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The need for speed

Samuel Rosset[a], Pit Gebbers[a,b], Benjamin M. O'Brien[c] and Herbert R. Shea[a]

[a]Ecole Polytechnique Fédérale de Lausanne, Switzerland;
[b]Zürcher Hochschule für Angewandte Wissenschaften, Winterthur, Switzerland;
[c]The Auckland Bioengineering Institute, University of Auckland, New-Zealand

ABSTRACT

Development of dielectric elastomer actuators has been mainly targeted towards achieving giant static strain with little attention paid to their response speed, which can, depending on materials used, be as long as tens of seconds. However, most of the practical applications require actuators capable of changing shape quickly, therefore a careful choice of materials and technologies for the dielectric and electrodes must be made. Test oscillating actuators, made with a range of silicone membranes with different hardness were tested, and the compliant electrodes were made with different technologies: carbon powder, carbon grease, conductive rubber and metal ion implantation. The transient response of the actuators to a step input was measured with a high speed camera at 5000 frames per seconds for the different combinations of membrane material and electrodes. The results show that the dynamic response of the actuators is extremely dependent on the membrane material, as expected, but also on the compliant electrodes, whose impact cannot be neglected.

Keywords: Silicone, response speed, metal ion implantation, conductive rubber, carbon grease

1. INTRODUCTION

Because of their ability to display gigantic strains, dielectric elastomer actuators (DEAs) have attracted wide attention since the first major publication in the domain in 1998.[1] Since then there has been an on-going competition to achieve higher and higher actuation strains with the current record sitting at an impressive 1600% (surface) in certain clever configurations.[2] For the standard circular test actuator, illustrated on figure 1, surface strains up to 93% for silicone and 350% for 3M VHB acrylic[3] have been reported. However, information about the response speed of these actuators is seldom given, and speed is critical for many applications. Literature about the response time of such acrylic-based suspended membrane actuators is unfortunately scarcer. According to a study by Michel et al. on an acrylic VHB F-9473PC membrane, the response time was shown to be higher than 60 seconds,[4] thus explaining why authors often prefer to discuss about the strain level they can obtain out of their actuators, rather than about the time necessary to obtain the said strain.

1.1 The Need for Speed

There is a lot of potential commercial applications for the DEA technology. Among the existing products are haptic feedback devices (Artificial Muscle Inc) and Laser speckle reducers (Optotune AG). Other potential applications include image stabilization devices, flexible motors, biological cell stretchers, tunable lenses, tunable gratings, or actuators for soft robotics. All these applications can directly benefit from the high strain levels that can be obtained from DEAs, but they also require fast response times, from 200 ms (biological cell stretcher) to 1–5 ms (haptic feedback). No matter what revolutionary product you would design using DE actuation, you need it to react to the user input in a reasonable amount of time. For example, the large strains provided by EAPs can be advantageously used to make tunable lenses[5,6] and an optical zoom for a camera. The potential user will probably be amazed by how compact the EAP-based zoom is, but he won't buy if it doesn't react quickly: a response time of 60 seconds is not realistic for such an application, and a more realistic figure would be below 100 milliseconds. Strain is an important factor, but the speed at which the actuators move is equally important, and except for lab demonstrations VHB membranes have no potential for commercial applications that require both fast actuation and stable strains, combined with long lifetime and high reliability.

Further author information: send correspondence to Samuel Rosset: samuel.rosset@a3.epfl.ch

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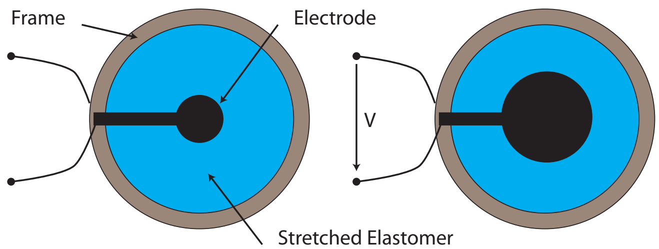

Figure 1. The standard area strain actuator consists of a membrane stretched on a frame on the center of which a circular active zone is patterned. Upon application of a voltage, the active area expands with surface strains that can exceed 100%.

Compared to 3M VHB acrylic adhesives, silicone elastomers present a faster response time and represent the second main category of dielectric elastomers used for DEAs. In addition to reduced viscous losses, silicones exhibit other advantages: larger operating temperature range, possibility to make membranes of any desirable thickness, and not subject to tear when stored in a prestrained condition. However, they exhibit smaller strain capabilities, and VHB is therefore still often preferred by researchers, as it allows to present more impressive results, as long as the response time is not mentioned.

1.2 The Influence of the Dielectric Membrane

There is an incredibly large panel of silicones commercially available, and researchers have tested a few of them as dielectric membranes for DEAs, such as DowCorning HS3,[7] Nusil CF19-2186,[7,8] DowCorning Sylgard186,[9,10] BJB TC-5005,[11,12] etc. Furthermore, silicones can be modified with inclusion of nano-particles in order to increase their dielectric constant.[13–15] This leads to an extremely large range of silicone materials that can be used as dielectric elastomers, and because of their different properties, they will exhibit different performance.

