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Frequency-domain trade-offs for Dielectric Elastomer Generators

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ABSTRACT

Dielectric Elastomer Generators (DEGs) are an emerging energy harvesting technology based on a the cyclic stretching of a rubber-like membrane. However, most design processes do not take into account different excitation frequencies; thus limits the applicability studies since in real-world situations forcing frequency is not often constant. Through the use of a practical design scenario we use modeling and simulation to determine the material frequency response and, hence, carefully investigate the excitation frequencies that maximize the performance (power output, efficiency) of DEGs and the factors that influence it.

Keywords: dielectric elastomer generators, energy harvesting, energy generation, wave energy

1. INTRODUCTION

Dielectric elastomers (DEs) are an emerging technology for electromechanical conversion, and, in particular, for energy harvesting.^{1,2} Applications include wave energy generation,³⁻⁸ human motion energy harvesting,⁹ among other less explored possibilities (vortex induced vibrations,¹⁰ hydro power¹¹ and combustion engines¹²). DEs consist of flexible capacitor-like structures: an isolating rubber-like membrane coated with flexible conductive layers on each side. Once stretched, the capacitance of the DE increases due to the reduction in thickness and expansion in area, similarly, when relaxed,; its capacitance decreases.¹ To convert mechanical to electrical energy, Dielectric Elastomer Generators (DEGs) use a cycle with appropriately timed charging and discharging. Once charged in its maximum stretch state, and allowed to relax, the area reduction causes like charges to be pushed together and opposite charges to be taken further apart; as a consequence, the overall electric energy stored in the material increases.¹³

Although a promising technology, there are still several gaps in the understanding of DEG behavior that remain to be addressed, so that real-world implementation can become a reality. In general, the design of DEG energy harvesting devices is made without considering a wide band of excitation frequencies. In reality we know that, apart from specific losses due to the mechanisms used for the DEG deformation, effects such as viscoelasticity, charging/discharging time and resonance will affect the DEG performance.^{14,15} Higher frequencies of excitation will lead to higher viscoelastic losses, as a consequence, decreasing the efficiency and, the amount of deformation obtained. In contrast, lower excitation frequencies reduce the obtained power, since energy is generated on a per cycle basis. That suggests an optimal energy harvesting frequency, and implies that understanding how the performance metrics of DEGs change with frequency is an important factor for their successful application.

In this study, we analyze the frequency response of DEGs in a wave energy generator conceptual design. To evaluate how to optimize the performance, we compare the effects of two different cycles and different biasing voltages for the charging state.

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2. MODEL AND ENERGY HARVESTING DEVICE DESIGN

In order to evaluate the frequency response of DEGs, we chose a wave-energy harvesting device, as it represents a popular scenario. Using a design process obtained from literature and already validated models, we obtained the model used to evaluate the frequency response analysis.

2.1 Device design

In order to evaluate a wave energy harvesting scenario, we adopted a design approach used to compare VHB and natural rubber for wave energy converters reported in the literature.¹⁶ It uses a conceptual design consisting of several disc-shaped DEGs connected at their centers to a moving piston, and to the internal part of a static cylinder at their edges.⁸ It is estimated that the pistons can be pushed with force of 34kN.⁸ Similarly to the cited study, we considered the membrane to be 1mm thick, with an internal radius of 25cm and external radius of 50cm. The load per membrane was defined as a function of the stretch desired. In order to obtain a reasonable amount of energy harvested, we considered a maximum stretch of 3.85, and a minimum stretch of 1.25, in order to follow the suggested optimal pre-stretch.¹⁶ Using the stress-strain curve for the material chosen and considering the cone-shaped geometry of the deformed DEG, we obtain a maximum forcing of 8000*N* and a minimum of 550*N* per membrane.

2.2 Model

Selecting a low stiffness and high stretchability electrode, we use the stress-strain curve from Theraband LFRB-Y¹⁷ to obtain the parameters for the Ogden material model.¹⁸ Model dynamic parameters were validated comparing the output curves with the stress-strain curves from tests of Theraband LFRB-Y with constant strain rate obtained from literature.¹⁷ To simulate the DEG behavior, we adapted a validated dynamic model developed in for circular dielectric elastomer actuators¹⁸ and implemented it using the Simulink package from MATLAB. The model is based on a circular DE which maintains a perfectly conic shape when deformed out-of-plane; this allows us to deal with a pure-shear deformation.

