Power dissipation in stick-slip based cryogenic positioners is of importance as it can cause the experiment to heat up during use. Many ways of representing this power dissipation can be used and it is very easy to draw the wrong conclusions.
This application note distinguishes the contribution of several dissipation sources; piezo, friction and cable loss and compares these for 3 types of piezo; 150 V linear stack, 60 V linear stack and 500 V shear piezo. Benchmark dissipation values are determined based on a stick-slip positioner driven with a sawtooth signal.

## 1. Stick-slip positioner

Stick-slip positioners operate by driving the piezo with a sawtooth-like voltage at pk-pk amplitude $U_{pp}$, equivalent to piezo stroke $S_p$. During the slow ramp $t_0$ - $t_1$ the table sticks to the plate, but during the fast ramp $t_1$ - $t_2$ table inertia will cause it to slip with respect to the fast-retracting plate. After a cycle $t_0$ - $t_1$ - $t_2$ the piezo and plate have returned to their initial positions, but the table has moved a distance $S_p$. Repeating such steps will result in macroscopic motion.

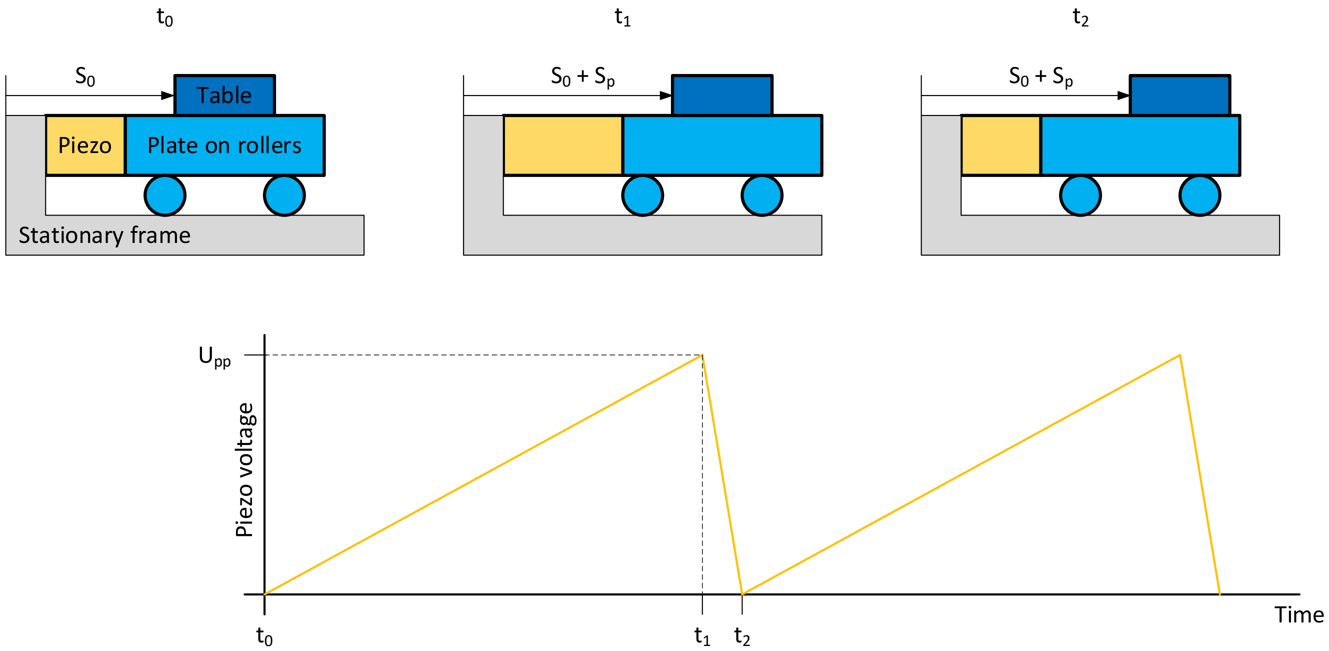


*Fig 1: Stick-slip positioners and drive signal*

## 2. Power loss mechanisms (sawtooth signal)

### 2.1 Energy loss per step

The lost energy per step of a positioner is the sum of the losses in the piezo, friction and cabling. Details can be found in 2.1.1 to 2.1.3.

$$E_{step} = E_{piezo} + E_{friction} + E_{cable}$$

$$E_{step} = tan\delta C U_{pp}{}^2 + F_h S_p + C^2 U_{pp}{}^2 R \left[\frac{1}{t_f} + \frac{1}{t_s}\right]$$

#### 2.1.1 Piezo loss per step

A piezo behaves as a capacitance C and when charged it contains energy E. A fraction $E_{piezo}$ of this energy is lost in the piezo during both the charge and discharge cycle (1 full step). A measure of this loss is the material loss factor tanδ.

$$E = \frac{1}{2} C U_{pp}{}^2$$

$$E_{piezo} = 2\frac{1}{2} tan\delta C U_{pp}{}^2 = tan\delta C U_{pp}{}^2 \ \ (tan\delta = loss\ factor)$$

