deformations via change in properties of the dielectric material attached to electrodes. An electrode pattern on the surface can be easily manufactured by photolithographic process. With proper selection of electrode orientations and structure of dielectric material, an array of single-plate sensors is capable to resolve a distribution of normal and shear stress components over the surface. Presented in Figure 2 is a single-plate capacitance sensor, which is composed of a layer of dielectric material deposited on interdigitated electrodes. The electrodes form a pattern of equal width lines, which are spaced equally apart. Both thickness of the dielectric layer, h, and length of the electrode, ℓ, are much larger than distance between the electrodes, $2a$ ($h/a, \ell/a \ll 1$). Deformation of the dielectric layer affects the dielectric constant of the material and, therefore, the sensor capacitance. It is advantageous to combine single-plate sensing elements in an array, where each element has a different structure of the dielectric material and different orientation of the electrodes. Such arrays, with at least three sensing elements, will be capable to resolve a normal and two shear components of deformation. A larger array may be required to map a distribution of deformation over some area. In this study two arrays of four single-plate sensing elements were tested. The dielectric material was silicon rubber with random and anisotropically distributed alumina particles.

Capacitance of Interdigitated Electrodes

The capacitance of any capacitor is defined by expression

$$C = \frac{Q}{V}, \tag{3}$$

where Q is the charge required to produce the potential difference, V. This relationship can be considered as a definition of capacitance for any system of electrodes. At the same time Eq. 3 shows how variation in capacitance can be measured. For example, one could fix the charge, Q, on the capacitor electrodes then, $\Delta C/C = \Delta V/V$, since $Q = const$. Variation in capacitance can be registered as a variation in voltage across the capacitor. Or, one could fix the voltage, V, between the electrodes then, $\Delta C/C = \Delta Q/Q$, since $V = const$. Variation in capacitance can be registered as a current flow across the capacitor.

Let us consider the capacitance of an interdigitated system of electrodes with isotropic dielectric on top. Due to symmetry of the field distribution near interdigitated electrodes, the whole system of interdigitated electrodes can be modeled as just two electrodes of width a and length, $L = \ell n$ each with positive surface charge, $+\sigma$, and negative surface charge, $-\sigma$. The electric field in an isotropic dielectric can be approximated as

$$E = \frac{V}{\pi r}, \tag{4}$$

where r is the radial distance from the point located equidistance from either electrode. [1] Electrode charge density, σ, can be defined in terms of the electric field near the electrode surface

$$\sigma = 2\epsilon_0 \epsilon E, \tag{5}$$

where ϵ is dielectric constant of the material. The differential charge on the surface can be written as

$$dQ = \sigma L \cdot dr. \tag{6}$$

Total charge, Q, can be obtained through integrating the charge over the electrode surface. The capacitance is determined from the relationship between the charge on the surface and the potential between the two electrodes

$$C = \frac{Q}{V} = \frac{1}{V}\int_a^{2a} dQ = \ln 4 \frac{\epsilon_0 \epsilon L}{\pi}. \tag{7}$$

Variation of Capacitance with Deformation

Deformation of elastic dielectrics affects its dielectric properties. Even initially isotropic material becomes anisotropic in the direction of deformation. This phenomenon, called electrostriction [8, 10, 13], is employed as a sensing mechanism in the single-plate sensor design. Two processes contribute to the variation of capacitance, $\Delta C/C$: (a) change in dielectric properties of the material with deformation, $\Delta\epsilon/\epsilon$; (b) change in electric field near electrodes with deformation, $\Delta E/E$

$$\frac{\Delta C}{C} = \frac{\Delta \epsilon}{\epsilon} - \frac{\Delta E}{E}. \tag{8}$$

Note, that term $\Delta E/E$ in this equation, has same physical meaning as term $\Delta h/h$ in Eq. 2.

For example, a normal deformation of dielectric layer, $\Delta h/h$, affects its dielectric constant

$$\frac{\Delta \epsilon}{\epsilon} = K_n^{\epsilon}\frac{\Delta h}{h}. \tag{9}$$

At the same time, compression of the dielectric affects the electric field distribution near electrodes, which is linear for small deformations

$$\frac{\Delta E}{E} = -K_n^{E}\frac{\Delta h}{h}. \tag{10}$$

The field contribution appears because Eq. 4 should be modified for anisotropic materials. The total capacitance response for a normal deformation is

$$\frac{\Delta C}{C} = K_n \frac{\Delta h}{h}, \tag{11}$$

where parameter $K_n = K_n^{\epsilon} + K_n^{E}$ is defined by the material composition and can be theoretically estimated or directly measured (see Refs. [6, 10, 11, 12]).