In order to visualize clearly the effects of the charging/discharging during limited time, the viscous behavior and charge leakage, we neglect the inertial effects, avoiding, thus, resonance. We also consider that the forcing is a sinusoidal wave with constant period and amplitude.

3. PERFORMANCE METRICS

Design optimization requires a clear choice of performance metrics. We consider three that are relevant to DEG applications: overall energy efficiency, power output, and energy density.

3.1 Overall Energy Efficiency

The overall energy efficiency is the ratio between the energy generated in a cycle (output electrical energy less the amount used to polarize the DEG), and the total mechanical work absorbed by the DEG in a cycle. Ideally one would store the generated energy in a battery or supercapacitor, or use it further for another task, though this is beyond the scope of the present study, For such cases, the metric should also include the energy harvesting circuit efficiency.

3.2 Power output

Another important metric is the power output: how much energy is generated in a given interval. It is in the power output that we find a trade-off for the performance of DEGs regarding their the frequency response. Although design specific (more material, will lead to higher power), it allows us to draw conclusions about the feasibility of DEGs for a chosen scenario.

3.3 Energy density

In order to alleviate the design specificity of power output, we also consider energy density: the energy output per unit mass of material used to generate it. Energy density has been claimed as an advantageous characteristic of DEGs in comparison with other technologies:¹² typical electromagnetic devices have maximum energy density of 4J/kg¹² and piezoelectric ceramics 10J/kg,¹² while for DEGs energy density as high as 400J/kg has already been reported.¹²

4. DEG ENERGY HARVESTING CYCLES

A classic DEG cycle, here called Mode 1, consisting of the constant charge¹³ case for the relaxing phase is shown in solid lines in Figure 1. The cycle is composed of four phases: 1) from a relaxed and non-charged state, the DEG is deformed; 2) once stretched, the DEG is electrically charged with a bias voltage; 3) in an open circuit condition, the DEG is then relaxed and has its voltage rising consequentially; 4) finally, from its maximum voltage state, the DEG is discharged. Note that the stretch ratio at the end of the relaxing phase, and prior to the discharge is higher than after the discharge phase, due to the electrostatic pressure over the membrane, meaning the charges on the membrane generate an electrostatic force that pushes the membrane to a higher stretch ratio than it would have after the discharge.

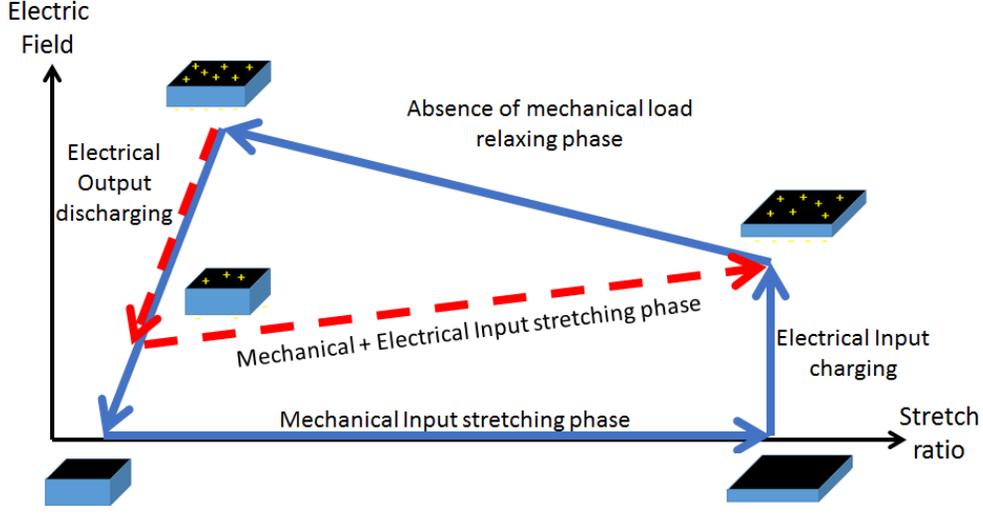


Figure 1: DEG Energy harvesting cycle in constant charge during relaxing phase, complete discharge and charging after stretch

