Redefining Energy Density for an uniaxial Dielectric Elastomer Actuator
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The dielectric elastomer actuator (DEA) is a technology known to potentially provide high energy density (0.3 – 0.4 J/cm³). However, in the literature, few demonstrations have been done to evaluate this figure. To well understand the ability of this technology, this paper redefines the energy densities which allow to classify the DEA and better understand the values presented in the literature. For this study, the Elastosil® film from Wacker has been used and an uniaxial planar actuator has been studied. According to the considered limits and loads, it is shown that the energy density could pass from 0.2 J/cm³ to ten times lower. The first approach provides a theoretical value for the DEA and is called practical energy density, while the second definition (specific energy density), considers the real work provided to a constant load. The pre-stretch of the DEA is a widespread way to increase the deformation of any dielectric actuators. By keeping in mind the objective to provide energy to a constant load, the results of this study show that the obtained energy density could be doubled through this way. Finally, another biasing element with a negative force-displacement characteristic already published in the literature is investigated. The special mechanical characteristic of this element allows to increase both the displacement and the energy density. The latter provides five times the energy density obtained with the constant-stress biasing element which validates its beneficial aspect.

I. Introduction

In the domain of soft technology, one, which is often studied, is the dielectric elastomer actuator (DEA). The more cited advantages for this technology consist in the large displacement (bigger than 300%) and the achievable high energy density (up to 0.4 J/cm³).

In the literature, the energy density is generally studied for the dielectric elastomer generator3,4 (DEG). The mechanical energy converted into electrical one is provided through the voltage-electrical charge characteristic. Koh5 has obtained a theoretical value up to 2 J/cm³. To obtain such quite huge value, a very specific and non-trivial cycle should be performed. This definition gives a global insight but is not adequate for providing the effective energy density of a simple actuator (e.g. to lift a mass).

Concerning the actuator, the well-known assumption is always that if the displacement is larger, the provided energy is also bigger, without really addressing the energy aspect5,6. However, an energy balance should be performed over a complete cycle to affirm such a hypothesis. By example, in the previous cited cases no energy is transferred to the mass. In such a situation, the potential energy provided to the load is restored to the electrical source once the voltage is turned off.

In the meantime, the maximum displacement is always limited by the electrical breakdown reached during the electromechanical instability8 (EMI). The researches have mainly been focused on a way to push further this limiting parameter such as for planar9 or cylindrical10 actuators. In order to remove the electromechanical instability and to increase the displacement of the actuator, the pre-stretch9,11 and the pre-load have been introduced.

The pre-stretch consists in initially stretch the actuator in one or several directions and to maintain the pre-deformed state before to activate the DEA. Concerning the pre-load, it represents a load hanged, or more generally mechanically combined, to the actuator to change the mechanical characteristic of the system: DEA and pre-load. This pre-load could be a constant load (e.g. mass) or a spring with a specific force-displacement characteristic. An interesting one is the negative biasing spring which has a negative force characteristic. It has been introduced by Wingert12 and Hodgins13 and has been used to significantly increase the deformation of the actuator. However, all these elements have been studied according to their possibility to increase the displacement and not the energy density.

This paper aims to give a deep insight of the energy available in DEA and shows how to improve the performance. In the first part of this paper, the studied actuator is detailed. It has been decided to focus on an uniaxial planar actuator with the objective to climb a constant load. The methodology, the initial hypothesis and the main equations to describe the DEA are provided in the next section. Then, according to the various considered electrical and mechanical failures of the material, the energy densities are redefined. In the second part, an uniaxial actuator composed of the Elastosil® film from Wacker is studied. The energy densities and the displacement of such actuator are computed and the influence of the pre-stretch, the constant and the negative biasing element as pre-load are analyzed.

II. Definition of the energy densities

A. Methodology

Generally speaking, the energy density is an appropriate parameter to compare any actuators aiming to provide a work to a load. Here, it has been decided to focus on an uniaxial and planar actuator, fixed to a rigid frame at the top, to provide work to an external constant load against the gravity (e.g. to lift a mass).

