Amplifier Piezoelectric Actuator APA300ML - Test Bench

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Contents

The goal of this test bench is to extract all the important parameters of the Amplified Piezoelectric Actuator APA300ML.

This include:

- Stroke
- Stiffness
- Hysteresis
- Gain from the applied voltage V_a to the generated Force F_a
- Gain from the sensor stack strain δL to the generated voltage V_s

- Dynamical behavior

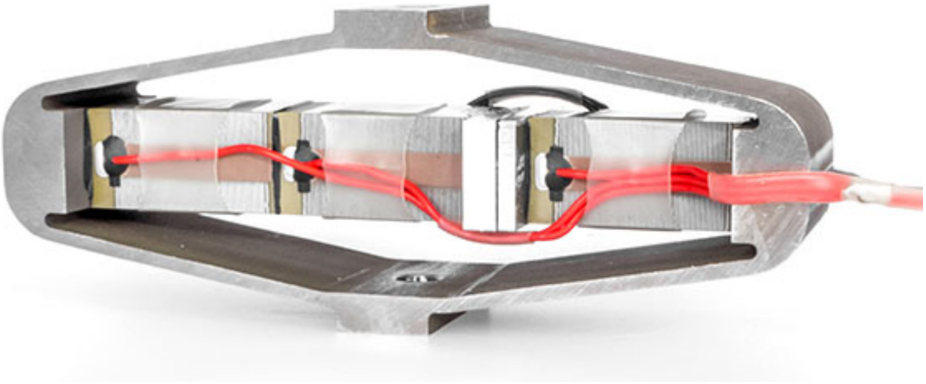

Figure 0.1: Picture of the APA300ML

1 Model of an Amplified Piezoelectric Actuator and Sensor

Consider a schematic of the Amplified Piezoelectric Actuator in Figure 1.1.

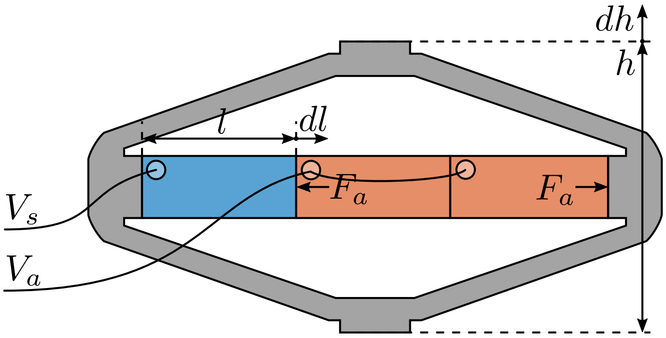

Figure 1.1: Amplified Piezoelectric Actuator Schematic

A voltage V_a applied to the actuator stacks will induce an actuator force F_a:

$$F_a = g_a \cdot V_a \tag{1.1}$$

A change of length dl of the sensor stack will induce a voltage V_s:

$$V_s = g_s \cdot dl \tag{1.2}$$

We wish here to experimental measure g_a and g_s.

The block-diagram model of the piezoelectric actuator is then as shown in Figure 1.2.

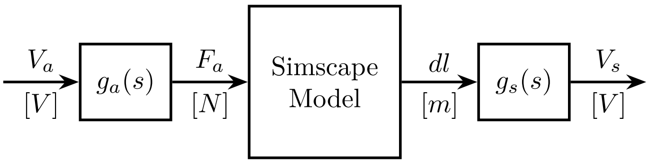

Figure 1.2: Model of the APA with Simscape/Simulink

2 Geometrical Measurements

The received APA are shown in Figure 2.1.

