Development of elastomeric flight muscles for flapping wing micro air vehicles

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Development of elastomeric flight muscles for flapping wing micro air vehicles

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ABSTRACT

Common drivers of flapping wings are a motorized crank mechanisms, which convert the motor rotation into wing reciprocation. Energetic efficiency of the motorized wing flappers can be quite low due to the lack of elastic storage and high friction. This paper relook into the flapping flight apparatus of natural flyers and draw inspiration to develop flight muscles capable of elastic storage, in addition to the frictionless thoracic compliant mechanisms. We review the recent findings on the use of dielectric elastomer actuators as flight muscles. We also discuss the challenges and the prospects of using dielectric elastomer minimum energy structure to create large and fast bending/unbending, possibly for wing flapping.

Keywords: Dielectric elastomer actuator, flight muscles, flapping wing, compliant mechanisms

1. INTRODUCTION

Birds and insects can fly agilely in open sky or garden. Their flight adapts to the environment and need. For example, a hummingbird can hover while feeding on flower's nectar; it fly forwards for distant migration. Birds flights are robust to avoid obstacles in bushes as they transit smoothly to perch on a tree branch or a ledge of a building. Further study shows that aerodynamic efficiency of flapping wings at a relative low speed can be higher than that of rotating propeller. In addition, flapping flight is relatively quiet at a low travel speed as compared to the noisy quad-copters. These natural flyers have inspired many research efforts to develop flapping-wing micro air vehicles in the past decades.

Flapping-wing micro-air vehicles (FWMAVs) of hummingbird size are useful and handy for quiet surveillance indoor and ourdoor in the crowded urban. Common drivers of flapping wings are a motorized crank mechanisms, which convert the motor rotation into wing reciprocation. Yet, their development is more challenging as compared to the development of quadcopters. These challenges include: 1) moderate efficiency of a small motor (less than 5 gram); 2) sophisticated design of crank mechanism for wing reciprocation, 3) the friction over the crank joint due to the normal reciprocated load; 3) need for high torque to drive a pair of wings (less than 30cm span); 4) substantial loss of inertia power to accelerate and decelerate the wings. As a results, the flapping wing flight appear energetically less efficient than the rotor flight, which involve a much simple mechanism, i.e. spur gear trains that overcome only a tangential load.

The energetic efficiency of wing flappers can be quite low to convert an input electric power to an aerodynamic force. For example, a 5 gram rigid-body wing flappers based on a motorized crank-slider mechanism can convert only 30% of its shaft power to to keep it aloft in air while the rest of the power input is lost through friction and inertial power loss. In the absence of elastic storage, friction loss contributes to a big chunk of the energy loss. Elastic elements can effectively recover the kinetic energy of 25Hz flapping wings, but increase the starting torque requirement. After all, the energetic efficiency of flapping wings are still low at a 2-3 gram force/W thrust to electric power ratio, much lower than a faster rotating propeller's 5 gram/W driven by the same motor. This could be due to the high torque requirement and moderate motor efficiency.

A relook into the flight apparaturs of natural flyers could inspire engineering innovation to solve these problems of FWMAV of hummingbird sizes. We shall first review the anatomy of flight apparatus of a hummingbird, a dragonfly, and a housefly before reviewing the bio-inspired thoracic mechanisms developed so far. Next, we evaluate the feasibility of developing artificial flight muscles out of dielectric elastomer actuators.

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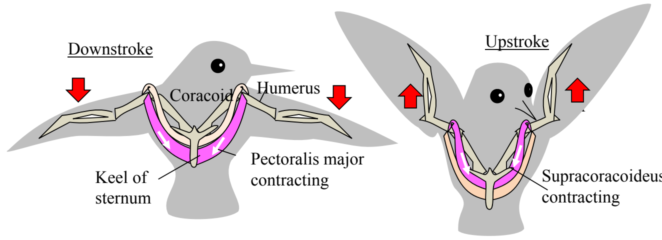

