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Lightweight Mechanical Amplifiers for Rolled Dielectric Elastomer Actuators and Their Integration with Bio-inspired Wing Flappers

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Dielectric elastomer actuators (DEAs) are attractive for use to bio-inspired flapping-wing robots because they have high work density (specific energy) and can produce a large actuation strain. Although active membrane of dielectric elastomer is lightweight, the support structure that pre-tensions the elastomeric membrane is massive and it lowers the overall work density. If DEA was to be used successfully to drive the flapping-wing robots, its support structure must be as lightweight as possible. In this work, we designed, analyzed, and developed a lightweight shell using cross-ply laminate of carbon fibre reinforced polymer (CFRP) to pre-strain a rolled DEA. The CFRP shell was shown to weigh 24.3% of total mass for the whole DEA assembly while providing up to 35.0% axial pre-strain to a rolled DEA (BJB-5005 silicone rubber). This DEA assembly using the CFRP shell achieved 30.9% of the theoretical work density for BJB-TC5005 membrane at 33.5MV/m. In comparison, the spring rolls with a massive spring core were reported with overall work density merely 10-20% of the maximum value. Furthermore, this CFRP shell can amplify an axial DEA stroke into a larger transverse shell deformation. With these deformation characteristics, this CFRP shell and a rolled DEA were successfully integrated with an insect-inspired thoracic mechanism and they were shown feasible to drive it for flapping wing.

I. INTRODUCTION

Dielectric elastomer actuators (DEAs) can produce large actuation strains at high work density (specific energy), like natural muscles¹⁻⁵. These features make DEAs attractive for use as artificial muscles in many biomimetic robots^{3,4,6-17}. For example, Pei et al of SRI⁸⁻¹⁰ first developed rolled DEAs with a spring core, also known as spring rolls, for a small walking robot. Kovacs et al.^{11,18} developed and deployed spring rolls in an agonist-antagonist configuration to drive the arm-wrestling robot.

High work density of DEA could be very useful to flapping-wing robots, where weight is a major concern. In 2002, SRI researchers conceived the idea to develop a stack of membrane DEA for a flapping-wing mechanism^{3,19}. They found that work densities of the silicone or acrylic elastomers themselves are supposed to be high. However, the structural support needed to keep the elastomer membranes in tension dramatically lowers the total work density because the DEA assembly have only 10-20% active dielectric elastomer film mass as compared to the total weight^{3,5}. The initial attempt to use DEA to drive an approximately 500 gram flapping wing air vehicle was not successful^{3,19}. Yet, DEAs could be useful to a smaller flapping-wing air vehicles, which sizes less than 20 grams²⁰⁻²².

Rolled DEAs, albeit bigger in size, could possibly be configured as musculature for flapping wing micro air vehicle (FWMAV), just like flights muscles for insects. Fig. 1 illustrates a conceptual design to integrate a rolled DEA in a wing flapper. However, in practice, a passive support, such as a helical spring core^{8,10-13,23} or an external deadweight²⁴ that are needed to pre-stretch the rolled DEA, contributes to substantial weight. For example, a

helical spring core contributes to 90% of the total weight of the spring roll^{12,13}. To increase the overall work density towards the maximum value, the mass fraction of the support structure needs to be reduced. There is a strong need for a lightweight pre-tensioning structure for the rolled DEAs.

FIG. 1. Conceptual design to integrate a rolled DEA for direct driving a wing lever.

This paper will present design, analysis, and development of a lightweight shell using cross-ply laminate of carbon fibre reinforced polymer (CFRP) to pre-strain a rolled DEA. This study will show that use of the lightweight CFRP shell in the DEA assembly improves the overall work density. Interaction between the shell and the rolled DEA is important to the actuator performance. Subsequent sections will present a large-displacement analysis for the CFRP shell and its coupling with the rolled DEA. Furthermore, we shall show that this CFRP shell and a rolled DEA can be integrated with an insect's inspired thoracic mechanism, arranged in a configuration like insect's exoskeletons and musculature.

II. BRIEF REVIEW ON PRE-TENSIONING MECHANISMS

Various other pre-tensioning mechanisms were previously developed to pre-stretch bi-axially planar membranes of dielectric elastomer. For example, articulated frames, which consist of rigid plastic spars and flexible hinges, were used in bow-tie and bow actuators¹⁴, and diamond^{25,26} or lozenge²⁷ actuators. A flexible hinge can be made by cutting a notch into a plastic spar^{25,26} or applying a hinge tape between two spars²⁷. As a mechanism, the articulated frames are kept stable by bi-axial tensions in the dielectric elastomer membranes^{25,27,28}, but they may not be stable to keep uni-axial pre-tension in a rolled actuator. In addition, these frames are neither light in weight. In the example of a 9.2g bi-stable diamond actuator^{25,28}, the Delrin articulated frame contributed 98% of the total weight while the active dielectric elastomer membranes contributed merely 2% weight.

On the other hand, ‘Moonie’ or ‘Cymbal’ structures that have been integrated with piezoelectric stack actuators^{29–35} could be useful as the external frame for the rolled DEAs. These structures are metal^{36,37} and composite shells³⁷, that can pre-compress a piezoelectric stack and magnify the axial piezoelectric actuation (less than 1% strain) into a larger transverse stroke through the shell deformation. However, these metal and composite shells are as stiff as the piezoelectric ceramic stack. Hence, they are too rigid to be actuated by the rolled DEA.

