1. **Design (and/or select) the bearings, bearing rails, and actuator to handle the loads and provide the stiffness and accuracy as indicated from your previous error budgeting work: (3 pts)**
   a. **Label the sensitive directions!**
   b. **Hand sketch and create/use design spreadsheets to consider as options sliding contact and rolling elements:**
      i. **How will you preload the bearings and actuator so as to not have too much error due to clearance (aka backlash)?**
         1. **Can you use gravity and a kinematic arrangement?**
         2. **Do you need to use a "captured" design and if so, how will the preload "spring" accommodate alignment and bearing rail errors?**
         3. **How does preload affect life and controllability (sliding friction)?**

The bearings for my scissor actuator are at the revolute joints that connect the scissor segments to one another. The holes in the segments have been precision reamed to fit the 3/16" dowel pins, so the diametrical clearance is very small (<0.001" by the best measurements I can make). There is no preload mechanism along the diameter, but there is a spring that compresses the segments together at each joint to help eliminate the z-axis sag from Abbe errors. Retaining rings keep the spring in place. The segments sliding against one another will eventually cause some degradation, but the spring should help to compensate for this. The friction between the segments is not ideal, and could perhaps be reduced by adding a thin thrust washer made of a low friction material like PTFE (an idea currently being explored).

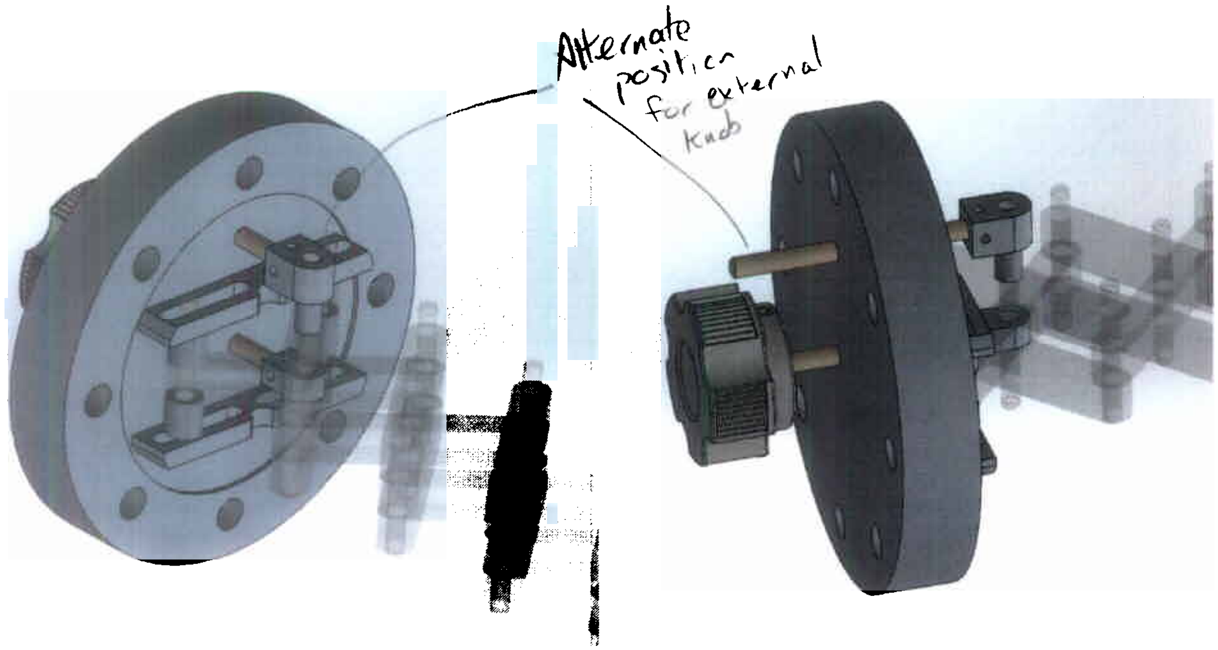
okay ... ...

      ii. **Perform load life calculations (include preload), to make sure the bearings and actuator will be stiff enough and last**
         1. **You must consider alignment tolerances: how will misalignment affect loads on these elements as the machine moves?**
         2. **If after first round it does not seem like things can work out well... you may have to select a different design and/or bearing or actuator...)**

The lifetime of the scissor actuator segments and pins is hard to calculate, but they will likely degrade as the number of extend and retract cycles increases. This will increase the sag, but fortunately, the current design makes it reasonably easy to replace both segments and pins (<5 minutes once the actuator is removed from the system).