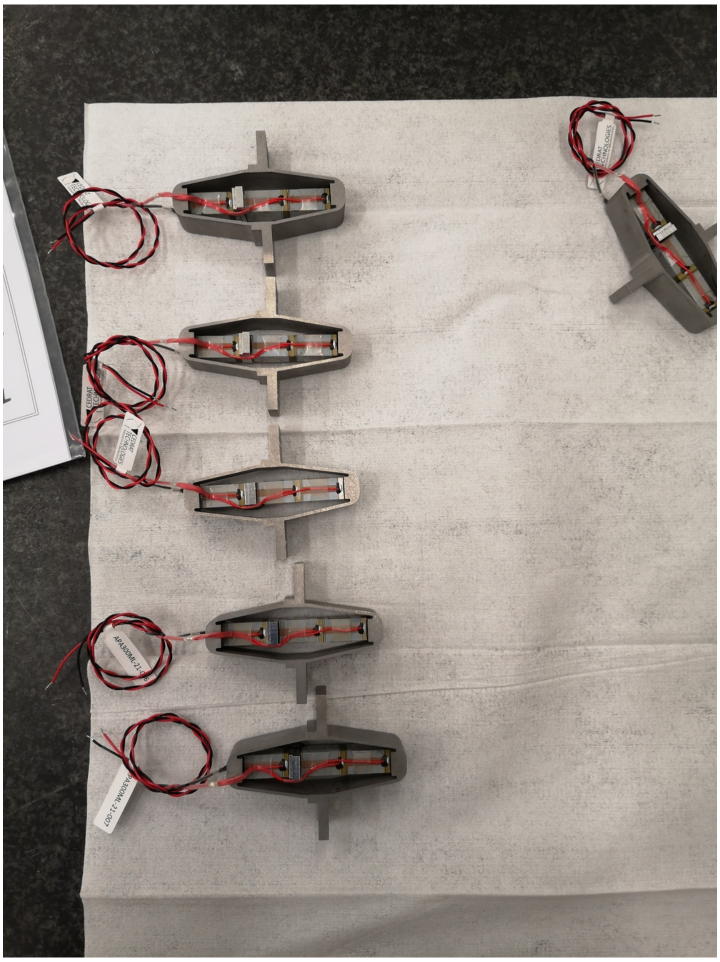

Figure 2.1: Received APA

2.1 Measurement Setup

The flatness corresponding to the two interface planes are measured as shown in Figure 2.2.

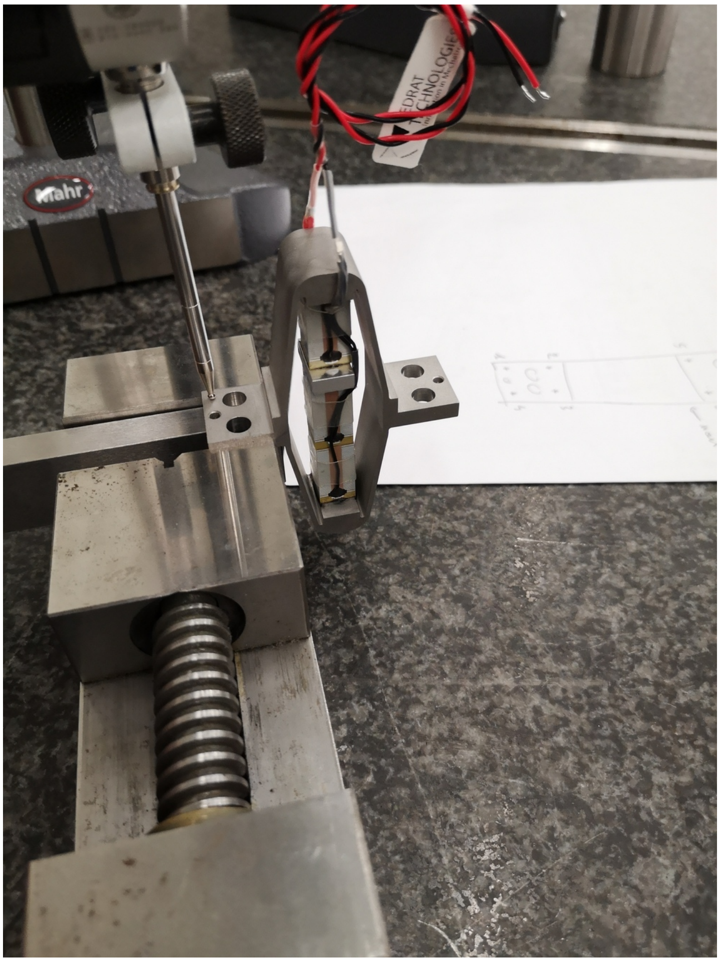

Figure 2.2: Measurement Setup

2.2 Measurement Results

The height (Z) measurements at the 8 locations (4 points by plane) are defined below.

Matlab

```
apa1  = 1e-6*[0, -0.5 , 3.5  , 3.5  , 42   , 45.5, 52.5 , 46];
apa2  = 1e-6*[0, -2.5 , -3   , 0    , -1.5 , 1   , -2   , -4];
apa3  = 1e-6*[0, -1.5 , 15   , 17.5 , 6.5  , 6.5 , 21   , 23];
apa4  = 1e-6*[0, 6.5  , 14.5 , 9    , 16   , 22  , 29.5 , 21];
apa5  = 1e-6*[0, -12.5, 16.5 , 28.5 , -43  , -52 , -22.5, -13.5];
apa6  = 1e-6*[0, -8   , -2   , 5    , -57.5, -62 , -55.5, -52.5];
apa7  = 1e-6*[0, 19.5 , -8   , -29.5, 75   , 97.5, 70   , 48];
apa7b = 1e-6*[0, 9    , -18.5, -30  , 31   , 46.5, 16.5 , 7.5];
apa = {apa1, apa2, apa3, apa4, apa5, apa6, apa7b};
```

The X/Y Positions of the 8 measurement points are defined below.

