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Self-sensing Algorithms for Dielectric Elastomer Multilayer Stack-Transducers

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Abstract: Due to their unique properties transducers based on dielectric elastomers (DE) can be used as actuators, generators, sensors or even in combined operation mode. In case of DE-based sensors especially the stretch-dependent DE capacitance is used for the identification of the mechanical state. Within this contribution, the authors present algorithms based on the recursive extended least squares method to estimate the electrical parameters of the DE transducer. The estimation results can be improved by using a variable forgetting factor that ensures on the one hand a fast adaption of the estimates during transient operation, while measurement noises is suppressed sufficiently, on the other hand. Finally, these algorithms are experimentally validated using a silicone-based DE multilayer stack-transducer.

Keywords: parameter identification, dielectric elastomers, multilayer stack-transducer, self-sensing, sensors

1. INTRODUCTION

Smart materials have gained a lot of attention within the last years, as they offer extensive opportunities to realize scalable, efficient and easy to integrate transducers. These smart materials have unique mechanical as well as electrical properties that enable advantageous features for a various range of applications as actuators, sensors and generators.

Dielectric elastomers (DE) represent a class of these smart materials offering a relatively high amount of deformation with considerable force generation. In general, a DE consists of a hyperelastic polymer as dielectric that is sandwiched between compliant electrodes, see Fig. 1. Based on the electromechanical coupling, DE transducers can be operated as actuators (Giousouf and Kovacs (2013); Maas et al. (2015); Hoffstadt and Maas (2015)), sensors (Anderson et al. (2012); Hoffstadt et al. (2014)), generators (Pelrine et al. (2001); Koh et al. (2009); Graf et al. (2014)) or even in combined operation mode.

Due to the design of a DE transducer it behaves like a shape-varying capacitance, i.e. its electrical parameters depend on the deformation. Therefore, in terms of DE-based sensors it is meaningful to identify the electrical parameters to determine the mechanical state. Based on this general idea a DE can be used exclusively as sensor, or simultaneously as electromechanical transducer and sensor by identifying the electrical parameters of the whole transducer. These very popular approaches are denoted as self-sensing concepts. With suitable identification algorithms the mechanical state is determined by measuring the terminal voltage and current of the transducer. Thus, on the one hand there is no need to integrate further measurement equipment, e.g. a position sensor, into a certain application. On the other hand, the measurement of the terminal voltage and current are required anyway for the inner control of the driving electronics, i.e. these quantities are available for a subsequent processing without additional effort.

The idea of self-sensing was already introduced in several publications and an overview was given by Anderson et al. (2012). To realize such a concept the transducer voltage v_{DE} must consist of the driving voltage $v_{transducer}$ used for the actuation and an additional superimposed sensor voltage v_{sensor} for identifying the stretch dependent parameter variations.

For this purpose, online identification algorithms in the frequency domain have been published, e.g. by Jung et al. (2008), Chuc et al. (2008) and Hoffstadt et al. (2014), that evaluate the amplitudes of a sine voltage and its resulting current to determine the DE capacitance under consideration losses.

Gisby et al. (2013) proposed a new algorithm based on the time domain, which also requires an arbitrary oscillation in voltage or charge under consideration of the losses of a DEAP transducer. Rizzello et al. (2016) use a least

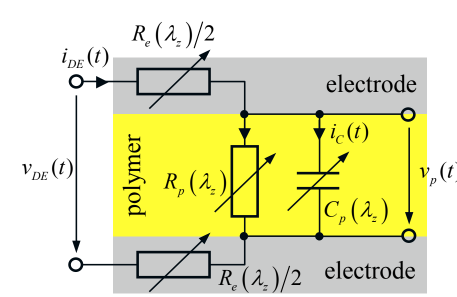

Fig. 1. Equivalent circuit diagram of a planar DE transducer.

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squares method for a simplified DE model that neglects the polymer resistance to identify the DE capacitance and the electrode resistance by exciting the considered DE actuator with sine voltage.

Within this contribution we propose a time domain-based online identification algorithm for a DE multilayer stack-transducer under consideration of its electrical losses in the electrode and the polymer. Multilayer topologies are used to scale the deformation and force of the transducer and the considered stack topology is briefly introduced in Sec. 2 especially in terms of its electrical characteristics. The identification algorithm is based on a recursive extended least squares (RELS) method, e.g. published by Haykin (2002) and Isermann and Munchhof (2011), and given in the subsequent Sec. 3. This method is chosen to obtain a bias-free estimation. Finally, in Sec. 4 the experimental setup including a DE stack-actuator (Maas et al. (2015)) used for the validation is presented.