Similar analysis can be provided for a shear deformation as well. A parallel displacement, $U = \gamma h$, where thickness of the dielectric layer $h = const$, causes a shear deformation $\gamma/2$. Analysis shows that [6]

$$\frac{\Delta \epsilon}{\epsilon} = (K_n^{\epsilon} + K_\tau^{\epsilon})\frac{\gamma^2}{2}. \tag{12}$$

Variation of the electric field near electrodes with shear deformations can be presented as

$$\frac{\Delta E}{E} = -K_\tau^{E}\frac{\gamma^2}{2}. \tag{13}$$

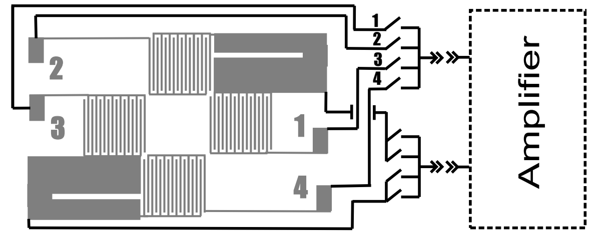

Figure 3. The sensor is arranged in an array of four sensing elements: elements 1 and 3 have electrodes oriented along the shear direction, and elements 2 and 4 are perpendicular to the shear direction.

[1]Note, that the relation (4) is correct only for an isotropic dielectric material. It should be corrected for a deformed dielectric material, which becomes anisotropic after deformation.

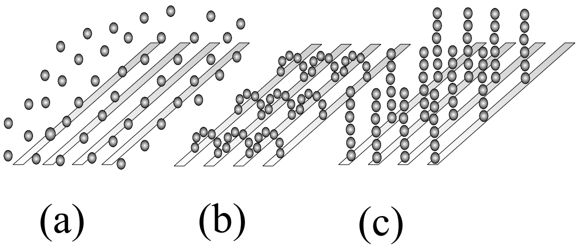

Figure 4. Microtailored dielectric composite is obtainable by applying electric field during curing process: (a) random structure, (b) arch-like structure, (c) chain-like structure
.

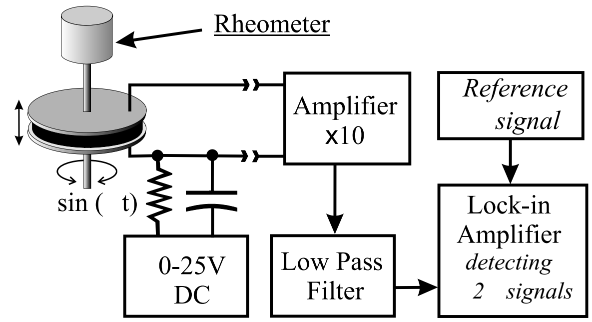

Figure 5. Power supply provides bias DC electric field; high impedance AC signal due to sample deformation is measured by Lock-in-Amplifier and compared with rheometric data.

The total capacitance response for a shear deformation is

$$\frac{\Delta C}{C} = K_\tau \frac{\gamma^2}{2}. \tag{14}$$

Parameter $K_\tau = K_n^\epsilon + E_\tau^\epsilon + K_\tau^E$ can be estimated or directly measured.

SENSOR DESIGN

Sensor Construction

Particular sensor design discussed here is developed for testing with a parallel plate rheometer. The rheometer provides controllable shear and normal deformations which are compared with the sensor response. Presented in Figure 3 is the sensor arranged in an array of four sensing elements. Elements 1 and 3 have electrodes oriented along the direction of shear, and elements 2 and 4 are oriented perpendicular to the shear direction. The same polymer composite—silicone rubber from (Silicons, Inc.) with alumina particles—is cast and cured on the sensing element array. Various areas of the composite (see Figure 4) have a random structure of dispersed particles (a) near elements 1 and 2, and particles arranged in either arch-like (b) or chain-like (c) structures near elements 3 and 4. An electrode pattern is created using photosensitive copper coated boards (from Kaypro Electronics).