III. THE PRESENT DESIGN AND PRINCIPLE

In this work, we designed, analyzed, and developed a lightweight shell using cross-ply laminate of carbon fibre reinforced polymer (CFRP) to pre-strain a rolled DEA. This CFRP shell is a flexure with distributed compliance like ‘Moonie’ or ‘Cymbal’ structures. It can amplify the axial stroke of the roll elastomeric actuator into a larger shell deformation in the transverse direction. As it is an external pre-tensioning structure, it can avoid the interfacial stress concentration, which was caused by a spring core to the elastomeric roll^{8,9,15,23,38}.

Figure 2 shows our design of a mechanical amplifier that can be used with rolled DEAs. The mechanical amplifier is a monolithic shell, which is shaped as an irregular convex octagon. The octagonal shell appears like a rhombus, whose four vertices were flattened. It has four identically inclined sides, two vertical sides and two horizontal sides that connect the inclined sides.

As shown in Figure 2a, this octagonal shell has an overall length of $2x_0$ greater than its width $2y_0$ such that its four inclined sides of length D subtend an small inclination α_0 above the horizontal plane of symmetry. When used to pre-stretch a rolled DEA, this shell is compressed longitudinally from $2x_0$ to $2x_p$ and widened simultaneously from $2y_0$ to $2y_p$ (see Figure 2b). As a result, the

FIG. 2. Operating principle of a mechanical amplifier for rolled DEA: (a) the shell and the rolled DEA before assembly (b) the shell, which pre-stretch the inactivated DEA roll, is under compression; (c) the shell is relaxed in compression and elongates longitudinally when the DEA is activated by Maxwell stress.

rolled DEA of an initial length L_0 is pre-stretched to a new length L_p .

Under activation by Maxwell stress, the rolled DEA elongates to the activated length L' (see Figure 1c) and produces a longitudinal extension e_x :

$$e_x = L' - L_p, \quad (1)$$

Activation of the rolled DEA reduces the shell compression and consequently the shell elongates to an activated length $2x'$. Meanwhile, the activated shell width reduces to $2y'$ and a transverse stroke e_y is generated:

$$e_y = 2y' - 2y_p, \quad (2)$$

Due to lever amplification effect as shown in Fig. 3, the inclined sides of the shell can move a transverse displacement larger than the longitudinal stroke under the axial compression.

Past design experience with amplified piezoelectric actuator^{31,32,36} suggested that the inclined beams for a rhombus-shape mechanical amplifier should subtend a small initial angle in order to achieve stroke magnification. The same design rule is expected to apply to our design of cross-ply CFRP amplifier, which deforms substantially for pre-tensioning a rolled DEA. However, this cross-ply CFRP amplifier is expected to flex and rotate into a larger deformation, as compared to the stiff piezo-mechanical amplifier.

FIG. 3. Angled view of the assembly of a rolled DEA and a cross-ply CFRP mechanical amplifier (Design I). In the assembly, the rolled DEA is under tension while the CFRP shell, i.e. the mechanical amplifier, is under compression

IV. LARGE-DISPLACEMENT ANALYSIS FOR MECHANICAL AMPLIFIER

A small-displacement analysis^{36,39} was previously reported for metal shells, which magnify a small piezoelectrically induced stroke. However, it is not adequate to account for large deformation. Pseudo-rigid-body model, which was previously used to analyzed compliant mechanism with notched joints⁴⁰, can be extended for large-displacement analysis for a flexible shell. This can be done by representing the flexural beam as a rigid linkage and lumping flexural flexibility as torsional springs at the linkage ends. Subsequently paragraphs will elaborate extraction of the lumped stiffness. In addition, interaction and coupling between the flexure and the rolled DEA will be analyzed.

This analysis considers a rhombus-shape flexure, which has four inclined beams and axially compressed by a force pair (see Fig. 4a). Its elastic deformation can be solved by applying the unit force method⁴¹. Fig. 4b shows a symmetry half of the flexure), which is a bent beam with two straight beam segments of equal length D and inclination α_0 above the horizontal plane of symmetry. As the bent beam is loaded with an axial force F at the free guided end point A , its loaded end travels horizontally by $2u_A$:

$$2u_A = \left(\frac{FD^3}{6EI} \right) \sin^2 \alpha_0, \quad (3)$$

in which EI is the flexural rigidity of the inclined beam. Derivation of this expression is elaborated in the Appendix A.

Meanwhile, point B of the bent beam is displaced vertically by v_B :

$$v_B = \left(\frac{FD^3}{12EI} \right) \sin \alpha_0 \cdot \cos \alpha_0 \quad (4)$$

As such, the bent beam is predicted with a linear magnification factor ($M.F.$):

$$M.F. = \frac{v_B}{u_A} = \frac{1}{\tan \alpha_0}, \quad (5)$$

FIG. 4. A linear elastic model for the rhombus-shape flexure, and comparison of the flexural deformation with rigid body rotation for the purpose of extracting the equivalent torsional stiffness

which is valid for small deformation. This suggests that the bent beam can amplify the transverse stroke if its beam inclination α_0 is less than 45° . Such flexural stroke amplification involved flexing and rotation of the inclined beam (see Fig. 4c). But, it is largely attributed to rotation, just like that achieved by a rigid-body lever, which is inclined and guided on two orthogonal planes symmetry (see Fig. 4d).

