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On the failure modes and maximum stretch of circular dielectric elastomer actuators

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Abstract

Dielectric elastomer actuators have been widely studied theoretically and experimentally thanks to its superior attributes such as large deformation. The actuator failure has long been an issue placing barriers to large deformation in practical applications. In this paper, we investigate the various failure modes and the maximum stretch of the circular dielectric elastomer actuator. An analytical model depicting the actuation mechanism of the dielectric elastomer actuator is proposed to help analyze the failure onset. Several types of normally observed failure modes, i.e. electromechanical instability, loss of tension, and electrical breakdown, are analyzed theoretically based on the proposed model. A 3D figure that interprets the relationship of the corresponding factors and the possible failure modes are proposed as well, by which we could know the possible failure onset, as well as the associated maximum stretch under specific conditions. Experiments are carried out and the results are in accordance with the prediction by the proposed 3D figure.

1. Introduction

While dielectric elastomer actuators (DEAs) are readily applied in various practical fields thanks to its merits such as large deformation and high energy density [1–5], the study on failure modes of DEAs is still worthwhile as the maximum deformation that DEAs can achieve is largely limited by its failure onset in practical applications [6, 7]. It has long been an important topic to investigate the failure modes and maximum stretch of DEAs. DEAs suffer several types of failure modes such as electromechanical instability (EMI), loss of tension (LOT), and electrical breakdown (EB) [5, 8, 9]. Plenty of works focusing on the failure study have made great contributions to a better understanding of the failure mechanism of DEAs [5, 10–17]. In [5], Plante et al made theoretical and experimental analyses on pull-in and electrical breakdown. Zhao et al [11] were among the first researchers who proposed a method to study the electromechanical instability with Hessian matrix, which requires that the sum of the second-order variations of free energy W with respect to the stretches and electric displacement must be positive to ensure the safety of the DEAs. Later, similar methods based on Hessian matrix were also demonstrated by Leng [12], Diaz-Calleja [13], Liu [14], Zhu [15], and Huang [16]. This approach theoretically provides the criterion to identify the possible failure modes, and it is essentially an eigenvalue problem of the Hessian matrix. Later, the study of electromechanical instability based on the voltage-charge curve describing the phase transition was proposed and developed by Zhou [8], Huang [16], and Zhu [18]. This approach estimates the electromechanical instability based on the energy change represented by the area enclosed by the curve in a voltage-charge plot. The stable state requires the energy equilibrium of the system, which is reflected as the equal area representing the work done by external voltage. Compared with the Hessian matrix, the latter way is less complex yet intuitively shows the possible onset point of the instability across the whole process. Kollosche [19] investigated the failure modes of unilaterally-clamped DEAs based on the
voltage-charge curve theoretically and experimentally. In addition, an analytical model was proposed to analyze the failure, and both the temporal behaviors and failure onset can be captured by the analytical model. Recently, Godaba [20] employed a similar approach to study the instability wrinkles of a circular DEA. On the other hand, failure studies on DEAs of specific configuration, such as circular DEAs, were also reported in literatures [20, 21]. Circular DEAs are popular for their brief structure and multidirectional motion. However, limited work was reported on the impact of some factors such as the radii ratio and stretch rate on both the failure modes and maximum stretch. The failure onset and the associated maximum stretch, however, plays an important role in study of DEA applications, such as the maximum stroke of soft robots based on circular DEAs.

In this paper, we theoretically analyze the onset of the three types of failure modes based on the proposed analytical model which is capable of interpreting and predicting the performance of the circular DEAs by accounting for both the viscoelastic effect of this DE material as well as the inhomogeneous effect due to the circular configuration. The impact of some factors, like prestretch, stretch rate, and radii ratio, is also investigated. A 3D figure is then proposed based on the theoretical analyses to provide investigation of the possible instability modes and the associated maximum stretch, which also provides guidelines for optimization work of circular DEAs to suppress possible instability modes and increase maximum stretch. Groups of experiments are carried out and the results show that the experiments are in accordance with the predictions by the 3D figure. Details of the instability phenomena are discussed as well.