Matlab

```
W = 20e-3;   % Width [m]
L = 61e-3;   % Length [m]
d = 1e-3;    % Distance from border [m]
l = 15.5e-3; % [m]

pos = [[-L/2 + d; W/2 - d], [-L/2 + l - d; W/2 - d], [-L/2 + l - d; -W/2 + d], [-L/2 + d; -W/2 + d], [L/2 - l + d; W/2 - d],
↪  [L/2 - d; W/2 - d], [L/2 - d; -W/2 + d], [L/2 - l + d; -W/2 + d]];
```

Finally, the flatness is estimated by fitting a plane through the 8 points using the `fminsearch` command.

Matlab

```
apa_d = zeros(1, 7);
for i = 1:7
    fun = @(x)max(abs(([pos; apa{i}]-[0;0;x(1)])'*([x(2:3);1]/norm([x(2:3);1]))));
    x0 = [0;0;0];
    [x, min_d] = fminsearch(fun,x0);
    apa_d(i) = min_d;
end
```

The obtained flatness are shown in Table 2.1.

Table 2.1: Estimated flatness

	Flatness $[\mu m]$
APA 1	8.9
APA 2	3.1
APA 3	9.1
APA 4	3.0
APA 5	1.9
APA 6	7.1
APA 7	18.7

3 Electrical Measurements

Note

The capacitance of the stacks is measure with the LCR-800 Meter (doc)

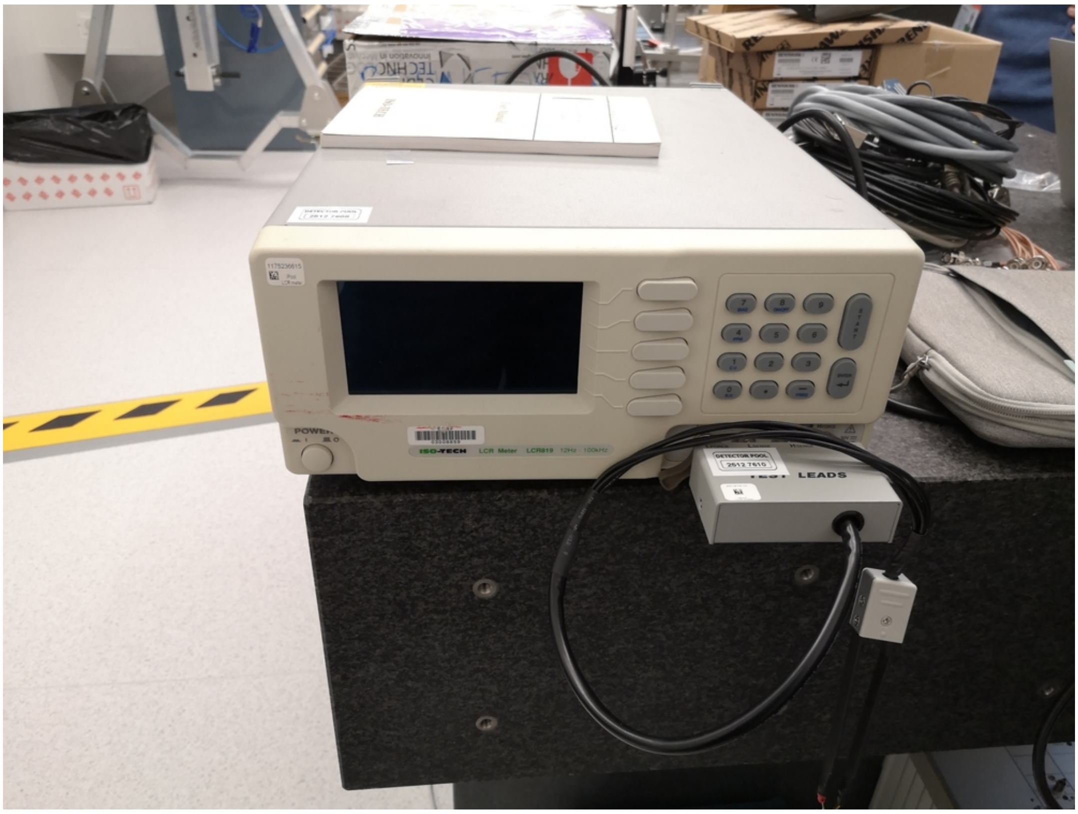

Figure 3.1: LCR Meter used for the measurements

The excitation frequency is set to be 1kHz.