By comparing the transverse displacement induced by flexural deformation with that induced by rigid-body rotation, one can extract an equivalent rotation θ :

$$\theta = \frac{DFy}{12EI} \quad (6)$$

Hence, an equivalent torsional stiffness k_{α_0} for the inclined beam is:

$$k_{\alpha_0} = \frac{Fy}{\theta} = \frac{12EI}{D}, \quad (7)$$

in which Fy is the reaction moment. This expression only accounts for beam bending, but not axial beam compression. It may deviate from the actual measured deformation at small beam inclination.

Fig. 5 shows a pseudo-rigid-body model, which consists of the above-mentioned inclined lever and guided end supports by two torsional springs. Fig. 5b shows that the rigid-body lever rotates from an initial inclination α_0 to a loaded inclination α when it is compressed axially by a force F at the point A . The external axial force F is countered by the induced reaction forces and internal spring moment as shown in Fig. 5c. A vertical reaction force R_V is induced at the end point A on the horizontal symmetric plane, while a horizontal reaction force R_H is induced at the end point B on vertical symmetric plane. Meanwhile, the torsional springs at the end points A and B rotate and induce counter moments M_A and M_B respectively.

FIG. 5. Large-displacement analysis using a pseudo-rigid model, which consists of an inclined rigid-body lever and torsional springs at its two ends: (a) the initially unloaded state; (b) the loaded state: with (i) showing the kinematic relationship and (ii) indicating the reaction forces.

By applying the free-body force analysis, geometry identity, and Hooke's law to this pseudo-rigid-body model, the final inclination α can be solved as a function of the axial load F , such that

$$FD \sin \alpha = (k_A + k_B) (\alpha - \alpha_0), \quad (8)$$

in which the total hinge stiffness is equal to the equivalent stiffness, i.e. $k_A + k_B = k_{\alpha 0}$, according to Eq. 7

As a result of the lever rotation, the guided end B travels vertically by

$$v_B(\alpha) = y(\alpha) - y_0 = D(\sin \alpha - \sin \alpha_0), \quad (9)$$

whereas the other guided end A travels horizontally by

$$u_A(\alpha) = x_0 - x(\alpha) = D(\cos \alpha_0 - \cos \alpha). \quad (10)$$

As such, the magnification factor for this amplifier is a function of the inclinations,

$$M.F.(\alpha) = \frac{v_B(\alpha)}{u_A(\alpha)} = \frac{\sin \alpha - \sin \alpha_0}{\cos \alpha_0 - \cos \alpha}, \quad (11)$$

in which the loaded inclination was solved from Eq. 8.

Fig. 6a showed the assembly of a rolled DEA and the rhombus-shape mechanical amplifier. In the assembly, the rolled DEA is pre-stretched by the mechanical amplifier. As a result, the pre-tension F_p to the rolled DEA is equal to the pre-compressive force acting on the mechanical amplifier:

$$k_x(2x_0 - 2x_p) = k_L(L_p - L_0), \quad (12)$$

in which k_x and k_L are the axial stiffnesses, for the mechanical amplifier and the rolled DEA respectively, at the in-active state.

FIG. 6. Axial force equilibrium

A rolled DEA under a constant pre-tension produces a free axial stroke e_{free} when activated by a voltage. Due to coupling with the mechanical amplifier, the assembled rolled DEA reduces in tension and produces a smaller stroke e_x (see Fig. 6b) when activated by the same voltage.

During the activation, the reduced tension F' in the activated DEA is accompanied by reduced pre-compression in the mechanical amplifier. This is reflected in the force equilibrium:

$$k_x(2x_0 - 2x_p) - k_{x'}e_x = k_L(L_p - L_0) + k_{L'}(e_x - e_{free}), \quad (13)$$

in which $k_{x'}$ is the amplifier stiffness during the active state while $k_{L'}$ is the active rolled DEA stiffness. Force increment in the rolled DEA from the inactive state to the active state is contributed by tensile force increment due to further extension, i.e. $k_{L'}e_x$, minus electrostatically-induced axial force relaxation, i.e. $-k_{L'}e_{free}$. The negative force relaxation induced electrostatically is analogous to the effect of thermal strain on mechanical stress.

Substituting Eq. 12 into Eq. 13 yields the activated extension e_x of the actuator assembly in relation to the free stroke of a rolled DEA under constant pre-tension:

$$e_x = \left(\frac{k_{L'}}{k_{L'} + k_{x'}} \right) e_{free}. \quad (14)$$

This relationship suggests that the mechanical amplifier should be designed with minimal stiffness in order to maximize the axial stroke of the rolled DEA assembly.

V. FABRICATION

The CFRP shell and the rolled DEA were fabricated separately before they were assembled. Their fabrication details are described below.

A. Fabrication of CFRP shell

FIG. 7. Top view of two designs of the mechanical amplifiers, which was fabricated using one-ply CFRP: (top) Design I with a larger initial inclination angle; (bottom) Design II with a smaller initial inclination angle.

In this work, two rhombus-like-shaped amplifier designs were developed: one with a moderate inclination $\alpha_0 = 20^\circ$ (for Design I), and one with a small inclination $\alpha_0 = 5^\circ$ (for Design II) as shown in Fig. 7. The amplifier shell is made of a cross-ply laminate of carbon-fibre-reinforced polymer (CFRP). The composite laminate is manufactured from unidirectional carbon fibre preregs (HexPly 913) with epoxy matrix. It is molded into the desired shape using vacuum bagging technique⁴².