2. **Design the support structures for the bearings and actuator and its attachment (this is where details covered in FUNdaMENTALS and PMD come to bear) to the rest of the machine to meet the stiffness and accuracy required: (2 pts)**

The support structure for the scissor actuator is shown in the SolidWorks renderings below:



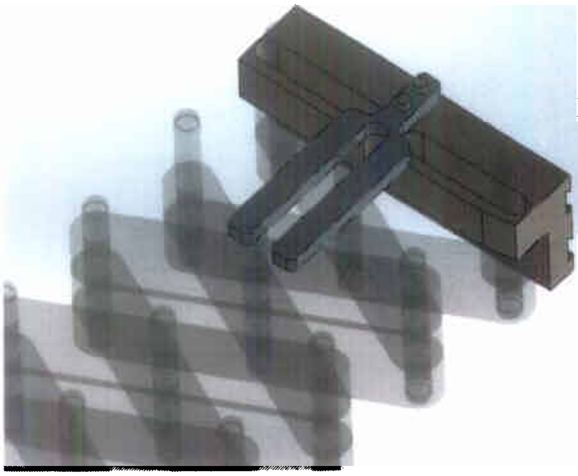

There are two different actuator pins shown. Ideally, the center pin will be used, but it requires making a somewhat complicated segment piece in order to fit. If this proves too unwieldy, the eccentric actuator pin can be used. The knob will be attached to the actuator pin, and be used to extend and retract the actuator. By using carefully dimensioned spacers on the external portion of the actuator pin, the travel of the knob can be controlled, and thus the full extension length of the transfer arm can be controlled. This should make the user experience dead simple ("push it all the way in to load" and "pull it all the way out to unload").

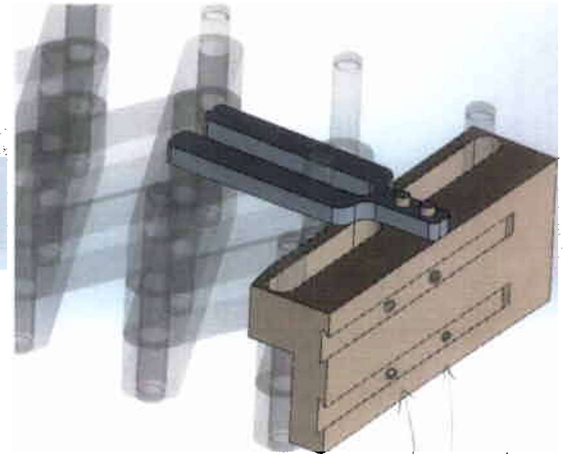
The sliding slots for the scissor actuator will be precision machined and fitted into matching slots machined on the mounting flange. From there they can be fastened to the flange using vented screws (to minimize outgassing) *(these features are not yet shown in the SW model)*.

See the uploaded SolidWorks model ("Gould_Scissor_Actuator.sldasm") and Excel file ("Gould_PUPS_7_Error_Budget_Scissor.xlsx") for additional details.

3. **Design the carriages and attachment to the bearings (or rails) and to which other elements will be attached, to meet the stiffness and accuracy required: (2 pts)**

   The "carriage" structure for the scissor-based transfer arm is shown in the SolidWorks renderings below:





magnet positions

The "carriage" structure, which will be used as the anchoring point for the wafer carrier, has two main parts, the attachment block (tan) and the centering fork (gray). The attachment block has two precision slots that mate to the dowel pins at the furthest edge of the scissor actuator. As the actuator extends (and gets narrower (y-axis)), these pins move toward the center of the slots. The centering fork forces the attachment block to stay centered between these two pins. Whether this specific fork design is stiff enough to reliable keep the attachment block centered is currently being explored. If it proves to compliant, a taller fork, or one that fits totally over the actuator pins could be used. The width of the fork at its tines can also be used as a stop mechanism that prevents further actuation by constraining the motion of the pins along the outer holes of the scissor segments.

The front of the attachment block currently contains two dovetail grooves for mounting the wafer carrier. These grooves should prevent the carrier from sagging and allow the carrier to be loaded and unloaded to the actuator from the side (a key functional requirement for the current load lock). Magnets embedded along the base of the dovetail groove can add some additional holding power (although the expected forces on the chuck will be small).