Figure 1. Hummingbird and its flight apparatus

2. FLIGHT APPARATUS OF NATURAL FLYERS

Among the natural flyers, hummingbirds are few birds that can hover like Dipteran insects. A small hummingbirds (Archilochus colubris)[1] weigh as light as 3.7 gram, beating two 45mm long wings for a 120° stroke fast at 52Hz. Giant hummingbirds (Patagona gigas)[1] weigh 20gram, beating two 130mm long wings for 120° stroke slower at 15Hz. As shown in Figure 1, a hummingbird has massive muscles: (1) a prominent breast muscle, called pectoralis major, that originates from the sternum (i.e. the breastbone) and attach near the bottom of humerus (i.e. the upper arm bone); and (2) supracoracoideus muscle, which connects between the keel of the sternum and the top of the humerus. When the pectoralis major contracts, wings beat down. In the upstroke, wings are raised by the contraction of supracoracoideus muscle. According to Tobalske's study[2] on rufous hummingbird (3gram), the strain of the hummingbird pectrolia muscles is 10.8% at a 42 Hz wingbeat frequency. There were no data available on the stress change of the hummingbird muscles. In comparison, pigeons have the pectrolia muscles undergone with a maximum shortening of 8-12% strain and 50-58 kPa stress during 7Hz wing beating.[3]

A Brauer dragonfly (Anaxparthenope Julius)[4] of 0.79 gram weight have a pair of fore wings that span for 100mm and a pair of hind wings that spans for 97mm. Their wings beat normally for a stroke angle close to 50-60° at a wingbeat frequency of 26-28 Hz. Dragonfly wings are directly attached to large muscles within the flight thorax. Elevators muscles, which attach to the thorax base, connect to the inner side of a pivoted wing base; whereas, depressor muscles connect to the outer side of the pivoted wing base. Elevator muscles pull the wings up; whereas, depressor muscles pull the wing down. Direct muscles of dragonfly are synchronous muscles that are characterized by the synchrony between muscles electrical and mechanical activity. Marden's study[5] on Drury dragonflies (Libellula pulchella) shows that the basalar muscle (DVM3) of the mesothorax, which undergoes a shortening cycle of up to 10% strain, produces a peak net stress change between 30kPa to 110kPa.

Dipteran insects are smaller flyers. For example, a fruitfly (Drosophila virilis) weighs only 2mg. It has a pair of 3mm long wings fast at 240Hz over a 150° stroke. Dipteran wings are extensions of a thoracic excoskeleton. There are two sets of muscles attached with the thorax, namely 1) vertical (dorsal ventral) muscles that connect from the thorax base to roof; 2) longitudinal (dorsal longitudinal) muscles that connects between the front (anterior) and back (posterior) ends of the thorax. Contraction of the vertical muscles pull the thorax roof down, lifting up the wing up. Contraction of the longitudinal muscles bow the thorax roof upward, flipping the wings down. The indirect muscles of Dipteran insects are asynchronous muscles, which are characterized by synchrony between muscle electrical and mechanical activity. Tracking of the thoracic deformation leads to the estimate of muscles' peak-to-peak strain amplitudes: 3.5% for dorsal longitudinal muscles and 3.3% for dorsal ventral muscles.[6] Dickinson estimated a muscles mean stress of 40.4kPa from respirometrically estimated muscle power output.[7]

3. DIPTERAN-INSECT INSPIRED THORACIC COMPLIANT MECHANISM

It is useful to first review the thoracic mechanics of a Dipteran (two-winged) insect as the thoracic mechanism inspire various thoracic compliant mechanism design for flapping-wing micro-air vehicles. These thoracic compliant mechanism can be linearly actuated by various motor to produce the wing flapping motion.