The rest of this paper is organized as follows. In section 2, we present the theoretical analyses on the different modes of instabilities. Experiments are carried out in section 3, as well as the discussion on the final results. The conclusion of this paper is presented in section 4.

2. Theoretical analyses

In this section, an analytical model capable of interpreting and predicting the behavior of circular DEAs is proposed firstly. Based on the proposed model, EMI, LOT, and EB are theoretically exhibited. Meanwhile, the relationship between failures and three factors, i.e. the prestretch, stretch rate, and the radii ratio of AA and PA are investigated. Subsequently, the 3D figure is introduced, as well as the instructions and drawing steps.

2.1. Analyses on instabilities

As schematically shown in figure 1, the circular DEA is manufactured by fixing a prestretched DE membrane on a rigid circular frame. Compliant electrodes are brushed on both sides of the central circular region. The membrane is thus divided into two regions, i.e. the active area (AA) with electrodes and the passive area (PA) without electrodes. When external voltage is applied to AA, AA will expand while PA contracts. As for AA, the equilibrium state requires that,

\[ \varepsilon \lambda_{\text{AA}}^4 \frac{V}{h_0^2} = \lambda_{\text{AA}} \frac{\partial W}{\partial \lambda_{\text{AA}}} \]

where \( \varepsilon \) is the elastomer permittivity with its value \( 4.16 \times 10^{-16} \text{ F/m} \) [22, 23], \( V \) is the applied voltage, and \( h_0 \) is the initial thickness of the elastomer 1 mm. The first term and second term on the left-hand side represent the mechanical stress and Maxwell stress applied to AA, respectively. \( \sigma_{\text{PA}} \) presents the elastic stress on the radial direction due to the expansion of PA and can be computed based on \( \sigma = \lambda_{\text{PA}}^2 \frac{\partial W}{\partial \lambda_{\text{PA}}} \). The term on the right-hand side presents the internal elastic stress due to the expansion of AA and \( W \) is the free energy function. AA suffers homogeneous deformation, which leads to \( \lambda_r = \lambda_\theta \) where the subscript \( r \) and \( \theta \) represent the radial stretch and
hoop stretch, respectively. So $\lambda_{AA}$ is used to represent the radial/hoop stretch of AA in the following sections. At the boundary between AA and PA, the hoop stretch of PA equals to the stretch of AA according to the non-slip theory [5, 24, 25], such that $\lambda_{\partial PA}$ at the boundary between $AA$ and $PA = \lambda_{AA}$. PA suffers inhomogeneous deformation as the outer edge is fixed on the rigid frame while the inner boundary varies with the expansion and contraction of AA, so the equilibrium state of PA requires that

$$\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_e}{r} = 0$$  \hspace{1cm} (2)

$$\frac{d\lambda_{\partial}}{dR_{\partial A}^r} = \frac{1}{R_{\partial A}^r}(\lambda_r - \lambda_{\partial})$$  \hspace{1cm} (3)

where the superscript $r_{\partial}$ and subscript $r_A$ represent the inner radius and outer radius of PA respectively [20, 24, 26–29]. And the radial stretch and hoop stretch of PA can be computed based on

$$\lambda_r = dr/dR_{\partial A}^r, \lambda_{\partial} = r/R_{\partial A}^r.$$

(4)

So, the inhomogeneous effect is reflected by the variation of the mechanical stress $\sigma_{PA}$ applied to AA, which is closely related to the radii ratio of AA and PA according to the equations above. Accordingly, instability of DEA is affected by the radius of both AA and PA as well. Radii ratio is determined by the configuration design and exhibits how much AA takes up the whole area of the membrane.

