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Optimal dielectric elastomer generators: universal design curve and benefits of ceramic filler addition

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Abstract

The main goal in the field of dielectric elastomer generators (DEGs) is the optimization of these devices, undergoing a typical four-step load-driven cycle, where applied load and electric charge are alternately held constant. The amount of energy extracted during this cycle is limited by various mechanisms of failure, namely electric breakdown, ultimate stretch, loss of tension and electromechanical instability. Indeed, the optimal cycle complying with these limits is identified by solving a constrained optimization problem. The outcome of the optimisation process is a universal curve, in the plane dielectric strength – ultimate stretch , defining an upper bound on the amount of energy harvested in function of the ultimate stretch ratio [2]. In order to extract the maximum energy form the DEG it is important that the pair of electromechanical properties of the material $(\bar{E}_{eb}, \lambda_U)$lie as close as possible to the universal curve.

To this end, composite materials with improved electromechanical coupling could be employed in the realization of enhanced electromechanical transducers. Promising materials are random composites [1], where ceramic fillers with a high dielectric constant are dispersed in a silicone matrix. In the realization of dielectric elastomer generators (DEGs), among ceramics, the most adequate dispersed reinforcements are lead magnesium niobate-lead titanate (PMN-PT) and lead zirconate-titanate (PZT).

Two different composites are here taken into consideration, both based on a matrix of poly-dimethyl-siloxane (PDMS). The first one is reinforced with a 10% in volume of PMN-PT powder, the second one is reinforced with a 1% in volume of PZT [3]. The electromechanical properties of both these composites lie very close to the universal curve, allowing to leverage the material obtaining a better performance with respect to pure PDMS.

The soft dielectric elastomer generator

We consider a three-dimensional dielectric elastomer generator, composed of a homogenous neo-hookean ideal dielectric film embedded between two compliant electrodes and subjected to an equi-biaxial stress state ($\lambda_1 = \lambda_2 = \lambda$), see Fig. 1.

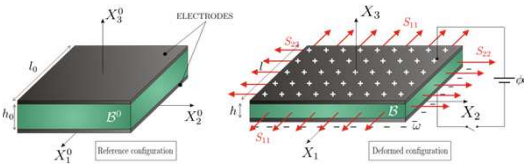


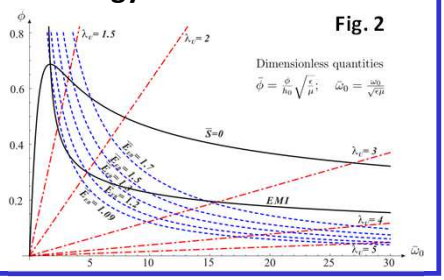
Fig. 1

The failure modes and the maximal energy achievable

The performance of dielectric elastomers is limited by various modes of failure, namely electric breakdown, electromechanical instability, loss of tension and rupture by stretch. The failure curves enclose the area of admissible states for the generator, which represents the maximal energy convertible by the dielectric elastomer generator.

We can plot the failure curves both on the mechanical and electrical plane by fixing the ultimate stretch λ_U and the dimensionless electric breakdown threshold $\bar{E}_{eb} = E_{eb}\sqrt{\epsilon/\mu}$, as shown in Fig. 2.

Fig. 2

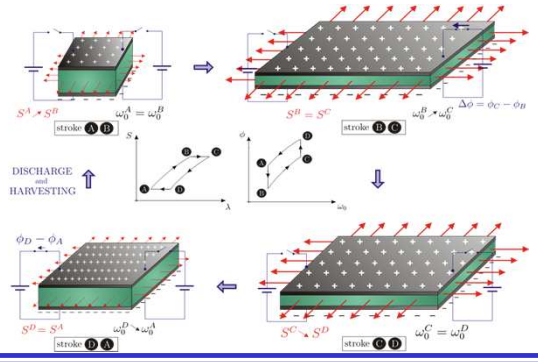


The load-driven harvesting cycle

The harvesting cycle Fig. 3, in which the tensile load and the charge are alternately held constant, is composed of the following four stroke:

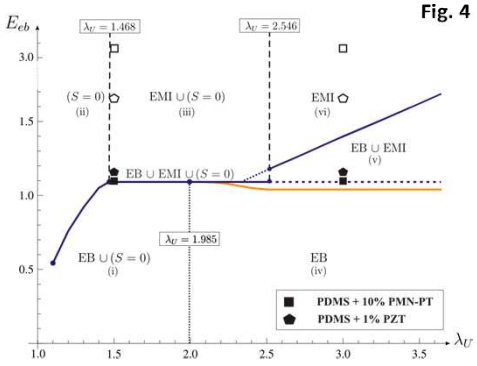
1. **A-B**: stretching of the layer by increasing the in-plane dead load from $S^A$to S^Bunder open circuit condition. During this stage the charge w on the electrodes is fixed, $\omega^A = \omega^B$.
2. **B-C**: increasing the charge on the electrodes, at the stretched configuration, from $\omega^B$to $\omega^C$by applying a voltage $\Delta\phi$. During this stage the dead load is held fixed, $S^B = S^C$.
3. **C-D**: elastically releasing the stretch by decreasing the load from S^C to $S^D = S^A$, under open circuit condition. In this way the charge is kept constant, $\omega^C = \omega^D$.
   Note that during this step the electric potential between the two electrodes increases, reaching a maximum value at state D.
1. **D-A**: harvesting electrical energy by removing the surplus of charge $\omega^C - \omega^A$ from the electrodes at high voltage, under constant load $S^D = S^A$.

Fig. 3



Optimisation of the DEG: the universal curve

Fig. 4

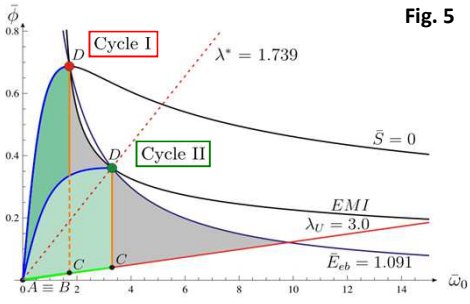


The optimal cycle within the admissible state region is identified by solving a constrained optimisation problem. The harvested energy not only depends strongly on the ultimate stretch ratio but also is bounded by a universal limit on the dielectric strength of the DE beyond which the optimal cycle is independent of this parameter.

The universal curve, for a DEG under equibiaxial loading, is represented by the solid blue line in Fig. 4.

Reporting on the plane $\bar{E}_{eb} - \lambda_U$ the electromechanical properties of both the random composites and the relative pure PDMS, it is evident that the outcome of the addition of the ceramic fillers is to approach the PDMS to the universal curve, allowing a better performance of the device.

Fig. 5



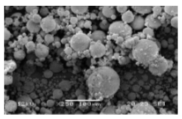
For λ_U=1.5 on the solid blue line only one cycle is possible (**Cycle I** see Fig. 5) and it is characterized by the contemporaneousness of loss of tension (S=0), electromechanical instability (EMI) and electric breakdown (EB). Above the universal curve the cycle failure is not determined by the electric breakdown (EB), the cycle is like **Cycle I**.

For λ_U=3 on the dashed blue line two cycle are possible (Fig. 5):
Cycle I and **Cycle II**, which is characterized by contemporary electromechanical instability (EMI) and electric breakdown (EB). This second cycle maximize the harvested energy.

Enhancing the material : ceramic fillers

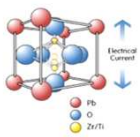
PMN-PT Lead Magnesium Niobate - Lead Titanate $Pb(Mg_{1/3}Nb_{2/3})O_3$- $PbTiO_3$

	PDMS □	PDMS + 10%PMN–PT ■
μ [kPa]	20.7	33.33
ϵ_r	7.32	10.32
E_{eb}[MV/m]	55	21
$\bar{E}_{eb} = E_{eb}\sqrt{\epsilon/\mu}$	3.07	1.093
λ^*	5.334	1.745
ρ [kg/m^3]	970	1660



PZT Lead Zirconate Titanate $Pb\,[Zr_{1-x}\,Ti_x]O_3$

	PDMS ⬠	PDMS + 1%PZT ⬟
μ [kPa]	34	42
ϵ_r	3.5	10
E_{eb}[MV/m]	55	25.208
$\bar{E}_{eb} = E_{eb}\sqrt{\epsilon/\mu}$	1.66	1.157
λ^*	2.836	1.908
ρ [kg/m^3]	970	1030



Optimised DEGs

The gained energy per unit volume for the optimised DEGs is:

Material i)		Pure PDMS □	PDMS-10% PMN-PT ■	Increment
$\lambda_U = 1.5$	Cycle I	-10.102 kJ/m^3	-16.294 kJ/m^3	61.3%
$\lambda_U = 3$	Cycle I	-17.824 kJ/m^3	-28.748 kJ/m^3	61.3%
$\lambda_U = 3$	Cycle II	*not admissible*	-29.089 kJ/m^3	63.2%
Material ii)		**Pure PDMS ⬠**	**PDMS-1% PZT ⬟**	**Increment**
$\lambda_U = 1.5$	Cycle I	-16.620 kJ/m^3	-20.530 kJ/m^3	23.5%
$\lambda_U = 3$	Cycle I	-29.323 kJ/m^3	-36.222 kJ/m^3	23.5%
$\lambda_U = 3$	Cycle II	-19.9339 kJ/m^3	-40.283 kJ/m^3	37.4%

The higher dielectric strength difference among the PDMS-10% PMN-PT composite and the pure PDMS is reflected in the higher improvement entailed in the gained energy.

Note that the **Cycle I** allows the same energy improvement both at λ_U=1.5 and at λ_U =3. But, for λ_U= 3, **Cycle II** allows a further increment in the gained energy.

Acknowledgments

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