Warning

There is clearly a problem with APA300ML number 3

Table 3.1: Capacitance measured with the LCR meter. The excitation signal is a sinus at 1kHz

	Sensor Stack	**Actuator Stacks**
APA 1	5.10	10.03
APA 2	4.99	9.85
APA 3	1.72	5.18
APA 4	4.94	9.82
APA 5	4.90	9.66
APA 6	4.99	9.91
APA 7	4.85	9.85

4 Stiffness measurement

4.1 APA test

Matlab
```matlab
load('meas_stiff_apa_1_x.mat', 't', 'F', 'd');
```

Matlab
```matlab
figure;
plot(t, F)
```

Matlab
```matlab
%% Automatic Zero of the force
F = F - mean(F(t > 0.1 & t < 0.3));

%% Start measurement at t = 0.2 s
d = d(t > 0.2);
F = F(t > 0.2);
t = t(t > 0.2); t = t - t(1);
```

Matlab
```matlab
i_l_start = find(F > 0.3, 1, 'first');
[~, i_l_stop] = max(F);
```

Matlab
```matlab
F_l = F(i_l_start:i_l_stop);
d_l = d(i_l_start:i_l_stop);
```

Matlab
```matlab
fit_l = polyfit(F_l, d_l, 1);

% %% Reset displacement based on fit
% d = d - fit_l(2);
% fit_s(2) = fit_s(2) - fit_l(2);
% fit_l(2) = 0;

% %% Estimated Stroke
% F_max = fit_s(2)/(fit_l(1) - fit_s(1));
% d_max = fit_l(1)*F_max;
```

Matlab
```matlab
h^2/fit_l(1)
```

Matlab

```
figure;
hold on;
plot(F,d,'k')
plot(F_l, d_l)
plot(F_l, F_l*fit_l(1) + fit_l(2), '--')
```

5 Stroke measurement

We here wish to estimate the stroke of the APA.

To do so, one side of the APA is fixed, and a displacement probe is located on the other side as shown in Figure 5.1.

Then, a voltage is applied on either one or two stacks using a DAC and a voltage amplifier.

Note

Here are the documentation of the equipment used for this test bench:

- **Voltage Amplifier**: PD200 with a gain of 20
- **16bits DAC**: IO313 Speedgoat card
- **Displacement Probe**: Millimar C1216 electronics and Millimar 1318 probe

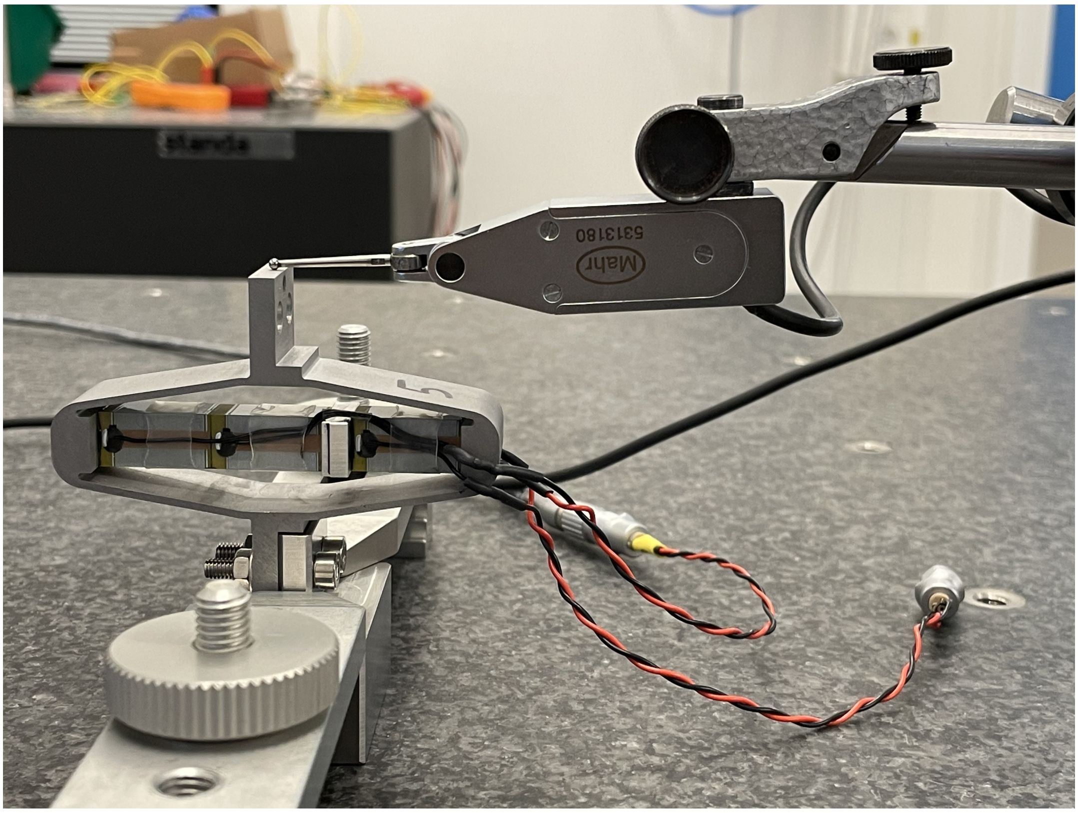

Figure 5.1: Bench to measured the APA stroke

5.1 Voltage applied on one stack

Let's first look at the relation between the voltage applied to **one** stack to the displacement of the APA as measured by the displacement probe.

The applied voltage is shown in Figure 5.2.