To account for the viscoelastic behavior of DEAs, the well-developed rheological model is employed as shown in figure 2: the spring $\alpha$ in parallel with the spring $\beta$ and dashpot $\eta$ [25, 30–34]. The stretches of the spring $\alpha$, spring $\beta$, and dashpot $\eta$ are denoted by $\lambda$, $\lambda^\alpha$, and $\xi$ respectively. Here, we adopt the multiplication rule which gives $\lambda = \lambda^\alpha \xi$. Thus Gent model employed to describe the free energy function $W$ can be written as equation (5) [24, 33].

$$W_{\text{stretch}} = -\frac{\mu^\alpha}{2} J_{\text{lim}}^\alpha \log \left(1 - \frac{\lambda^\alpha_0 + \lambda^\alpha_2 \lambda_0^2 - 3}{J_{\text{lim}}^\alpha} \right)$$

$$- \frac{\mu^\beta}{2} J_{\text{lim}}^\beta \log \left(1 - \frac{\lambda^\beta_0 \xi^2 - \lambda^\beta_2 \xi_0^2 + \lambda^\beta_2 \xi_0^2 \xi^2 - 3}{J_{\text{lim}}^\beta} \right)$$  \hspace{1cm} (5)

where $\mu^\alpha$ and $\mu^\beta$ are the shear modulus, $J_{\text{lim}}^\alpha$ and $J_{\text{lim}}^\beta$ are the stretch limits of the spring $\alpha$ and $\beta$. Therefore, equations (1)–(3) constitute the model describing the behavior of circular DEAs characterized by viscoelasticity and inhomogeneous deformation. The voltage then can be computed as follows. The stretch of AA is set to increase at a given stretch rate. Therefore, $\lambda_{AA}$ of each time node is known given a proper time interval $\Delta t$. At initial time $t = 0$, all of the stretches of AA and PA equal to prestretch. At $t_1 = 0 + \Delta t$, the stretch of the dashpot can be obtained according to equation (6). So the radial stretch of PA at $t_1 = 0 + \Delta t, \lambda_{\partial, PA}$ at $t_1 = 0 + \Delta t$ can be computed by solving equations (2) and (3) using shooting method. Accordingly, the required voltage $V_{t_1 = 0 + \Delta t}$ is obtained by plugging the related variables into equation (7). The next iteration loop is run for $t_2 = t_1 + \Delta t$, the values of all the associated variables are updated again and the above steps are repeated till the ultimate stretch. And the relationships between stretch $\lambda$ and the deformation $d$ of the actuator is given as equation (8) where $R_{AA}$ represents the initial radius of AA.

$$\frac{d\xi_r}{\xi_r \Delta t} = \frac{1}{3\eta} \left[ \frac{\mu^\beta (\lambda^\beta_0 \xi^2 - \lambda^\beta_2 \lambda_0^2 \xi^2 \xi^2)}{1 - (\lambda^\beta_0 \xi^2 - \lambda^\beta_2 \lambda_0^2 \xi^2 \xi^2 + \lambda^\beta_2 \lambda_0^2 \xi^2 \xi^2 - 3)/J_{\text{lim}}^\beta} \right. $$

$$- \frac{\mu^\beta (\lambda^\beta_0 \xi^2 - \lambda^\beta_2 \lambda_0^2 \xi^2 \xi^2)}{1 - (\lambda^\beta_0 \xi^2 - \lambda^\beta_2 \lambda_0^2 \xi^2 \xi^2 + \lambda^\beta_2 \lambda_0^2 \xi^2 \xi^2 - 3)/J_{\text{lim}}^\beta} \right.$$

$$(6a)$$
\[
\frac{d\xi}{\xi dt} = \frac{1}{3\eta} \left[ \frac{\mu^3 (\lambda^2 \xi^2 - \lambda_y^2 \xi_y^2 - \xi_y^2 \xi_y^2)}{1 - (\lambda_y^2 \xi_y^2 + \lambda_y^2 \xi_y^2 + \lambda_y^{-2} \xi_y^2 \xi_y^2 - 3) / J_{\text{lim}}^3} \right]
\]

\[
V = \frac{h_0}{\varepsilon^{1/2} \lambda_{\text{AA}}} \left( \frac{\partial W}{\partial \lambda_{\text{AA}}} - \sigma_{\text{PA}} \right) \lambda^{-1/2}
\]

\[
\lambda = \lambda_{\text{pre}} + \frac{d}{R_{\Lambda}}
\]