Fabrication steps for the CFRP shell are described below. Firstly, a cross-ply preregs were prepared by laying up two plies of unidirectional prepreg. The cross-ply preregs were cut into 10 mm strips. The prepreg strips were then laid up over an octagonal-shape basswood mould to form a closed-form shell, which has four inclined sides and four orthogonal sides as shown in Fig. 7. The shell wall consists of only a layer of the cross-ply preregs, except that two ends of the symmetric halves were lap joined by another two short strips of prepreg.

Afterwards, the prepreg lay-up is pressured on the mould using vacuum. This process starts first by laying up a vacuum bag assembly over the composite laminate and the mould. The vacuum bag lay-up consists of several layers, namely a permeable peel ply, a breather layer, and a non-permeable peel ply. Finally, the lay-up assembly was sealed in an air-tight envelope and thermally cured in vacuum at 21 inHg (-71.1 kPa) and 150

$^\circ\text{C}$ on a hot plate. Furthermore, a heat blanket was used to cover the vacuum bag in order to maintain a preset curing temperature and to minimize heat loss. After an hour, the lay-up was cooled down and the cured composite laminate was removed from the assembly and the mould.

As a result of this fabrication process, a cross-ply CFRP laminate has an average thickness of 0.363 mm. A cantilever made of the laminate is measured with an flexural rigidity of $EI=0.612\text{Nm}^{-2}$.

B. Fabrication of Rolled DEA

In the application to bio-inspired flapping-wing robots, a rolled DEA need to flap wings at least 5Hz, just like the wing beat frequency of a large insects such as a butterfly or a small bird such as a swallow⁴³. Therefore, need for speed will determined choice of dielectric elastomeric material to build the rolled DEA.

Acrylic elastomers are commonly use to make large-actuation DEAs, but they are subjected to viscoelastic effect that slows down the actuator's response. Silicone rubber is less viscous and more elastic^{44,45}, and consequently it makes faster DEAs though producing a lesser actuation strain as compared to that of the acrylic DEAs^{46,47}. In view of these, this work used silicone rubber (BJB TC 5005) to make a rolled DEA.

BJB TC 5005 silicone rubber was previously used to make large-deformation DEAs^{48,49}. In the previous works, a softener is usually added to the BJB silicone base, as much as 45% weight, in order to decrease the Young's modulus of the resulting dielectric elastomer membrane and consequently to produce a large actuation. However, the added softener resided in matrix of cured silicone rubber and resulted in a slow response. In order to achieve fast actuation response, we added only a little amount of softener, 10% weight to the base resin.

A rolled DEA is basically a roll up of a stack of multiple dielectric elastomer membranes, which were interleaved with compliant electrodes. Its fabrication requires a few steps: i) preparation of silicone dielectric elastomer (DE) films; ii) smearing of compliant electrodes and laying of copper foil leads, iii) laying up and stacking of electrode-clad dielectric elastomer membranes to form a laminate capacitor; and iv) rolling up the dielectric elastomeric laminate into a roll. Rolling process of the produced silicone membrane is done manually in a similar way to that developed by Zhang^{12,13} for acrylic elastomeric laminate.

BJB TC5005 silicone pre-polymers come in three liquid parts, namely, part A of silicone rubber base, part B of tin catalyst, and part C of plasticizer (softener)⁵⁰. These three pre-polymers need to be mixed and degassed before their mixture are cast and cured into a solid elastomeric film. The mixture was prepared in the following steps. Firstly, 10 part of A (silicone base resin) was mixed with 1 part of B (catalyst). Afterwards, 1 part of C (softener) was mixed with 10 part of the interme-

FIG. 8. Fabrication of rolled DEA

diate mixture (A+B). The end mixture (A+B+C) was degassed in vacuum to remove air bubbles. Finally, the liquid mixture was drawn cast over a mylar substrate using an automatic film applicator (Sheen 1137) and an applicator block. The wet spread of silicone mixture was then cured at room temperature for one day. Eventually, a solid film of silicone was cured on the mylar substrate and it was peeled off the substrate to yield a free DE film.

A flat laminate capacitor is a stack of multiple DE films, interleaved with compliant electrodes. It is prepared by laying up dielectric elastomer membranes and compliant electrodes. The steps of preparing a layer are described as follows. Firstly, a free DE film is pre-stretched bi-axially and tacked on (with silicone tackiness) a rigid acrylic frame. Subsequently, a rectangular shape electrode is coated on the DE film by smearing graphite powder (TIMREX Graphite KS6). Afterwards, a strip of copper foil (30 μ m thick, 3M 1181 tape) is adhered with silicone adhesive on the longer edge of each graphite compliant electrode. Each copper foil strip acts as both an electrical interconnect and a reinforcement layer, and it is eventually rolled up together with the DE membrane and fastened to an end cap by a conducting wire.

Subsequently, a dielectric layer of the pre-stretched DE film is transferred on the substrate of the first electrode-clad DE film, before it is topped by a second electrode-clad DE film. These steps yield two thinner dielectric layers, which is sandwiched between the two electrodes. Two thinner dielectric layers are preferred to a thicker single dielectric layer because a thinner layer can be drawn cast with better thickness uniformity and less bubbles trapped. In addition, electrical interconnects for opposite electrodes are staggered to avoid overlapping and electrical shorting. The fourth transfer of a dielectric layer eventually seals the top electrode. As shown in Fig. 8, a flat DEA laminate were done on a rigid frame.