As a reminder, the definition of the energy density for a DEA submitted to a nominal electric field (E) is given by Suo14:

\[ W_E(\lambda_1, \lambda_2, E) = W_s(\lambda_1, \lambda_2) - \frac{\varepsilon}{2} E^2 (\lambda_1 \lambda_2)^2 \]  (1)

where \( \lambda_1, \lambda_2 \) are the stretches in the planar directions, \( \varepsilon \) (\( = \varepsilon_0 \varepsilon_r \)) is the permittivity of the elastomer and \( W_s \) is the strain energy density function used to describe the hyperelastic material (e.g.
Yeoh or Gent model). The nominal electric field, which corresponds to the applied voltage divided by the initial thickness ($\hat{E} = u/L_3$), is used instead of the true electric field because it consists in a normalized image of the voltage. The three parameters ($\lambda_1, \lambda_2, \hat{E}$) form the useful set of state variables. The stretch in the thickness direction $\lambda_3$ is deducted due to the consideration of the incompressibility of the material. From the previous equation, the nominal stress in the studied direction ($\lambda_1$) could be determined and is given by:

$$T_n = \frac{\delta W_E(\lambda_1, \lambda_2, \hat{E})}{\delta \lambda_1}$$

Those equations allow to represent the nominal stress-stretch characteristic of the DEA. The area enclosed by any closed loop in this representation provides the energy density.

**B. Definitions of the regions**

The conventional mechanical and electrical limits of the DEA technology are well defined in the literature. The combination of all limits allows to determine the different reachable zones and thus evaluating the energy density. Driving the DEA on a closed curve composed of each limit maximizes energy density. The considered limits are given in Fig.1 where the stretch and the nominal stress are represented. The upper limit is always given by the characteristic of the membrane when no voltage is applied between the electrodes (dark red lines). The maximum strain, which is reachable before that the elastomer mechanically breaks, is given by the vertical dark blue lines. In terms of electrical limit, the limiting stretch and stress for which the electrical breakdown occurs, are given by the black dashed line. According to the considered definition of the energy density, other limitations are introduced and explained in the following paragraph.

The loop for which the energy density is maximum, is presented in Fig.1a (Part I + II), i.e. *maximum energy density*. Generally, the whole cycle is not realistic because the elastomer could not be in compression. Thus, the limit $T_n \geq 0$ (green line) is introduced in order to remove the possibility to have a compression state. Anyway, this definition still does not represent a realistic energy density of any actuators.

Besides these limits, the phase transition should be added. One particularity of DEAs and which has been mainly related by Suo$^{15}$ and Zhu$^{16}$, is the possibility for the actuator to be deformed in an inhomogeneous state. Indeed, the energy profile of DEAs for a given electric field is such that the actuator prefers to be split into two regions to ensure the global stability of the actuator and to minimise its internal energy. A problem occurs when, for a specific applied voltage, a state is further than the electrical breakdown limit (black dots in Fig.1b). In the literature, the phase transition is generally not considered which tends to increase the value of the energy density. The area enclosed by the zone considering all the aforementioned limits is the *practical energy density*. However, even if the possibility to work in this complete domain is possible, a special electronic control should be used to adjust the applied voltage according to the deformation state of the DEA. For a simple actuator, this cycle is not still adequate.

![Fig. 2: Example of DEA with two loads. The actuator is composed of a membrane sandwiched between two compliant electrodes.](image)
C. Influence of external loads

Optimising the energy conversion between heat and mechanical work is a well-known topic in the thermodynamic domain and can be showcased by the Carnot Cycle. This cycle guarantees an optimum conversion process. For the DEG (dielectric elastomer generator) based energy harvesting systems, the square cycle in the characteristic $u$ vs $q$ is often represented. However, the problem is entirely different for dielectric elastomer actuators. The mechanical load and the application itself influence a lot the energy density and impose other boundaries. Thus, the followed cycle should be determined.

To provide the real cycle done by an actuator, let us consider the DEA in Fig. 2. The objective is to provide some energy to the load ($T_2$) initially located in the position $\lambda_3$. Concerning the load ($T_1$) located in $\lambda_2$, it is used as constant pre-load. This pre-load is useful to pre-stress the elastomer and thus to work in an optimised region of the mechanical characteristic of the material.

The proposed steps to provide potential energy to a load is represented in Fig. 2 and the equivalent cycle on the nominal stress-stretch characteristic is given in Fig. 3a. This stress characteristic allows to represent the mechanical stress characteristic of the DEA when it is at rest (OFF) and when it is submitted to a constant voltage (ON).

Initially, the actuator states in position "0" and when it is activated, the DEA reaches the position $\lambda_2$ (1). At this position, the pre-load $T_1$ is hanged to the actuator (2). The system reaches the position $\lambda_3$ where the load $T_2$ is hanged to the actuator (3). The DEA plus the two loads go down to the position $\lambda_4$. At this height, the two loads have transferred their potential energy to the DEA in the elastic form. Then, when the voltage is turned off, the three elements goes up to $\lambda_2$ (4). Therefore, the second load $T_2$ which is moved up from $\lambda_3$ to $\lambda_4$ wins potential energy proportional to the difference of the two heights. This load is left at this level, and the system of the DEA and the pre-load move up to $\lambda_1$ (5).

This complete cycle highlights the practical energy density, however the energy density provided to the load $T_2$ is only defined through the blue area (Fig. 3b). Indeed, the steps (3) and (4) could be done simultaneously which allows to obtain the path given by the green dashed arrow. In the previous explanation, these two actions were done separately. The area enclosed by the two previously mentioned steps are not considered because, it represents an energy provided by the load and restored during the deactivation.

In the highlighted zone (blue area), the part I and III correspond to kinetic energies and the zone II is the potential energy. It has been decided to consider these three zones to define the specific energy density which is dependent on the pre-load. By considering these three zones for a given pre-load, a good estimation of the energy density for several loads ($T_2$) is obtained. According to the latter, more or less kinetic or potential energy is provided.

**Fig. 3: Schema of the nominal stress-strain characteristic to determine the specific energy density**

### III. Performances of common silicone

A common elastomer engineered for the DEA and commercially available is the Elastosil® from Wacker. In this paper, it has been characterised with a pull-tester in order to obtain the parameters of the hyperelastic model\(^{17}\) through a fitting process. The studied sample consists of a membrane with a width, a length and a thickness of 100 m$m$, 10 m$m$ and 50 $\mu$m respectively. The membrane has been stretched ten times before starting the measure in order to remove the influence of the Mullins effect and the shift of the force due to the first deformations. The considered dielectric constant and the electrical breakdown limit are respectively 2.8 and 100 $V \cdot \mu m^{-1}$. The speed of deformation for the pull-test is fixed to 1 $mm \cdot s^{-1}$ to consider a static deformation and the membrane has been stretched up to $\lambda = 3.5$. Considering the Yeoh model ($W_e$ in Eq.1), the parameters which describe the elastomer are as followed: $C_{10} = 140670 Pa$, $C_{20} = -4035 Pa$, $C_{30} = 489 Pa$.

**A. Practical energy density**

The practical energy density found for this elastomer is 0.22 $J \cdot cm^{-3}$ which is in the same order of magnitude than the one in the literature for ordinary silicone\(^{18}\) (0.3 – 0.4 $J \cdot cm^{-3}$).

Thus, the practical energy density provides a good prediction of the maximum value. However, such a cycle is difficult to follow for an actuator as seen previously.
B. Specific energy density

The nominal stress characteristic of the Elastosil ® is given in Fig.4a for different nominal electric fields and with two main limits previously defined (stress characteristic of the non-activated DEA and the electrical limit).

The specific energy density for the example of $T_{\text{const}}$ is highlighted by the blue area. Fig.4b provides the results of the specific energy density and the variation of the stretch of the film for different loads ($T_n = T_{\text{const}}$).

Concerning the studied elastomer, the optimum specific energy density is around 0.02 $J \cdot cm^{-3}$ for a stretch of around 37% and a $T_n$ of 0.46 MPa. This value of energy density is ten times lower than the values provided in the literature and the one given through the practical energy density (0.22 $J \cdot cm^{-3}$). However, this cycle is more realistic in terms of actuation compare to the previous one.

As already mentioned in the literature, an optimum for the specific energy density as well as the stretch is present (Fig.4b) for the same $T_{\text{const}}$. The mechanical stress characteristic of the elastomer is divided into three parts. The first one increases rapidly with a concave shape, then a flatter region (“plateau”) occurs, and finally, an increase of the stiffness with a convex curve is present. When getting close to the flatter region, the equivalent Young’s modulus (stiffness) is lower which tends to improve the specific energy density. The advantage of a well-chosen constant pre-load is the fact that the actuator could work near this flat region.

**Influence of the pre-stretch in the width direction**

Another essential parameter consists in the pre-stretch in the in-plane direction opposite to the actuation one. The membrane is initially stretched in the direction as mentioned above, before maintaining it in this pre-stretch state. Thus, the specific energy density and the variation of stretch are obtained according to the load and the pre-stretch (Fig.5).

Concerning the specific energy density, it is clear that the pre-stretch improves the performance: up to 0.05 $J \cdot cm^{-3}$. This parameter tends to “stretch” or “bunk” the characteristic that induces a softening of the elastomer in the preferential direction and then the energy density is increased. Moreover, by pre-stretching the membrane, the stress characteristic is smoothed.
(i.e. the first concave region is removed) and thus the phase transition is cancelled. The "plateau" is reached for smaller constant loads. For a certain pre-stretch ($\lambda_{2,pre} = 2.25$), no more pre-load is necessary to reach the optimum because the softer region starts from the beginning of the characteristic.

For the variation of the stretch, the effect is similar. However, an optimum appears which is not coincident with the optimum of the specific energy density. In terms of improvement, the effect on the stretch is not as significant as for the specific energy density. Indeed, the variation of stretch is improved by a factor $1.3$ versus $2$ for the energy density.

In order to obtain better specific energy density, either the pre-load could be adapted, or the pre-stretch is also useful. Both allow to work near the flatter region of the characteristic.

**Negative biasing pre-load**

In this section, the negative biasing element is introduced, and the pre-stretch is no more considered. In the nominal stress ($T_n$) and stretch ($\lambda_1$) representation, the negative stiffness spring, characterised through the equation of a line, is represented in Fig.6. Two different negative characteristics ($s_1$ and $s_2$) are presented with the specific energy density for one of them (blue area). It is straightforward that with such a pre-load, better performance in terms of displacement could be obtained compared to a constant pre-load. It could be explained by the fact that the slope of the characteristic of the membrane and the one of the pre-load have the same sign (monotonically increase).

This specific biasing element is characterised through a slope and its intercept. The influence of each one will be further analysed. For the same slope, the intercept could be varied in order to shift downward or upward the linear characteristic. The corresponding intercept is defined as the initial $T_n$. This stress is equivalent to a pre-load of the elastomer as previously defined.

In this section, three interesting results of the various characteristics have been studied (Fig.7a and Fig.7b). The first case show that the maximum energy density is around $0.03 \pm 0.04 \, J \cdot cm^{-3}$. These values are higher than the ones obtained in the previous section without pre-stretch. The second case is a special one where better performance has been reached. However, some problems are highlighted for specific $T_n$.

The first case show that the maximum energy density is around $0.03 \pm 0.04 \, J \cdot cm^{-3}$. These values are higher than the one obtained in the previous section without pre-stretch. Concerning the case in Fig.7a, the per cent of the increase of the energy density is not as high as expected compared to the stretch improvement.

For the third case (Fig.7b), an energy density around $0.1 \, J \cdot cm^{-3}$ seems reachable. The solutions given by the dashed lines represent "non-reachable" ones. This zone has been considered non-reachable because of the uncertainty of the stable position. The characteristics of the negative load cross several times the polymer stress characteristic, which implies several stable positions (e.g. $s_2$ in Fig.6). Thus, it is challenging to predict in which one the system will exist.

For the slope $0.15 \, MPa$, the maximum stretch corresponds to the maximum energy density. In this sense, the idea to increase the stretch in order to reach the maximum energy density is validated. For the results in Fig.7b, this conclusion is no more verified. It exists a configuration for which the optimal displacement does not correspond to the optimal energy density. It could be imagined that for another negative line which
passes through the initial stretch but with a bigger slope \(s_{1, \text{bis}}\), the stretch is increased quite fast. However, the area enclosed by the loop (specific energy density) does not necessarily increase as fast as for the stretch. As for other actuators, it exists a compromise between optimizing the displacement or the energy density.

IV. Conclusion and perspective

The high energy density is often used in order to introduce the DEA. However, this aspect has been poorly investigated in the literature. In this paper, considering different boundary conditions, a better understanding of this assessment parameter was provided.

The introduced practical energy density, mainly used in the literature with quite significant values, is detailed. However, it seems that the whole cycles could not be obtained when potential energy should be provided to a constant load.

The specific energy density was introduced in order to better represent the performance of a dielectric elastomer used such as an actuator. Indeed, this definition seems to better reflect the energy that the technology could provide to an external load compared to the one presented in the literature.

In order to improve the performance of the DEA, the main objective is often to increase the stretch. In this study, the initial pre-stretch, the constant-stress biasing element (pre-load) and a biasing element with a negative stress characteristic have been used in order to improve the stretch and the energy density of linear actuators.

The pre-stretch and the constant pre-load provide better performance. They allow to work in the flat region of the mechanical characteristic of the elastomer. Through a negative biasing element, the obtained energy density is amplified due to the similar sign of the slopes of the elastomer and the biasing element. This study confirms that better results (until five times bigger) are reached with this kind of element.

The influence of the three aforementioned parameters demonstrated that for some particular cases, the Elastosil\(^\text{TM}\) film reaches the bigger variation of stretch or the optimum specific energy density for different working conditions. Thus, the popular believes that the increase of stretch allows to increase the energy density, is validated for specific values of pre-stretches and biasing loads. However, it is not true for all of them.

Finally, the electrical breakdown limit was considered as constant. However, this parameter seems to vary according to the deformation\(^\text{19}\). This phenomenon tends to increase the energy density and should be considered in the model of the energy density. This parameter will be focused on the subsequent research stages of the work.


\(^{2}\) S. Rosset, “Metal ion implanted electrodes for dielectric elastomer actuators,” , 150 (2008).