In most published results, the elastomer is assumed to be purely elastic and the time dependence of the actuation is often overlooked. Because of the large strains involved and the possible presence of a mechanical prestrain in the membrane, non-linear hyperelasticity is used to model the elastomer's elasticity. In the case of free boundary conditions (for example the actuator of figure 1, when the diameter of the active zone is much smaller than the total diameter of the membrane) the relation between the voltage V applied to the electrodes and the linear stretch ratio $\lambda = r/r_0$ (r_0 being the initial radius of the electrode) is given by the following relation:[16]

$$V = \frac{z}{\lambda^2\sqrt{\epsilon}}\sqrt{f(\lambda_p\lambda) - f(\lambda_p)\lambda}, \tag{1}$$

where z is the initial thickness of the *prestretched* membrane (i.e. thickness without applied voltage), ϵ is the permittivity of the membrane, λ_p is the mechanical equi-biaxial prestretch of the membrane, and $f(\lambda)$ is the bi-axial stress-stretch relationship. In the absence of prestrain, or for small strains, the bi-axial Hook law is a possible approximation ($f(\lambda) = Y(1 - \frac{1}{\lambda^2})$, with Y the Young's modulus of the elastomer), but more complex hyperelastic models can also be used (Yeoh, Gent, etc.) to accurately model the complete stress-stretch curve. It should be noted that λ represents the *visual* stretch ratio (i.e. the stretch ratio of the electrodes, which can be recorded by a camera for example), and not the stretch ratio of the dielectric membrane under the electrode, because of the possible presence of prestrain. The membrane stretch ratio in the active zone is given by $\lambda_m = \lambda\lambda_p$.

Silicones elastomer are however not purely elastic and dissipate energy when cyclically stretched, as represented on figure 2 left with a dissipative element (dashpot) in parallel with the elastic behaviour. The Kelvin-Voigt material model is chosen here only as a schematic representation of the co-existence of both an elastic and viscous component, and it is not assumed that silicone elastomers can be accurately represented by such a simple model. Because the static strain is the main focus of DEA research, silicones with a low stiffness, high dielectric constant (increased by the addition of fillers), and high dielectric strength have been favoured for DEA applications. The response speed is however also an important characteristic, and two different silicones which have a similar stiffness will lead to comparable strains when stretched, but the speed at which they actuate can

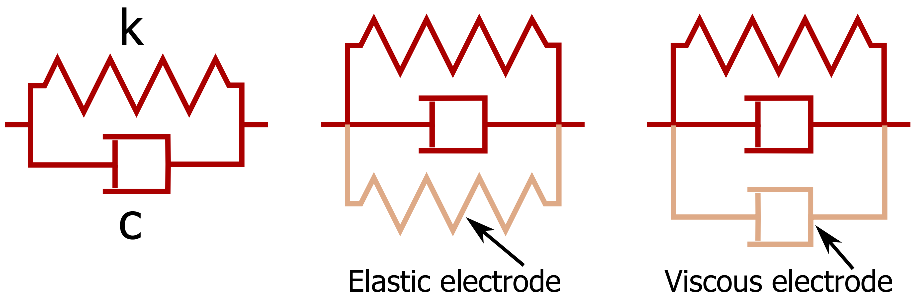

Figure 2. Left: silicone elastomers are not purely elastic but viscoelastic, as schematically represented here with a spring in parallel with a damping element, representing respectively the elastic and viscous behaviour of the material. Center: Impact of a purely elastic electrode; the static strain will be reduced. Right: Impact of a purely viscous electrode (e.g. conducting liquid); no effect on the final static strain, but slower response speed.

vary. Additionally, softer silicones lead to larger deformations, but are often more lossy, leading to the existence of a trade-off between speed and displacement.

1.3 The Influence of the Electrodes

DEAs consist not only of a dielectric membrane, but also of compliant electrodes, a fact which is often overlooked. The perfect electrode for DEA is infinitely compliant and can bring the charges quickly on the membrane without impact on its mechanical properties. However, this perfect electrode does not exist, and the electrodes commonly used for DEAs do have an influence on the mechanical properties of the DEA sandwich, with the exception of the *electrode-free* devices of Keplinger et al. which are based on spraying charges directly on the dielectric.[17] The impact of loose carbon powder, often used in combination with the adhesive VHB is also probably negligible, but loose powders are not applicable to single-layer silicone membranes. The electrodes can be elastic (figure 2 center), for example in the case of metallic electrodes such as gold ion implantation. In that case, they mainly impact the static strain by stiffening the membrane. In the other hand, they can also be purely viscous (figure 2 right), for instance in the case of a conductive fluid. In that case, the electrode does not impact the static strain of the actuator, but negatively affects the response speed. In most cases, the electrode exhibits a viscoelastic behaviour and contribute both to the stiffening of the membrane and to viscous losses. This would be the case of conductive rubber electrodes: conductive particles (usually carbon black or graphite) mixed in an elastomeric matrix. In any case, DEAs have a sandwiched structure comprised of two electrodes and an elastomer membrane. The performance of the actuator depends on the properties of all the layers, and are not only controlled by the dielectric membrane.

2. ACTUATOR FABRICATION

Circular actuators (figure 1) were fabricated to investigate any possible difference in static strain between measurements and a theoretical model, thus exhibiting the stiffening impact of the electrodes which reduces the output strain. Then, dynamic characterization were performed on different actuators consisting of a $\varnothing 14$ mm membrane with a pair of electrodes patterned on one of the membrane's sides. A small 13 mg mass was placed at the center of the membrane and served as an oscillating mass (figure 3). Upon application of a voltage, the electrodes expand, thus shifting the mass towards the passive side (i.e. without electrodes) of the membrane. For the characterization, a voltage step input was applied to the electrodes, and the in-plane displacement of the mass was tracked with a high speed camera.

