Final MAE MEng report

ASML Small Bolt Pretensioner

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Objective

The objective of the project is to be able to apply a precise and known tension to a bolt, while minimizing the effects of friction-caused defects. The tension applied to the bolt should be around 90% of the bolt's yield stress. The limiting case is an M3 bolt made with A4-80 steel, and the method developed should be clean room compatible, and additionally be applicable to M3 bolts spaced 8 mm apart.

Approach

The first step I took was to characterize the tension required. ASTM F378-02 is a list of specifications for stainless steel bolts. Depending on the grade of steel, there are different forces required to yield the bolt. A4-80 steel has a yield strength of 600 MPa, and so the force required is around 3.02 kN according to the table. Noteworthy is that the stress area is not the area of a circle with the diameter of the bolt; taking the threads into account, the stress area is:

$$A = 0.7854(D - 0.9382P)^2$$

where D = nominal size, mm, and P = thread pitch, mm. M3 bolts have a nominal diameter of 3 mm, and a thread pitch of 0.5 mm. The stress area is therefore 5.03 mm^2.

The next step was to consider the methods of tightening bolts. Traditional methods including wrenches and torque drivers are not allowed due to the creation of surface defects. I decided that the model hydraulic tensioners use would be the best for the project. The operation of a hydraulic tensioner is shown in fig. 1.

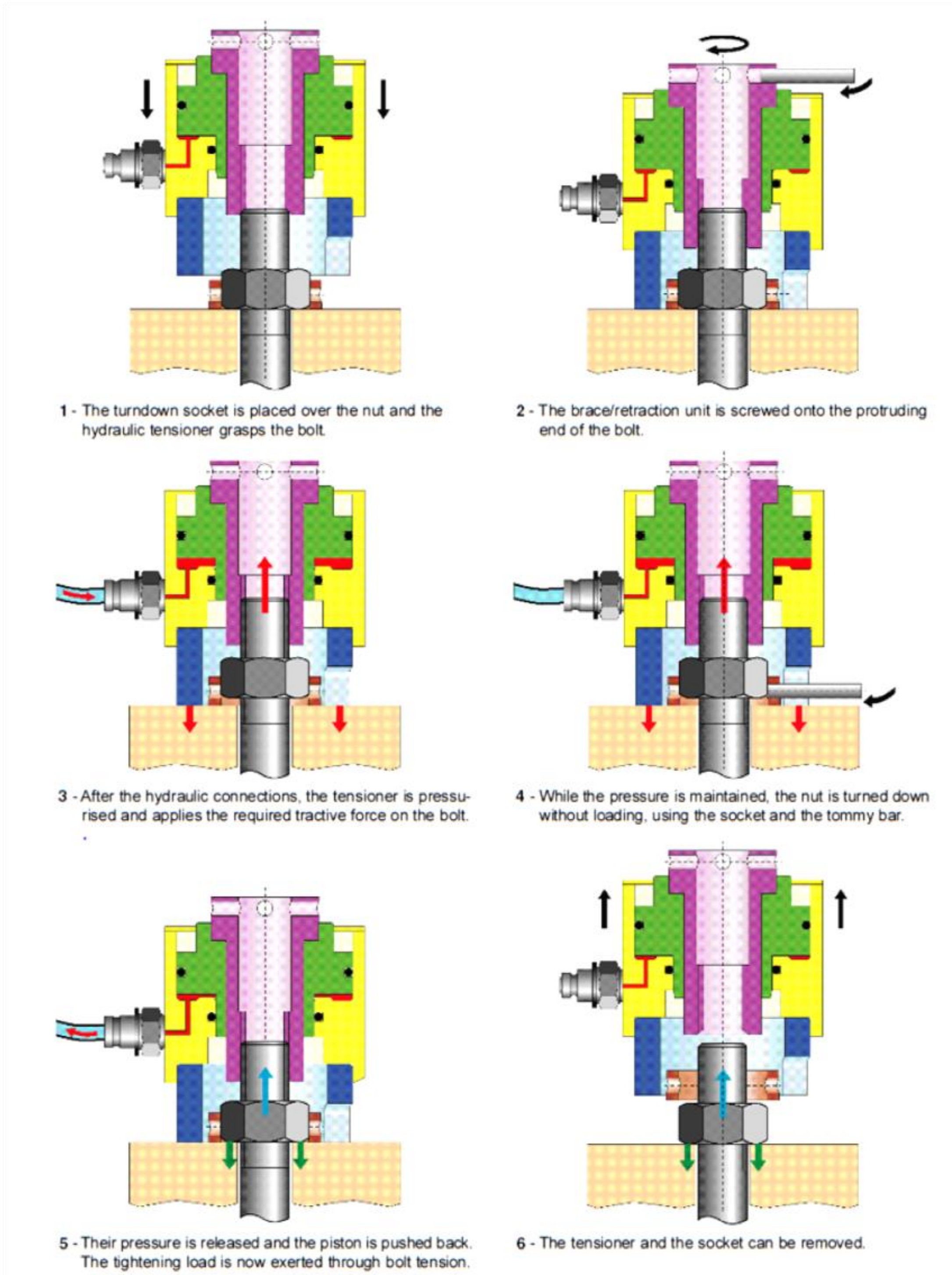

Figure 1:Hydraulic tensioner operating principles

Fluid pressure actuation is not compatible with clean rooms due to the use of lubricants however. I decided that a piezoelectric actuator might be the solution to that problem, since commercial actuators have demonstrated force of the same magnitude we require while being small in dimensions. Actuators considered were the P-016 ring actuator series from Physik Instrumente and the HPST 150/14 series from American Piezo. The blocked force of those actuators are around 4500N, the outer diameter of the actuator is 15mm and the inner diameter is 9 mm. Using the stiffness given by the manufacturer, I calculated the Young's modulus for the stack actuator to be 26.8 GPa, with the spring constant formula for axial loading of a beam:

$$k = \frac{EA}{L}$$

Where A is the cross sectional area of the beam, L is the length of the beam, E is the Young's modulus of the beam material.

The next step is to analyze the force loading of the model. The cross section view and isometric wireframe view of the model I used is depicted in fig. 2a and 2b.

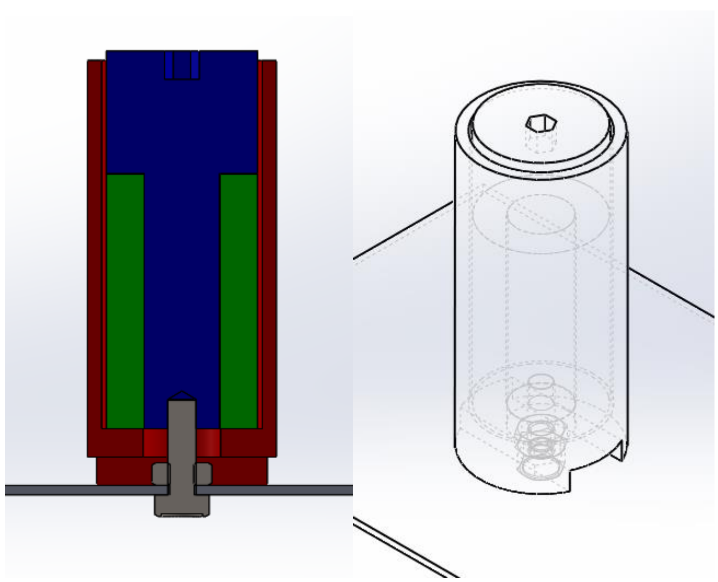

Figure 2a and 2b. Cross sectional view and wireframe view of model.

Where the green represents the piezoelectric stack actuator, the blue is the piston, and the red is the casing. The dark grey represents a clamped part, and the lighter gray is the nut and the bolt. The loading and the FBD of the loading is depicted in fig 3a and 3b.

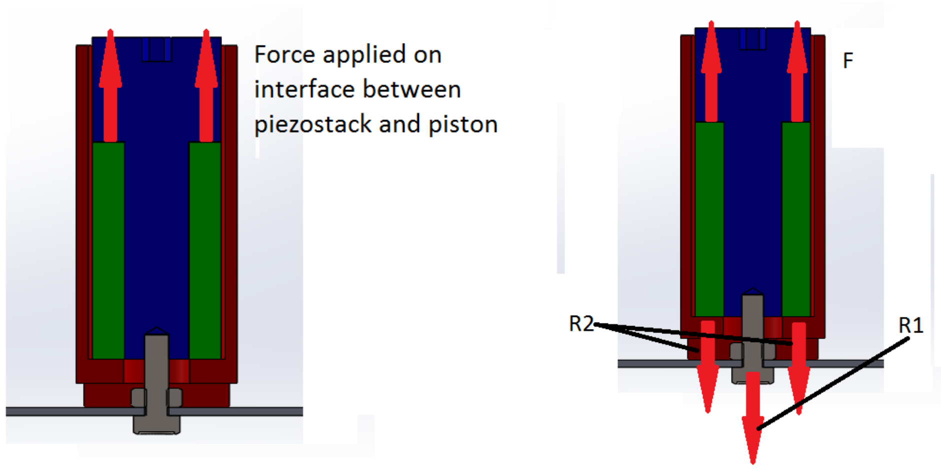

Figure 3a and 3b. Loading and FBD of model.

The piezoelectric stack actuator has a spring constant of its own, and the force exerted decreases as the displacement increases due to that. The piston and the bolt are screwed together, so they are considered two springs in series. The piston-bolt assembly and the piezoelectric stack actuator have to displace the same amount, so they are considered two springs in parallel. A simplified model is shown in fig 4.

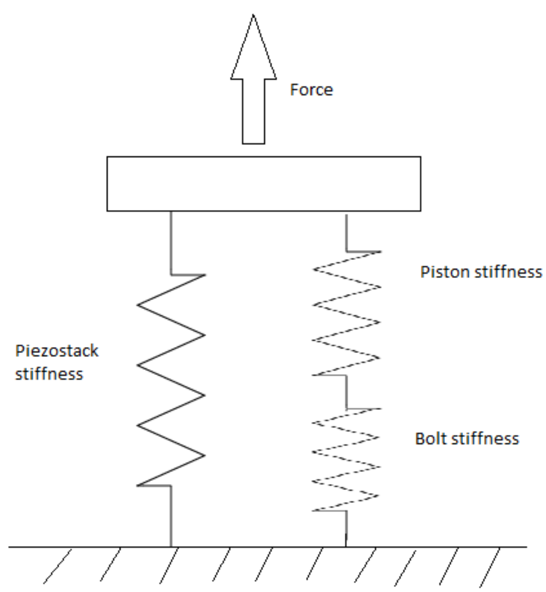

Figure 4. Simplified model

The force equations that characterize this system are

$$\sum F = 0$$

$$F + R_2 + R_1 = 0$$

$$R_2 = -F_2$$

$$R_1 = -F_1$$

$$F = F_1 + F_2$$

The displacement of a piezoelectric stack actuator is given by

$$u_s = \frac{1}{k_s} f + u_o v$$

Where k_s is the short-circuit stiffness of the piezoelectric stack given by

$$k_s = \frac{Y_3 A}{L_s}$$

And u_o is the free displacement of the stack per unit voltage input, f is the force applied to the piezostack.

$$f = -k_{eff} * u = -F_1$$

$$u = -\frac{k_{eff}}{k_s} u + u_o\ v$$

$$u = \frac{k_s}{k_s + k_{eff}} u_o v$$

So the force applied on the piston-bolt assembly can be found by multiplying the displacement by the combined spring constant.

$$-F_1 = -k_{eff} * u = -\frac{k_s * k_{eff}}{k_s + k_{eff}} u_o v$$

At max voltage,

$$k_s * u_o * v = f_{bl}$$

$$-F_1 = -k_{eff} * u = -\frac{k_{eff}}{k_s + k_{eff}} f_{bl}$$

The negative sign in front of F_1 is because the force applied to the piezoelectric stack is the opposite of the force applied to the piston-bolt assembly. For the piston-bolt assembly, we can calculate the spring constant of the assembly to be

$$k_{bolt} = \frac{E * A_1}{L_1}$$

$$k_{piston} = \frac{E * A_2}{L_2}$$

$$k_{eff} = k_{bolt} * \frac{k_{piston}}{k_{bolt} + k_{piston}}$$

The bolt we consider is 10 mm long, and 2 mm is being gripped by the hole tapped in the piston. Setting all variables except for the length of the piezoelectric stack actuator constant, I used MATLAB to calculate what length of the stack actuator is needed to apply enough force to cause 540 MPa of stress in the bolt. Note that we use the stress area rather than the area calculated from the diameter. The result is around 68 mm.

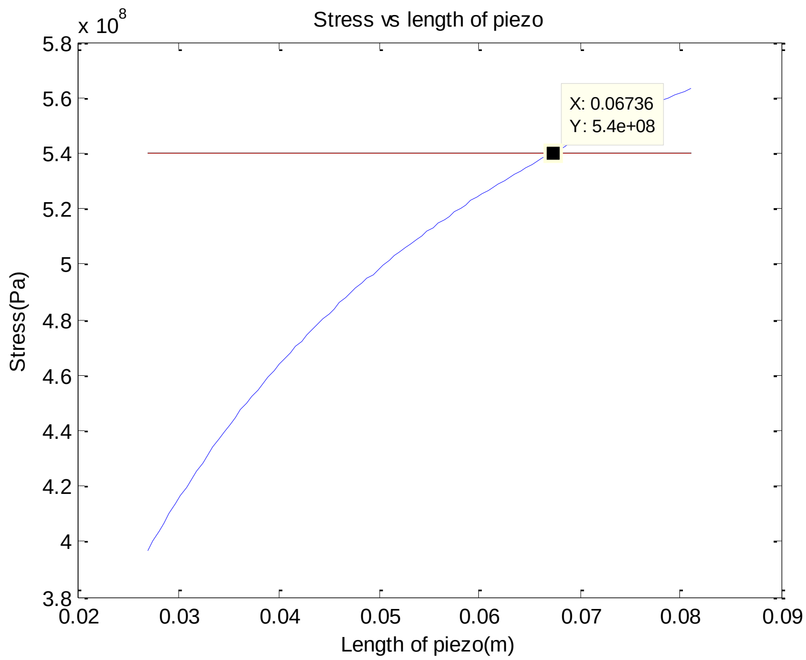

Figure 5. MATLAB plot to determine length of piezoelectric element

Results

The model was modified slightly to account for real life needs (fig 6a) and to remove computational difficulties (fig 6b).

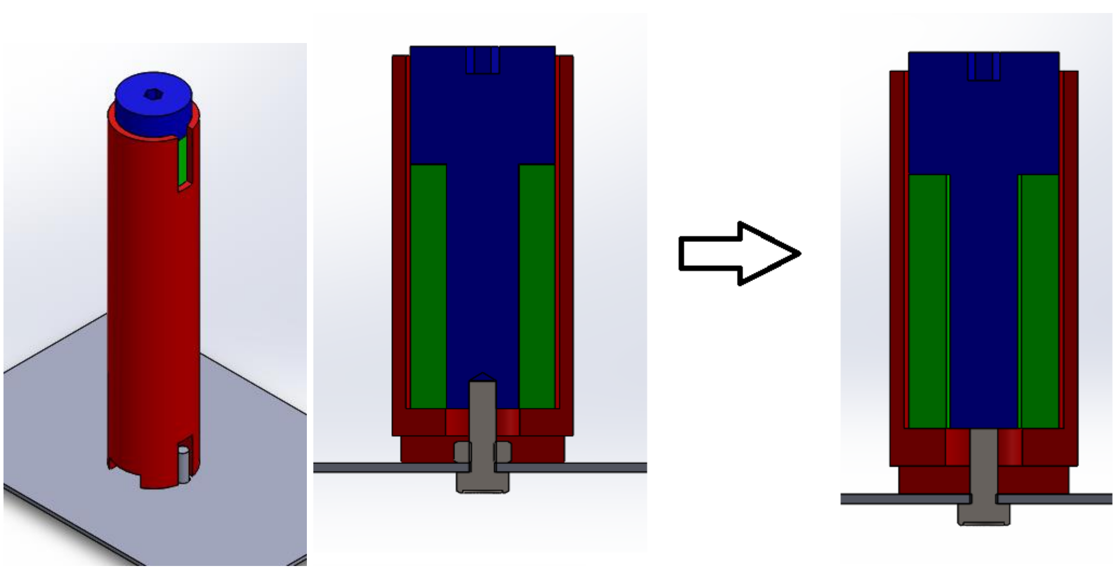

Figure 6a and 6b. Creation of slots on the model and removal of tapped hole from piston.

$$f_{bl} = d_{33} Y_3^E A_p / t_p v$$

On the top two slots have been cut out for the electrodes of the piezoelectric actuator. On the bottom four more slots have been cut out. The two wider and shorter ones are to put in a wrench to screw down the nut after tensioning is complete. The longer and narrower ones are to compensate for the screws placed closely. We allow roughly 3 mm of clearance for the screws placed next to each other, and the piezo actuator has been shifted up accordingly, and the piston has been elongated by 5 mm more than the piezoactuator. The hole in the piston has been removed and the surface of the end of the bolt was bonded to the bottom of the piston due to nonlinear contact difficulties between the hole and the threads of the bolt.

ANSYS was used for an FEA simulation.

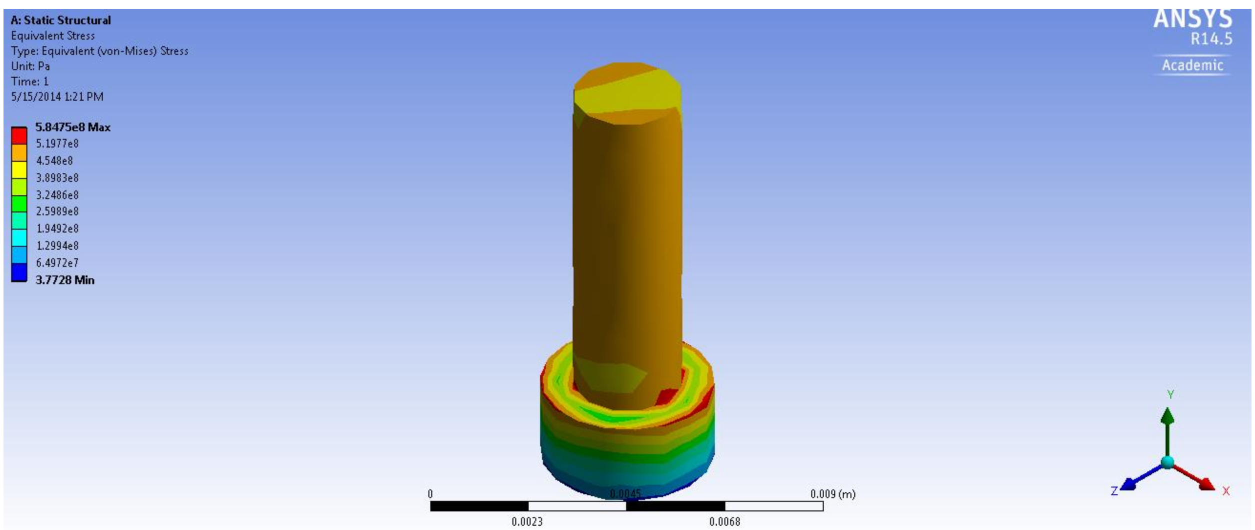

Figure 7. Stress distribution on the bolt.

The von-Mises stress over time has a maximum value of 584.75 MPa. Detailed files are included in appendices.

There are more options to be explored, such as custom piezoelectric actuators. The blocking force of a piezoelectric actuator is given by

$$f_{bl} = d_{33} Y_3^E A_p / t_p v$$

The spring constant of the piezoelectric actuator is also dependent on the elasticity of the material. A MATLAB calculation was done with the APC materials, holding the piezo length constant at 27mm:

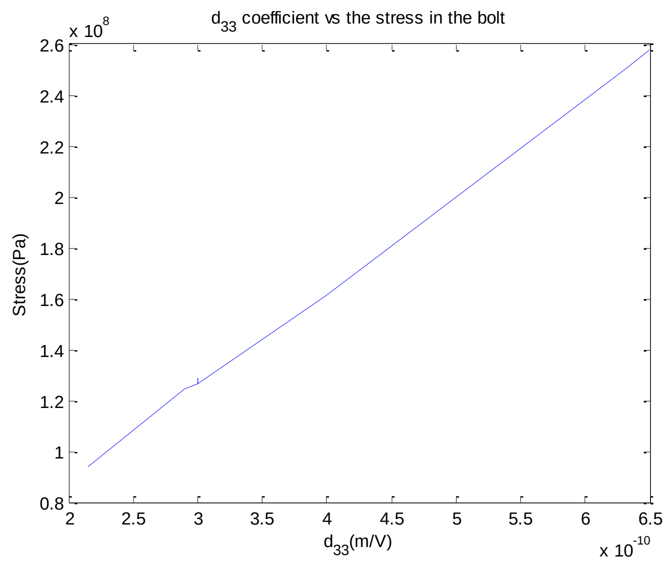

Figure 8. Stress on bolt as a function of d33

The results suggest that the d_{33} coefficient(Piezoelectric charge constant) scales up the force faster than the Young's modulus scales down the force, implying that if we were to use a custom piezoelectric element, we should choose the softest material possible.

Another option to be explored is the height of the piezoelectric element. The force of the piezoelectric element increases with area, and so we can consider the HPSt 150/20-15/xx series, which has a blocking force of 8000N, an outer diameter of 22 mm and an inner diameter of 14.5 mm. Referring back to fig 6a, if we make the slots for the bolts deeper, we can potentially avoid the spacing issue and use the larger area piezoelement instead. A MATLAB plot is included below to illustrate that we can use a much shorter length of piezo for our purposes.

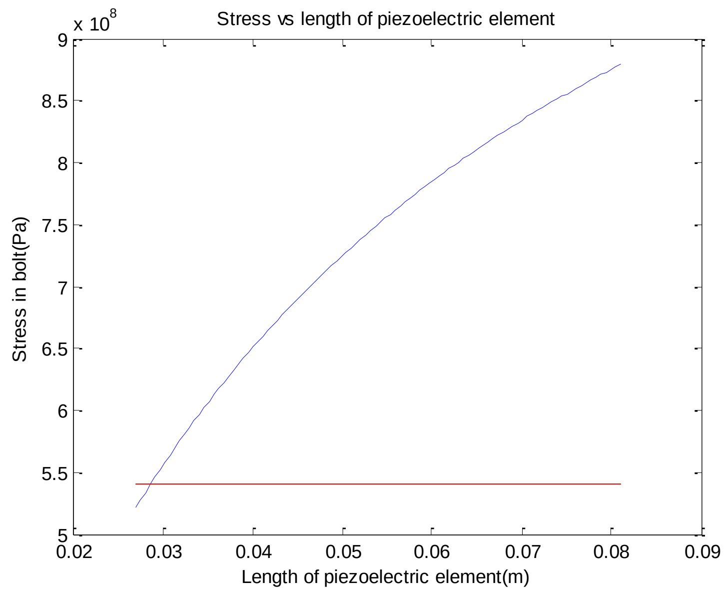

Figure 9. Shorter length required with a larger area

Overall, future steps to be taken before building a prototype is to determine the exact piezoelectric actuator to be used (custom or not), and whether a larger area is viable with the slot idea.

Acknowledgments

I'd like to thank Matt Ulinski for his guidance in the early stages of the project, and Professor Garcia for his valuable advice on the design of the device.

Appendices

All MATLAB files, Solidworks files and the ANSYS Workbench files can be found at

http://goo.gl/vA2Rhx

American piezo ring actuator specs taken from

https://www.americanpiezo.com/images/stories/content_images/pdf/apc_stack_specs.pdf

APC material specs taken from

https://www.americanpiezo.com/images/stories/content_images/pdf/apc_materials_properties.pdf

Physik Instrumente ring actuator specs taken from

http://www.physikinstrumente.com/en/pdf/P010_xxH_Datasheet.pdf