### 2.1.2 Friction loss per step

Stick-slip positioners will generate heat in the friction contact between plate and table:

$$F_h = holding\ force$$

$$S_p = piezo\ stroke$$

$$E_{friction} = F_h S_p$$

### 2.1.3 Cable loss per step

Drive currents will cause resistive energy losses in wiring to the piezo. For a sawtooth signal:

- Fast flank

$$I_f = C\frac{U_{pp}}{t_f}$$

$$P_f = {I_f}^2 R$$

$$E_{cable\_f} = {I_f}^2 R t_f = C^2\frac{{U_{pp}}^2}{t_f}R$$

- Slow flank

$$I_s = C\frac{U_{pp}}{t_s}$$

$$P_s = {I_s}^2 R$$

$$E_{cable\_s} = {I_s}^2 R t_s = C^2\frac{{U_{pp}}^2}{t_s}R$$

- Total cable loss per step

$$E_{cable} = E_{cable\_f} + E_{cable\_s} = C^2 {U_{pp}}^2 R\left[\frac{1}{t_f} + \frac{1}{t_s}\right]$$

## 2.2 Energy loss per covered distance

In chapter 2.1 the dissipated energy $E_{step}$, per step $S_p$ of a stick-slip positioner driven with a sawtooth signal was calculated to be

$$E_{step} = tan\delta C {U_{pp}}^2 + F_h S_p + C^2 {U_{pp}}^2 R\left[\frac{1}{t_f} + \frac{1}{t_s}\right]$$

When one needs to cover a distance $S_{distance}$ a series of steps is needed and the dissipated energy becomes

$$E_{distance} = \frac{S_{distance}}{S_p} E_{step}$$

$$E_{distance} = \frac{S_{distance}}{S_p}\left[tan\delta C {U_{pp}}^2 + F_h S_p + C^2 {U_{pp}}^2 R\left[\frac{1}{t_f} + \frac{1}{t_s}\right]\right]$$

A normalized value per mm covered distance for <u>piezo dissipation only</u> is given by:

$$E_{piezo\_1mm} = \frac{E_{piezo}}{S_p} = \frac{tan\delta C {U_{pp}}^2}{S_p}$$

## 2.3 Energy loss at given speed

In chapter 2.1 the dissipated energy $E_{step}$, per step $S_p$ of a stick-slip positioner driven with a sawtooth signal was calculated to be

$$E_{step} = tan\delta C {U_{pp}}^2 + F_h S_p + C^2 {U_{pp}}^2 R \left[\frac{1}{t_f} + \frac{1}{t_s}\right]$$

When one needs to move at speed v a number of steps per second f is needed and the dissipated power becomes:

$$f = \frac{v}{S_p}$$

$$P_{speed} = f E_{step}$$

$$P_{speed} = f \left[tan\delta C {U_{pp}}^2 + F_h S_p + C^2 {U_{pp}}^2 R \left[\frac{1}{t_f} + \frac{1}{t_s}\right]\right]$$

# 3. Piezo operation at cryogenic temperatures

For each piezo used in the analysis of chapter 4 specific material parameters have been determined, based on datasheets and additional data on the internet. These specific values will be mentioned in the analysis, but to a large extend the following basic relations apply:

**Loss factor**
On datasheets small signal values are given. In the analysis large signal values are used, which are typically a factor 7 above small signal values. The value for shear piezos is approximately a factor of 2 larger than longitudinal stack piezos. At cryogenic temperatures values drop by a factor ≈2,5.

**Stroke**
Piezo stroke will reduce by a factor of 10 at cryogenic temperatures. Longitudinal stacks are assumed to be driven unipolar, shear piezos bipolar.

**Capacitance**
On datasheets small signal values are given. In the analysis large signal values are used, which are typically a factor 1,7 above small signal values. At cryogenic temperatures values drop by a factor ≈5.

# 4. Benchmark comparison of 3 piezo types

For the dissipation analysis only a very limited set of benchmark values at 4 K is needed:

- Fast ramp with duration $t_f$ = 10 µs
  - It is not unusual for stick-slip positioners to operate at even lower values, while it is a minimal value for JPE positioners.
- The slow ramp duration $t_s$ = (1/f- $t_f$), with f the driving frequency (steps per second)
  - This results in the sawtooth profile of figure 1.
- Loss of stroke is 50 nm
  - Finite structural stiffnesses will cause a part of the piezo motion to be lost in elastic micro deformations throughout the positioner and in the piezo itself. It is as if the piezo stroke is reduced by this value.
- Holding force between plate and table $F_h$= 5 N
- Cable resistance to the piezo R = 1 Ω
  - This is equivalent to approximately 0.3 m of low thermal conductivity phosphor bronze wire, or several hundred meters of copper wire.
- Minimal achievable speed v = 100 µm/s