According to Gullan *et. al.*,[8] a Dipteran flight thorax consists of stiff plates connected with flexible membranes, as shown in Fig. 3. These plates are tergum (the dorsal plate), pleurals (two side plates), and sternum

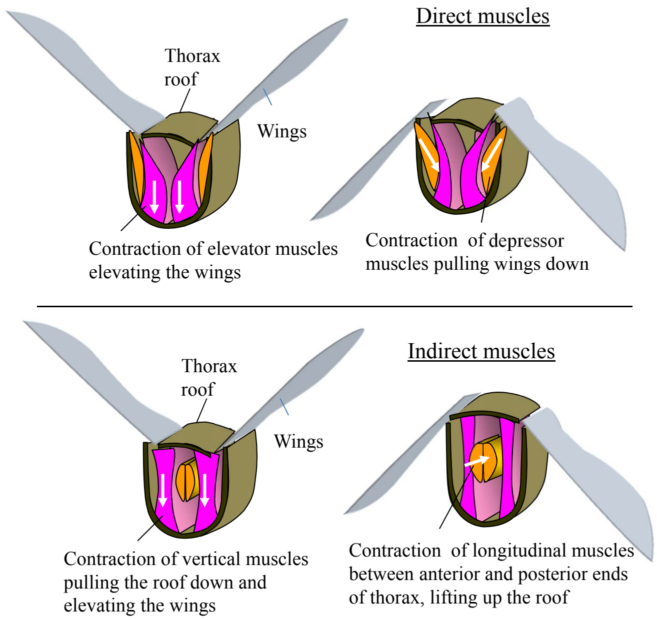

Figure 2. Insects and their flight apparatus: (row 1) direct muscles; (row 2) indirect muscles

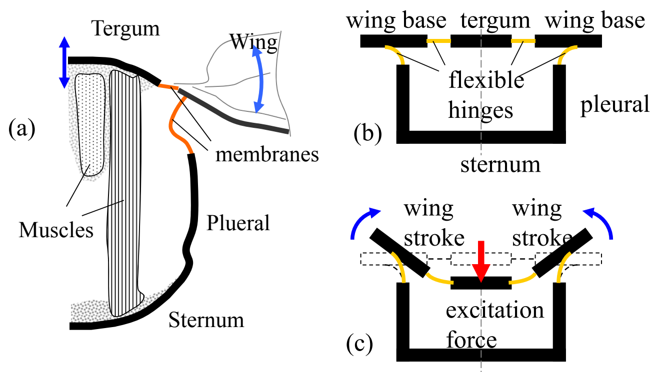

Figure 3. Dipteran-insect inspired thoracic compliant mechanism

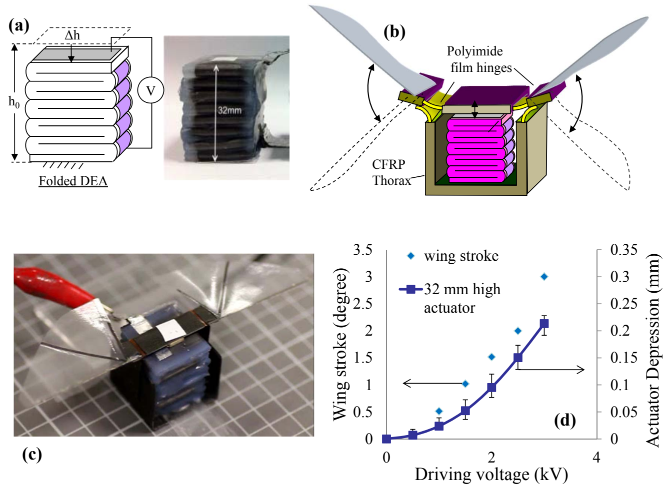

Figure 4. Folded DEA as indirect vertical muscles

(the ventral plate). The side plates (pleurals) are joined as one piece with the ventral plate (sternum). The tergum is connected to the wing bases through flexible membranes (the pleural wing process), and each wing base is attached to the pleural through an elastic hinge, as shown in Fig. **??**. The flexible membranes and wing hinges are composed of resilin, which provides elasticity to the thorax. The elastic elements function like torsional springs in the pseudo rigid body sense, allowing the wing base to rotate about the pleural fulcrum.