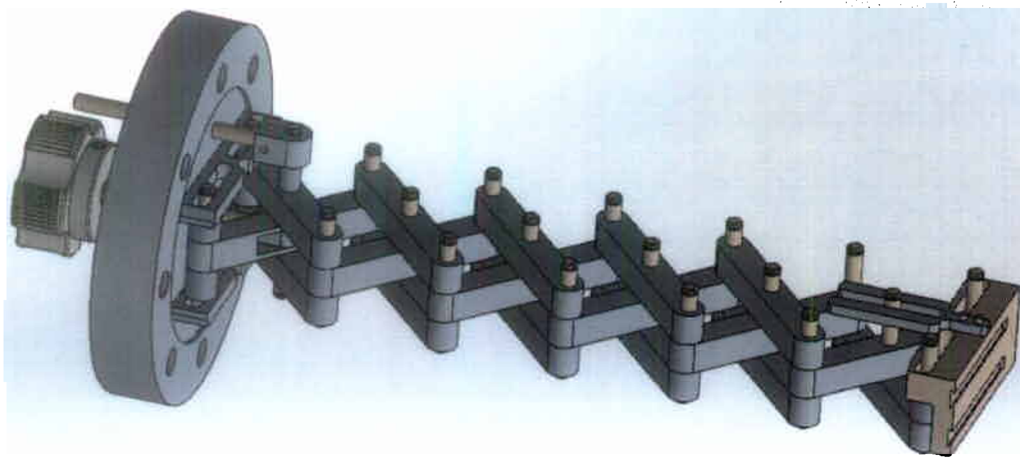
4. **Update the error budget and FRDPARRC table and if needed iterate on the design. (1 pt)**

See the uploaded Excel files ("Gould_PUPS_7_Error_Budget_Scissor.xlsx") and ("Gould_PUPS_7_FRDPARRC.xlsx").

5. **Solid model with just enough detail the linear motion axis parts and assembly to enable you to make part toleranced part drawings to build the most critical axis of your machine. (2 pts)**
   a. **Final safety review, considering not only operation, but maintenance.**

See the uploaded SolidWorks model ("Gould_Scissor_Actuator.sldasm"). Safety isn't really a big worrying factor with this design; the only real hazard is perhaps pinching yourself between segments of the actuator while servicing it.

Do you have a cleaning procedure for your assembly before putting into vacuum chamber? Ultrasonic cleaning?



