REPORT FOR VARIABLE STIFFNESS SUSPENSION

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Contents

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1. Manufacture

1.1. **Dielectric.** For the electric material of EAPs, the best overall performances have been shown by mainly silicone and acrylic films [5]. The fabrication methods based on these two materials are comparatively mature.

In [10], three kinds of high-performing EAP electric materials (HS3 silicone, CF19-2186, silicone VHB 4910 acrylic) were detailedly compared by planar and linear stretch test. Test results is showed in Table 1.

In the tests [10], VHB 4910 acrylic polymer (acrylic adhesive) has the highest performance, the comparison showed as below:

- **Acrylic**: 100% relative strain level without break, but has high viscoelastic loss which limits the working frequency to 30-40 HZ and induce hysteresis.
- **Silicone**: Good property in viscoelasticity but the energy density is only one fifth of the acrylic.

For making highly strong suspension with small volume and weight of material, the energy density is critical. And the hysteresis could possibly be avoided and compensated by low strain and certain configuration. Therefore, VHB4910 acrylic polymer might be a better choice.

1.2. **Electrode.** Based on stretched acrylic dielectric film, there are mainly three kinds of electrode layers that have been tried.

- **Conductive carbon grease**: Mixture of carbon powder and silicone oil, works well but is constantly wet with comparatively rough surface [4].
- **Cured carbon-silicon electrode**: Carbon power and silicon rubber mixture and spray-coated. Dry, homogeneous, strong and better activated strain than conductive carbon grease [7]. Though cured carbon-silicon

Material	Prestrain (*x*,*y*) (%)	Actuated relative thickness strain (%)	Actuated relative area strain (%)	Field strength (MV/m)	Effective compressive stress (MPa)	Estimated $^1/_2e$ (MJ/m^3)
			Circular strain			
HS3 silicone	(68,68)	48	93	110	0.3	0.098
	(14,14)	41	69	72	0.13	0.034
CF19-2186 silicone	(45,45)	39	64	350	3.0	0.75
	(15,15)	25	33	160	0.6	0.091
VHB 4910 acrylic	(300,300)	61	158	412	7.2	3.4
	(15,15)	29	40	55	0.13	0.022
			Linear strain			
HS3	(280,0)	54	117	128	0.4	0.16
CF19-2186	(100,0)	39	63	181	0.8	0.2
VHB 4910	(540,75)	68	215	239	2.4	1.36

Table 1. Circular and linear strain test results. (Resource: [10])

layer could increase the suspension's none-actuatable stiffness, this extra stiffness has been achieved to be quite small by controlling the layer thickness [6].

- **Carbon powder electrode**: Made by simply scattering carbon powder on adhesive acrylic film and suction cleaning [5]. The acrylic could be coated without being stretched and remains functional under 200%x200% stretching.
- **Conductive cover tape**: 3M Inc. Cover Tape 2668. Consist of two polyester film, one of which is none-conductive. 150% elongation, 0.061mm thickness, 7N/mm(width) tensile strength. It might be possible to use it as EAP electrode:
  - Two layers of this cover tape with non-conductive films adjacently attached.
  - Two layers of this cover tape attach on both side of stretched acrylic film with non-conductive film faced to acrylic.

  This method could extremely simplify the manufacture procedure, but the dielectricity of the non-conductive polyester film is still unclear though 3.2 dielectric constant for one kind of flexible polyester sheet has been found (Mylar [2]).

1.3. **Multi-layer.** Multi-layer EAPs is necessary to scale up variable stiffness. So far, mainly four ways of building multi-layer EAPs have been explored:

- **Stacked**: Making independent units of EAP, pile them up with connection on the frame [4].
  –Limitation: Large time consumption for big number of layers.
- **Pile-up**: Simply piling up electric and dielectric layers alternately without any adhesion [5]. Since only one layer of electrode between two dielectric layer, maxwell pressure would push adjacent units attached with each other. Sticky surface is also helpful for this connection.
  –Limitation: Two adjacent units should be closed enough to each other.
- **Fold-up**: Similar with pile-up method. Building multi-layers with one sheet and fold them up [1]. Further simplifying the manufacture procedure with well-designed geometry.
- **Glue-up**: Using adhesive to connect layers[8].
  –Limitation: Adhesive layer might cause extra un-actuated stiffness.

