# Considering 1 cell specification from whole design

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Honda R&D

# Desire Specification for Variable Stiffness and Other Variable Stiffness Devices

Electrical
Variable Stiffness and
Variable Damping

| Item | AWAS-Ⅱ (IIT) | FSJ (DLR) | EVSVD (Type SL) |
|---|---|---|---|
| Range of Motion | -150～150 deg | -180～180 deg | -180～180 deg |
| Range of angular Deflection | 17 deg | 3 – 15 deg | 4.5 deg |
| Range of Stiffness | Zero to Rigid | 52.4 to 826 | 600 to 3000 |
| Time of changing stiffness | 0.8 s | 0.33 s | 0.05 s |
| Maximum Energy | 5.8 J | 5.3 J | More than 32 J |
| Peak Output Torque | 80 Nm | 67 Nm | 100 Nm |
| Overall Weight | 1.1 kg | 1.41 kg | Under 1k g |

Motor 0.7k g
Gear 100 g
Device 200 g

Before TypeSL Joint (Step 3)
we try to create TypeEL(Until Step2)

# Device Steps toward Humanoids

The number of layers( supposing 3 cells in 1 layer )

600

200

50

2014/2

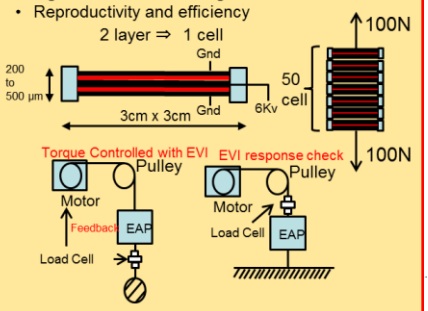
2015/5

2016/9

## Step 1 Research Subject

Multi-Layered EAP for variable stiffness device

- Larger allowable force in 1 cell
- Lighter and Smaller design
- Reproductivity and efficiency




<Validating items>

- How different between design and experiment
- Ability of reproductivity and mechanical repeatability
- Usability of mechanical characteristics

## Step 2 Research Subject

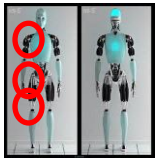
Hybrid actuator system

**2.1 Variable Stiffness Actuator for robot manipulator**

- Transition to rotational move
- Realizing integrated system
- Suitable stiffness rage for robot task
- Co-actuated with main actuator

**2.2 Large Torque VSA for humanoid**

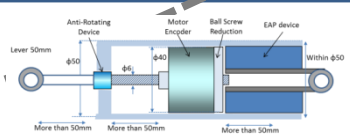
- 200Nm order allowable
- Super light device with material/electrode change
- Ensure electrical safety



### Multi-Layer VSD

### TypeEL VSD Hybrid Actuator

Stiffness 79-392Nm/rad
Deflection 9.12 degree
MaxTrq 48.3 Nm
Volume 196.25cm3
Absorb Energy 4 J
Mass 100g