A thorax-like compliant mechanism design appear like a hollow rectangular box. The mechanism consists of rigid segments (for the tergum, pleurals and sternum, and two wing bases) and flexible hinges, which connect among the rigid segments. The rigid segments are connected with flexible hinges in a similar manner as a Dipteran's thorax. This thoracic compliant is made of carbon-fibre-reinforced polymer (CFRP) plate and polyimide film hinge. It fabrication is by folding and adhesive joining of a basic flexure, which is made of polyimide film between two rigidly reinforced plates. The CFRP prepreg and polyimide film are manually cut and bonded together using vacuum bagging and thermal curing on a hot plate in the same method as reported in.[?, 9] A pair of 50-mm long wing spars and foils are attached to the wing base. The wing foils are shaped in a semi-circular profile, similar to wings of a mono-plane-like rubber-band-powered ornithopter[10] or a hawkmoth.[11] Each wing are made of 5-μm (1 mil) thick polyethylene terephthalate (PET) foil reinforced by 0.5mm diameter carbon-fibre rods.

4. DIELECTRIC ELASTOMER AS FLIGHT MUSCLES

Dielectric elastomer actuator are comparable to natural muscles in term of stress and strain. For example, acrylic DEA of 0.5-1MPa modulus can produce a voltage induced linear strain of up to 100% under a Maxwell stress of up to 1MPa. Yet such large voltage induced strain and high Maxwell stress are only achievable by very high field activation (close to 300MV/m) and very high membrane pre-stress. A single layer of DEA membrane does not have enough stiffness to match with the flapping wing. Multilayer DEAs are stiffer. But their performances are worse off than a single-layer DEA due to thermal insulation. In addition, high pre-tension needs to be supported by a bulky passive structure. These lead to the adding extra passive weight to the flapping-wing system, reducing the total active power density.

Researchers at SRI[12, 13] had pioneered the development of DEA as the flight muscles for a four-wing flapping micro air vehicles. A silicone multilayer DEA was integrated to a compliant mechanism with four wings hinged to stainless steel leaf springs. Activation of the DEA stack can beat each wing for a 40 degree wing stroke at a 9Hz wingbeat frequency. The major limitation lies with the need of passive structure to keep the pre-stretches that improve the voltage-induced strain. As a result, the active dielectric elastomer contributes only 10-20% of

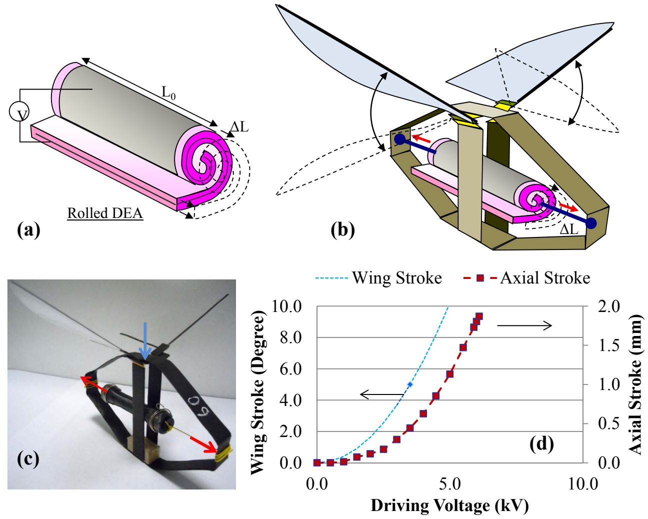

Figure 5. Rolled DEA as indirect longitudinal muscles

the total system weight. The DEA developed are still far short of power and were not successful scaled up to meet the power need by a 454g micro air vehicles.

Our group tried to develop DEAs for driving a smaller flapping-wing air vehicle, with a weight less than 20 gram. We have developed a folded DEA as the vertical indirect muscles. Thickness change of membrane DEA is usually small, without pre-stretching the membrane (Carpi et al, 2007). To accumulate the contractive strain in the thickness direction, a DEA membrane can be folded and adhesively bonded between free interfaces into a stack. Activation by compressive electrostatic force at high voltage causes a height decrement to the folded elastomeric stack. Such folded elastomeric actuator could be integrated in an insect-like thoracic mechanism. Contraction of the elastomer actuator pulls down the thorax roof, flipping wings up

Figure 4 shows a 32mm-high and 25mm-wide stack, which were obtained by folding a 7-layer silicone dielectric elastomer membranes interleaved with 6 graphite - powder electrodes. The folded actuator has an axial stiffness of 3.847kN/m. It generated a small stroke of 0.2mm at t he driving voltage of 3kV. The effective axial strain is merely 0.625% due to 50% passive height of overcoat layers and low dielectric strength. Such actuator stack was integrated in a compliant thoracic mechanism. A 0.2mm axial contraction of the folded actuator could induce a 3 degree wing stroke, far shorter than the stroke requirement of at least 30°.