An issue of this cycle is that, with two fast charging/discharging processes, it yields large electrical losses.¹⁹ In face of the significant losses in the charging/discharging phases, we also investigate performance using an alternative cycle, shown in dashed lines in Figure 1, here called Mode 2. Differently from Mode 1, the DEG is exposed to a bias voltage since the beginning of its stretching phase. Moreover, to prevent the high losses from the discharge phase, we also use a partial discharge, stopping it at the bias voltage we intend to charge the material, which is not included in the literature we based this cycle.¹⁹

For a theoretical comparison between the cycles, we consider an ideal position-based scenario (with the DEG oscillating between two fixed positions) where the stretch level alternates between a minimum, λ_{\min} , and a maximum, λ_{\max} . Mode 1, being charged with voltage V_{in} , will have an initial electric energy input of

$$U_{\text{in}_1} = C_0 \lambda_{\max}^2 V_{\text{in}}^2, \quad (1)$$

where C_0 is the capacitance of the undeformed DEG. After the relaxing phase, in open-circuit conditions (constant charge), it will discharge an electrical energy output of

$$U_{\text{out}_1} = \frac{C_0 \lambda_{\max}^2 V_{\text{in}}^2}{2} \lambda_{\text{R}}^2, \quad (2)$$

where λ_{R} is the ratio $\frac{\lambda_{\max}}{\lambda_{\min}}$. Consequently, the harvested energy will be

$$U_{\text{harv}_1} = C_0 \lambda_{\max}^2 V_{\text{in}}^2 \left(\frac{\lambda_{\text{R}}^2}{2} - 1 \right). \quad (3)$$

For the second proposed cycle, Mode 2, the electric energy input is given by

$$U_{in_2} = C_0 \lambda_{min}^2 V_{in}^2 (\lambda_R^2 - 1), \quad (4)$$

while its output, discharging from the maximal voltage obtained up to V_{in} can be estimated by

$$U_{out_2} = \frac{C_0 \lambda_{min}^2 V_{in}^2}{2} (\lambda_R^4 - 1). \quad (5)$$

Consequently, the energy harvested per cycle is

$$U_{harv_2} = \frac{C_0 \lambda_{min}^2 V_{in}^2}{2} (\lambda_R^2 - 1)^2. \quad (6)$$

We can see the advantage of Mode 2 over Mode 1 regarding the charging/discharging losses if we notice that we need $\lambda_R > \sqrt{2}$ in Mode 1 in order to output more energy that was consumed polarizing the DEG. In contrast, $U_{harv_2} > 0$ for all λ_R , since $\lambda_{max} > \lambda_{min}$ by definition, leading to $\lambda_R > 1$.

To evaluate the proposed cycles, we consider the energy harvesting circuit to be composed of a high voltage supply, a DEG, and a resistive load in parallel.²⁰ A charging switch (S1) connects the high voltage supply to the DEG and a discharging switch (S2) connects the DEG to the resistive load. We adopt the cycles charging and discharging control in an open loop manner. We consider that for a given excitation period, T , both modes have a discharging window lasting 10% of T . Specifically, Mode 1 starts charging after 50% of T and it lasts 10% of T , while Mode 2, starts the charging phase right after the 10% of T discharging end and last 45% of T . during the charging window, S1 is closed and S2 is open, meaning the DEG is connected directly to the bias voltage supplied. Discharge interval was chosen to start at the point where the material capacitance would be minimum if stretch and forcing are in phase. Analogously, Mode 1 charging starting time was chosen to match the maximum DEG capacitance state if it matches the maximum forcing point. Mode 2 charging starts after the discharge switch is opened finishes after the maximum forcing point to overlap part of the charging phase for Mode 1, although all the suggested charging/discharging were not chosen based on a formal optimization process.