For the dynamic tests, 3 silicones with different Shore hardness were used as membrane materials: DowCorning Sylgard 186 (Shore A 24), Nusil CF18-2186 (Shore A 18) and BlueStar Silbione LSR 4305 (Shore A 5). The membranes were casted on a glass plate with a Zehntner universal applicator with settable gap. Because of its high viscosity, Sylgard 186 was diluted with isooctane (PDMS:solvent 2:1 wt) prior to casting. The height of the gap was set to obtain membranes of $45-50\ \mu$m. The cross-linking of the membranes was performed at 80^0C in an oven, and the membranes were subsequently removed from the glass plate and placed on frames. The

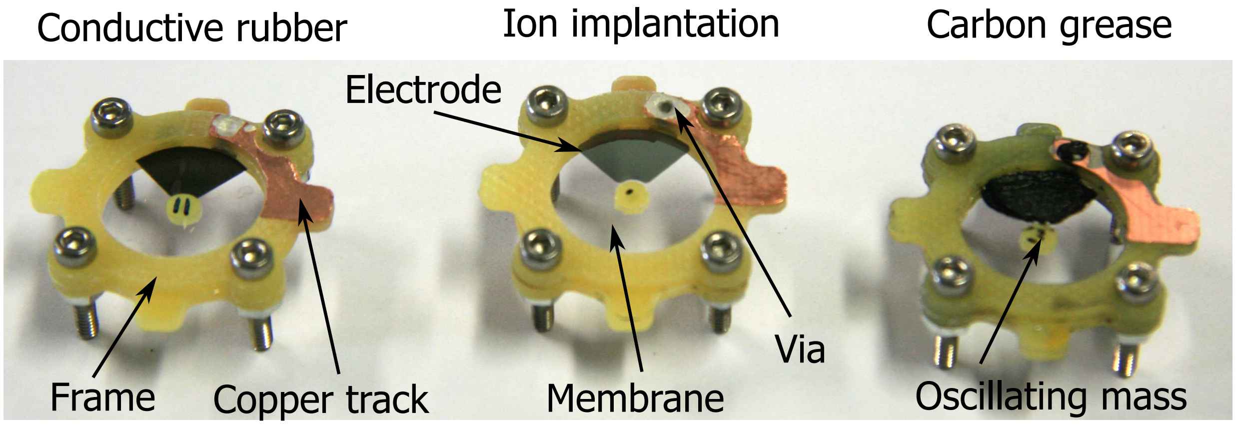

Figure 3. Actuators for the dynamic characterization. Left: conductive rubber, center: gold ion implantation, right: carbon grease.

membranes were then equi-biaxially prestreched and fixed on adhesive coated support frames. The prestrech ratio was determined by measuring the thickness of the membrane before and after prestretching.

Regarding the electrodes, 3 different compliant electrodes were tested: conductive rubber, carbon grease and FCVA gold ion implantation. Conductive rubber consists of conductive particles dispersed into an elastomer matrix. The properties of conductive rubber electrodes depend on the elastomer used as matrix and the type and quantity of conductive particles. Optotune AG (Dietikon, Switzerland) has developed a formulation that offers good conductivity, low stiffness and low viscous losses. Additionally, the company has a method to precisely pattern the electrode solution on an elastomeric membrane. Prestretched membranes of the different silicones mentioned above have therefore been sent to Optotune for the patterning of the actuators' electrodes with conductive rubber. Gold ion implanted electrodes were made in our own laboratory with our filtered cathodic vacuum arc implanter.[10, 18, 19] In this case, the patterning of the electrodes is achieved through the use of a shadow mask protecting the membrane in the zone which must remain free of ions. The implantation was conducted with an acceleration potential of -1.25 kV ($\sim$ 2.5 keV ion energy) on a 22.8×24.8 mm^2 area and with an atom surface density of $\sim 1.5 \times 10^{16}$ at/cm^2. Finally carbon grease electrodes were made with NyoGel 756G (Nye Lubricants), which was smeared on the membrane through a steel mask.

Once the membranes are coated with the compliant electrodes, an epoxy frame with a copper track on the backside and through-vias is glued on the membrane. Finally conductive silver varnish (Electon 40 AC) or carbon grease is used to fill the vias in order to provide contact between the electrode and the copper. Figure 3 shows the finished actuators for the three types of electrodes. The advantage of conductive rubber and ion implantation compared to carbon grease regarding the patterning of the electrode is well visible on the picture.

3. STATIC ACTUATION

Static actuation tests can be used to exhibit the stiffening impact of the electrodes by comparing the strain obtained on a circular actuator with the displacement predicted by the theoretical model (equation 1). The biaxial hyperelastic stretch-stress characteristic of the silicone was obtained by conducting a uniaxial pull-test on a strip of the material and fitting the experimental data with an hyperelastic material model. In the case of Sylgard 186, for stretch ratios between 1 and 3, the Gent model leads to an excellent fit ($R^2 > 0.999$), and the following parameters were obtained: $\mu = .39$ MPa and $J = 19.39$ (figure 4 left). These values were then used to calculate the equi-biaxial stretch-stress law $f(\lambda)$, which can then be inserted into equation 1. Then, a circular test actuator (figure 1) made with a 25.3 μm Sylgard 186 membrane (thickness after the prestretch), equi-biaxially prestretched to 1.32 and with carbon-grease electrodes was fabricated. The electrode diameter was 2 mm, and the membrane had an overall diameter of 14mm. Sylgard 186 was chosen for this test because it is the hardest silicone amongst those tested, and carbon grease because it should have the lowest stiffening effect of the three chosen methods. It is thus expected that the impact of the electrode on the displacement should be small.

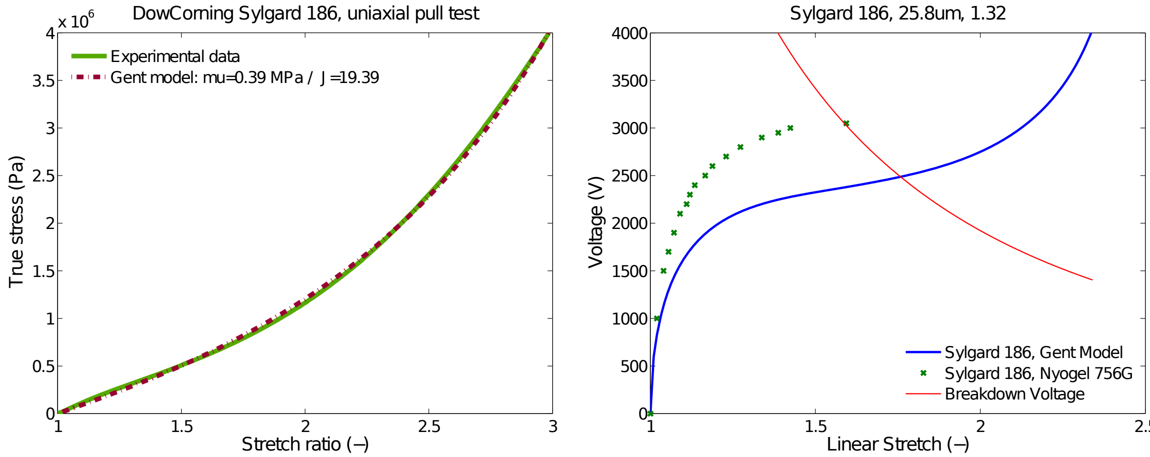

Figure 4. Left: uniaxial pull test on Sylgard 186 and fit with Gent model. Right: Theoretical Voltage-stretch curve and measured datapoints for a 25.3 μm membrane with an equi-biaxial prestretch of 1.32 (Membrane thickness is given after the prestretch). Carbon grease was used as electrodes for the actuator.

The actuator was characterized by placing it under an optical microscope equipped with a digital camera and taking photos of the electrodes for different applied voltages, from 0 V up to dielectric breakdown (3050 V). Using an image processing software, the diameter of the electrode was measured along 3 different directions and averaged. For each voltage value, the linear stretch ratio was calculated and plotted together with the theoretical values obtained from equation 1 with the Gent material model.

Figure 4 right shows the measured and calculated visual stretch (i.e. stretch of the electrode; the stretch ratio of the membrane is mulitplied by the prestretch). It can be seen that the voltage required to reach a given strain is higher than predicted by the theory, because the model does not take the mechanical impact of the electrodes into account. This result shows that even very compliant electrodes made with carbon grease have an impact on the displacement of the actuator, which thus doesn't depend exclusively on the mechanical properties of the dielectric membrane.

Apart from the obvious impact of the electrodes, figure 4 right shows some exciting results for a silicone membrane actuator: a linear stretch of 1.6 at breakdown, which corresponds to a surface strain of 156%. To the author's knowledge, this is the highest surface strain reported for this type of circular actuators with a silicone membrane. This is made possible by the use of well chosen prestrech value: high enough to suppress the pull-in instability, but low enough not to stiffen the material too much.

The impact of the electrodes becomes more dominant in the case of compliant metallic electrodes on a softer polymer: for gold ion implantation on Silbione LSR 4305, the voltage necessary to obtain a given strain is about 2.5 times higher than predicted by the model.

4. DYNAMIC ACTUATION

4.1 Test Setup and Model

Analysing the transient response of a DEA actuator to a step voltage input allows obtaining information on the time-dependence behaviour of the actuator and on its dissipation factor, thus giving information about the speed of the actuator. Actuators in the form of in plane resonators (c.f. section 2 and figure 3) were driven with a step voltage input. The two harder silicones (Sylgard 186 and Nusil CF18-2186) were driven at a field of 70 V/μm, while the softer silicone (Silbione LSR 4305) was actuated at 40 V/μm. The voltage step was generated at 1 Hz with a signal generator connected to a high Voltage amplifier Trek 609E6. The voltage rise time of the amplifier is of ~ 30 μs. The oscillating mass with its mass of ~ 13 mg was chosen to have mechanical rise times of the actuators about an order of magnitude slower, in order to neglect the rise time of the voltage input signal. The motion was tracked with a microscope-mounted Vision Research Phantom V210 high speed camera. The lateral

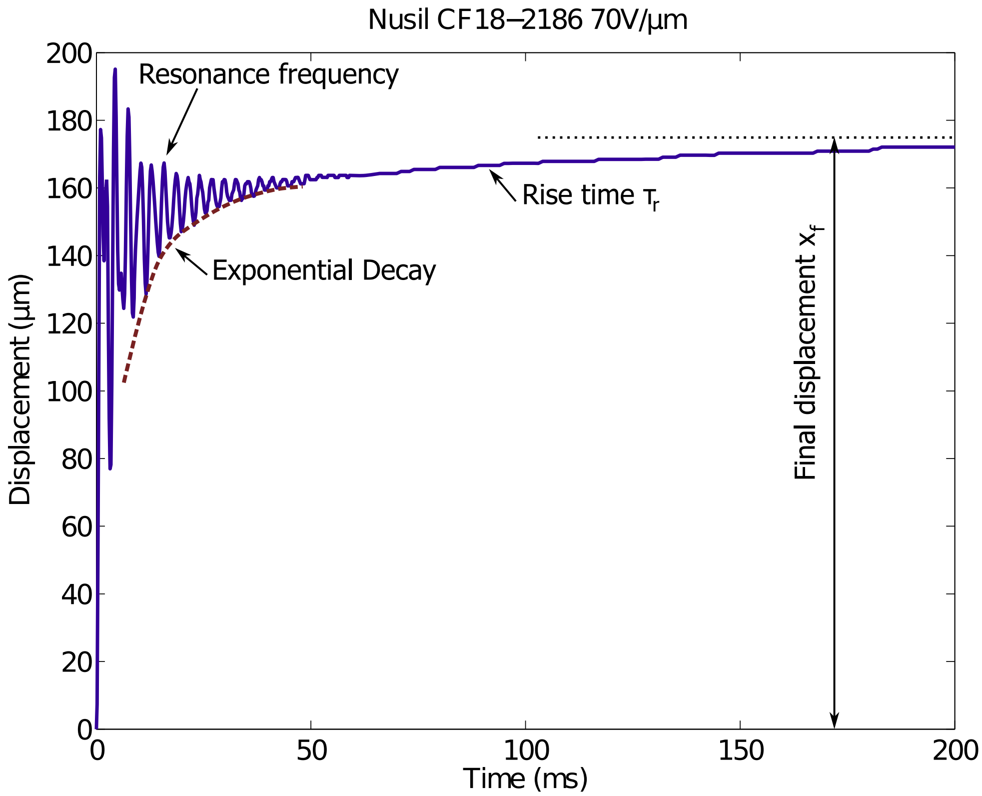

Figure 5. Typical curve obtained from the analysis of the camera frames, representing the lateral shift of the oscillating mass. The displacement exhibits an underdamped behaviour with exponentially-decaying oscillations at the damped natural frequency, and a more longer term drift (rise time) up to the equilibrium strain. This particular example was obtained for a Nusil CF18-2186 membrane with conductive rubber electrodes driven at 70 V/μm.

resolution of the optical setup is 1.63 pixel/μm. A recognizable feature on the center of the oscillating mass is selected and tracked with the help of an image analysis software (ImageJ). Two different acquisition rates were used: the first 60 ms following the voltage step were recorded at 5000 frames per second in order to track the oscillations at the damped natural frequency, and the 60 ms – 300 ms range was filmed at 1000 fps to look at the longer term viscoelastic response of the actuator.

Figure 5 shows the typical curve obtained for the step response measurements, in this case for a Nusil CF18-2186 membrane and conductive rubber electrodes driven at an electric field of 70 V/μm. For a few tens of miliseconds, the response is dominated by oscillations of the mass at the damped natural frequency, which are exponentially decaying. The resonance frequency f_{res} was obtained by calculating the Fourier Transform of the displacement response, and the time constant τ_1 of the damping of the oscillations was obtained by fitting an exponential decay to the envelop of the response. Using a damped oscillator model $m\ddot{x} + c\dot{x} + kx = 0$, the spring constant k and the damping factor c can be calculated from the resonance frequency f_{res} and the damping time constant τ_1. Furthermore, instead of oscillating around a constant displacement value x_f representing the equilibrium position when $t \to \infty$, one notices an additional larger time constant at which the displacement reaches the equilibrium value. From this slower viscoelastic behaviour, the actuator rise time t_r is calculated, and represents the time necessary to go from x_{10} to x_{90}, with $x_{10} = 0.1 \cdot x_f$ and $x_{90} = 0.9 \cdot x_f$. The more commonly used *response time* (i.e. the time taken to reach 63.2% of full scale) is not used in this case, because the viscoelastic response does not follow a first order exponential response of the form $x(t) = (1 - e^{-t/\tau})$, and has therefore no physical meaning. Furthermore, it would give overoptimistic results, as the response first increases rapidly to about 80% of its full-scale displacement before slowing down for the remaining 20%. It was observed that the low-frequency part of the displacement can be modelled by $x(t) \propto (1 - e^{-t^{\alpha}/\beta})$, leading to the following approximated empirical model for the transient response:

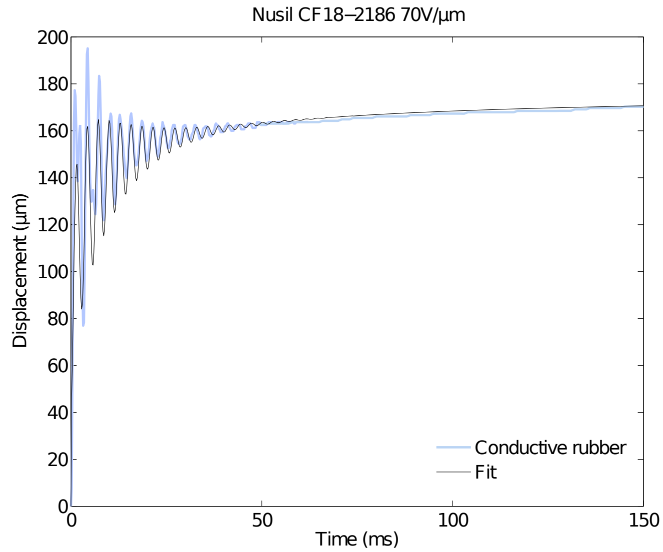

Figure 6. Comparison of the model with measured data for the Nusil CF18-2186 membrane with conductive rubber electrodes.

$$x(t) = x_f \left(1 - A\frac{e^{-\xi\omega_0 t}}{\sqrt{1-\xi^2}} sin\left(\sqrt{1-\xi^2}\omega_0 t + \psi\right)\right)\left(1 - e^{\frac{-t^\alpha}{\beta}}\right), \tag{2}$$

with $\omega_0 = \sqrt{k/m}$ the undamped natural frequency, $\xi = c/(2m\omega_0)$ the damping ratio, $\psi = tan^{-1}(\sqrt{1-\xi^2}/\xi)$ the phase shift, A, α and β, three unknown parameters obtained through fitting with experimental data. The first part of the equation represents the damped oscillations and the last part represents a slower viscoelastic drift of the displacement. Both the damped oscillations and the drift have their own time constant. Figure 6 presents the model fitted to the experimental data from the Nusil CF18-2186 membrane with conductive rubber electrodes. The exponential decay, resonance frequency, phase shift and slower viscoelastic response are well predicted. However, there is a discrepency between the model and data concening the amplitude of the oscillations, particularely during the first few miliseconds following the step. The response is quite different from a simple damped harmonic oscillator, and consequently the simple Kelvin-Voigt model (a spring in parallel with a dashpot, figure 2 left) can not be applied to the silicone/electrode sandwich.

4.2 Results

The step response for gold implanted electrodes on different membrane materials are shown on figure 7 left. Because the soft polymer (Silbione LSR-4305) could not be tested at the same electric field as the two harder materials, the displacement is normalized with the square of the electric field E, because the actuation force $F \propto E^2$. As expected, the response of the different polymers is clearly linked to their hardness through the different final displacements x_f and the frequencies f_{res} of the oscillations. Sylgard 186, the hardest silicone of the lot (Shore A 24) exhibits a smaller static deflection and a higher resonance frequency, and the opposite is observed for Silbione LSR-4305. Furthermore, the dynamic measurements also show differences in energy dissipation, with different decay times of the oscillations, and therefore different dissipation factors c and quality factors $Q = \sqrt{km/c^2}$.

Figure 7 right shows the step response for the three different electrodes that we tested (gold implantation, conductive rubber and carbon grease) applied on Nusil CF18-2186 membranes and driven with an electric field of 70 V/μm. The results highlight the crucial impact of the electrode on the static and dynamic response. As expected, metal ion implantation leads to a more pronounced stiffening of the membrane and consequently to a reduced static displacement x_f. However, because the ion-implanted electrode is purely elastic, it leads to a much higher quality factor compared to the two other electrode types. Furthermore, the actuators made with ion-implanted electrodes do not exhibit the slower viscoelastic drift of the displacement, as is the case for the

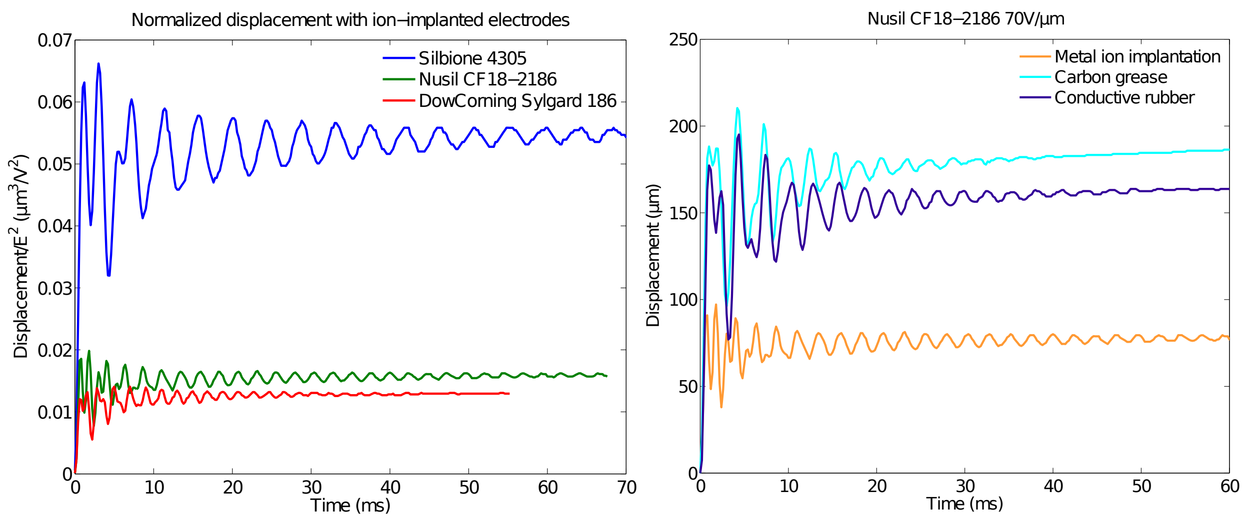

Figure 7. Left: Normalized transient response to a step voltage input for actuators with membranes made out of different silicones and with ion-implanted electrodes. Right: Step response for Nusil CF18-2186 membrane with different electrode technologies

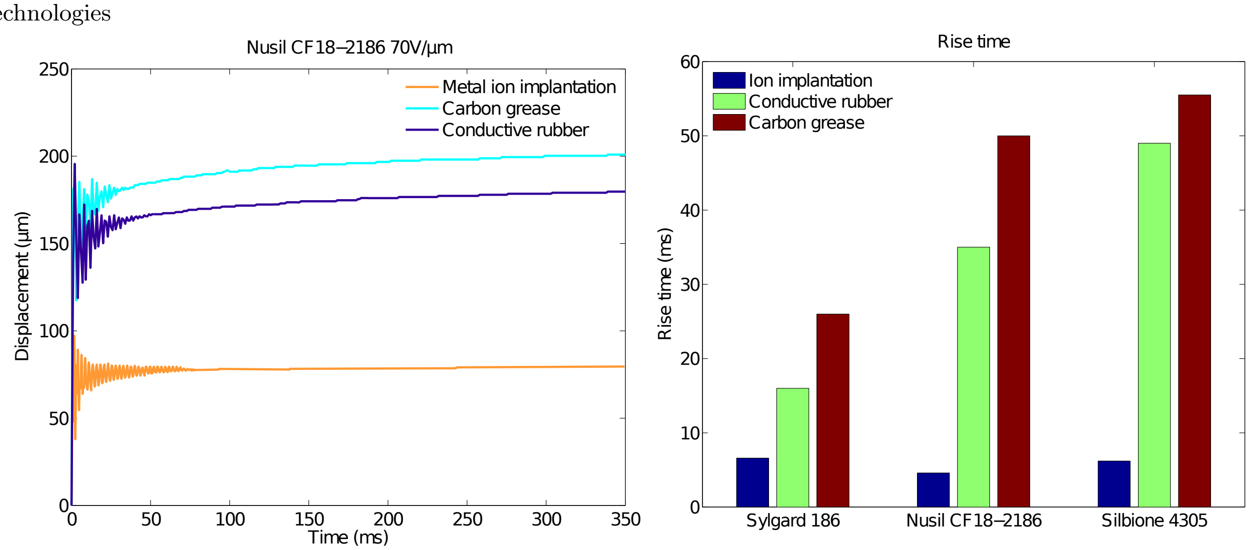

Figure 8. Left: same as figure 7 right but with the complete range of data, up to 350 ms. The slow viscoelastic response is well visible for the carbon grease and conductive rubber electrode. Right: Calculated rise times t_r for the different membranes and electrodes combinations.

two other methods, and particularly for the carbon grease. This is well visible if the complete range of data is plotted, from 0 to 350 ms (figure 8 left).