In the final process, the flat laminated elastomeric ca-

pacitor is rolled up to form a DEA roll. The rolling process is assisted by a shaft with two end caps, each of which is temporarily fixed to the shaft by a set screw. Two copper strips in the laminate are wound over the end caps and the winding process slowly brings the flat DEA laminate off the substrate as shown in Fig. 8. A metal wire is then used to fasten the roll over the end caps and penetrate through the copper strips to complete the electrical interconnect. As such, the hoop pre-strain remains constant. After completing the steps above, the shaft is retracted from the roll. A finished prototype of a rolled DEA is obtained without axial pre-stretch as shown in Fig. 8.

C. Assembly

Finally, the rolled DEA is assembled with the CFRP shell. During the assembly, the rolled DEA is stretched by two tensioning nylon wires, of which each connects between a flat side of the CFRP shell and the end cap of the roll. The assembly has the rolled DEA pre-stretched to the desired axial pre-stretch as shown in Fig. 3. In summary, design parameters for the rolled DEA and the CFRP shells are summarized in Table 1.

VI. EXPERIMENTAL TESTING AND RESULTS

The mechanical amplifiers, i.e. CFRP shells, and rolled DEA were separately tested for their mechanical properties before they were assembled as a whole and tested for actuation performance.

A. Mechanical Properties

In the tests to measure the magnification factor and axial stiffness, a CFRP shell is oriented such that its longer axis is aligned vertically and it is compressed axially by dead weights, that were added incrementally. The induced deformation of the shell was measured using a laser displacement sensor (Keyence KC-2440) and photogrammetry.

Fig. 9 shows that the measured transverse displacement increases at a decreasing rate with an increasing axial compression. In the other words, the magnification factor decreases with increasing compression. This observed trend of diminishing magnification factor with compression agrees well with Eq. 11. In addition, it is noted that shell design, i.e., the initial beam inclination, strongly influence the attained stroke magnification. For example, the shell Design II, which has an 5° initial inclination, exhibited a higher initial magnification factor of 3.78, in comparison to 2.24 for the shell Design I, which has an 20° initial inclination. As both shell designs were compressed further, their inclined beams rotate with increasing inclination and consequently their magnification

TABLE I. Some design parameters for a typical rolled DEA and a mechanical amplifier, i.e. the CFRP shell

	Specifications
Rolled DEA (15% pre-stretch)	
Overall dimensions	Diameter = 11 mm Initial length, $L_0 = 54$ mm Final length, $L_p = 61$ mm
Number of wounds	7.5 wounds
Weight	5.3 gram
Dielectric elastomer membrane	
Material	BJB TC-5005 A/B, 10% Part C
Initial film thickness	110 - 140 μm thick
Number of DE layers	4
Compliant Electrode	
Material	Graphite powder, Timrex KS6
Application method	Smearing
Coated area	157.5 x 38.5 mm ²
Active area (overlap)	157.5 x 30.5 mm ²
Number of coated area	2
Interconnect/Lead	
Material	Copper foil, 3M 1181 tape
Dimension	160 x 8 x 0.017 mm ³
Amplifying Shell (Design I)	
Material	CFRP, HexPly 913 prepreg
Overall length (initial)	$2x_0 = 122$ mm
Overall width (initial)	$2y_0 = 51$ mm
Inclined segment length	$D_i = 49$ mm
Beam inclination (initial)	16°
Weight	~ 1.7 gram

factors decrease. For example, the magnification factors decreased to 1.49 for the shell Design II and 1.26 for Design I respectively when both shells were compressed by 15% pre-strain (with reference to the inclined beam lengths D respectively).

FIG. 9. Transverse deformation of the mechanical amplifier under axial compression

FIG. 10. The axial load required to compress the mechanical amplifiers

FIG. 11. Axial stiffness for CFRP shells and rolled DEA

Fig. 10 shows that the force required to compress the CFRP shell increases at a decreasing rate with increasing compressive strain. This observation agrees with the pseudo-rigid model, which parametrically plots $F(\alpha)$ versus $u_A(\alpha)$ using Eq. 8 and Eq. 10 respectively. Deviation between the measurement and theory could be attributed to a more complex geometry and deformation of the actual shell as compared to the rhombus shape in the model.

In addition, Fig. 11 showed that the measured axial stiffness of the CFRP shell decreases with increasing beam inclination. This inclination dependence agrees with Eq. 3 for initial axial stiffness: $k_{x0} = F/(2u_A) = 6EI/(D^3 \sin^2 \alpha_0)$. The shell Design I with an 20° initial inclination is axially softer than the shell Design II with an 5° initial inclination. As the shells are compressed further from 10% to 35% axial strain, axial stiffness of the shell Design I decreases from 102N/m to 48 N/m, whereas axial stiffness of the shell Design II decreases from 1027N/m to 282N/m.

On the other hand, transverse stiffnesses of the CFRP shells are much smaller than their axial stiffness, but less sensitive to beam inclination. The transverse stiffness for

the shell Design I was measured to be 41.9N/m, whereas that for the shell Design II is 43.2N/m.

Axial stiffness for the rolled DEA was also measured, but using a universal tensile tester (Instron 5565). The rolled DEA has an initial diameter of 11 mm and an initial length of 54mm. Figure 11 shows that axial stiffness of the rolled DEA decreases from 374 N/m to 167 N/m as the pre-strain increases from 10% to 35%. This is attributed to Poisson's ratio effect such that the roll diameter reduces with increasing axial stretch. This rolled DEA was found axially stiffer than CFRP shell Design I but softer than shell Design II. To exert the same pre-strain to a rolled DEA, a softer shell is compressed more. It was measured that a softer shell Design I was compressed 7%, in comparison to a 2% compressive strain in the shell Design II, to pre-stretch a rolled DEA by 15% strain.