Micro Tailored Structure of Sensing Media

Alumina particles of diameter $63 < d < 90\mu m$ and volume fraction $\phi \approx \; 5 \; vol\%$ were mixed with base prepolymer of silicon elastomer (from Silicons, Inc.) and de-gazed in vacuum chamber. With added cross-linking agent, the mixture was evacuated for 10 min and transferred to casting cells 35 mm in diameter and 3 mm thick. A composite with micro tailored particle structure was formed in casting cells by maintaining an electric field during the first two hours of curing time. The structure of the sensor media was modified to obtain an array of sensors with a desirable structure. During a single process using an electric field in the preferred direction with a specially designed electrode all three structures described in Figure 4 are obtained. An isotropic structure with a random particle configuration is obtained in the absence of an electric field. Chain-like structures are formed using a parallel plate configuration. Arch-like structures are formed using a single plate configuration and an electric field created by voltage potential between the surface electrodes. To form a arch-like structure, high voltage potential of 1.0 kV has been applied across the sensor electrodes. Electric potential of 4.0 kV, applied across an additional top electrode and one of the sensor's electrodes forms a chain-like structure.

Modification of the sensor media structure enhances the shear and normal strain detection. A random structure is most sensitive and provides information relative to volume deformation. The chain-like structure is very sensitive to normal deformation; while the arch-like structure has different sensitivity to shear deformation depending on if deformation is along or perpendicular to the arch-like structure. Information about normal and shear deformation can be extracted from the measured response of different sensing elements.

SENSOR TESTING

Setup

AR 1000 rheometer from TA Instruments with parallel plate configuration was modified for testing and employed for electrostriction and electrorheological characterization of a single-plate solid-state sensor. Sensitivity to shear and normal detection of the micro-tailored structure was tested for various normal and shear strains. Each sensor is capable of delivering four different signals, which provide information about deformation occurring in locally sensitive areas. The voltage variation due to shear and normal electrostriction was registered with an experimental set up (see Figure 5). A voltage produced by the sample has enormously high source impedance, which cannot be measured by conventional instrumentation having input im-

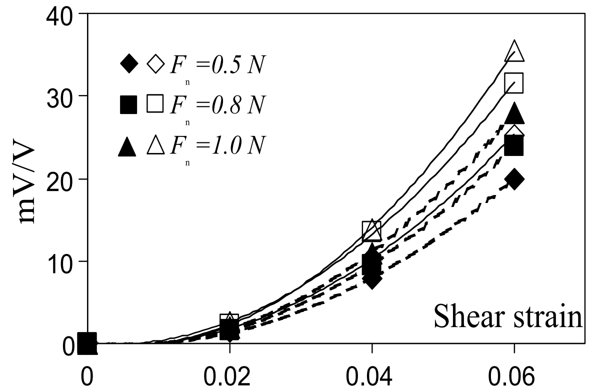

Figure 6. Shear response of random composite for various normal pressures and various shear directions.

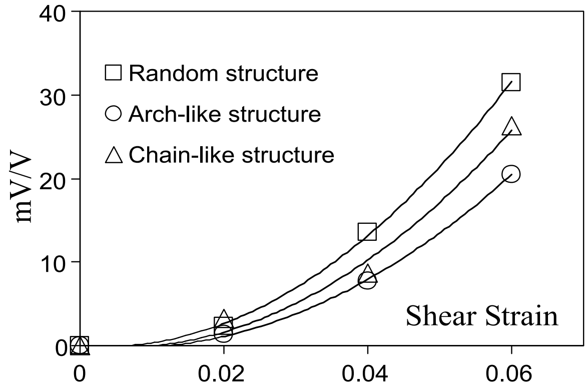

Figure 7. Oscillatory shear response of random (a), arch-like (b) and chain-like (c) structures with respect of strain magnitude.

pedance of $1M\Omega$. Electrostriction measurements of the sensor resemble a dynamic potential technique implemented in capacitance microphones for amplifying deformation induced potentials [4]. A DC power supply provides a constant dielectric displacement $\mathbf{D}$ to the sensor. The AC signal due to deformation on the sensor media is buffered and amplified by a high impedance amplifier and measured by Stanford Research Systems Lock-in-Amplifier.

Results and Discussion

Shear and normal response of the single-plate sensor has been tested for three different structures of the dielectric material presented on Figure 4: (a) - composite with a random distribution of inclusions, (b) - composite with an arch-like and (c) - composite with a chain-like structures. Each sensor element array has been organized in such a way that a comparison can be made between the response of random and modified structures, either arch-like (b) or chain-like (c). Each testing array has electrodes of the sensing elements oriented along and perpendicular to the shear direction for each structure. Our goal at this stage is to demonstrate the feasibility of organizing sensing elements, which are capable of resolving shear and normal forces applied to the surface. Rheometer was used to apply a normal force in the range $0.5 - 1.0\ N$, which produces a normal pressure 700 Pa. At the same time, an oscillatory shear torque was applied by rheometer causing up to 6% shear deformation of the polymer, which is equivalent to a shear stress up to 1200 Pa. Sensor response, which is proportional to a capacitance change with deformation has been registered as a voltage variation across the sensing element

$$\Delta V = -\frac{\Delta C}{C} V, \qquad (15)$$

where V is a bias voltage across the sample. This expression follows from the capacitance-voltage relation $V = Q/C$ when the charge, Q, is constant. According to Eq. 12, variation of capacitance is proportional to square shear rate, γ^2, which means that oscillatory shear deformations occurring at frequency ω produces a voltage signal ΔV with frequency 2ω. Furthermore, the voltage response must be quadratic with the shear magnitude.