The rise time of the different membrane materials / electrode technologies tested (i.e. the time necessary to go from 10% to 90% of the full scale static displacement) is summarized in figure 8 right. This graph shows that:

- Ion implanted electrodes, being purely elastic leads to a much faster rise time compared to the two other technologies by a factor 3 to 10. Grease is the worst performer of the three, which is not surprising as this electrode material is supposed to be almost entirely viscous.
- Softer silicones tend to present longer rise times than harder silicones, however, regarding rise time, the electrodes are the dominating factor for the three chosen silicones.

The steady state amplitude for the different silicones is represented on figure 9 left. Because of the different driving voltage used, the results have been normalized by the square of the electric field. Assuming a similar

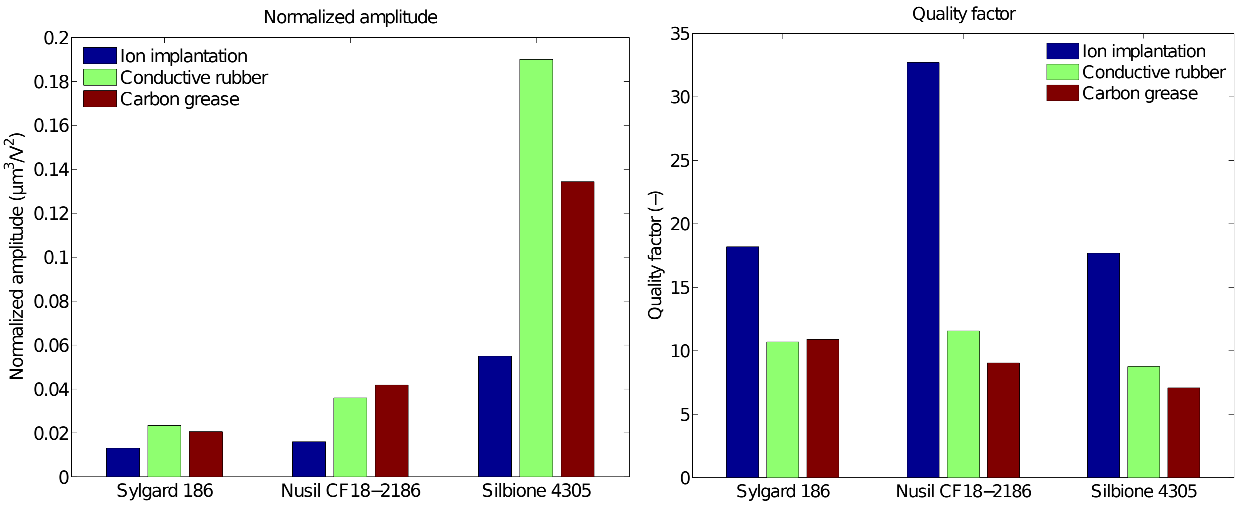

Figure 9. Left: Normalized static amplitude for the different electrodes and membranes combinations. Right: calculated quality factor Q from the measurement of the frequency and exponential decay of the oscillations for the different membranes and electrodes combinations.

permittivity for the 3 silicones, the static amplitude is a direct indication of the stiffness of the actuator sandwich. It is well visible from the graph that both the membrane dielectric and the electrodes contribute to the static displacement. Static displacement obtained for the carbon grease is almost equal (Sylgard 186), larger (Nusil CF18-2186) or smaller (Silbione LSR 4305) than the conductive rubber. This variation is due to the fact that the amount of grease applied on the membrane is hardly controllable, leading to a different stiffness impact.

The quality factor Q of the oscillations is shown on figure 9 right, and represents the viscous losses in the material, with a low quality factor for material with high viscous losses. The three tested polymers presents quality factors higher than one and thus all exhibited an under-damped behaviour with clearly-visible oscillations. Similar to the rise time, the harder polymers presents better quality factor than the softer one, but the electrode is again the dominating factor, with gold implantation leading to the highest Q values.

4.3 Electrical Impact of the Electrode

In the previous section, we have assumed that the impact of the electrodes was purely mechanical: contribution to the stiffness of the membrane and to the viscous losses. However, the primary role of the electrodes is to bring the charges to the membrane's surface. This doesn't happen instantly, but at an electrical response time τ_e, which is governed by the device's capacitance and the series resistance of the electrodes. It is therefore important that the electrical cut-off frequency is higher than the mechanical resonance frequency of the devices, in order to have a mechanically-dominated response, as was the case for the results presented here. However, if the electrode resistance is too high, then the speed is not dominated by the actuator's viscoelastic properties any more, but by the speed at which the charges are brought on the surface of the membrane, which can lead to a much slower response time. This is well visible on figure 10 which represents the response to a step voltage input of a ion-implanted Silbione LSR 4305 membrane. After a sucessful measurement at 40 V/μm, the field was increased to 50 V/μm. Because of a defect in the membrane, localized dielectric breakdown occurred. Ion-implanted electrodes present the advantage of self-clearing and can thus survive localized breakdowns. However, in this case, the current which was drawn from the amplifier during the breakdown, was high enough to damage the electrode at the contact point, which caused a dramatic increase of the series resistance. This can be seen on the 50 V/μm: the actuator is still reaching the expected strain, but much slower (rise time increased from 6 to 25 ms), and no oscillations are visible.