Our group also developed a rolled DEA as the dorsal longitudinal muscles that connect between the front and back of a thoracic mechanism through a CFRP diamond-shape amplifier shell.[14] The rolled actuator is made of pre-stretched silicone membrane. The pre-stretch is necessary to to prevent membrane wrinkling. End caps keep the hoop stretch, while the a diamond-shape CFRP shell supports the the axial stretch. During activation, elongation of the rolled actuator relax the initially compressed shell to be flatter. In turn, the thoracic mechanism is depressed to elevate a pair of wings.

A 11-mm diameter and 61 mm long rolled actuator was obtained by rolling 3 dielectric elastomeric layers, interleaved with 2 graphite electrodes. The roll has axial stiffness varies with pre-stretch. A 15% equi-biaxially pre - stretch is found to maximize the dielectric strength of the rolled actuator. At this pre-stretch, the roll has an axial stiffness of 305N/m, which is 3 times stiffer then the diamond-shape CFRP shell. This 61mm long actuator produced a 1.87 mm stroke at a maximum driving voltage of 6kV. This yields merely 3.1% axial strain due to low dielectric field of the lightly pre-stretched silicone membrane. This 3.5kV-activated DEA roll can indirectly beat a pair of wings for a 5-degree wing stroke amplitude at and 0.6Hz.

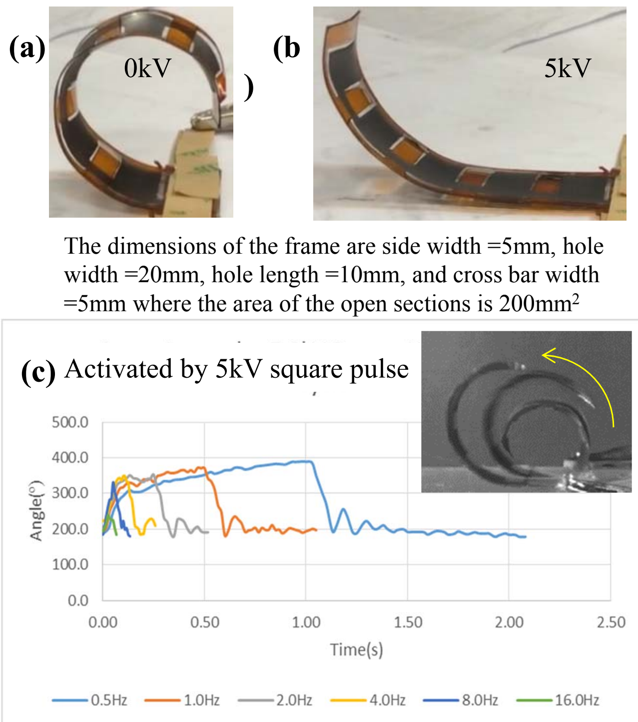

Figure 6. Rollable dielectric elastomer minimum energy structure

5. CHALLENGES AND PROSPECTS

These initial study found that the DEA prototypes developed so far are too massive . With the passive structure added, they are not compact enough to produce high torque like a brushless electric motor are for driving a lightweight flapping wing micro air vehicles. Lumped active mass of DEA is separated from the lumped elasticity of the thoracic compliant mechanism. As a result, the system resonant frequency is low and the the DEA cannot do much work to drive the flapping wings. The viscoelasticity of silicone and low pre-stretch also limit the DEA's response. These problems encountered lead to a question if DEA fits to be flight muscles and a second question if a Dipteran-insect inspired thoracic compliant mechanism scales well to the larger-size MAV.

Despite the doubts, there are recently some initial successes in creating resonant flapping wing by using dielectric elastomer minimum energy structure that has distributed elasticity over a DEA. These distributed elasticity is realized by the use of flexible frame that keeps the planar pre-stretch in DEA. The flexible frame curls large under the pre-stress by DEA membrane. Voltage activation can undo the bending by electrically vanishing the membrane pre-stress. Zhao and others[15] show that 3-Hz resonance of acrylic dielectric elastomer rotary joint can move a 1.2 gram load for close to 180°. The dynamic angular amplitude decreases with the increasing driving frequency beyond the resonance. For example, the dynamic amplitude at 5Hz excitation decreases to 60°.

Our group also re-created a rollable multi-segment dielectric elastomer minimum energy structure.[16] This rollable DEMES has a acrylic dielectric elastomer actuator bonded on a polyimide frame. Dimensions of the frame are: side width =5mm, hole width =20mm, hole length =10mm, and cross bar width =5mm where the area of the open sections is 200mm^2. A acrylic tape (VHB4905) is highly pre-stretched for 3 times longitudinal and 2.5 times transversely to induce a large frame bending. The rollable actuator has a initial curling of 200°. A square voltage pulse of 5kV voltage amplitude at frequencies, ranges from 0.5 Hz to 16Hz, are applied to activate the DEMES. Testing shows that the 8Hz, 5kV pulsed activated actuator curls and uncurls for a large angle of up to 147°. But the speeds of curling and uncurling differ: 34.07 rad/s for curling and 51.11 rad/s for uncurling.

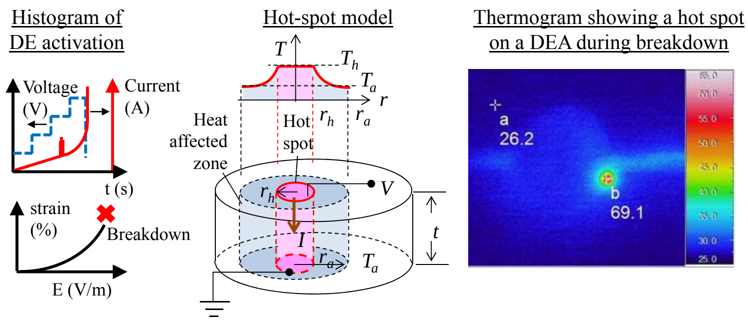

Figure 7. Electrothermal breakdown of DEA

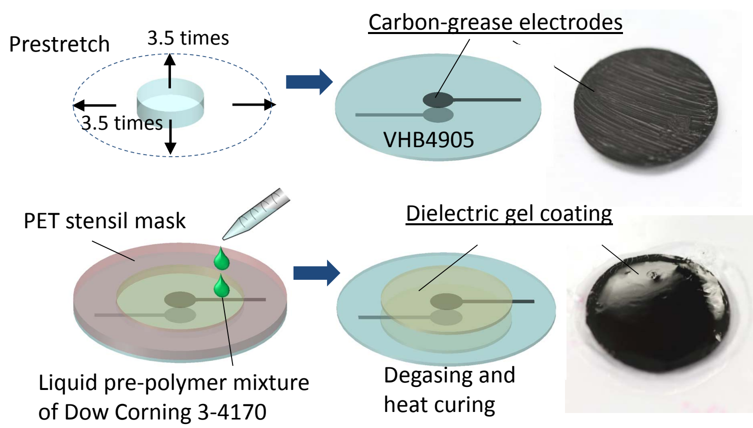

Figure 8. Gel coating of DEA

Yet, these DEMESes have yet demonstrated flapping of a larger wing (<100 mm wing span) due to their limited force generation[16]

6. SOLUTION TO MATERIAL LIMIT

Premature breakdowns of dielectric elastomer actuators limit the maximum voltage induced strain and stress.[17,18] The electrical breakdown is very localized; a spark and a pinhole (puncture) in dielectric ends up with short-circuit (see Figure 7). Our recent work[18] shows that dielectric gel encapsulation or coating (Dow Corning 3-4170) helps protect acrylic elastomer (VHB 4905), making it thermally more stable and delaying its thermal oxidation (burn) from 218 °C to 300 °C. Dielectric-gel-coated acrylic DEAs can withstand higher local leak-induced heating and thus achieve higher dielectric strengths than non-coated DEAs do. As a result, the silicone gel coated acrylic DEA with pre-stretch has (see Figure 8) its ultimate breakdown delayed up to to a higher electric field of up to 532 MV/m, much higher than 34MV/m dielectric strength of pristine non-prestretched VHB tape (VHB 4905). Similarly, the silicone dielectric gel coating helps inhibit the electrothermal breakdown of DEAs with graphite-powder compliant electrodes, even for multilayer configuration[19] (see Figure 9. These gel-coated acrylic DEAs show great potential to make stronger artificial muscles.