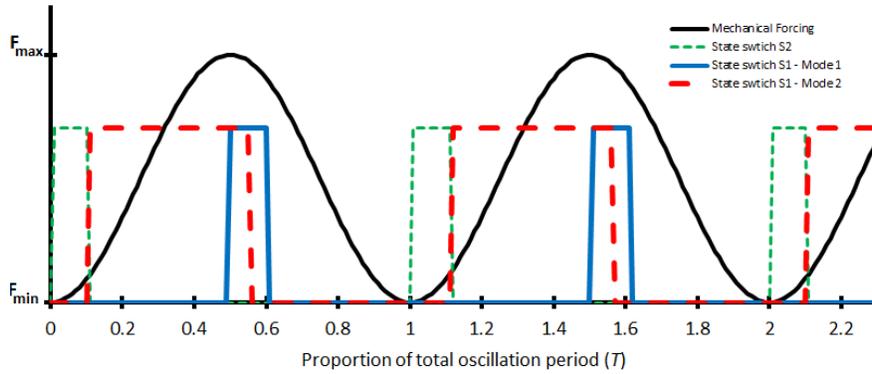


Figure 2: Charging/Discharging scheme through the cycle for both modes. high states represent that switch is closed and current is allowed to flow.

As the above calculations represent a position-based scenario and our design uses a piston free to move by oscillating wave pressure, there are some clear limitations. Equations 3 and 6 do not account for charge leakage through the membrane, which reduce the amount of stored energy in the DEG at the end of a cycle. Moreover, the theoretical calculations do not account for the fact that the charges in the material affect its stretch, so that the charging/discharging does not occur in a single stretch ratio, since the voltage level in it will affect its

capacitance. Both of these factors are taken into account in the dynamic model and affect the DEG scenario in different levels for each cycle.

5. RESULTS AND DISCUSSION

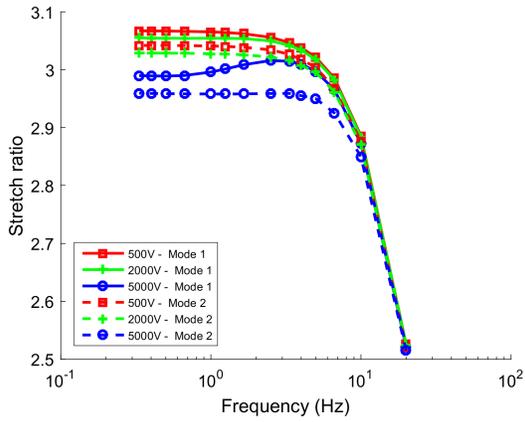
A first step into investigating the performance of DEGs is observing how much they can be deformed. Since we are evaluating a force-based scenario, to allow comparison with the theoretical calculations above, we consider that the maximum stretch ratio is achieved at the end of the charging window of the cycle, and that minimum stretch happens prior to discharge, at the end of an excitation period, Figure 3a shows the resultant stretch ratios of Modes 1 and 2, as a function of frequency, for three different voltages (500V, 1000V and 2000V). Mode 2 has its maximum stretch delayed in relation to the peak force in a cycle, and therefore has a smaller stretch ratio than Mode 1. In addition, Figure 3a shows the effect of the damping due to the material viscoelasticity: higher frequencies tend to reduce the stretch ratio obtained for most of the scenarios, except for Mode 1 in specific cases that will be explained ahead. Figure 3a also illustrates how higher bias voltage leads to a reduction in the stretch ratio. That is a consequence of the dual behavior of DEs, which are deformed when there is an electric potential applied. When the electric potential is higher (using higher biasing voltages), there is higher electrostatic pressure in the membrane, which acts to increase the stretch level.

Given the limited time window for the DEG charge, increasing cycle frequency reduces the charging time, and high frequency cycles may not have enough time to reach the desired bias voltage, as seen in Figure 3b. Note that for Mode 2 the voltage after the charging window converges to the bias voltage happens at a higher frequency when compared to Mode 1, given its charging window is broader. Nonetheless, Mode 2 only achieves its desired bias voltage for frequencies lower than 2Hz, reflecting the fact the expanding capacitance during its charging phase also disturbs the charging process.