5. DISCUSSION

The characterization of the transient response of DEAs to a voltage step input puts in evidence two important facts:

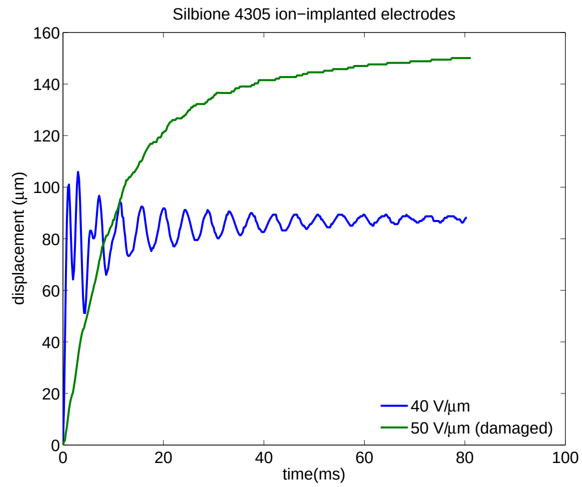

Figure 10. Illustration of going from a response time that is mechanically-dominated (40 V/μm) to a response time that is electrically-dominated (50 V/μm) due to an increase of the resistance of the electrode caused by a spark-induced damage. Ion-implanted electrodes on a Silbione LSR 4305 membrane.

- The static strain produced by an actuator is only part of the actuator's properties. The speed at which this strain is reached is also an important factor with important variations.
- The response of an actuator is determined not only by the mechanical properties of the dielectric membrane, but also by the electrodes whose impact, both on the static strain and response speed, cannot be neglected.

The impact of the silicone elastomer used as dielectric membrane is linked to the stiffness of the material. As expected, the stiffer the elastomer, the smaller the static strain. The impact on the rise time is reversed, with stiffer silicones presenting faster speeds and higher quality factor. The three silicones that have been tested present a fast response time and an under-damped behaviour with all three tested electrode types. These 3 particular silicones were selected precisely because preliminary tests have shown that they were good candidates for DEAs. This is not the case for all silicones, as shown on figure 11 for an ion-implanted membrane made with Nusil MED4901. Our batch of this elastomer has a shore hardness of Shore OO 42, which is very close to that of Silbione LSR 4305 (Shore A 5 or OO 45). However, the response of MED4901 shows a much more pronounced viscoelastic drift, which leads to a rise time of 350 ms, i.e. much higher than the 4–6 ms observed for the three polymers of this study in case of ion implantation. Additionally, in their study of the silicone DowCorning 3481 (Shore A 21–25), Michel et al. have observed a rise time of 590 ms with electrodes made out of conductive carbon paint,[4] i.e. much more than what we report for Sylgard 186, which has a similar hardness.

There are additional criteria in the selection of a silicone elastomer aside from output strain and response speed, such as dielectric breakdown strength, elongation at break, etc. Manufacturability also plays an important role: for our process, it is easier to work with polymers having long pot life and low viscosity in order to produce high quality membranes.

This study also puts in evidence the impact of the compliant electrodes on the response of DEAs. Even if the electrodes developed for DEAs can demonstrate extensive stretching before loosing conductivity, they are still physically present on the membrane and consequently have an impact on the actuator's performance. This is not only true for metal-based compliant electrodes, but also for the more commonly used carbon grease or conductive particles suspended in an elastomer matrix. Not only do the electrodes contribute to the stiffness of the membrane thus impacting the static strain, but they also have a crucial influence on the response time of the actuators. Ion implantation leads to very fast response time and no long-time viscoelastic drift for the 3 tested silicones, while carbon grease leads to a particularely pronounced viscoelastic drift. This slow drift is not particularly problematic for applications that require a rapid motion (all tested actuators exhibited underdamped, resonance-frequency-limited response) without the need to control the amplitude extremely precisely (haptic feedback, laser speckle

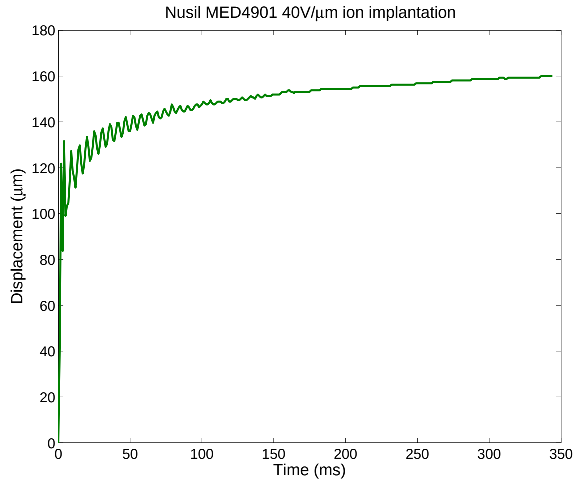

Figure 11. Ion-implanted membrane made with Nusil MED4901 (shore hardness OO 42). A slow viscoelastic response is clearly visible.

reduction, etc.). However, this drift is much more problematic for applications that require to hold a stable steady-state position, such as a mechanical positioner or an optical zoom.

It should be pointed out that the results presented for the conductive rubber cannot be taken as generally true for all electrodes of this type. Indeed, the behaviour of this kind of electrodes will be intimately linked with their composition, namely the type of conductive particles and quantity thereof, as well as the elastomer used as the matrix. For this study, we have used a proprietary formulation from Optotune AG which has been optimized to minimize the stiffening impact on the membrane while not adding too much viscous losses. This has allowed us to obtain actuators with conductive rubber electrodes that presented static displacement 2 to 3 times higher than their ion-implanted counterparts, while having reasonable rise time of less than 50 ms.

6. CONCLUSIONS

The present results show that the performance of dielectric elastomer actuators are governed not only by the dielectric membrane, but also by the electrodes, which contribute both the the stiffening of the membrane and to the viscous losses.

In addition to the strain performance of an actuator, its response speed is also of primary importance, as the major applications of DEAs not only require large displacements, but displacements that can be performed quickly, in a matter of a few tens to a hundred of milliseconds. We have identified three silicones of different hardness that have all exhibited under-damped behaviours and that can be used for applications requiring bandwidth of a few hundred hertz. Combined with ion implantation electrodes, rise times as fast as 6 ms can be obtained.

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