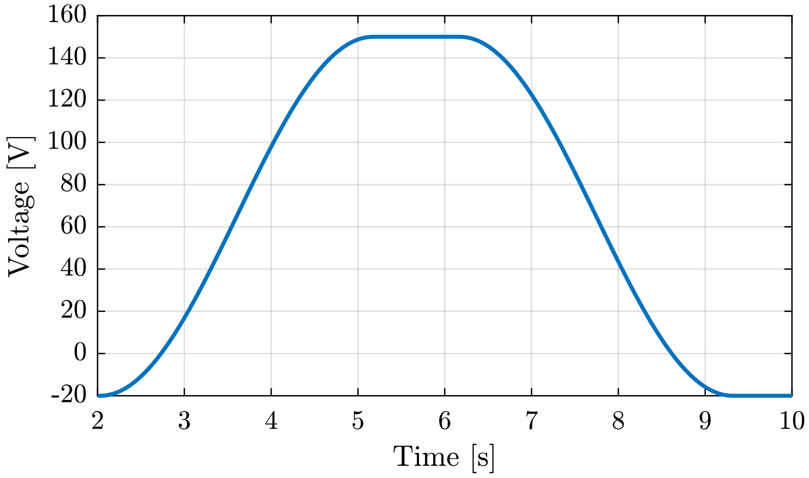

Figure 5.2: Applied voltage as a function of time

The obtained displacement is shown in Figure 5.3. The displacement is set to zero at initial time when the voltage applied is -20V.

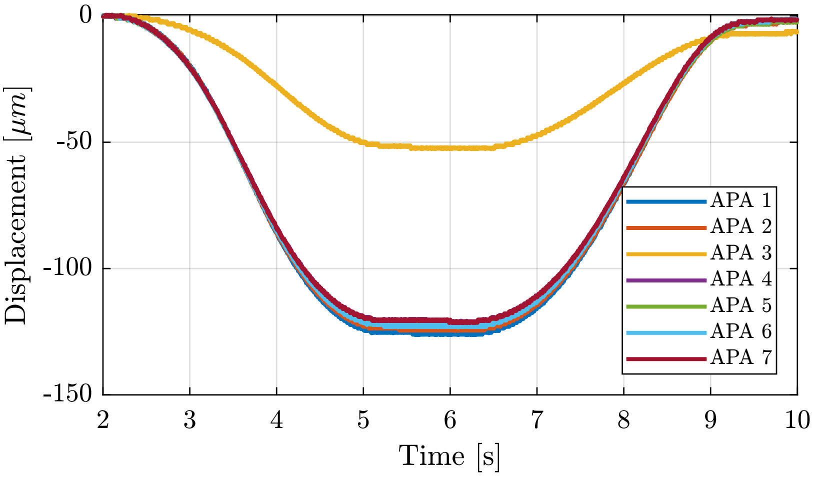

Figure 5.3: Displacement as a function of time for all the APA300ML

Finally, the displacement is shown as a function of the applied voltage in Figure 5.4. We can clearly see that there is a problem with the APA 3. Also, there is a large hysteresis.

Important

We can clearly see from Figure 5.4 that there is a problem with the APA number 3.

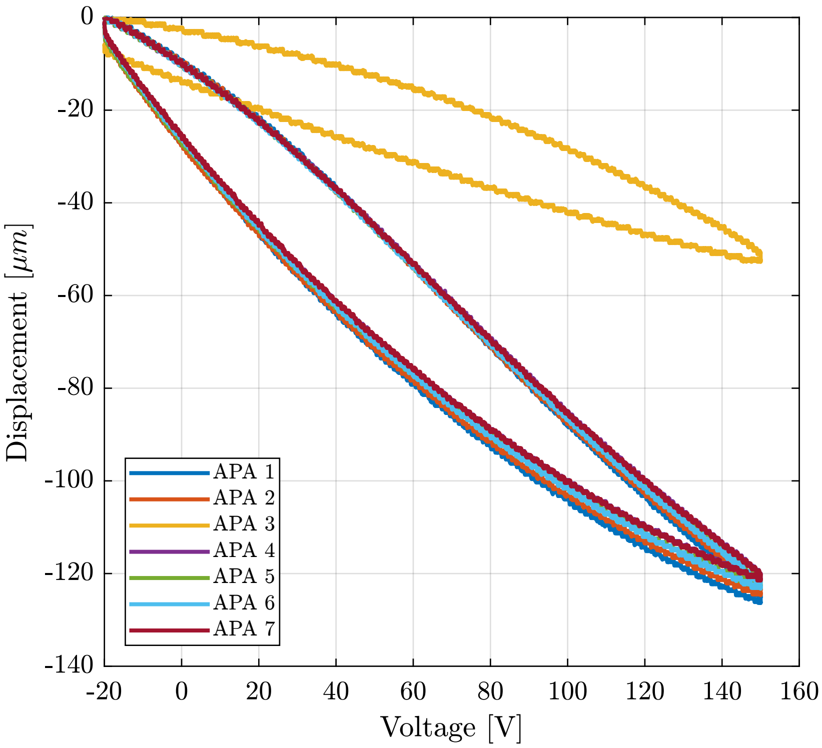

Figure 5.4: Displacement as a function of the applied voltage

5.2 Voltage applied on two stacks

Now look at the relation between the voltage applied to the **two** other stacks to the displacement of the APA as measured by the displacement probe.

