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Model-based self-sensing algorithm for dielectric elastomer transducers based on an extended Kalman filter

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ABSTRACT

Self-sensing enables electromechanical transducers of being simultaneously used for actuating and sensing without additional, external sensors. In case of dielectric elastomer (DE) transducers the shape-varying, strain-dependent capacitance is usually considered for this purpose and estimated based on the measured terminal voltage and current. In the literature most self-sensing algorithms for DE transducers require an explicit superimposition of an additional AC excitation signal. Thus, only power supplies providing the opportunity of superimposing this excitation signal can be used for this purpose. Within this contribution we propose a new approach based on an extended Kalman filter. It operates with any arbitrary driving signal and thus does not require a superimposed excitation. Here, the extended Kalman filter is used for both the estimation of the inner states and parameters of the nonlinear process. The accuracy and dynamics of the estimation results obtained with proposed self-sensing approach are demonstrated by comparing the estimated with the measured transducer strain. The measurements are conducted with two different power supplies showing the applicability and robustness of the proposed self-sensing approach ensuring reliable and accurate estimation results independent of the kind of excitation signal. Here, the utilized high voltage amplifier represents a common power supply for experimental studies in laboratory environment. In contrast, the bidirectional flyback-converter is an energy-efficient and economical opportunity for feeding of DE transducers in technologically sophisticated applications. However, due to its operation principle it does not provide the opportunity to superimpose particular sensing signals so that this new approach is required to enable the self-sensing capability.

1. Introduction

Amongst other advantageous properties, transducers based on dielectric elastomers (DE) are promising alternative electromechanical transducers for various applications for example in automation and consumer products due to their self-sensing capabilities. Self-sensing describes the capability of a transducer of simultaneously actuating and sensing a process. In various disciplines of engineering self-sensing systems have been introduced for diverse applications, e.g. for electromagnetic [1,2] or electrostatic drives [3], in civil engineering for the damage detection of a building [4] or for new electromechanical transducers based on smart materials [5–7].

As shown in Fig. 1(a) a DE transducer consists in general of a thin elastomer film with thickness d as dielectric that is covered with compliant and conductive electrodes on its two opposing surfaces with area A_e. Due to this it behaves like a shape-varying capacitor, see Fig. 1(b), i.e. the electrical parameters depend on the deformation of the transducer. Namely, these are the capacitance C_p, the electrode and polymer resistance R_e and R_p respectively all depending on the strain ε_z. If the strain-dependency of the electrical parameters is known, the DE transducer can be operated as a sensor by identifying these parameters in real-time [8–10]. Based on the electromechanical coupling, DE transducers can be operated as actuators [11–13] and generators [14–16], as well.

Thus, 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 as already mentioned above for other transducer systems. 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 often required anyway for the inner control of the driving electronics, i.e. these quantities are available for a subsequent processing without additional effort and can be used for

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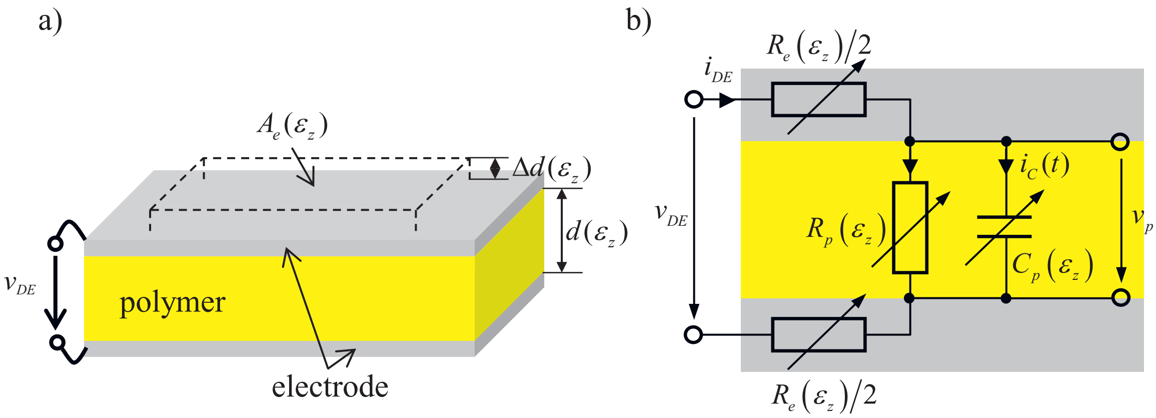

Fig. 1. Schematic design of a planar DE transducer with active area A_e and thickness d (a) and its equivalent circuit diagram (b) fed by the voltage v_{DE} and current i_{DE} with lumped parameters for the electrode and polymer resistance R_e and R_p respectively and the capacitance C_p that vary with the strain ε_z.

example as feedback signal for closed loop control schemes [17,18].