| **Functional Requirements** | **Design Parameters** | **Analysis** | **References** | **Risks** | **Counter-measures** |
|---|---|---|---|---|---|
| Whole thing fits inside the current load lock | The whole thing needs to fit in the bottom half (in Z) of a cylinder with a diameter (spanning the Y-Z plane) of 3in (76mm) and a length (X-axis) of ~4.5in (115mm).<br>The part that extends needs to be able to fit through the gate valve door and associated flanges, which have a minimum diameter of 2.75in. | The whole reason for this thing is have a self-contained transfer mechanism. It will significantly reduce the footprint of our vacuum-chamber-based tools. | Current tool (DRIE) setup and configuration | It's a really small volume | Technically, the backside of the load lock can be extended, but avoiding this is preferrable. |
| When retracted, the carrier lines up with the load/unload door | The door is ~3in behind the gate valve. | For ease of use and potential future automation, the wafer carrier needs to be at a consistent position in front of the load/unload door. | Previous experience | | |
| Wafer carrier must be loadable/unloadable from the side (when actuator is retracted) | The carrier needs to slide in and out of the load lock along only the Y-axis | Space is super limited inside the load lock, so a "lift and pull" movement is out, and for future automation, a single-axis motion for load/unload is much more convenient | Previous experience / toil | This makes the actual attachment mechanism more critical | Magnets + dovetail slots |
| When extended, the carrier lines up with the chuck assembly (in all 3 axes) | The X-axis travel must be >10in (The distance between the center of the carrier door and the middle of the chuck assembly) with a tolerance of ±0.5mm, the Y-axis must also be good to ±0.5mm, and the Z-axis droop/sag must be <1mm. | The wafer carrier locks onto the chuck assembly using a twist-lock- or Luer-lock-like geometry. This process is infinitely easier if the two are well aligned. | Previous experience | The droop/sag of the transfer arm assembly may make mating to the flat top surface of the chuck assembly difficult | Make it "mega-stiff" |
| Can reliably stop at predefined points (e.g. for loading or attaching the carrier) | Positioning accuracy of ~0.5mm in the X-axis with user-defined stop points. | To be a useful transfer mechnism, the user should be able to specify whatever position is needed and have the carrier move it there. From a user-perspective, it needs to be comically simple. | Previous experience | Reliability of stop points over time | Rigidly mounted electronic end stops |
| Everything is vacuum-friendly / vacuum-combatible | Metals: 304 SS, 6061 Al<br>Plastics: PTFE, PEEK, Polyimide | Certain materials outgas a lot in vacuum environments, or may not be combatible with exposure to residual levels of the fluorine-based compounds used for etching. | Previous experience, http://www.southern-pvd.com/vk/evkbasics3.htm | most of the time materials rubbing together = particle generation | Some material combos are better than others for particle generation, lubrication can trap particles |
| Easily serviceable and modifiable | Installation may require removing the load lock from the system, but servicing should ideally only requiring opening the carrier load/unload door and (maybe) removing one other flange.<br>If more travel is needed, adding additional stages should be simple. | User-serviceability is a big design parameter for the entire DRIE system, so it should hold for this piece too. | Previously defined design principles for 1" Fab tools. | Generally this adds complexity to the manufacturing process | Cleverness |
| Low Cost | <$200 ideally | Our whole system is designed to be low-cost, so this transfer arm needs to be low-cost too. | McMaster, previous experience | Precision stuff is expensive | You may not need much precision stuff if you're clever. |
| (Maybe) Both manual and motorized operation | Manual is pretty easy, but a pneumatic actuator or a linear motor could be integrated to automate the process | For an automated system, this Is essential | Existing production tools | Automation adds the possibility of false actuation, which could break other portions of the machine (e.g. the gate valve, samples, the actuator itself) | Interlocks that don't allow actuation unless certain conditions are met. |
| (Maybe) Feedback or notification when the carrier is at a specified position | Limit switches likely the best options | | | | |

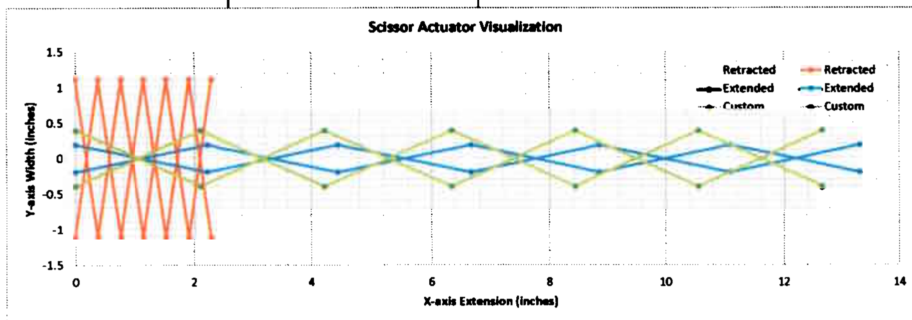
Scissor-Based Telescoping Wafer Transfer Mechanism Dimensioning and Error Budgeting
PUPS 7