The parameters in the equations above are determined as follows. The value of \(\mu^2, \mu^3, J_{\lim}^3, J_{\text{lim}}^3\), and \(\eta\) are 16.2 kPa, 65 kPa, 105, 105, 0.5 mPa-s respectively. Detailed identification process please refer to our previous work [35]. Based on the calculation iterations above, the voltage-stretch curve can then be plotted as shown in figure 3. Meanwhile, the three types of failure modes, EMI, LOT, and EB, are marked on the voltage-stretch curve as well. The EMI is graphically interpreted in figure 3(b) with the voltage-charge curve. The two shaded regions (green region and blue region) have equal area, which is a construction analogous to the Maxwell rule in thermodynamic phase transition [20]. The green line interacts with the voltage-charge curve at three points that share the same energy since the enclosed area by the curve and x-axis represents the energy done by electric field. Interconversion of the elastomer stretch among the three points is thus possible, which leads to an unstable state where both flat and wrinkled regions can coexist [18–20]. That is the EMI wrinkle. The critical stretch for EMI can be obtained from figure 3(a) according to the critical voltage determined in figure 3(b). On the other hand, LOT is the case that there is no mechanical stress applied on AA, which means \(\sigma_{\text{PA}} = 0\). The critical value of stretch satisfying LOT can be obtained by keeping \(\sigma_{\text{PA}} = 0\) in equation (1), which means AA suffers external Maxwell stress only. Wrinkles also accompany LOT, though, the wrinkle form of LOT is different from the EMI wrinkles (further discussed in later section). Except for EMI and LOT, the membrane may also suffer EB when the electric field exceeds the electrical breakdown limit of the elastomer. This limit is determined by its dielectric strength \(E_B\). And the voltage corresponding to \(E_B\) is determined as

\[
\Phi_B = E_B H \lambda^{-2}
\]

\(E_B\) can be modified by adopting a power-law relationship as:

\[
E_B = E_B (1) \lambda^R
\]

where \(E_B (1)\) is dielectric strength when the stretch \(=1\) and the value of \(E_B (1)\) is taken as 30 MV/m according to Koh [36]. The superscript \(R\) shows how sensitive \(E_B\) is towards stretch. We take the value of \(R\) being 1.13 from literature [36]. Based on equation (9), the curve of EB can be plotted as shown in figure 3(a). Accordingly, the intersection of the EB curve and the voltage-stretch curve represents the onset of EB, and the associated value of the horizontal ordinate represents the maximum stretch before EB happens.

2.2. Analyses of the corresponding factors

The prestretch, radii ratio, and the stretch rate are three factors that show significant impact on the actuator behavior, as well as the failure and maximum stretch. The impact of the radii ratio and the stretch rate has been introduced above. The impact of prestretch can be reflected by the initial stress \(\sigma_{\text{Fl}}^0\) (the superscript 0 refers to...
initial state $t = 0$) which provides initial mechanical stress to AA. The initial stress $\sigma_{PA}^0$ resulted from the prestretched PA, is determined by the prestretch. So, the study can be divided into various groups based on its initial prestretch state. And in this paper, we choose three typical cases of which the prestretch are 2, 3 and 4 respectively. For each group, the value of radii ratio is set to be 1/10–1/2 and the value of the stretch rate is set to be 0.01/s–1/s.

A novel 3D figure which depicts the relationships of the two factors, stretch rate, and radii ratio, and the maximum stretch is developed to exhibit the possible failure and the related maximum stretch under a specific condition, as shown in figure 4. In addition to the information of maximum stretch and failure onset, we are also able to know the best condition and how these factors affect the maximum stretch according to the 3D figure. As shown in figure 4, the blue surface in the 3D figures represents the critical stretch that leads to EMI, the red surface represents the critical stretch leading to LOT, and the green surface represents the critical stretch leading to EB. $x$-axis shows the stretch rate, $y$-axis shows the radii ratio, and $z$-axis represents the maximum stretch. Therefore, any point in the 3D figures can be described by the corresponding coordinates $\{SR, RR, MS\}$, where $SR$, $RR$, $MS$ stand for the stretch rate, radii ratio, and maximum stretch respectively. $\{SR, RR, MS\}$ is a coordinate where the previous two value presents the specific conditions while the last value presents the associated maximum stretch.

The steps to obtain the 3D figure is described in table 1, and the three surfaces representing different failure modes are attained separately. We first draw the EMI surface. As for a circular DEA under a specific condition $\{SR_1, RR_1\}$, we are able to know the critical stretch $MS_1$ which leads to EMI according to figure 3. Therefore, we get a coordinate $\{SR_1, RR_1, MS_1\}$. Next, we keep $SR$ constant which is denoted as $SR_1$ while changing RR ranging from 1/10 to 1/2. Then we can get a group of values of MS associated with $\{SR_1, RR\}_{1/10–1/2}$. Following, IR is assigned to another value which is denoted as $SR_1$, and RR ranges from 1/10 to 1/2 again. Thus we get another group of values of MS associated with $\{SR_2, RR\}_{1/10–1/2}$. Repeat the steps above, and groups of MS are obtained given each specific $\{SR_i, RR\}_{1/10–1/2}$. Then we are able to draw the surface representing the EMI based on the obtained groups of data/coordinates $\{SR_i, \ldots, RR\}_{1/10–1/2, MS}$. To get the LOT surface, the critical stretch that satisfying $\sigma_{PA} = 0$ is required as discussed above. Similar to the way getting EMI, we vary RR from 1/10 to 1/2 while keeping $SR$ constant which is denoted as $SR_i$, so that we get a group of data which shows MS before LOT happened under a specific condition $\{SR_i, RR\}_{1/10–1/2}$. By repeatedly varying the stretch rate from 0.01/s to 1/s, we are able to get groups of MS representing the critical stretch for LOT. And the LOT surface is then available. For EB surface, the value of MS can be obtained based on the intersection of the EB curve and voltage-stretch curve shown in figure 3. Adopting the similar ways above, we get groups of the MS representing the critical stretch for EB. And we can draw the EB surface.

If the EMI, LOT, and EB surfaces are plotted in a single figure, we get the 3D figure capable of predicting the maximum stretch, as shown in figure 4. $x$-axis and $y$-axis in the figures refer to $SR$ and RR respectively. As is well known that prestretch is helpful to suppress EMI, therefore no EMI phenomenon is observed when the membrane is prestretched by 4 times or larger. Only LOT and EB surfaces exist in figure 4(c).

Introductions are given as follows on how to use the proposed 3D figure to predict the maximum stretch a DEA can achieve under a specific condition before any instability. Take the case prestretch $= 2$ as an example. For a certain condition that the stretch rate $= 0.5$/s and radii ratio $= 1/5$, the related point in the figure has the planar coordinate $\{0.5, 1/5\}$. We draw a vertical line with its $x$ and $y$ coordinates $\{0.5, 1/5\}$, and the vertical line intersects with the EMI, LOT and EB surfaces at three points, shown as the subfigure in figure 4(a). According to the subfigure, we can see that the vertical line intersects with EMI face firstly at point E, which means that EMI happens prior to LOT and EB under the condition $\{0.5, 1/5\}$. In other words, EMI would be the limitation to a larger deformation for the sample with $R_{AA}/R_{PA} = 1/5$ and stretch rate $= 0.5$/s. The coordinate value of $z$-axis of the point E is then the maximum stretch that the circular DEA could obtain. The same method works for prestretch 3 and 4. The 3D figure not only provides information about failure mode and the maximum stretch, it also tells how...
Table 1. Steps for drawing the 3D figure depicting the maximum stretch and instabilities.

| Step | Operation |
|------|-----------|
| A    | EMI surface |
| A1   | for m = 0: 100: |
| A2   | for n = 0: 100: |
| A3   | Set stretch rate (SR) = (0.01 + 0.01*m)/s, radii ratio (RR) = 1/10 + (1/2–1/10)*n/100; |
| A4   | According to figure 3, get the maximum stretch MS_{EMI-mn}; |
| A5   | Get the coordinate: 
|      | \{(0.01 + 0.01*m)/s, 1/10 + (1/2–1/10)*n/100, MS_{EMI-mn}\}; |
| A6   | n + 1; |
| A7   | end |
| A8   | m + 1; |
| A9   | end. |
| A10  | Draw EMI surface based on dataset \{SR, RR, MS_{EMI}\}. |
| B    | LOT surface |
| B1   | for m = 0: 100: |
| B2   | for n = 0: 100: |
| B3   | Set stretch rate (SR) = (0.01 + 0.01*m)/s, radii ratio (RR) = 1/10 + (1/2–1/10)*n/100; |
| B4   | By solving equation (1), get the maximum stretch MS_{LOT-mn} satisfying \sigmaPA = 0; |
| B5   | Get the coordinate: 
|      | \{(0.01 + 0.01*m)/s, 1/10 + (1/2–1/10)*n/100, MS_{LOT-mn}\}; |
| B6   | n + 1; |
| B7   | end |
| B8   | m + 1; |
| B9   | end |
| B10  | Draw LOT surface based on dataset \{SR, RR, MS_{LOT}\}. |
| C    | EB surface |
| C1   | for m = 0: 100: |
| C2   | for n = 0: 100: |
| C3   | Set stretch rate (SR) = (0.01 + 0.01*m)/s, radii ratio (RR) = 1/10 + (1/2–1/10)*n/100; |
| C4   | According to the intersection of EB and voltage-charge in figure 3(a), get the maximum stretch MS_{EB-mn}; |
| C5   | Get the coordinate: 
|      | \{(0.01 + 0.01*m)/s, 1/10 + (1/2–1/10)*n/100, MS_{EB-mn}\}; |
| C6   | n + 1; |
| C7   | end |
| C8   | m + 1; |
| C9   | end |
| C10  | Draw EB surface based on dataset \{SR, RR, MS_{EB}\}. |

End

to postpone or even avoid the possible instability. For instance, with the increase of radii ratio, EMI is gradually suppressed, which is shown as the blue surface bending upwards gradually. However, both EB and LOT are promoted with the increase of radii ratio. In addition, a moderate radii ratio and a moderate stretch rate are helpful to enlarge the maximum stretch according to the figure. Samples with way too large radii ratio would possibly suffer LOT and get smaller stretch since a large radii ratio means that AA takes much space of the whole membrane. In that case, the mechanical stress provided by the extension of PA is limited because of the small area of PA, and LOT is prone to happen. On the other hand, the membrane will suffer EMI if the stretch increases way too slow. Possible reasons may be viscoelastic attributes and overcharging. Therefore, the 3D figure offers guidelines to suppress possible failure and obtain larger deformation with optimized configurations. Based on the 3D figure, the local maximum is obtained when the planar coordinates are close to \{0.1, 0.4\}, which means that the sample with the stretch rate of stretch = 0.1/s and \(\frac{R_{AA}}{R_{PA}} = 0.4\) would generate the maximum stretch.

3. Experiments

Experiments exploring the maximum stretch under various conditions have been carried out in this section. Both the desired stretch and the experimental data, as well as the related actuating voltage for each certain
condition are firstly shown in figures 5, 7, and 9. The failure modes and maximum stretch are then shown as figures 6, 8, and 10.