Output of the sensing elements with respect to shear deformation are plotted on Figures 6 and 7 for sensing elements with different orientations of the electrodes and different material structures. Figure 6 presents shear responses of random composite for various normal pressures and various shear directions. Figure 7 compares shear response of random (a), arch-like (b) and chain-like (c) structures.

Obtained experimental data indicates that the second harmonic of the voltage response is quadratic with respect to shear deformation. The response varies with the sensing element orientation and the microstructure of the composite. All structures demonstrate different response for different orientations of the electrodes. Overall analysis of the data suggests that by manipulating the sensing elements we could extract information about all three components of a load on the sensing surface.

In our test we also observe a voltage signal at frequency ω. This signal appears because the dielectric polymer material used as a sensing media has viscoelastic properties. The total deformation, γ, is composed of two contributions—elastic deformation, γ_e, and plastic deformation, γ_p, where $\gamma = \gamma_e + \gamma_p$. Only elastic deformation, γ_e, contributes to the electrostriction effect. Thus for oscillatory shear deformations $\gamma = \gamma_p + \gamma_{e0} \cdot sin(\omega t)$ and the voltage response, which is proportional to γ^2 will have two harmonic frequencies of oscillation $2\gamma_p\gamma_{e0}sin(\omega t)$ and $\gamma_{e0}^2 sin(2\omega t)$.

CONCLUSION

We have demonstrated the feasibility of employing electrostriction phenomenon for shear stress/strain sensing in a single-plate capacitance setup. Such simple manufacturing of sensors can be applied in many different areas. There is a potential to combine an array of sensing elements and polymer composites with micro-tailored structure to resolve three components of a load distribution over the sensing surface. A novel shear electrostriction phenomenon requires future investigation and designing materials with optimal sensing response.

ACKNOWLEDGMENTS

The authors thanks Shannon K. Cobb for discussion and help with measurements. This work was supported in part by the University of Wisconsin I&EDR grant #2002038.

REFERENCES

[1] Doebelin, E. O. Measurement systems: application and design, 4 ed. McGraw-Hill, Inc., 1990.

[2] Fearing, R. S. Tactile sensing mechanisms. International Journal of Robotics Research 9, 3 (1990), 3–23.

[3] Holman, J. P. Experimental methods for engineers, 6 ed. McGraw-Hill, Inc., 1994.

[4] Horowitz, P., and Hill, W. The Art of Electronics. Cambridge University Press, 1998.

[5] Howe, R. Tactile sensing and control of robotic manipulation. Journal of Advanced Robotics 8, 3 (1994), 245–261.

[6] Kim, G., and Shkel, Y. M. Electrostriction Effect in Solid-State Electrorheological Composites for Sensing Applications, Proceedings of the 8^{th} International Conference on Electro-Rheological Fluids and Magneto-Rheological Suspensions, Nice, France, July 9-13, 2001.

[7] Kovacs, G. Micromachined Transducers: Sourcebook. MacGraw-Hill, 1998.

[8] Landau, L., and Lifshitz, E. Electrodynamics of Continuous Media. Pergamon, New York, 1984.

[9] Shkel, Y. M., and Ferrier, N. J. Electrostriction enhancement of solid-state capacitance sensing. Submitted to IEEE/ASME Trans. on Mechatronics (28 Jan. 2000).

[10] Shkel, Y. M., and Klingenberg, D. J. Material parameters for electrostriction. J. Appl. Phys. 80 (1996).

[11] Shkel, Y. M., and Klingenberg, D. J. Electrostriction of polarizable materials. comparison of models with experimental data. J. Appl. Phys. 83, 12 (1998), 7834–7843.

[12] Shkel, Y. M., and Klingenberg, D. J. A continuum approach to electrorheology. J. Rheol. 45, 5 (1999), 1307–1322.

[13] Stratton, J. Electromagnetic Theory. McGraw-Hill, New York, 1941.