FIG. 12. Deformation of CFRP shells when activated by rolled DEA under high voltages

FIG. 13. Axial actuation of the rolled DEAs, which was assembled in the shell Design I, at various pre-stretch

FIG. 14. Effect of pre-stretch on the breakdown electric field and ultimate actuation strain for the rolled DEAs, which was assembled in the shell Design I

FIG. 15. Effect of CFRP amplifier design on actuation strains for the rolled DEA

B. Quasi-static Actuation

Fig. 12 showed an assembly of a CFRP shell amplifier and a rolled DEA. In the quasi-static actuation test, the rolled DEA in the assembly was activated using a high voltage power supply (Trek Model 610E) while the shell deformations were measured using a laser displacement sensor (Keyence KC-2440). The driving voltage is increased at a 500V step for 10s until it reaches the breakdown voltage. Meanwhile, leakage current was limited to a threshold not more than $80\mu\text{A}$ to prevent excessive current surge during the electrical breakdown. Readings of voltage and displacement were monitored and collected using a data logger (NI) connected to a PC.

Pre-stretch is known to have profound effect on DEA performance⁵¹. The first test is to find out the optimum pre-stretch that maximizes the axial actuation of the rolled DEA. Samples of rolled DEA were prepared with varying biaxial pre-strains: 10%, 15%, 25%, and 35%, while their electrode length remains the same to be

$L_p=30.5\text{mm}$. These samples of rolled DEAs were subsequently assembled in the shell Design I of low axial stiffness

Fig. 13 shows that the axial actuation or the stroke increases quadratically with the driving voltages. The maximum stroke and breakdown voltage vary with the pre-strain. Figs. 13 and 14 showed that the optimum pre-strain is found to be 15%. At this 15% pre-strain, the rolled DEA sustained a breakdown voltage of 6.2kV (i.e. dielectric strength of 33.5MV/m) and produced a maximum axial stroke of $e_x=1.87\text{mm}$. However, the breakdown electric field decreases with further pre-stretch beyond the optimum one because the thinner the dielectric membrane is the more it is susceptible to localized stress concentration and puncture^{52–54}. Failed samples of over-voltage rolled DEAs usually have the burnt spots located at the inner region of compliant electrodes, but not near to the copper foil strip. There is no clear evidence if the copper foil strip reduced dielectric strength.

Fig. 15 showed the influence of CFRP shell design on the actuation of the rolled DEA, which was pre-stained the same at 15%. The actuator assembly with soft shell Design I produces a maximum axial stroke $e_x=1.87\text{mm}$ and a smaller magnification factor at 1.79. In contrary, the rolled DEA assembly with the stiff shell Design II produced a maximum axial stroke of $e_x=0.70\text{mm}$ and a transverse stroke magnification of 3.5 times. The rolled DEA in the stiff shell produces lesser axial stroke than that in the soft shell because it broke down at a lower breakdown voltage of 4.4kV. These findings suggest that the 15% pre-stretch may not be the optimum for the same prepared DEA in the stiffer shell as it was for that in the soft shell. Further systematic experimental studies are needed to understand complex interaction between rolled DEA and its pre-tensioner because dielectric strength of DEA depends on many factors, including material, thickness, pre-stretch, boundary conditions and so on^{51,52,54}.

C. Pulsed Actuation

Next, the rolled DEA in the CFRP shell (Design I) was tested for a transient step response. The rolled DEA was activated with a square voltage pulse, which was ramped up from 0V to 6kV in 0.1s and subsequently held constant at 6kV for 20s before it was ramped down to 0V in 0.1s and finally settled at the low voltage. The time for voltage ramp, up or down, depends on charging current. In this test, a current threshold of $80\mu\text{A}$ was set to the voltage supply. This current threshold is adequately high so that charging or discharging of this DEA, which has a capacitance in the order of 1nF, is faster than its viscoelastic response.

Under this pulsed activation, the rolled DEA behaves like a linear viscoelastic solid⁵⁵. It creeps like the membrane DEAs^{44,45,56,57}. As shown in Fig. 16, during the voltage ramp to 6kV in the first 0.1s, the rolled DEA produced an immediate elastic stroke of 0.99 mm axially.

FIG. 16. Creep behaviour (strain versus time) for the rolled DEA, which was pre-stretched for 15% by shell Design I, during activation and de-activation

FIG. 17. Hysteresis loop (strain versus driving voltage) for the rolled DEA, which was pre-stretched for 15% by shell Design I

Afterwards, it elongated gradually to the final stroke of 1.80 mm at the 20s while the voltage is held constant at 6kV. The delayed stroke increases at a decreasing rate like a decaying exponential function, with a time constant of approximately 2s and an delayed amplitude of 0.80mm. The 63% of the final stroke happens at the 0.2s. Upon de-activation, the rolled DEA was restored to its in-activated length almost immediately (in 0.1s of the voltage ramp-down time). Yet, its residual stroke of 0.12mm (7% of the final stroke) took a few seconds to diminish.

Plotting the induced stroke versus the driving voltage, during the pulsed actuation cycle, yields a hysteresis loop as shown in Fig. 17. The effect of viscoelastic response is clearly seen in the hysteresis loop. Elastic stroke increased quadratically with the increase of driving voltage. The delayed stroke increased gradually while the driving voltage was held constant. Upon deactivation, the recovered stroke was almost immediate but the residual stroke remained for a while.