In comparison (see Figure 10), hard plastics of modulus greater than 1000MPa reported higher dielectric strengths, for example, 760MV/m for Nylon 6, 510MV/m for polyethylene terephthalate (PET), and ¿600MV/m for polyvinyldene fluoride (PVDF)[21]. Yet, hard plastics hardly deform under the Maxwell stress even at the breakdown field.

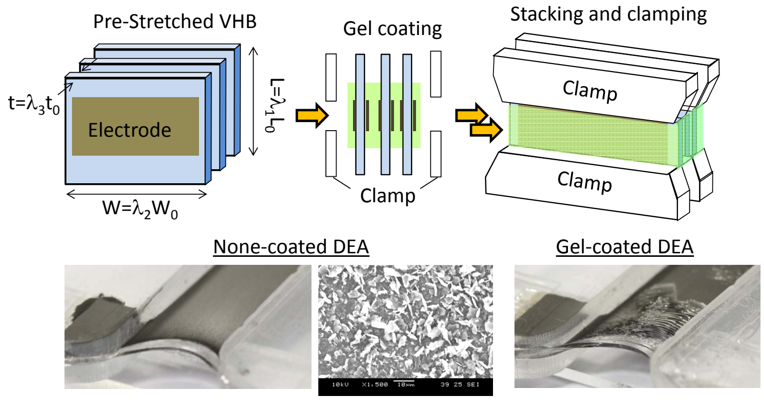

Figure 9. Multi-layer DEA with silicone gel coating

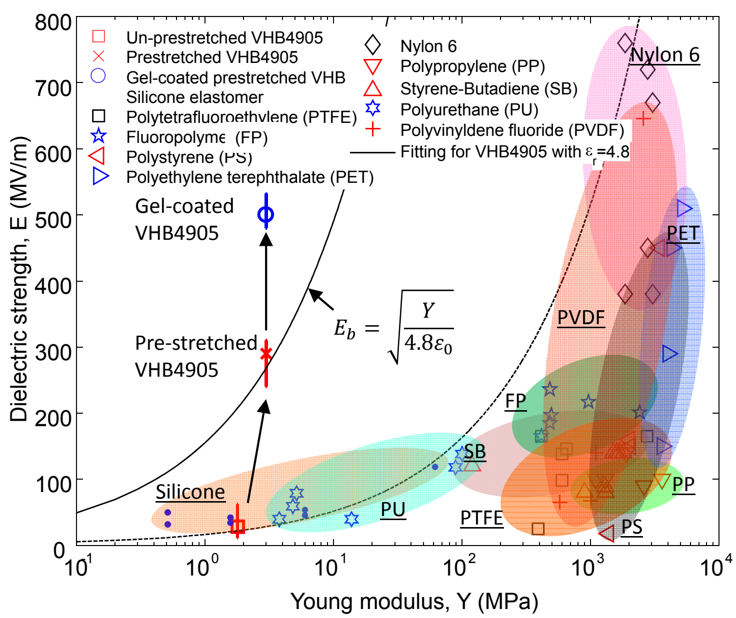

Figure 10. Dielectric strengths of various elastomers and plastics

7. CONCLUSIONS

The recently developed DEMES can possibly make artificial flight muscles capable of generateing fast and large actuation required for wing flapping. Existing design DEMES are still short of force and strength to drive external load. It is envisaged that integration of the multiple DEMES in a compact form could help increase the stiffness and force. Interfacial sealing by silicone gel would help the integrated DEMES withstand high electric field while the multilayer configuration helps accumulate the stroke and force.

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