1.4. **Discussion.** To greatly scale up the variable stiffness (more than 100 times), EAPs with large amount of layers is necessary. In this case, the shear and friction between adjacent layers becaome critical. With methods described above, the multi-layers configurations can fundamentally divided into two groups: layers with and without interval space.

- **Layers with interval space**: Such as stacked multi-layer. With space between different layers, friction and shear force no longer need to be worried about. But the down point is also obvious. To prevent adjacent layers from contacting requires enough interval space. For only 10-unit EAP with only 1mm, the thickness is already 10mm. The volume utilization is only 6%. Furthermore, spacing mechanism is also needed, which further complicates the design.

- **Layers without interval space**: This configuration enables compact design but the shear force and friction need to be considered. Two possible methods could deal with this problem:
  - Adjacent layers are completely adhered to each other. The adhesive should be strong enough to withstand and transmit shear force but also has comparatively low stiffness. Even with idea adhesive, with the overall thickness increase, the strain of layers in different layers would become disparate and cause nonlinearity.
  - Another possible way is acrylic layer and cured carbon-silicon electrode layer (coated) alternately piled up without adhesive. The cohesion of layers depend on sticky surface when resting and maxwell pressure when actuated. The smoothness and anti-abrasive of electrode is critical in this case and hence cured electrode is better than the other options.

In conclusion, if compactness is a challenge for the design, alternate pile-up of acrylic layer and cured carbon-silicon electrode without adhesive is the best choice among the three options discussed above.

2. Design

2.1. **Design Requirements and Criteria.** Table 2 is the design requirements from Honda. Within limited space, the EAP tunable suspension should achieve very large stiffness (800Nm/rad) when resting (without charge, EAP remains fully stretched) but still have light weight (less than 200g). Different from EAP actuator,

Factors	Reasons	Target Value for Asimo's Elbo
Wider stiffness range	Compatibility of Softness and Accuracy of move	200 – 800 Nm/rad
Change stiffness in real time	Maximum force is often occurred within 50ms in experimental robot collision data	Within 50ms
Lighter weight of device	Device weight affects linearly the energy of disturbance	Within 200g (device only)
Larger deflection of stiffness	To raise up the energy absorbance while collision	7 degree

Table 2. Design requirement. (Resource: [9])

this device is fundamentally a high-energy-density (ensure small volume) and super strong spring. When rotated by θ_{max}, it should be able to store energy of

$$E_{goal} = \frac{1}{2} K \theta_{max}^2 \tag{1}$$

with $K = 800Nm/rad, \theta_{max} = 7deg$. For unit volume of EAP with strain ε, the energy it can store is

$$E_{EAP}/V = \frac{1}{2} E \varepsilon^2 \tag{2}$$

where E is the elastic modulus. With certain strain, the fundamental goal for the design is equivalent with placing as much as volume.

Another fundamental requirement for the suspension is the stiffness linearity. Acrylic film has comparatively large viscoelasticity [10] which causes hysteresis, but at small strain the behavior does not deviate much from linear elasticity [11]. To prevent the hysteresis, maximum strain in EAP should keep under a certain value ε_{max}. Therefore, two fundamental design criteria for tunable EAP suspension with large stiffness could be drawn:

- Maximizing the volume of EAP in limited space (EAP volume utilization).
- Ensuring uniform distribution of strain ε_{max} over the EAP sheets when the suspension is rotated by θ_{max}.

2.2. **Comparison of Basic Suspension Mechanisms.** According to the direction of displacement, there are mainly two types of mechanism which have been explored: planar (along EAP plane) and diaphragm (perpendicular to EAP plane). Based on data provided in [4] and [3], related parameters are compared in Table 3.

	Planar	**Diaphragm**
Dimension (mm)	25*9*62.5	25(OD) 5.5 (ID)
Maximum Displacement (mm)	1.5	4
Maximum Force (N)	0.8	0.5
Maximum Strain (%)	16.7	7.7 (approximation)
Equavalent Elestic Coefficient (N/m)	530	102
Hysteresis (N)	0.4	0.05
Frequency for Hysteresis Tests (Hz)	2	1

TABLE 3. Comparison of two basic suspension mechanisms.

One notable advantage of diaphragm mechanism is its good linearity property (Fig 1), which can be explained by reasons as below:

- The maximum strain in the diaphragm is much smaller than the planar mechanism. Hysteresis caused by viscoelastic film is quite small when at low strain [10].
- The width of planar mechanism shrinks in the middle of the film when stretched hard (high strain), which is showed in Fig 2. This negative effect can be mitigated by limiting the strain and increasing the width.
- Nonlinear relation between displacement and strain in diaphragm suspension might compensate the hysteresis in some extent.
- There is another reason which is not about the mechanism. Hysteresis caused by viscoelasticity is positively correlated with stretching speed. The cyclic frequency used in hysteresis test for planar suspension (2Hz) is twice than for diaphragm (1Hz), thus induced larger hysteresis.

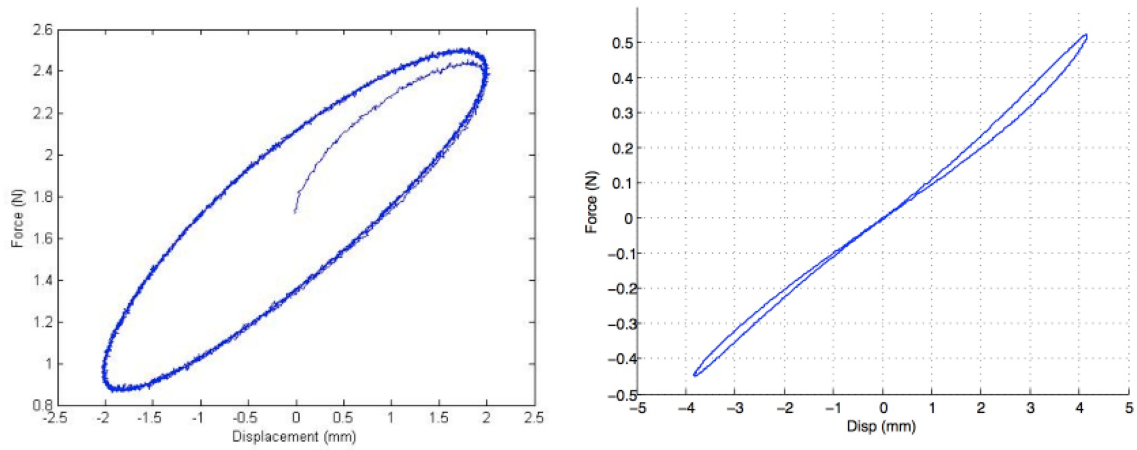

FIGURE 1. Hysteresis of two basic suspension mechanism. Planar in the left and diaphragm in the right (Resource: [4]).

Another advantage of diaphragm suspension is its durability. The EAP film is protected by circular frame, thus doesn't have free edge, and the structure is robust, which makes it more durable.

Despite of the hysteresis and durability, planar mechanism also has some strengths:

- At low strain and large width-length ratio, the strain distributed over the planar suspension is quite uniform and better satisfies the second design criterion, while in diaphragm mechanism, the strain concentrates in the middle and decreases along the radial direction.
- Planar suspension (530N/m) is stronger than diaphragm (102N/m), which is favorable in large stiffness suspension design.
- It also has much better compactness:
  - The displacement of planar mechanism is along the plane. The movement space is smaller than diaphragm (perpendicular to the plane).

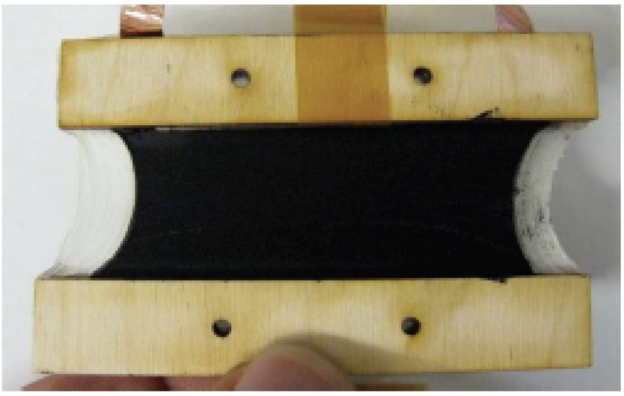

FIGURE 2. Width shrinkage caused by high strain in planar suspension (Resource: [3]).

- Rectangle shape of planar suspension is better than circular diaphragm in space utilization.

The main advantages of these two mechanisms are listed in Tab 4.

Planar	**Diaphragm**
Uniform strain distribution	Linearity
Compactness	Durability

TABLE 4. Advantages of two basic suspension mechanisms.

2.3. **Twisting Diaphragm.** Apart from the two basic mechanisms discussed above, there is another possible basic mechanism hasn't been explored so far, with center of the diaphragm rotating on the plane. This twisting diaphragm mechanism is showed in Fig 3.

This mechanism is highly compact and the rotary stiffness can directly generated by multi-layer EAPs on top of the motor, which might worth exploring. But there are several points need to be noticed:

- The strain distribution remains unknown, thus the linearity is unknown. Need to be further analyzed by simple experiment, simplified model or simulation software such as Ansys.
- Wrinkle caused by rotation should be prevented.
- Connection between central shaft and the EAP films is critical. Each layers should be directly connected to the central shaft thus ensure same strain distribution between different layers.

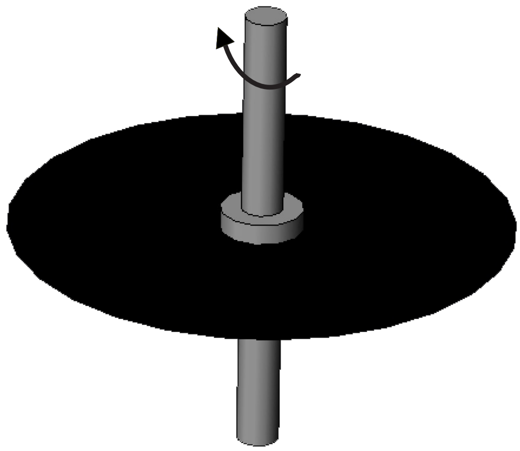

FIGURE 3. Twisting diaphragm mechanism.

2.4. **Discussion and Analysis of a Possible Design.** The planar and diaphragm mechanisms have complementary advantages. Actually, a diaphragm suspension can be approximated to an annular strip with displacement perpendicular to the plane. It is the displacement direction that increases the maximum displacement but reduce the equivalent elastic modulus. By changing the annular strip to rectangle one, a possible design solution is derived, which is showed in Fig 4.

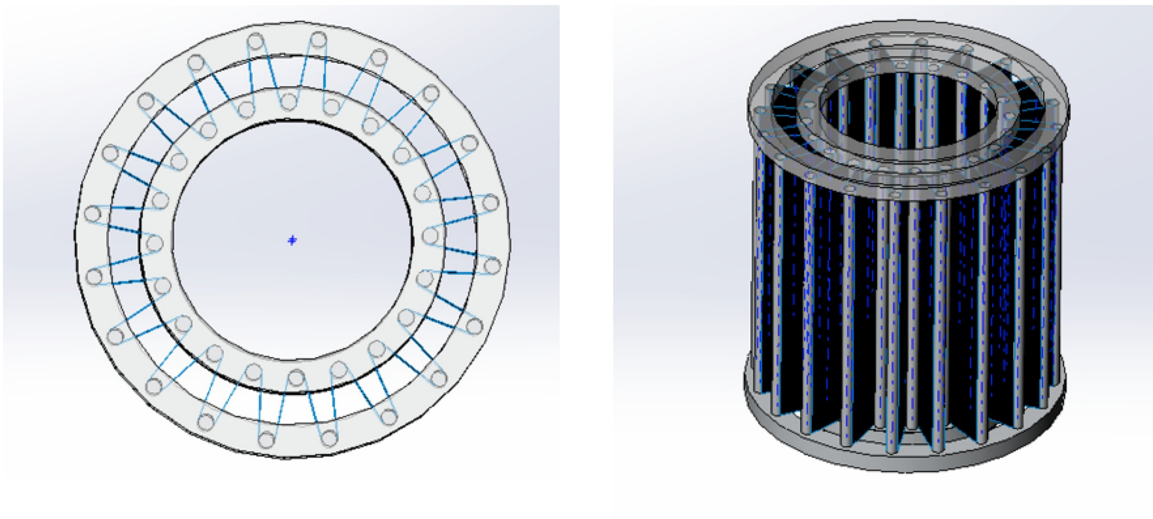

FIGURE 4. A possible design.