2. DIELECTRIC ELASTOMER STACK-TRANSDUCER

By applying an electric field strength E to the DE the resulting electrostatic pressure σ_{el} depending on the material's permittivity ε_r describes the electromechanical coupling by:

$$\sigma_{el} = \varepsilon_0 \cdot \varepsilon_r \cdot E^2 = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{v_p^2}{d^2} = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{v_p^2}{d_0^2} \cdot \frac{1}{\lambda_z^2}. \quad (1)$$

This pressure compresses the polymer film with an initial thickness d_0 resulting in the axial stretch $\lambda_z = d/d_0$. Since very thin polymer films with thickness d_0 are used to achieve high electric fields E with considerable low voltages v_p multilayer stack-transducers are meaningful for DE actuators to increase the absolute axial deformation. For this purpose, n planar DE layers as depicted in Fig. 2 are stacked on top of each other and thereby mechanically connected in series, while electrically connected in parallel (Maas et al. (2015)).

Assuming a high conductivity of the contacting of the single layers, an equi-biaxial in-plane deformation and taking into account the incompressibility of the polymer material, the overall DE stack-transducer capacitance C_p is given by (Hoffstadt and Maas (2015)):

$$C_p(\lambda_z) = n \cdot \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A_e}{d_0} \cdot \frac{1}{\lambda_z^2} \quad (2)$$

and the resulting polymer resistance reads as:

$$R_p(\lambda_z) = \frac{1}{n} \cdot \rho_p \cdot \frac{d_0}{A_e} \cdot \lambda_z^2. \quad (3)$$

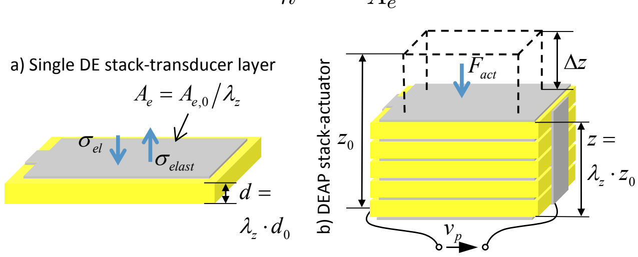

Fig. 2. General design and functional principle of a DE stack-transducer.

Here, A_e represents the active area of the layers that are covered with the compliant electrode. While these two parameters depend on the deformation, the resulting time constant only consists of material parameters but not of the transducer geometry and therefore is constant if the material parameters are constant, too:

$$\tau_p = C_p(\lambda_z) \cdot R_p(\lambda_z) = \varepsilon_0 \cdot \varepsilon_r \cdot \rho_p. \quad (4)$$

With these assumptions the electrical behavior of a DE stack-transducer can be modeled by an equivalent circuit diagram with lumped parameters as depicted in Fig. 1. In addition to the afore mentioned capacitance C_p and the polymer resistance R_p, of course the electrode has a finite conductivity, resulting in a loss resistance R_e, too. This resistance and especially its behavior under deformation strongly depend on the kind of utilized electrode material. Therefore, it is hard to derive a general model for R_e comparable to the Eqs. (2) and (3). However, this does not restrict the subsequent identification, but the other parameters seem to be advantageous to determine the mechanical stretch based on the identified parameters.

As already mentioned above, in the following a RELS algorithm is proposed for the parameter identification. These algorithms identify the coefficients of a discrete transfer function that represents a process. Therefore, to obtain this discrete transfer function for the considered DE stack-transducer first of all the admittance of the electrical model depicted in Fig. 1 is derived by a first order lead-lag element:

$$G_{DE}(s) = \frac{I_{DE}(s)}{V_{DE}(s)} = K_p \cdot \frac{1 + s \cdot \tau_p}{1 + s \cdot T_1}, \quad \text{with} \quad T_1 = C_p \cdot \frac{R_e \cdot R_p}{R_e + R_p}, \quad K_p = \frac{1}{R_e + R_p}. \quad (5)$$

Due to the stretch dependency of the electrical parameters, the admittance depends on the stretch, too. However, assuming a fast sampling, it is sufficient to expect that the electrical parameters do not change significantly within one sampling period, i.e. this modeling approach is feasible.

To capture the measured terminal voltage v_{DE} and current i_{DE} resulting in this admittance $G_{DE}(s)$ a digital signal processor (DSP) with sampling time T is used. The dynamics of the DSP can be taken into account by a sample and hold element $G_{SH}(s)$. This results in the overall transfer function

$$G_{DE,S}(s) = G_{SH}(s) \cdot G_{DE}(s) = \frac{1 - e^{-s \cdot T}}{s \cdot T} \cdot K_p \cdot \frac{1 + s \cdot \tau_p}{1 + s \cdot T_1}. \quad (6)$$

By applying the z-transformation (Ifeachor and Jervis (2002)) the discrete transfer function of the DE model results, finally:

$$G_{DE,S}(z) = \frac{I_{DE}(z)}{V_{DE}(z)} = \frac{\beta_0 + \beta_1 \cdot z^{-1}}{1 + \alpha_1 \cdot z^{-1}}, \quad \text{with} \quad \beta_0 = \frac{1}{R_e}, \quad \beta_1 = K_p \cdot \left(1 - e^{-T/T_1} - \frac{\tau_p}{T_1}\right), \quad \alpha_1 = -e^{-T/T_1}. \quad (7)$$