The obtained displacement is shown in Figure 5.5. The displacement is set to zero at initial time when the voltage applied is -20V.

Finally, the displacement is shown as a function of the applied voltage in Figure 5.6. We can clearly see that there is a problem with the APA 3. Also, there is a large hysteresis.

5.3 Voltage applied on all three stacks

Finally, we can combine the two measurements to estimate the relation between the displacement and the voltage applied to the **three** stacks (Figure 5.7).

The obtained maximum stroke for all the APA are summarized in Table 5.1.

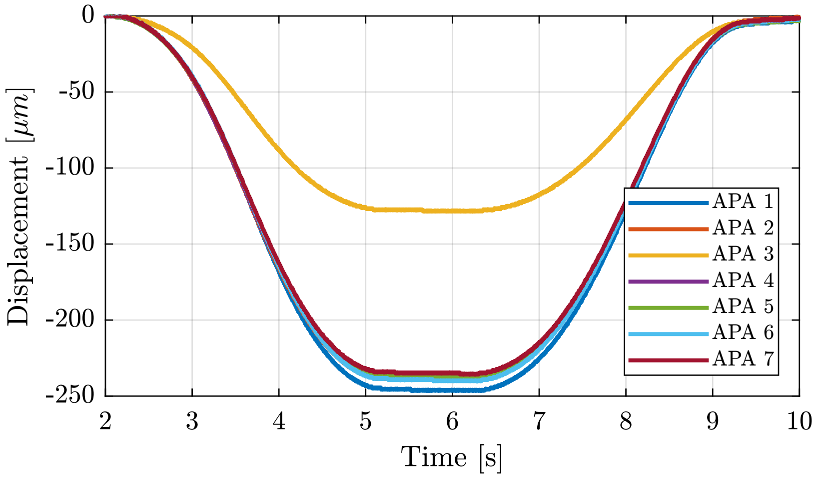

Figure 5.5: Displacement as a function of time for all the APA300ML

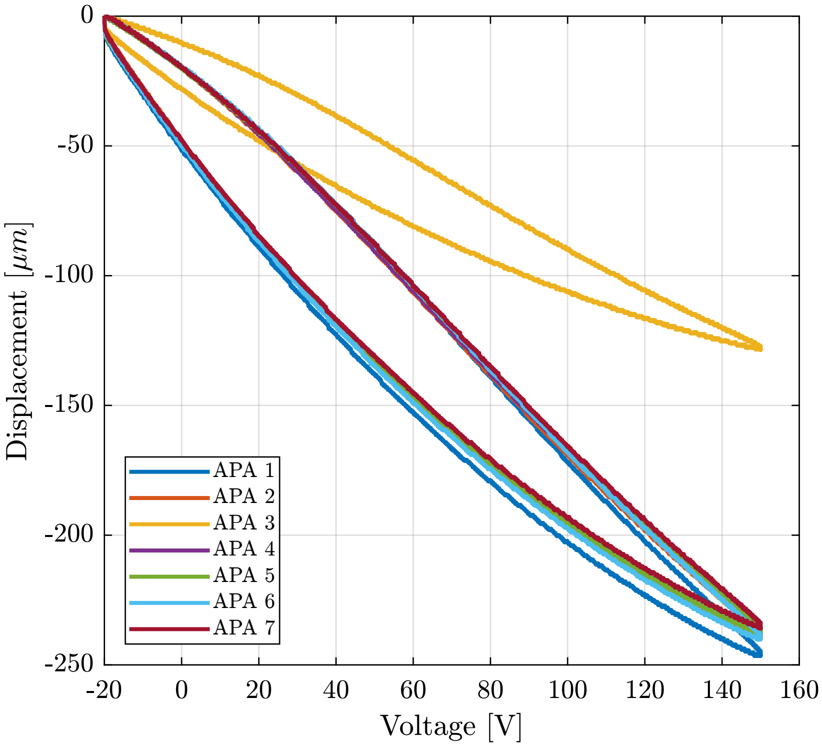

Figure 5.6: Displacement as a function of the applied voltage

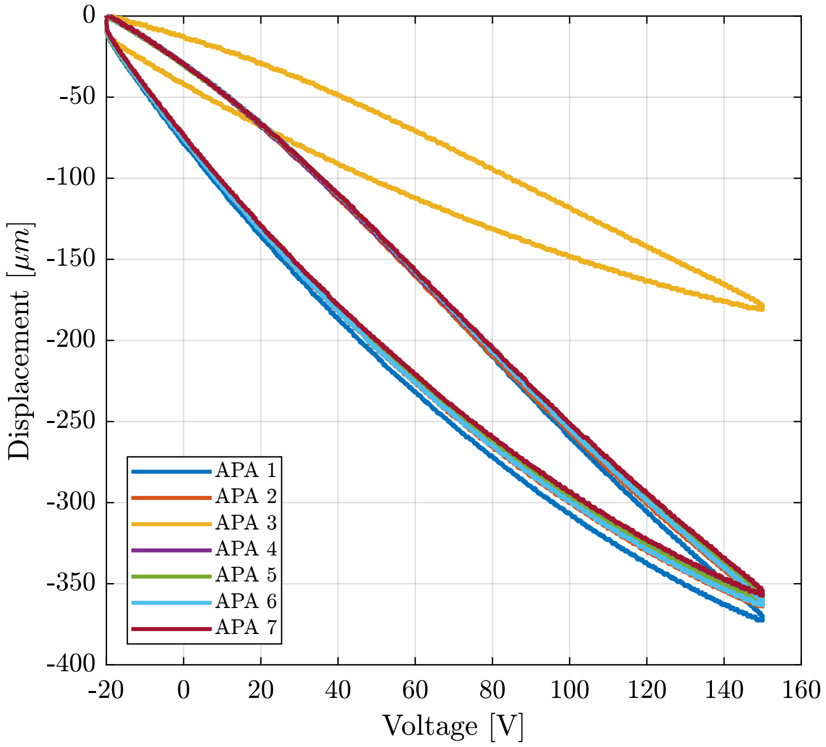

Figure 5.7: Displacement as a function of the applied voltage

Table 5.1: Measured maximum stroke

	Stroke [μm]
APA 1	373.2
APA 2	365.5
APA 3	181.7
APA 4	359.7
APA 5	361.5
APA 6	363.9
APA 7	358.4

6 Test-Bench Description

Note

Here are the documentation of the equipment used for this test bench:

- Voltage Amplifier: PD200