| | | | | | |
|---|---|---|---|---|---|
| Pin Spacing | ps | 2.25 | in | 57.15 | mm |
| Segment Width | w | 0.375 | in | 9.525 | mm |
| Full Segment Length | l | [illegible] | | [illegible] | |
| Pin Diameter | pd | 0.1875 | in | 4.7625 | mm |
| Min. Segment Angle | 2θ | [illegible] | [illegible] | [illegible] | [illegible] |
| Half of Segment Angle | θ | [illegible] | [illegible] | [illegible] | |
| Number of Segment Pairs | N | 6 | | | |
| Retracted Width | w_r | [illegible] | | [illegible] | |
| Retracted Length | l_r | [illegible] | | [illegible] | |
| *Retracted (pin-to-pin) width* | | [illegible] | [illegible] | [illegible] | [illegible] |
| *Retracted (pin-to-pin) length* | | [illegible] | [illegible] | [illegible] | [illegible] |
| Extended Width | w_e | [illegible] | [illegible] | [illegible] | [illegible] |
| Extended Length | l_e | [illegible] | [illegible] | [illegible] | [illegible] |
| *Extended (pin-to-pin) width* | | [illegible] | | [illegible] | |
| *Extended (pin-to-pin) length* | | [illegible] | | | |
| Full Stroke Length | sl | [illegible] | | [illegible] | [illegible] |
| External Stroke Length | esl | [illegible] | [illegible] | [illegible] | |
| Length Amplification | la | [illegible] | [illegible] | | |
| Number of Revolute Joints | nj | [illegible] | [illegible] | | |
| Top Segment Thickness | t1 | 0.375 | in | 9.525 | mm |
| Middle Segment Thickness | t2 | 0.375 | in | 9.525 | mm |
| *Bottom Segment Thickness* | *t3* | *0.375* | *in* | *9.525* | *mm* |
| Pin Diameter Mismatch | pdm | 0.0005 | in | 0.0127 | mm |
| Actual Pin Hole Size | apd | 0.188 | in | 4.7752 | mm |
| Abbe Angle Error (2 Segments) | aa2 | 0.000667 | radians | 0.038197 | degrees |
| **Abbe Angle Error (3 Segments)** | **aa3** | **0.000444** | **radians** | **0.025465** | **degrees** (current) |
| Segment Spacing Gap | ssg | 0.0001 | in | 0.00254 | mm |
| Segment Overlap Length (from pin center | sol | 0.1875 | in | 4.7625 | mm |
| Extra Segment Overlap | esl | 0.25 | in | 6.35 | mm |
| Total Overlap | to | 0.4375 | in | 11.1125 | mm |
| 2seg possible tilt from gap (no extra length) | | 0.000533 | radians | 0.030558 | degrees |
| 2seg possible tilt from gap (with extra length) | | 0.000229 | radians | 0.013096 | degrees |
| **3seg possible tilt from gap (no extra length)** | | **0.001067** | **radians** | **0.061116** | **degrees** (current) |
| 3seg possible tilt from gap (with extra length) | | 0.000457 | radians | 0.026192 | degrees |

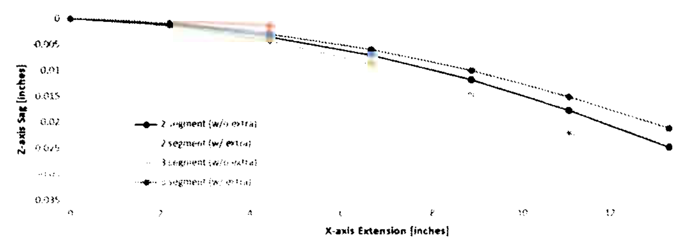
| | Retracted | | | | Extended | | | | Custom Length [illegible] inches | | | IN RANGE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Segment | x1 | y1 | x2 | y2 | x1 | y1 | x2 | y2 | x1 | y1 | x2 | y2 |
| 0 | | [illegible] | | [illegible] | | [illegible] | | [illegible] | 0 | 0.391118 | 0 | -0.39112 |
| 1 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2.109646167 | -0.39112 | 2.109646 | 0.391118 |
| 2 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 4.219292333 | 0.391118 | 4.219292 | -0.39112 |
| 3 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 6.3289385 | -0.39112 | 6.328939 | 0.391118 |
| 4 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 8.438584667 | 0.391118 | 8.438585 | -0.39112 |
| 5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 10.54823083 | -0.39112 | 10.54823 | 0.391118 |
| 6 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 12.657877 | 0.391118 | 12.65788 | -0.39112 |