This design absorbs the strengths from both planar and diaphragm mechanisms. Advantages of this mechanism are listed as below:

- **Linearity**: All the reasons which cause the hysteresis of planar suspension (discussed in Section 2.2) can be solved in this mechanism.
  - The way of deformation is similar with expanded diaphragm for the displacement direction is not along the plane.
  - The strain and maximum rotary angle could be well balanced by slightly adjusting the diameter of circulars where inner and outer pillars are located.
  - The length of planar film between two pillars is much smaller than the width.
- **Strain distribution**: Since the width of planar film is much larger than the length, the strain distribution is quite uniform and the maximum strain can be controlled by careful geometry design.
- **Compactness**: 45x2 rectangle segments are compactly aligned around the motor with increasing the actuator radius by 8mm (the calculation will be discussed later).
- **Manufacturability**: All the EAP segments can be fabricated on one sheet with pillars adhered on it and the entire suspension can be built by simply fixed the pillars around the actuator staggeredly on inner and outer rings.

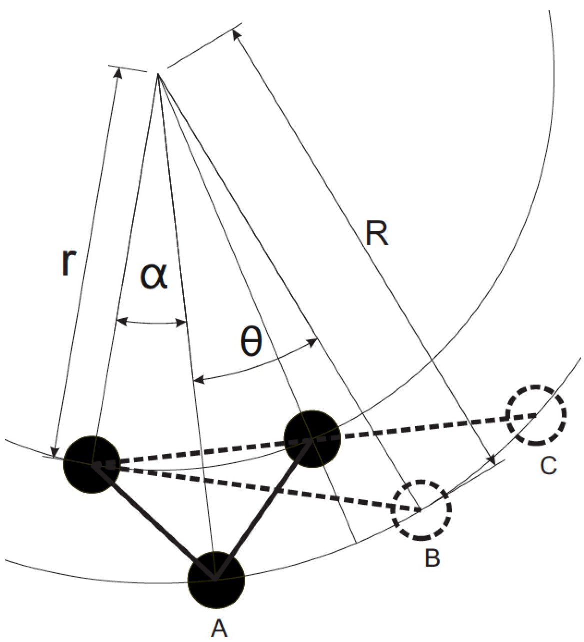

FIGURE 5. Geometry analysis.

According to the geometry illustrated in Fig 5, the relationship of different design parameters can be derived:

$$\frac{\sqrt{r^2(\frac{\alpha}{2}+\theta)^2+(R-r)^2}-\sqrt{(\frac{r\alpha}{2})^2+(R-r)^2}}{\sqrt{(\frac{r\alpha}{2})^2+(R-r)^2}}=\varepsilon_{max} \tag{3}$$

where, α is the angle between adjacent pillars and θ is the rotation angle. With $R = 25mm$ and $\alpha = 8deg$ (45x2 pillars) , when in maximum angle $\theta = 7deg$, the strain reaches $\varepsilon_{max} = 0.07$ (according to diaphragm). The inner radius of the suspension can be calculated: $r = 17mm$. The maximum angle the suspension can rotate without interference with adjacent pillars θ_{imax} is calculated using

$$\theta_{imax} = \pi/2 + \alpha - r(\frac{\pi/2-\alpha}{R}) \tag{4}$$

which is much larger than 7deg. Therefore, with the design parameters mentioned above, the energy storage of EAP can be scaled up by 45 times. But to achieve this performance, there are many challenges:

- How to safely adhere the pillars to the EAP film stably but also prevent strain concentration when being maximumly driven. Might consider changing the cross-section shape of the pillars.
- How to prevent possible tear from the free edge of EAP. Might consider coating the edge with low-stiffness material.
- The linearity of this mechanism should be further verified by tentative experiments.

3. Research Plan

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