- Amplified Piezoelectric Actuator: APA300ML
- DAC/ADC: Speedgoat IO313
- Encoder: Renishaw Vionic and used Ruler
- Interferometer: Attocube IDS3010

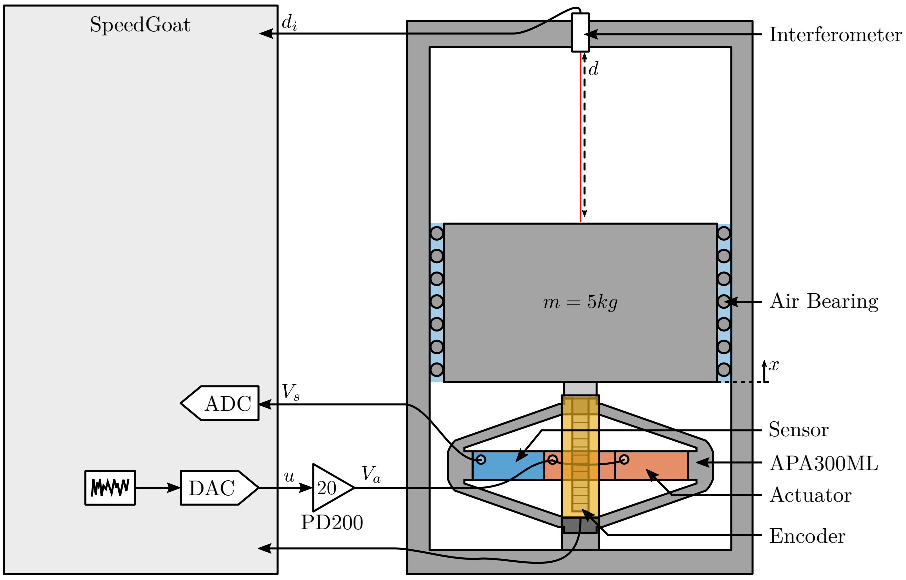

Figure 6.1: Schematic of the Test Bench

7 Measurement Procedure

7.1 Stroke Measurement

Using the PD200 amplifier, output a voltage:

$$V_a = 65 + 85 \sin(2\pi \cdot t)$$

To have a quasi-static excitation between -20 and 150V.

As the gain of the PD200 amplifier is 20, the DAC output voltage should be:

$$V_{dac}(t) = 3.25 + 4.25 \sin(2\pi \cdot t)$$

Verify that the voltage offset of the PD200 is zero!

Measure the output vertical displacement d using the interferometer.

Then, plot d as a function of V_a, and perform a linear regression. Conclude on the obtained stroke.

7.2 Stiffness Measurement

Add some (known) weight δmg on the suspended mass and measure the deflection δd. This can be tested when the piezoelectric stacks are open-circuit.

As the stiffness will be around $k \approx 10^6 N/m$, an added mass of $m \approx 100g$ will induce a static deflection of $\approx 1\mu m$ which should be large enough for a precise measurement using the interferometer.