### TypeSL VSD Hybrid Actuator

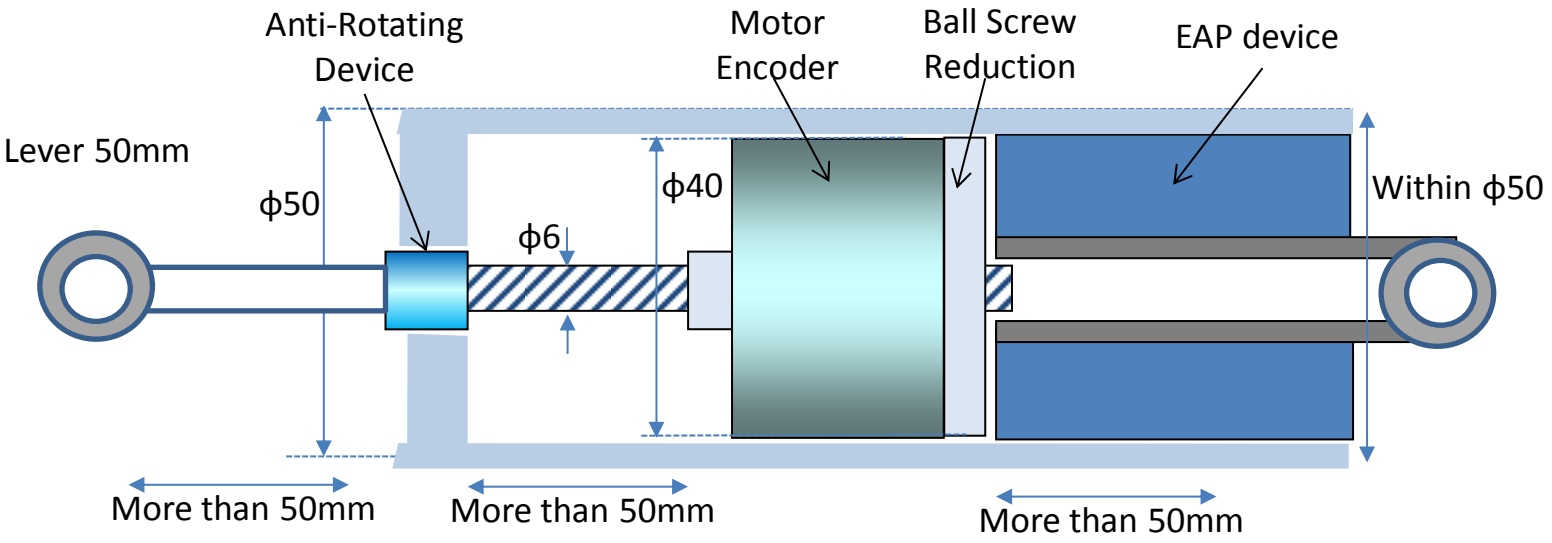
Stiffness 631-3139Nm/rad
Deflection 4.56 degree
MaxTrq 200 Nm
Volume 769cm3
Absorb Energy 32 J
Mass 200g

Main Challenge is toward Multi-Layer EAP(100+)

Challenges for Reducing Layers

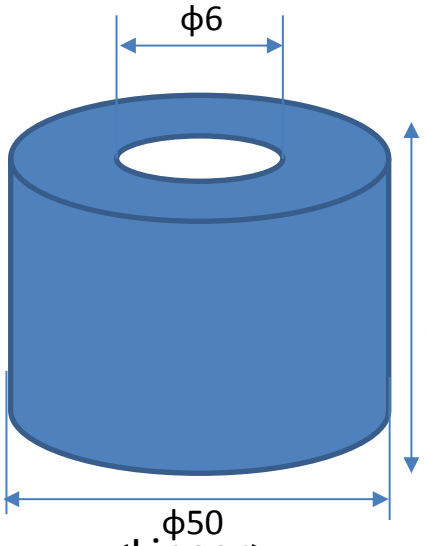
- Base performance
- Cell Design
- Optimizing Materials

# Possible Design for Robotic Elbow Joint [ linear joint version ]




| | Rotational | Linear(Lever60mm) |
|---|---|---|
| Stiffness Range | 80 – 400 Nm/rad | 22k – 109k N/m |
| Maximum Deflection | 9 deg | 9.5 mm |
| Stiffness Change Time | Under 50ms | ← |
| Joint Range | More than 90 deg | More than ±62mm |
| Maximum Torque | 50Nm | 805 N |
| Output Torque | 25Nm | — |
| Device Weight | Under 150g（Joint Total 500g） | EAP 100g |
| Device outer Diameter | — | 50 mm |
| Device inner Diameter | — | More than 6 mm |
| Device Length | — | More than 50 mm |

# Possible Design for EAP Layer [ linear joint version ]



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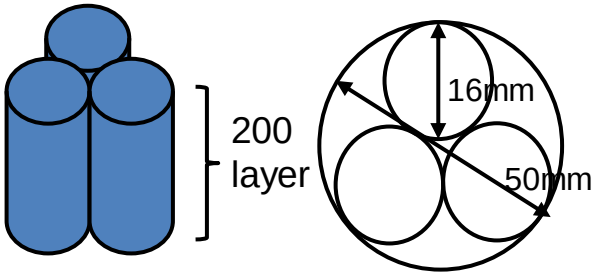