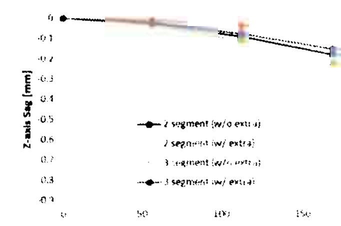
1.054823 12

distance between edge pins
0.594736 in




| Segment | 2 segment (w/o extra) Angle (rad) | Δx | Δz | x | z | 2 segment (w/ extra) Angle (rad) | Δx | Δz | x | z | (current) 3 segment (w/o extra) Angle (rad) | Δx | Δz | x | z | 3 segment (w/ extra) Angle (rad) | Δx | Δz | x |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0.000533 | 2.217596 | -0.00118 | 2.217596 | -0.00118 | 0.000229 | 2.217597 | -0.00051 | 2.217596701 | -0.00051 | 0.000667 | 2.217596 | -0.00148 | 2.217596 | -0.00148 | 0.000457 | 2.217597 | -0.00101 | 2.217597 |
| 2 | 0.001067 | 2.217596 | -0.00237 | 4.435192 | -0.00355 | 0.000457 | 2.217597 | -0.00101 | 4.435193287 | -0.00152 | 0.001067 | 2.217595 | -0.00296 | 4.435192 | -0.00444 | 0.000914 | 2.217596 | -0.00203 | 4.435193 |
| 3 | 0.0016 | 2.217595 | -0.00355 | 6.652787 | -0.0071 | 0.000686 | 2.217596 | -0.00152 | 6.652789756 | -0.00304 | 0.0016 | 2.217594 | -0.00444 | 6.652786 | -0.00887 | 0.001371 | 2.217596 | -0.00304 | 6.652788 |
| 4 | 0.002133 | 2.217595 | -0.00473 | 8.870382 | -0.01183 | 0.000914 | 2.217596 | -0.00203 | 8.87038611 | -0.00507 | 0.002133 | 2.217593 | -0.00591 | 8.870379 | -0.01478 | 0.001829 | 2.217595 | -0.00406 | 8.870383 |
| 5 | 0.002667 | 2.217594 | -0.00591 | 11.08798 | -0.01774 | 0.001143 | 2.217596 | -0.00253 | 11.08798235 | -0.0076 | 0.002667 | 2.217592 | -0.00739 | 11.08797 | -0.02218 | 0.002286 | 2.217595 | -0.00507 | 11.08798 |
| 6 | 0.0032 | 2.217593 | -0.0071 | 13.30557 | -0.02484 | 0.001371 | 2.217596 | -0.00304 | 13.30557847 | -0.01064 | 0.0032 | 2.217591 | -0.00887 | 13.30556 | -0.03105 | 0.002743 | 2.217594 | -0.00608 | 13.30557 |
| 7 | | | | | | | | | | | | | | | | | | | |
| 8 | | | | | | | | | | | | | | | | | | | |
| 9 | | | | | | | | | | | | | | | | | | | |
| 10 | | | | | | | | | | | | | | | | | | | |
| 11 | | | | | | | | | | | | | | | | | | | |
| 12 | | | | | | | | | | | | | | | | | | | |
| 13 | | | | | | | | | | | | | | | | | | | |
| 14 | | | | | | | | | | | | | | | | | | | |
| 15 | | | | | | | | | | | | | | | | | | | |
| 16 | | | | | | | | | | | | | | | | | | | |
| 17 | | | | | | | | | | | | | | | | | | | |
| 18 | | | | | | | | | | | | | | | | | | | |
| 19 | | | | | | | | | | | | | | | | | | | |
| 20 | | | | | | | | | | | | | | | | | | | |




**Bending Errors (negative z-axis)**

| | | | | | | |
|---|---|---|---|---|---|---|
| **Width** | [illegible] | | [illegible] | | | |
| **Thickness** | [illegible] | | | | | |
| **Moment of Inertia** | [illegible] | | [illegible] | | | |
| **Length** | 2.25 | in | 57.15 | mm | | |
| **Force Applied** | 2.248087 | lbf | 10 | N | | |
| **Elastic Modulus (6061 Aluminum)** | | | 68900 | N/mm^2 | | |
| **Mass density (6061 Aluminum)** | | | 2.7E-06 | kg/mm^3 | | |
| **Stiffness (k) (6061 Aluminum)** | | | [illegible] | | [illegible] | [illegible] |
| **Deflection (δ) (6061 Aluminum)** | [illegible] | | [illegible] | [illegible] | [illegible] | |
| **Mass (6061 Aluminum)** | [illegible] | | [illegible] | | | |
| **Resonant Frequency (6061 Aluminum)** | | | [illegible] | | | |
| **Elastic Modulus (304 Stainless Steel)** | | | 200000 | N/mm^2 | | |
| **Mass density (304 Stainless Steel)** | | | 0.000008 | kg/mm^3 | | |
| **Stiffness (k) (304 Stainless Steel)** | | | [illegible] | [illegible] | [illegible] | [illegible] |
| **Deflection (δ) (304 Stainless Steel)** | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | |
| **Mass (304 Stainless Steel)** | [illegible] | [illegible] | [illegible] | [illegible] | | |
| **Resonant Frequency (304 Stainless Steel)** | | | [illegible] | | | |

So, compared to the sag errors, the bending errors are insignificant

So, compared to the sag errors, the bending errors are insignificant