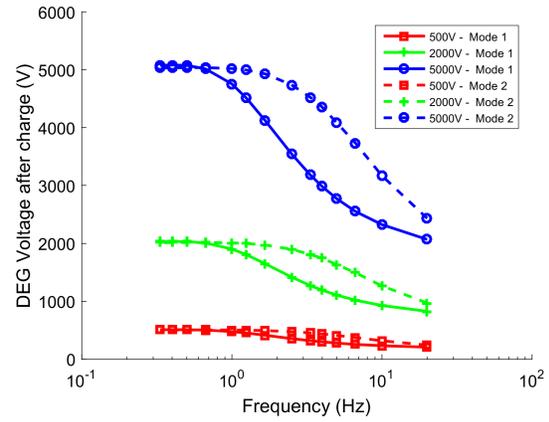
The valley in the minimum stretch for Mode 1 shown in Figure 3c and the consequent peak in the stretch ratio for the same mode happen because of two factors: the “actuation-like” behavior described above, and the incomplete charge for high frequencies in the open loop charging control proposed. As the viscous losses decrease when frequency decreases, the material is able to relax further (decreasing the minimum stretch), but, simultaneously, the charging process becomes more effective with the longer charging windows (overall larger periods) and the voltage previous to discharge increases. This increment in voltage leads to the “actuation-like” effect responsible for increasing the stretch of the DEG at the end of the cycle (minimum stretch) as the frequency reduces.

Figure 3d shows that, as expected, there is an increase in the overall energy efficiency as the bias voltage increases, for both modes. As there is more polarizing charge for the mechanical-to-electrical energy conversion, the energy generated will increase in comparison with the viscous losses, which are mostly frequency dependent. Thus, for higher frequencies, viscous losses increase significantly leading to an efficiency decrease. Comparing the cycles, Mode 2 is more efficient due to the reduced losses in the charging/discharging phases. The efficiency difference between the modes increases in the central region of the plotted area due to the voltage after the charging phase difference, as shown in Figure 3b and described above.

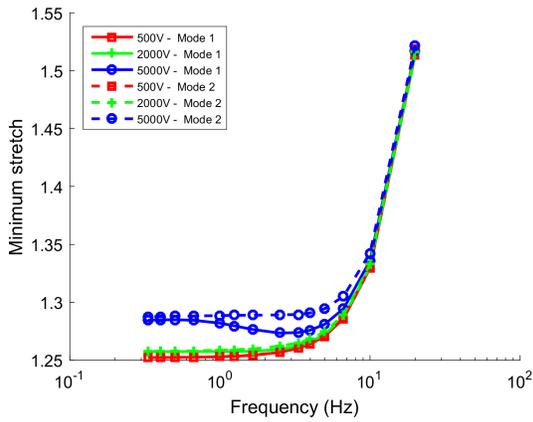
When evaluating the energy density shown in Figure 3e, it is clear that Mode 2 harvests more energy than Mode 1, as expected. As frequency decreases, the higher energy density is a consequence of the higher stretch ratio obtained. Moreover, as frequency decreases, Mode 2 increases its energy density more steeply than Mode 1, again, because of the charging window larger on Mode 2, lasting most of the stretching phase. The drop in energy density for larger frequencies is a consequence of the charge leakage through the membrane decreasing the output. It is, then, clear that there is an optimum point around 1.5-2Hz, where the trade off between the lower stretch ratios for high frequencies and the charge leakage for lower frequencies is met. notwithstanding this, the absolute values of energy density show promising results with values above 10J/kg for a broad range of frequencies even when the material is not charged to the desired. Note that theoretical values values shown in Figure 3e are inferior to those obtained through the dynamic model. That is a consequence of the discharging phase dynamics: As the voltage decreases and consequently the electrostatic pressure on the DEG, the elastomer relaxes even more, meaning the discharge does not occur fully in a single stretch level. As we consider the minimum stretch level for the theoretical model to happen at the beginning of the discharging phase, we obtain this underestimation of the energy obtained.