TABLE II. Comparison among various rolled DEA reported so far

	Pei et al (2002) ^{Ref. 8}	Zhang et al (2006) ^{Ref. 12}	Rajamani et al (2008) ^{Ref. 23}	Benslimane et al (2010) ^{Ref. 17}	This work
Dielectric Elastomer (DE)	Acrylic VHB	Acrylic VHB 4910	Acrylic VHB 4905	Silicone Wacker Elastosil RT 625	Silicone BJB TC-5005
Electrode material	Carbon black mixture	Graphite powder (Timrex LB1300)	Carbon grease	Corrugated silver	Graphite powder (Timrex KS6)
DE Roll Diameter	12 mm	12 mm	12mm [#]		11mm
DE Roll Length	70 mm	45 mm	116 mm	100 mm	61 mm
Pre-stretch ratio	5 x 1	3 x 6.5	2.3 x 3.5	1 x 1	1.15 x 1.15
Pre-tensioner	Spring	Spring	Spring	Core free	Shell Design I
Pre-tensioner stiffness		200 N/m	10.75 N/m	0 N/m	103.0 N/m
Rolled DEA Stiffness	1250 N/m	1440N/m ⁺	157N/m	3052N/m ^{\$}	305.0N/m ^{//}
Maximum active strain	26.0% ^{//}	31.25% ^{//} [~]	12.8% ^{//} (max)	7.0% ^{//} (max)	6.1% ^{//} 11.0% [⊥]
DE Breakdown field (E_b)	109 MV/m	68.2MV/m [*]	36MV/m [!]	35 - 40 MV/m	33.5MV/m
Frequency	Up to 5Hz				5-10 Hz
Pre-tensioner weight		7.2 g			1.7 g
Total Weight	11 g	8 g			7.0 g
Static Work Density	7.77 J/kg	2.25 J/kg			0.133J/kg
% of max. work density	11.0% [§]	20.7% [§]			30.9%

// longitudinal, ⊥ transverse

+ Calculated using max blocking force / max stroke = 7.2N / 5mm

~ Calculated using max displacement of actuator / active length = 5mm / 16 mm

* Calculated using activation voltage / [initial thickness / (pre-stretch factor)] = 3500V / [1mm / (3 x 6.5)]

! Calculated using max. voltage / thickness = 3330V / 93.92μm

Calculated using 2*core radius + 2*thickness* no. of layers = 2*4.77mm + 2*0.09392mm*14.25

\$ Calculated using blocking force / max stroke = (3N/cm²*500cm*0.0082cm) / (6.5%*62mm)

§ VHB properties: 1.8MPa Young's modulus, 4.7 dielectric constant, 960kg/m³ density

In summary, the rolled DEA made of BJB 5005 can be activated with 5Hz cycles, to achieve 63% of the final stroke. This speed is good enough for robotic applications^{44,45}. It could possibly be used to drive a flapping-wing robot. For faster speed, the dielectric elastomeric material for the actuator needs to be more elastic and the voltage supply needs to ramp voltage up or down faster.

D. Comparison with Previous Works

Table 2 lists the specifications and performance of the reported rolled DEAs, based on either acrylate elastomer (VHB) or silicone rubber. Either a spring core or this CFRP shell was used as the support structure to pre-stretch the rolled DEA. Performance of these rolled actuators varies substantially. The comparison shows that silicone-base DEAs produces less actuation strain and much less work density as compared to those VHB-base DEA. Poorer performance of silicone actuators is attributed to a lower dielectric strength and a lower pre-stretch. Yet, this study suggests that silicone rubber could produce faster response than VHB if it was free

of softer.

Ideally, one would like the actuator assembly to achieve a high overall work density. However, the support structure increases passive mass and reduces the overall work density to only a fraction of the maximum value, achievable by the active dielectric elastomer. Hence, it is desired to reduce the passive mass fraction of the support structure that pre-stretch the rolled DEA. In this work, a CFRP shell contributes only 24.3% of the total 7 gram weight of the actuator assembly and it contributes to 25.2% of the total actuator axial stiffness of 408N/m. In comparison, a spring core is reported with a 90% mass fraction of a spring roll and a 7-15% stiffness fraction^{8,12}. In short, the current CFRP shell is lighter in weight and could support an even stiffer and larger roll of DEA.

The effectiveness of a lightweight support structure to a DEA assembly can be measured by comparing the overall work density of the actuator assembly with the maximum work density of active elastomer itself. The theoretical maximum work density of active elastomer can be estimated from the specific energy, $\frac{\sigma_{\max}^2}{2Y\rho}$, where $\sigma_{\max}$ is the maximum Maxwell stress at the dielectric strength E_b , Y is the Young's modulus, and ρ is the density of the

elastomer membrane. As compared to silicone rubber, acrylic elastomer has a much higher theoretical maximum work density due to high dielectric strength at a larger pre-stretch.