Figure 5 shows the comparison between desired stretch and experimental data, as well as the computed actuating voltages for prestretch 2. And figure 6 shows the related maximum stretch predicted by the proposed 3D figure and the experimental records. In figure 5, the blue lines and the dotted lines represent the desired stretch and the experimental data respectively, and it shows that the experimental data agree with the desired stretch. The black cross stands for the failure onset point. The experimental result is also shown as the dotted line in figure 6 to demonstrate the ability of the proposed 3D figure on both maximum stretch and failure modes prediction, and the black cross with its coordinate \{0.05, 0.2, 2.28\} represents the position where real failure happens. The prediction of maximum stretch for this certain condition is exhibited in figure 6 as the blue surface lies at the bottom, which means that EMI happens prior to the other two failure modes in this case. And the associated coordinate of MS predicted by the 3D figure is 2.34. The related phenomenon picture is shown in figure 6(c), where EMI wrinkles nucleate near the edge between AA and PA. For another condition \{0.05, 0.4\}, the experimental result is shown as the dotted line in figure 6(b), and the black cross with its coordinate \{0.05, 0.4, 2.43\} represents the position where actual instability happens. The prediction is exhibited in figure 6 as the red surface lies at the bottom, which means that LOT happens first in this case. And the associated coordinate of MS predicted by the 3D figure is 2.45. The related phenomenon picture is shown in figure 6(d), where LOT wrinkles occur across the whole active area. According to the two samples of different conditions, both predicted
maximum stretches, \([0.05, 0.2, 2.34]\) and \([0.05, 0.4, 2.45]\), are in accordance with the actual maximum stretch, \([0.05, 0.2, 2.28]\) and \([0.05, 0.4, 2.43]\).

Figure 7 shows the comparison between desired stretch and experimental data, as well as the computed actuating voltages for prestretch 3. And figure 8 shows the related maximum stretch predicted by the proposed 3D figure and the experimental records. In figure 7, the blue lines and the dotted lines represent the desired stretch and the experimental data respectively, and it shows that the experimental data agree with the desired stretch. The black cross stands for the failure onset point. The experimental result is also shown as the dotted line in figure 8. For the condition \([0.025, 0.4]\), the black cross with its coordinate \([0.025, 0.4, 3.54]\) represents the position where actual instability happens. The prediction is exhibited in figure 8(a) as the blue surface lies at the bottom, which means that EMI happens first. And the associated coordinate of MS predicted by the 3D figure is 3.55. The related phenomenon picture is shown in figure 8(c), where EMI wrinkles nucleate in the central region. For the condition \([0.25, 0.4]\), the experimental result is shown as the dotted line in figure 8(b), and the black cross with its coordinate \([0.25, 0.4, 3.55]\) represents the position where actual instability happens. The prediction is exhibited in figure 8(b) as the red surface lies at the bottom, which means that LOT happens first in this case. And the associated coordinate of MS predicted by the 3D figure is 3.65. The related phenomenon picture is shown in figure 8(d), where LOT wrinkles occur across the whole active area. According to the experimental results of two samples of different conditions, both predicted maximum stretches, \([0.025, 0.4, 3.55]\) and \([0.25, 0.4, 3.65]\), are close to the actual maximum stretch, \([0.025, 0.4, 3.54]\) and \([0.25, 0.4, 3.55]\).
Figure 9 shows the comparison between desired stretch and experimental data, as well as the computed actuating voltages for prestretch 4. And figure 10 shows the related maximum stretch predicted by the proposed 3D figure and the experimental records. In figure 9, the blue lines and the dotted lines represent the desired stretch and the experimental data respectively, and the experimental data agree well with the desired stretch, which proves the effectiveness of our theoretical model. The black cross stands for the failure onset point. The experimental result is also shown as the dotted line in figure 10. For the condition \{0.025, 0.3\}, the black cross with its coordinate \{0.025, 0.3, 6.2\} represents the position where actual instability happens. The prediction is exhibited in figure 10(a) as the green surface lies the bottom, which means that EB happens prior to LOT. And the associated coordinate of MS predicted by the 3D figure is 6.2. The related phenomenon picture is shown in figure 10(c), where EB occurs and a sudden spark is observed. For the set of condition \{0.2, 0.5\}, the experimental result is shown as the dotted line in figure 10(b), and the black cross with its coordinate \{0.2, 0.5, 5.12\} represents the position where actual instability happens. The prediction is exhibited in figure 10(b) as the red surface lies at the bottom, which means that LOT happens first in this case. And the associated coordinate of MS predicted by the 3D figure is 5.3. The related phenomenon picture is shown in figure 10(d), where LOT wrinkles occur across the whole active area. According to the final experimental results, both predicted maximum stretches, \{0.025, 0.3, 6.2\} and \{0.2, 0.5, 5.3\}, are close to the actual maximum stretch, \{0.025, 0.3, 6.2\} and \{0.2, 0.5, 5.12\}. 