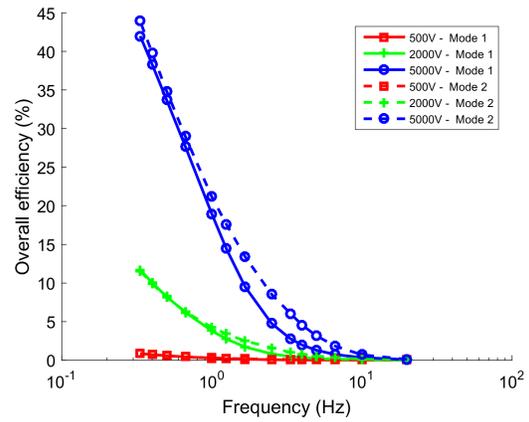
(a) DEG stretch ratio as a function of excitation frequency



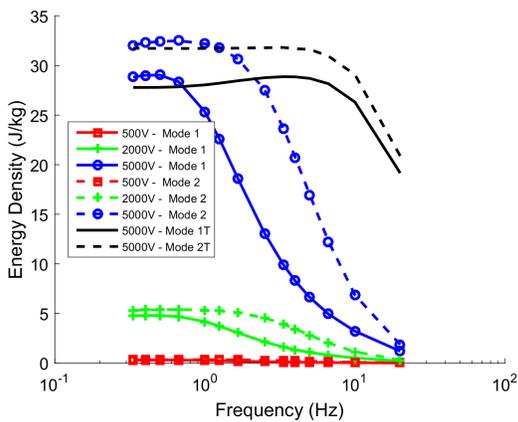
(b) DEG voltage at the end of charging phase as a function of excitation frequency



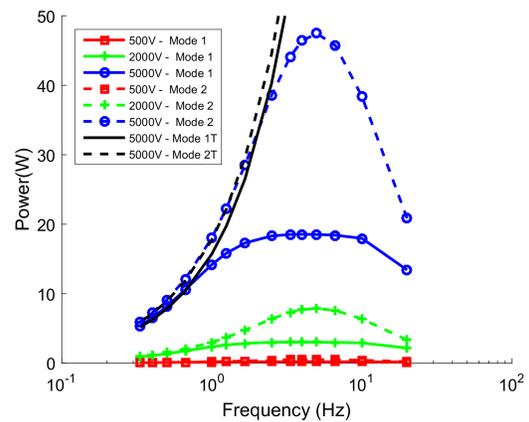
(c) DEG stretch ratio prior to discharge phase as a function of excitation frequency



(d) Overall Efficiency as a function of excitation frequency



(e) Energy density as a function of excitation frequency. Theoretical values for Mode 1T and Mode 2T output calculated using stretch ratio com simulations and equations 3 and 6.



(f) Power output as a function of excitation frequency. Theoretical power output for Mode 1T and Mode 2T calculated using stretch ratio shown in Figure 3a and equations 3 and 6.

Figure 3: Obtained results

Analyzing the power output for different excitation frequencies, shown in figure 3f, the trade-off in the frequency response for DEGs is again clear. Previous metrics already demonstrated that high frequencies are an issue for efficient use of DEGs and, in concordance, we can see the power output is also reduced as frequency increases. Lower frequencies not only present the issue of charge leakage, which had the effect demonstrated in the reduction of energy density, but also represent lower cycles and energy output in a given time, hence reducing the power output. For the scenarios considered here, we see that the output power peaks at around 4-7 Hz. Figure 3f also shows different behavior for Modes 1 and 2. While Mode 2 has a clear peak in its power, Mode 1 has a much flatter, plateau-like, power curve. We infer that the incomplete charging of Mode 1, and its consequent reduced energy output, for higher frequencies are the reason why there is not a clearer peak for Mode 1. This hypothesis is also emphasized by the similar trend for both modes, shown by the theoretical curves in Figure 3f. As before, the theoretical values obtained using the stretch states from the simulations are reasonably accurate for lower frequencies, when the charging process is completed within the time window specified. The theoretical values bound the maximum power possible, as the peak is a consequence of the viscous behavior. In order to increase those values the design would have to be modified (e.g. thinner membrane) to allow higher stretch ratios.

6. CONCLUSION

In this paper we have compared the frequency-domain behavior of DEGs undergoing two different cycles, and different biasing voltages. We observed that there are clear trade-offs for some metrics. We also confirmed that DEGs are able to perform competitively when compared to other technologies for energy harvesting. Future work will investigate the effect of inertial effects in the system dynamics, and also how to actively control charging/discharging timing for optimal performance. In conclusion, DEGs are shown to be a promising technology, but their non-linear behavior and the amount of tunable parameters pose a challenge to the development of a straight forward method to design wide-bandwidth DEGs, and so, more specific frequency response studies are still required.

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