Then the obtained stiffness is:

$$k = \frac{\delta mg}{\delta d} \tag{7.1}$$

7.3 Hysteresis measurement

Supply a quasi static sinusoidal excitation V_a at different voltages.

The offset should be 65V, and the sin amplitude can range from 1V up to 85V.

For each excitation amplitude, the vertical displacement d of the mass is measured.

Then, d is plotted as a function of V_a for all the amplitudes.

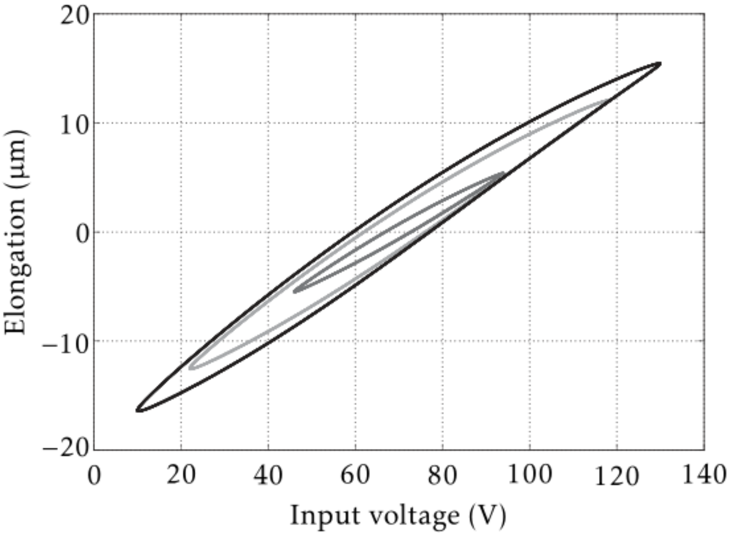

Figure 6.16: *Measured hysteresis loops for a single PE actuator, 70 V bias + 1 Hz sine wave: 60 V amplitude (black), 48 V amplitude (light grey), 24 V amplitude (dark grey)*

Figure 7.1: Expected Hysteresis ([1])

7.4 Piezoelectric Actuator Constant

Using the measurement test-bench, it is rather easy the determine the static gain between the applied voltage V_a to the induced displacement d. Use a quasi static (1Hz) excitation signal V_a on the piezoelectric stack and measure the vertical displacement d. Perform a linear regression to obtain:

$$d = g_{d/V_a} \cdot V_a \tag{7.2}$$

Using the Simscape model of the APA, it is possible to determine the static gain between the actuator force F_a to the induced displacement d:

$$d = g_{d/F_a} \cdot F_a \tag{7.3}$$

From the two gains, it is then easy to determine g_a:

$$g_a = \frac{F_a}{V_a} = \frac{F_a}{d} \cdot \frac{d}{V_a} = \frac{g_{d/V_a}}{g_{d/F_a}} \tag{7.4}$$

7.5 Piezoelectric Sensor Constant

From a quasi static excitation of the piezoelectric stack, measure the gain from V_a to V_s:

$$V_s = g_{V_s/V_a} V_a \tag{7.5}$$

Note here that there is an high pass filter formed by the piezo capacitor and parallel resistor. The excitation frequency should then be in between the cut-off frequency of this high pass filter and the first resonance.

Alternatively, the gain can be computed from the dynamical identification and taking the gain at the wanted frequency.

Using the simscape model, compute the static gain from the actuator force F_a to the strain of the sensor stack dl:

$$dl = g_{dl/F_a} F_a \tag{7.6}$$

Then, the static gain from the sensor stack strain dl to the general voltage V_s is:

$$g_s = \frac{V_s}{dl} = \frac{V_s}{V_a} \cdot \frac{V_a}{F_a} \cdot \frac{F_a}{dl} = \frac{g_{V_s/V_a}}{g_a \cdot g_{dl/F_a}} \tag{7.7}$$

Alternatively, we could impose an external force to add strain in the APA that should be equally present in all the 3 stacks and equal to 1/5 of the vertical strain. This external force can be some weight added, or a piezo in parallel.

7.6 Capacitance Measurement

Measure the capacitance of the 3 stacks individually using a precise multi-meter.

7.7 Dynamical Behavior

Perform a system identification from V_a to the measured displacement d by the interferometer and by the encoder, and to the generated voltage V_s.

This can be performed using different excitation signals.

This can also be performed with and without the encoder fixed to the APA.

7.8 Compare the results obtained for all 7 APA300ML

Compare all the obtained parameters for all the test APA.

8 Measurement Results

Bibliography

[1] Gerrit Wijnand van der Poel. “An Exploration of Active Hard Mount Vibration Isolation for Precision Equipment”. PhD thesis. University of Twente, 2010. ISBN: 978-90-365-3016-3. DOI: `10.3990/1.9789036530163`. URL: `https://doi.org/10.3990/1.9789036530163`.