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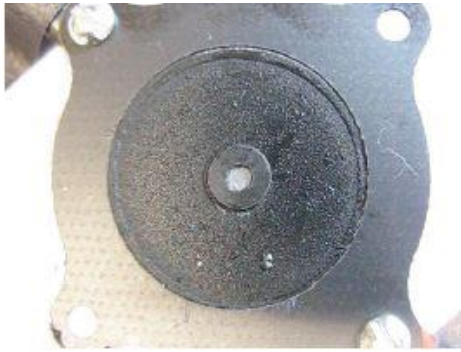
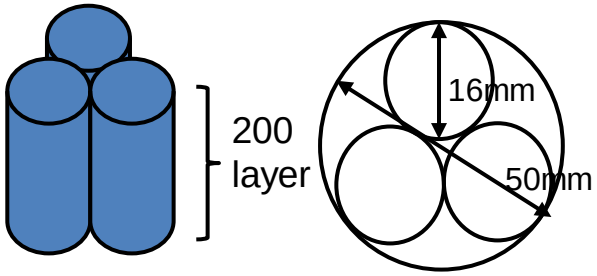
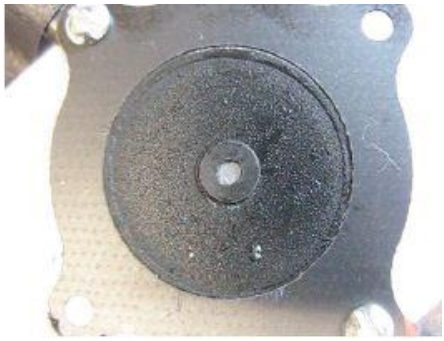

<Past Layer(Sanjay)>

| | Linear(Lever60mm) | Layer(600) | Past Layer Spec |
|---|---|---|---|
| Stiffness Range | 22k – 109k N/m | 37–182 N/m | 15–102 N/m |
| Maximum Deflection | 9.5 mm | 9.5 mm | 7 mm |
| Stiffness Change Time | 50 ms | 50 ms | 50 ms |
| Maximum Torque | 805 N | 1.4 N | 2 N |
| Device Weight | 100g | 0.16 g | 0.5 g |
| Device outer Diameter | 50 mm | 50 mm | 38 mm |
| Device inner Diameter | More than 6 mm | 6 mm | 5.5 mm |
| EAP outer Diameter | —— | 16 mm | 25 mm |
| Device Length | More than 50 mm | 0.25 mm | 0.3 mm |

# Trace Layer Spec to Current Geometry



<Layer(600cells)>

| | Layer(600cells) Spec | | Demanded Spec in Current Geometry |
|---|---|---|---|
| Stiffness Range | 37–182 N/m | | 10–60 N/m(6.2kV) |
| Maximum Deflection | 9.5 mm | | 28 mm |
| Stiffness Change Time | 50 ms | | 50 ms |
| Maximum Force | 1.4 N | | 1.7 N |
| Device Weight | 0.16 g | | Under 0.45 g |
| Device outer Diameter | 50 mm | | 50 mm |
| Device inner Diameter | 6 mm | | 10 mm |
| EAP outer Diameter | 16 mm | | 44.5 mm |
| Device Length | 0.25 mm | | --- mm |

# Q1 Check Items

1. Cell Test (Diameter 44.5mm, 20 cells)

| | | Demand Spec |
|---|---|---|
| Ave. Stiffness Range is from | ( ) to ( ) N/m | { 10 N/m – 60 N/m } |
| Max. Stiffness Range is from | ( ) to ( ) N/m | |
| Figure out the variance of cells | [ plot ] | |
| Ave. Reliable Charge(>4kV) up to | ( ) V | { 6200 V } |
| Plot of Maximum Charge in Cells | [ plot ] | |
| Ave. Max Deflection | ( ) mm | { 28 mm } |
| Plot of Max Deflection in Cells | [ plot ] | |
| Ave. Max Force | ( ) N | { 1.7 N } |
| Plot of Max Force in Cells | [ plot ] | |
| Cell Weight | ( ) g | { 0.45 g } |

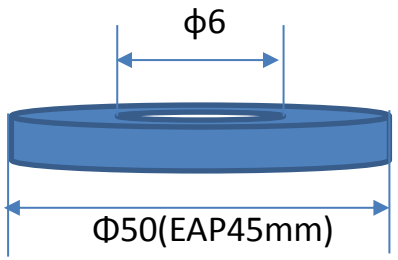
2. Multi-Layer Test ( 2,or 3-5 cells )

| | |
|---|---|
| Linearity of Max Stiffness | ( )/ave.cells |
| Min Stiffness | |
| Max Deflection | |
| Max Force | |

# Appendix

# Possible Design for EAP Layer [ linear joint version ]

<Analytical consideration>




Material : 3M VHB4910 ( Thickness 1mm )

Young Modulus E0-300%ave = 1.5 x 10^5 Pa[N/m2]

E300 = 13.6 x 10^5 Pa [N/m2]

Poisson's Ratio v = 0.49

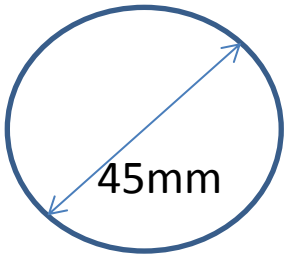
Cross Area A0 = Pi*L0*d0

= 3.14*45/1000*1/1000 m2

Density Constant

1 g / cm3

<Layer(200)>




L0=45mm

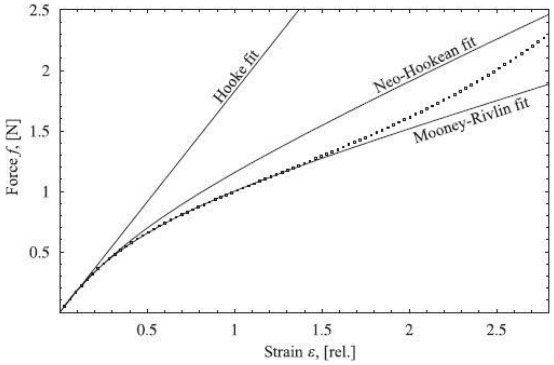
d0=1mm

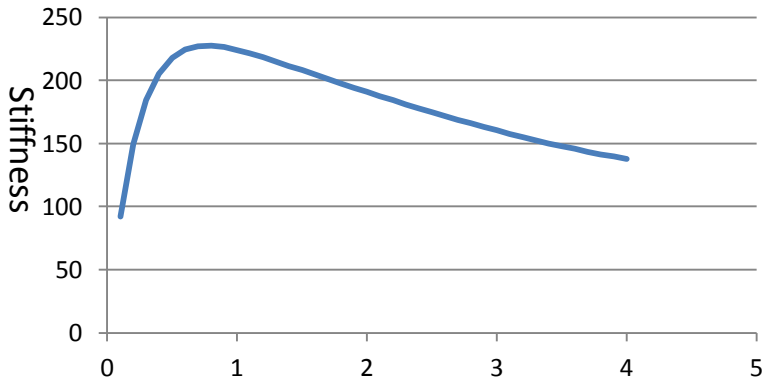
<Maximum Stiffness>

This is only dependent on the pre-strain

However young modulus is also dependent on the strain.

$$k_z^{V=0} = E_{pre}^0(r_{pre}) \cdot 2\pi \cdot d_{pre} r_{pre}$$



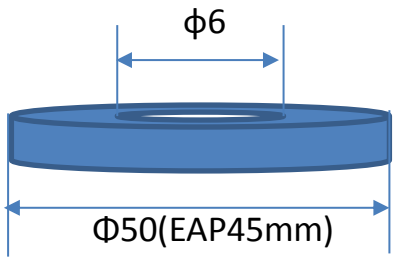

Pre-Strain=300%

(same to Sanjay's research)

$$k_z^{V=0} = 102 \text{ N/m}$$

# Possible Design for EAP Layer [ linear joint version ]

<Analytical consideration>

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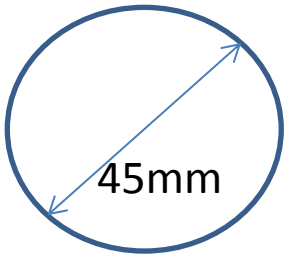
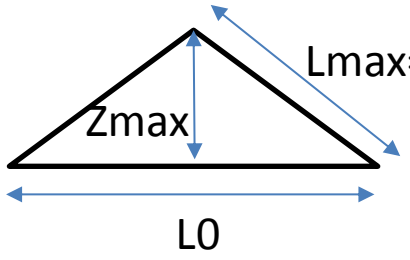



L0=45mm
d0=1mm

Material : 3M VHB4910 ( Thickness 1mm )
Young Modulus E0-300%ave = 1.5 x 10^5 Pa[N/m2]
E300 = 13.6 x 10^5 Pa [N/m2]
Poisson's Ratio v = 0.49
Cross Area A0 = Pi*L0*d0
= 3.14*45/1000*1/1000 m2
Density Constant
1 g / cm3
Maximum Stretch
480%

<Nominal Deflection>

Nominal Deflection without Maxwell Stress can be calculated




$$z_{\max} = \frac{L_0}{2}\sqrt{\left(4.5 - r_{pre}\right)^2 - 1}$$

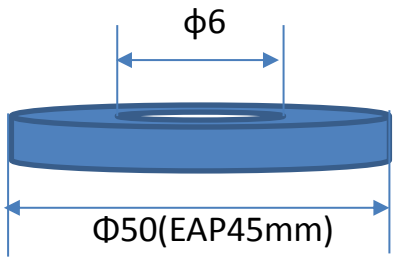
= 0.025 m

<Maximum Force in Stiff>

$$F_{\max}^{V=0} = k_z^{V=0} \cdot Z_{\max}$$ = 4.785 N

# Possible Design for EAP Layer [ linear joint version ]

<Analytical consideration>

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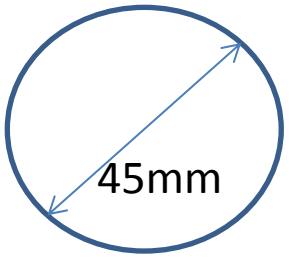


L0=45mm
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Material : 3M VHB4910 ( Thickness 1mm )
Young Modulus E0-300%ave = 1.5 x 10^5 Pa[N/m2]
E300 = 13.6 x 10^5 Pa [N/m2]
Poisson's Ratio v = 0.49
Cross Area A0 = Pi*L0*d0
= 3.14*45/1000*1/1000 m2
Density Constant
1 g / cm3
Maximum Stretch
480%

<Nominal Minimum Stiffness>

$$k_z = -(E_{pre}^{near} 2\pi \cdot d_{pre} + 2\pi \cdot d_{pre}\sigma_z^{ms})(\frac{\nu \cdot \sigma_z^{ms}}{E_{pres}^{near}}) + k_z^{V=0}$$

$$\sigma_z^{ms} = -\varepsilon\varepsilon_0\left(\frac{V}{d_{pre}}\right)^2$$

This is not dependent on L0

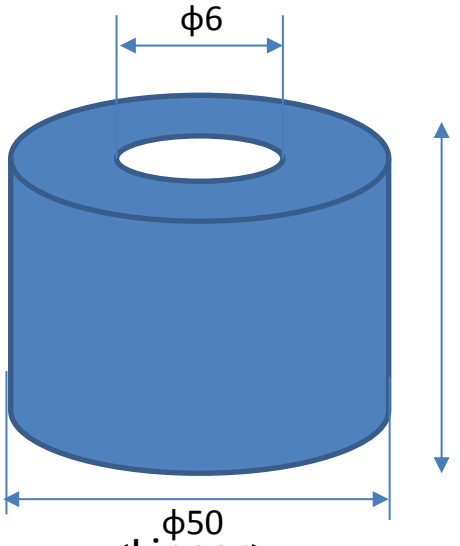
So using Simple Version

$$k_z = -\frac{\varepsilon_0\varepsilon_r V^2 w}{d_{pre}} + k_z^{V=0}$$

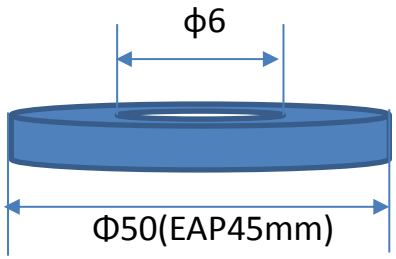
As the demand min stiffness is 10 N/m, and diff = 92

$$V_{demand} = 6170$$

# Possible Design for EAP Layer [ linear joint version ]




<Linear>




<Layer(100)>

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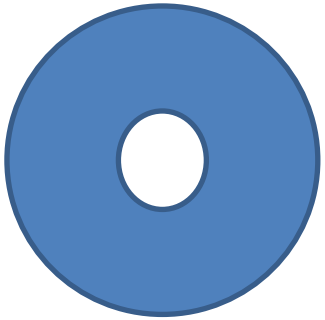
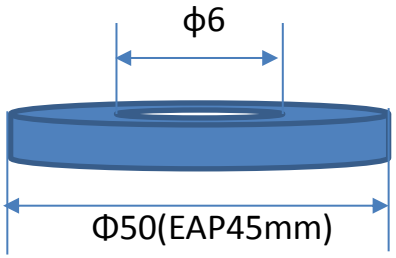
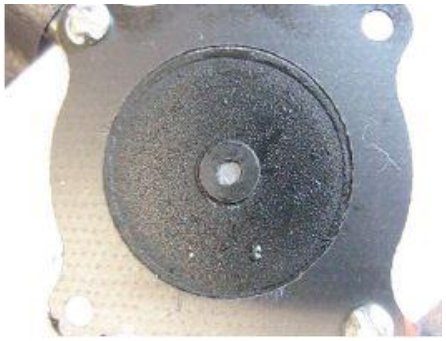


<Nominal Layer Spec>

| | Linear(Lever60mm) | Layer(200) | Nominal Possible Layer Spec |
|---|---|---|---|
| Stiffness Range | 1000 – 3000 N/m | 10–30 N/m | 10–102 N/m(6.2kV) |
| Maximum Deflection | 7 mm | 7 mm | 25 mm |
| Stiffness Change Time | 50 ms | 50 ms | 50 ms |
| Maximum Torque | 1000 N | 5 N | 4.785 N |
| Device Weight | EAP 150g | 0.75 g | --- g |
| Device outer Diameter | 50 mm | 50 mm | 45 mm |
| Device inner Diameter | 6 mm | 6 mm | 6 mm |
| EAP outer Diameter | ----- | 45 mm | 50 mm |
| Device Length | More than 50 mm | 0.25 mm | --- mm |

# Trace Nominal Layer Spec to Current Geometry



<Layer(100)>

| | Nominal Layer Spec | | Current Geometry Spec |
|---|---|---|---|
| Stiffness Range | 10–102 N/m(6.2kV) | | 10–102 N/m(6.2kV) |
| Maximum Deflection | 25 mm | | 13 mm |
| Stiffness Change Time | 50 ms | | 50 ms |
| Maximum Force | 4.785 N | | 2.6 N |
| Device Weight | Under 0.75 g | | Under 0.4 g |
| Device outer Diameter | 45 mm | | 25 mm |
| Device inner Diameter | 6 mm | | 6 mm |
| EAP outer Diameter | 50 mm | | 38 mm |
| Device Length | --- mm | | --- mm |

# Q1 Check Items

1. Cell Test

| | | Demand Spec |
|---|---|---|
| Stiffness Range is from | ( ) to ( ) N/m | { 10 N/m – 102 N/m } |
| Reliable Charge about | ( ) V | { 6200 V } |
| Max Deflection | ( ) mm | { 13 mm } |
| Max Force | ( ) N | { 2.6 N } |
| Cell Weight | ( ) g | { 0.4 g } |

2. Multi-Layer Test

| | | |
|---|---|---|
| Linearity is | ( ) /cells | { 1. is best } |

3. Fabrication Reliability

20 cells fabrication and test ( ) acquire data of 10-20 cells