Figure 9. Comparison between desired stretch and experimental data, as well as the computed actuating voltages for prestretch 4. (a) Designed stretch for the condition \{0.025, 0.3\}, (b) Actuating voltage for the condition \{0.025, 0.3\}, (c) Designed stretch for the condition \{0.2, 0.5\}, (d) Actuating voltage for the condition \{0.2, 0.5\}.

Figure 10. Failure modes and maximum stretch for prestretch 4. (a) The maximum stretch under condition \{0.025, 0.3\}, (b) The maximum stretch under condition \{0.2, 0.5\}, (c) EB observed under condition \{0.025, 0.3\}, (d) LOT observed under condition \{0.2, 0.5\}. 

According to the recorded photos, two types of EMI wrinkles are observed. Figure 6(c) shows a type of EMI wrinkles that nucleates around the edge between AA and PA, while figure 8(c) shows another type of EMI wrinkles that nucleates in the central area of AA. This phenomenon might be attributed to the manual fabrication which leads to the inhomogeneous thickness of the compliant electrode. In spite of the different onset region, wrinkles of both cases are closely arranged, and the wavelength and amplitude are always tiny compared with the wrinkles of LOT. Besides, the EMI wrinkles nucleate in a small region, grow and spread until the final breakdown according to the experiments. On contrary, LOT is always observed as larger wrinkles across the whole AA region. According to figures 6(d), 8(d), and 10(d), the wavelength and amplitude of LOT wrinkles are apparently larger than EMI wrinkles. And LOT wrinkles are not as well ordered as EMI wrinkles because the wrinkles are formed in an unconstrained state due to the absence of mechanical stress \( \sigma_{\text{mech}} \) applied to AA. Therefore, a hint before LOT happens is always observed that the whole membrane would vibrate slightly the moment before LOT wrinkle form. Unlike EMI, LOT can be observed in all prestretch cases. As is commonly known, prestretch is helpful to suppress the happening of EMI. In our experiments, no EMI is observed in the case that the prestretch is 4.

4. Conclusion

In this paper, we theoretically investigate the failures of circular DEAs and analyze the maximum stretch a circular DEA could obtain considering three important factors. With the assistance of the proposed analytical model, three types of failures, i.e. EMI, LOT, and EB, are well exhibited. The approach to obtain the corresponding critical stretch, namely the maximum stretch, is also introduced based on the proposed model. And the impact of the three factors, i.e. the prestretch, stretch rate, and radii ratio, are also depicted based on the failure analyses. Subsequently, the 3D figure is proposed according to the computed maximum stretch under certain conditions. In addition to the information about the possible failure modes and the maximum stretch, the proposed 3D figure also tells how the stretch rate and radii ratio affect the maximum stretch. The information shown in the 3D figure offers guidelines to help optimize the configurations of circular DEAs in order to acquire a larger stretch. Groups of experiments designed for exploring the maximum stretch are carried out, and the final results show accordance with the maximum stretch predicted by the proposed 3D figures. What is more, phenomenon details of the EMI wrinkles and LOT wrinkles are discussed based on the recorded pictures. Different types of EMI wrinkles are observed, though, the wrinkles share some features in common like closely arranged form and tiny wavelength, which could be the reference for identifying the EMI onset. Possible causes leading to the discrepancy are finally discussed.

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