The idea of self-sensing DE transducers was already introduced in several publications and an overview was given in [8]. 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. in [9,19,20], that evaluate the amplitudes of a sinusoidal sensor voltage and its resulting current to determine the DE capacitance. Different algorithms have been proposed for the identification of the complete equivalent circuit in Fig. 1 or for simplifications by neglecting either the electrode or polymer resistance. Typical electrode materials used for the contacting as well as for the electrode, e.g. a graphite-silicone mixture [12], have a conductivity that is magnitudes of order higher than the conductivity of the insulating elastomer. Due to this the resulting contacting and electrode resistance R_e is much smaller than the polymer resistance R_p. Thus, neglecting R_e is a suitable approximation if a low-frequency sensing signal is applied, while the assumption of an infinite polymer resistance ensures reliable results in the higher frequency range [9].

In contrast, Rizzello et al. [10] use a time domain algorithm based on the recursive least squares method to identify the DE capacitance and the electrode resistance of a simplified DE model that neglects the polymer resistance by exciting the considered DE actuator with sinusoidal sensor voltage. A comparable approach is extended in [21] by applying the recursive extended least squares method with variable forgetting factor in order to improve both the transient response as well as the steady state accuracy.

All of these approaches have in common that an AC excitation signal has to be superimposed to the time-varying DC driving voltage used for actuation. However, especially if tailored power electronics for DE transducers e.g. for industrial applications are used instead of high voltage amplifiers in laboratory environment, it is often quite hard or even not possible to superimpose the excitation signal depending on the kind of utilized power converter.

To overcome this issue, Gibsy et al. [18] proposed a new algorithm in the time domain for a PWM driven DE transducer by a synchronized sampling of the feeding voltage and current. In [22] the same authors present another model-based approach also requiring an arbitrary oscillation in voltage or charge but not a clear sinusoidal signal. Furthermore, in [9] for the already mentioned frequency domain-based identification algorithm, parasitic harmonics caused by the operation mode of the investigated power converter were used as excitation signal. Thus, no further superimposition is required.

Within this contribution we propose a new self-sensing algorithm that does not require any specific excitation, i.e. it estimates the capacitance of the DE transducer based on the model depicted in Fig. 1 and the measured driving voltage and current only. The final goal of the self-sensing algorithm is to determine the deformation of a DE transducer without measuring it directly. Although the proposed algorithm applies for various DE transducer topologies, here a DE stack-transducer is exemplary used and briefly introduced in the following Section 2. This multilayer topology is well known for its high energy density as it almost only consists of active material. In particular, the overall deformation of this kind of transducer can be increased by the number of stacked DE layers, while the force can be scaled up by the area of the layers. In the literature especially different manufacturing processes [12,23,24] as well as promising applications [11,25] of DE stack-transducers can be found.

The design of such a multilayer DE transducer is much more difficult than stacking single layers on top of each other, [26]. However, its electrical behavior can be sufficiently described by the same equivalent circuit diagram in Fig. 1 with lumped parameters because the electrode resistance R_e is in general much smaller than the polymer resistance R_p, [27].

The design of our new, model-based self-sensing algorithm is based on an extended Kalman filter (EKF) and described in detail in Section 3. The EKF estimates the inner states of the nonlinear electrical DE model as well as the capacitance of the DE transducer based on the measured quantities.

In Section 4 a first validation of the EKF is carried out using a high voltage amplifier for supplying the prototypic DE stack-transducer fabricated with the process and materials presented in [12]. As this power supply is only suitable for laboratory tests but much too expensive and oversized for applications e.g. in automation technology or consumer products, afterwards a bidirectional flyback-converter is used instead [28], as this topology represents an energy-efficient and economic electronics for feeding DE transducers. However, due to the operation mode of this converter, high-frequency current ripples occur. As the switching period is not constant, the frequency-varying higher harmonics cannot be used as excitation for the already mentioned identification approaches in the frequency domain. Furthermore, due to the high-frequency range a suitable signal conditioning is required for the proposed self-sensing EKF. For this purpose, a FIR filter with variable order is introduced. The final validation of the self-sensing EKF with the flyback-converter as power supply demonstrates the capability and robustness of the proposed approach independent of the kind of excitation signal. The comparison of estimated and measured strain proves both the good accuracy and high dynamics of the proposed self-sensing approach.