BJB-TC5005, which has a Young's modulus of 1.02 MPa, a relative dielectric constant of 3.0, and a density of 1009 kg/m³, is estimated with a maximum work density of 0.43 J/kg at 33.5MV/m. The rolled DEA assembly produced a measured maximum axial stroke of 1.87mm and a total axial stiffness of 408.0 N/m. The overall work density of the BJB rolled DEA assembly (inclusive of CFRP shell) is calculated to be 0.133 J/kg at 33.5MV/m, based on the axial work done by the rolled DEA. This overall work density is 30.9% of the theoretical maximum value for BJB-TC5005. In comparison, the spring roll with a massive spring core achieved a lesser percentage of the theoretical maximum work density. For example, Pei's 11 gram VHB spring roll⁸ attained 11% of the maximum value, whereas Zhang's 8 gram VHB spring roll¹² attained 20.7% of the maximum value. If the lightweight CFRP shell was used in place of the massive spring core, the VHB actuator could possibly achieve a higher overall work density.

E. Integration with Insect-inspired Wing Flappers

This CFRP shell and rolled DEA could be used to drive a bio-inspired wing flappers. As an illustration, Fig. 18 shows an assembly of CFRP shell, a thoracic mechanism, and a rolled DEA in an arrangement resembling that of insects' exoskeleton and musculatures. The insect-inspired thoracic mechanism^{58,59} consists of a pair of wing levers, which are connected to each other through a tergum plate and rotates about a torsional-spring-supported fulcrum each. Previously, we activated such thoracic mechanism by using a vibration motor⁵⁹ that reciprocated its tergum plate and caused wing flapping about the fulcrum. In this case, the tergum plate is reciprocated by transverse displacement of the CFRP shell upon pulsed activation by the assembled rolled DEA.

FIG. 18. Integration of a CFRP shell and rolled DEA with a thoracic mechanism to form an insect-inspired wing flapper

This assembly of the insect-inspired wing flappers with DEA musculature is not optimized yet in terms of work

density, mass fraction, and stiffness fraction. The whole assembly weighs 10.47 grams, of which 50% is due to the rolled DEA, 17.4% is due to the CFRP shell, and 17.8% is due to the thoracic mechanism. In this assembly, the CFRP shell is stiffened by the thoracic mechanism and it needs to be driven harder by the rolled DEA, as compared to a free shell. This wing flappers prototype proved the concept of indirect drive by a rolled DEA through a CFRP shell. Its wings (6-cm long and 0.16 gram each) were beaten with a merely 5-10° stroke at 1Hz. The actuator assembly have a great room for improvement, in order to achieve better flapping capability in terms of wing beat frequency and wing stroke.

VII. CONCLUSIONS

High work density is an important characteristic of DEA, which could be useful to drive bio-inspired wing flappers. However, a support structure, which is needed to pre-stretch the DEA, contributes to significant passive mass and lower the overall work density, as compared to the maximum work density achievable by active elastomer. This work showed that use of a lightweight CFRP shell as the support structure significantly reduces the passive mass fraction and improves the overall work density. Our CFRP shell was shown to weigh 24.3% of total mass for the whole DEA assembly while providing up to 35.0% axial pre-strain to a rolled DEA (BJB-5005 silicone rubber). This DEA assembly using the CFRP shell achieved 30.9% of the theoretical work density for BJB-TC5005 membrane at 33.5MV/m. This percentage of the maximum work density is higher than the reported 10-20% for VHB spring rolls, which have a spring core weighing more than 90% of the total weight.

In addition, this work successfully integrated a CFRP shell and a rolled DEA into an insect-inspired thoracic mechanism and showed that this concept of bio-inspired exoskeleton with DEA musculature is feasible to drive flapping wings. This case study showed that the successful drive by DEA requires a proper system design in terms of component mass and stiffness. In future, we shall plan to use other elastic dielectric elastomer to build a more powerful DEA and optimize the CFRP shell. In addition, DEA mass fraction should be increased further just like that of insects's flight muscles, which out-weigh its exoskeleton.

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Appendix A: Derivation of Bent-Beam Deformation

Deformation of a bent beam, as shown in Fig.19 can be calculated using the unit force method⁴¹. For illustration, derivation of the horizontal displacement $2u_A$ at the point A of the bent beam under a horizontal force F is presented below.

FIG. 19. Free body force diagram for a bent beam

With reference to Fig.19, the true moments internal to the beam segments are:

$$\begin{aligned} M(s) &= M_A - F s \sin \alpha_0, \text{ and} \\ M(s') &= M_A - F (D - s') \sin \alpha_0, \end{aligned} \quad (\text{A1})$$

in which the reaction moment at the point A is determined to be $M_A = \frac{1}{2}FD \sin \alpha_0$ from moment equilibrium of the bent beam.

Upon substitution of M_A , the true moments becomes

$$\begin{aligned} M(s) &= F \left(\frac{D}{2} - s \right) \sin \alpha_0, \text{ and} \\ M(s') &= -F \left(\frac{D}{2} - s' \right) \sin \alpha_0. \end{aligned} \quad (\text{A2})$$

The virtual internal moments are obtained below by removing all external forces and applying only a unit force at the same location and the same direction as $2u_A$:

$$\begin{aligned} m(s) &= -s \sin \alpha_0, \text{ and} \\ m(s') &= -(D - s') \sin \alpha_0. \end{aligned} \quad (\text{A3})$$

The horizontal displacement $2u_A$, which is induced by the horizontal force F , is determined to be:

$$\begin{aligned} 2u_A &= \frac{1}{EI} \int M(s)m(s)ds + \frac{1}{EI} \int M(s')m(s')ds' \\ &= \frac{D^3 F}{6EI} \sin^2 \alpha_0. \end{aligned} \quad (\text{A4})$$

Similarly, the transverse displacement at the apex of the bent beam can be determined using the same method.

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