| | | Piezo 1: PICMA | Piezo 2: Plate stack | Piezo 3: PICA |
|---|---|---|---|---|
| **Piezo characteristics** | | | | |
| **Supplier** | | PI Ceramic | Noliac | PI Ceramic |
| **Product code** | | P-883.11 | NAC2002-H08 | P-111.03T |
| **Material** | | PIC252 | NCE51 | PIC255 |
| **Type** | | Longitudinal stack | Longitudinal stack | Shear stack |
| **Footprint** | A x B | 3 x 3 mm | 3 x 3 mm | 3 x 3 mm |
| **Height** | H | 9 mm | 8 mm | 4,4 mm |
| **Max pkpk voltage** | $U_{pp}$ | 150 V (-30 to +120) | 60 V | 500 V (±250) |
| **Stroke at $U_{pp}$, 300 K** | $S_{p300}$ | 10 µm | 8,6 µm | 3 µm |
| **Stroke at $U_{pp}$ , 4 K** | $S_{p4}$ | 1 µm | 0,86 µm | 0,3 µm |
| **Small signal loss factor 300 K** | $\tan\delta_{s300}$ | 0,020 | 0,015 | 0,04 |
| **Large signal loss factor 300 K** | $\tan\delta_{l300}$ | 0,14 | 0,14 | 0,28 |
| **Large signal loss factor 4 K** | $\tan\delta_{l4}$ | 0,05 | 0,06 | 0,10 |
| **Small signal capacitance 300 K** | $C_{s300}$ | 210 nF | 1080 nF | 1,5 nF |
| **Large signal capacitance 300 K** | $C_{l300}$ | 357 nF | 1836 nF | 2,6 nF |
| **Large signal capacitance 4 K** | $C_{l4}$ | 81 nF | 317 nF | 0,6 nF |
| **Positioner characteristics** | | | | |
| **Loss of stroke** | $S_{vp}$ | 0,05 µm | 0,05 µm | 0,05 µm |
| **Effective stroke at $U_{pp}$ , 4 K** | $S_{p4}$ | 0,95 µm | 0,81 µm | 0,25 µm |
| **Positioner holding force** | $F_h$ | 5N | 5N | 5N |
| **Positioner covered distance** | $S_{distance}$ | 100 µm | 100 µm | 100 µm |
| **Positioner speed** | v | 100 µm /s | 100 µm /s | 100 µm /s |
| **Drive frequency** | f | v/ $S_{p4}$ = 105 Hz<br>500 Hz | v/ $S_{p4}$ = 123 Hz<br>606 Hz | v/ $S_{p4}$ = 400 Hz<br>4000 Hz |
| **Fast ramp time** | $t_f$ | 10 µs | 10 µs | 10 µs |
| **Slow ramp time** | $t_s$ | 1/f- $t_f$ | 1/f- $t_f$ | 1/f- $t_f$ |
| **Cable resistance** | $R_c$ | 1 Ω | 1 Ω | 1 Ω |
| **Dissipation results** | | | | |
| **Piezo loss per step** | $E_{piezo}$ | 91,1 µJ<br>5,7 µJ | 68,5 µJ<br>4,3 µJ | 15 µJ<br>0,9 µJ |
| **Friction loss per step** | $E_{friction}$ | 4,8 µJ<br>1 µJ | 4,1 µJ<br>0,8 µJ | 1,3 µJ<br>0,1 µJ |
| **Cable loss per step, total (fast ramp + slow ramp)** | $E_{cable}$ | 14,8 µJ (14,8 + 0,02)<br>0,9 µJ (0,9 + 0) | 36,2 µJ (36,2 + 0,05)<br>2,3 µJ (2,3 + 0) | 0,01 µJ (0,01 + 0)<br>0 µJ (0 + 0) |
| **Total loss per step** | $E_{step}$ | 110,6 µJ<br>7,6 µJ | 108,7 µJ<br>7,4 µJ | 16,3 µJ<br>1,1 µJ |
| **Total loss for 100 micron covered distance ( at speed 100 micron/s)** | $E_{distance}$ | 11,6 mJ<br>3,8 mJ | 13,4 mJ<br>4,5 mJ | 6,5 mJ<br>4,3 mJ |
| **Total power at 100 micron/s speed** | $P_{speed}$ | 11,6 mW<br>3,8 mW | 13,4 mW<br>4,5 mW | 6,5 mW<br>4,3 mW |

*Blue numbers: for drive voltage and piezo stroke reduced to 25% of the maximum values. The frequency is increased to maintain the minimum specified speed. A further reduction might cause positioners to stall, or speed cannot be achieved without unrealistic drive frequencies.*

## 5. Conclusion

**There is no clear advantage of a specific type of piezo over the others:**

- When driving stick slip positioners at maximum voltage it seems advantageous to use higher voltage piezos, with the shear piezo as the best example.
- However, increasing the step frequency while reducing the drive voltage is very effective to reduce the total dissipation per travelled distance or given speed. In fact, in this scenario it favors one of the linear piezo stacks.
- But keep in mind; differences are relatively small, especially when taking into account the limited accuracy of piezo characteristics in cryogenic conditions and the fixed value for the fast ramp duration of 10 µs. The latter value has a big influence on dissipation and depends on the actual positioner.



Sources: