Engineering Challenges

Professional Engineers of North Carolina
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Background: Physcient Develops Surgical Instruments with a focus on Dissection

Sharp Dissection = Many Options

Energy Dissection = Many Technologies

RF, ultrasound, bipolar, plasma, laser

Blunt Dissection = ancient tools

Significant opportunity for new technology

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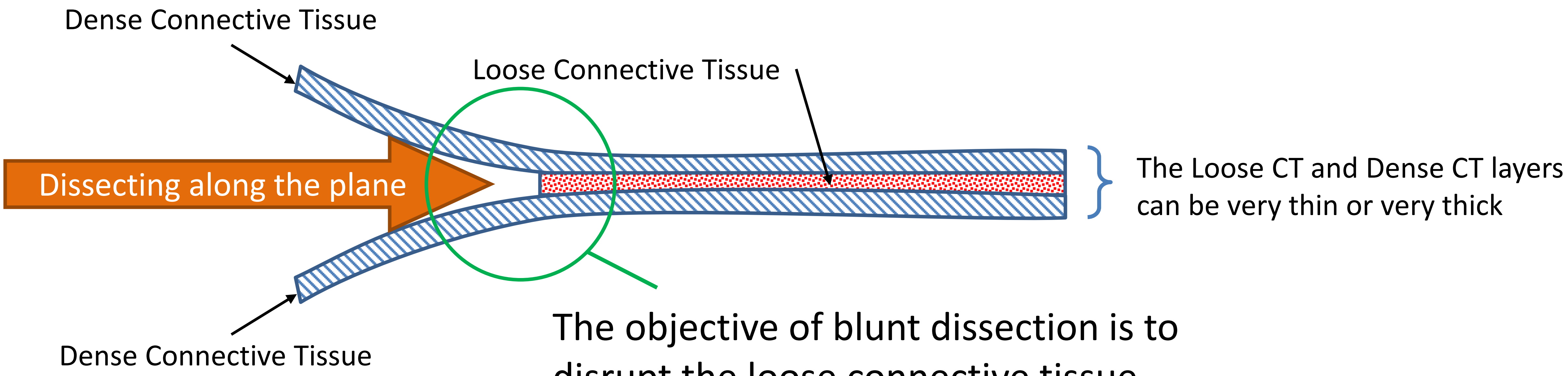
Blunt Dissection



The objective of blunt dissection is to disrupt the loose connective tissue while preserving the denser connective tissue

Surgeons prefer to dissect along natural tissue planes (preserves blood vessels, nerves, organs).

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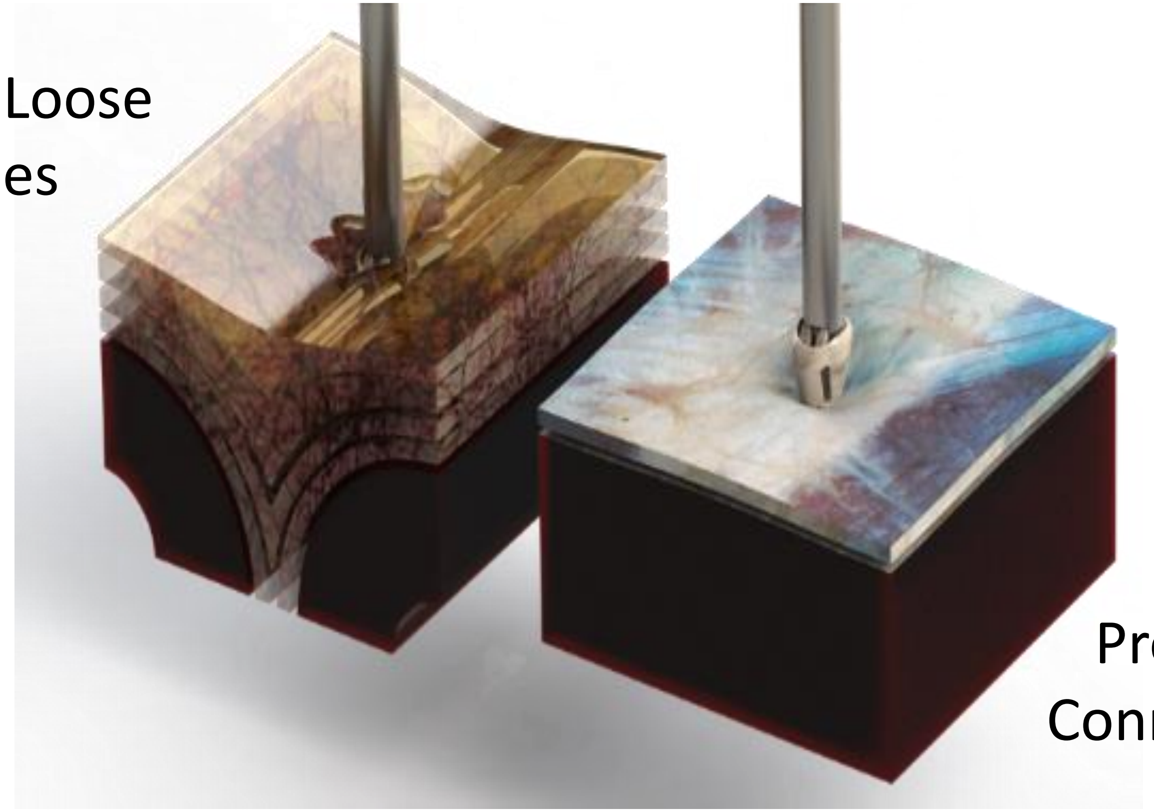
Large amplitude oscillation of particular shapes provides a significant advancement in blunt dissection capability

Quickly Disrupts Loose Connective Tissues

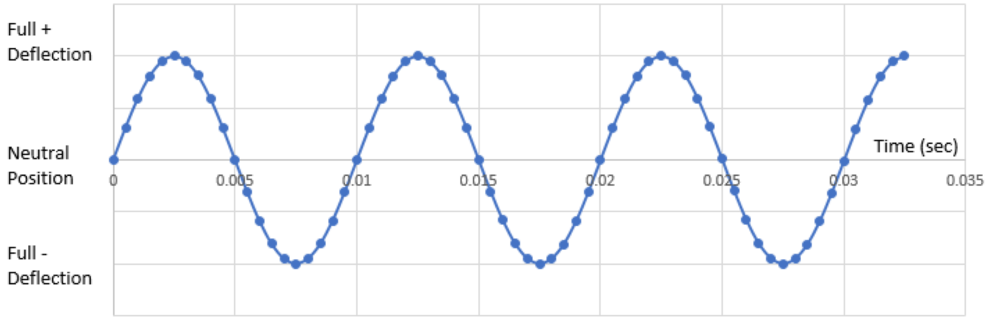


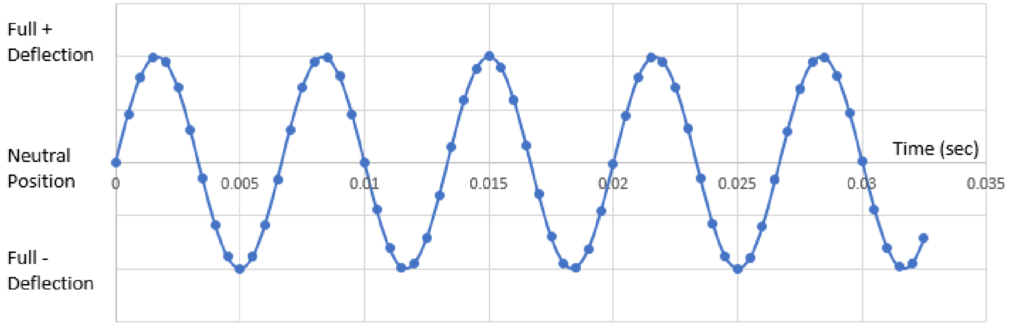
Preserves Dense Connective Tissues

Prototypes needed to have higher oscillation frequency

Assessment of Early Prototypes

- Amplitude was sufficient
- Speed / oscillation frequency needed to increase -> How?





- Mechanism was wearing and shedding particles -> Why?
- Mechanism required the use of higher risk more expensive components -> What, Why, What next?
- Prototypes would not survive force of application -> hand held

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Requirements Definition:

- Amplitude
- Oscillation frequency
- Force of application
- Duration of use

Engineering Challenges:

- Frequency and duration = cycle accumulation
- Amplitude and Force of application = susceptible to fatigue failure

Has this been done before? Industry Survey:

High Amplitude, Low Frequency:

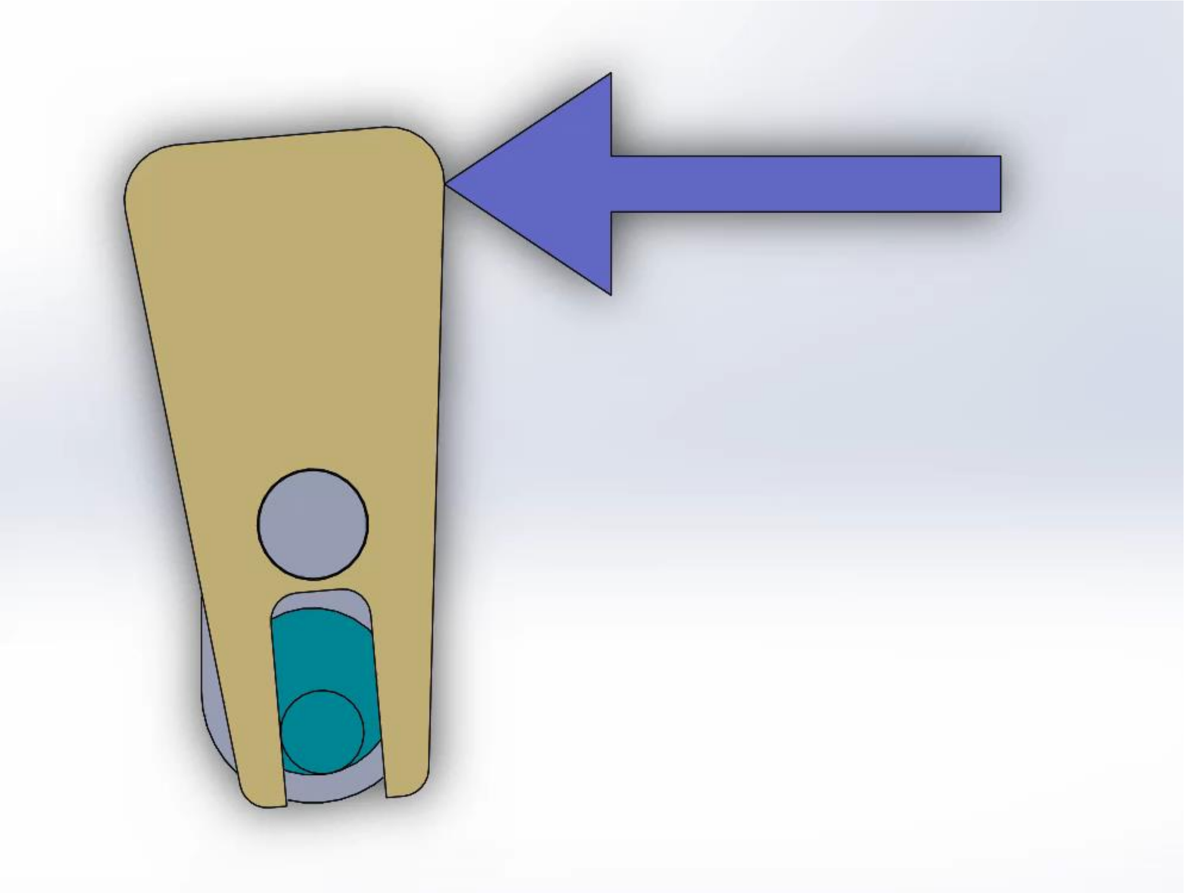
- 25mm amplitude, 35Hz

Low Amplitude, High Frequency:

- Fractional millimeter amplitude, many kHz

Investigate Prototypes:

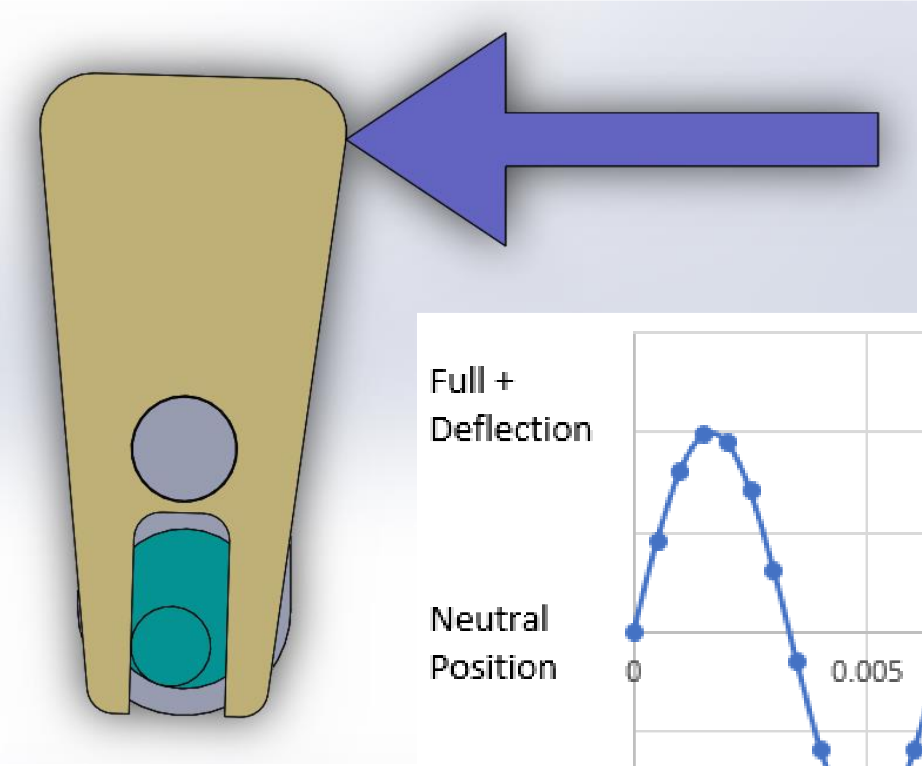
Constant Side Load:

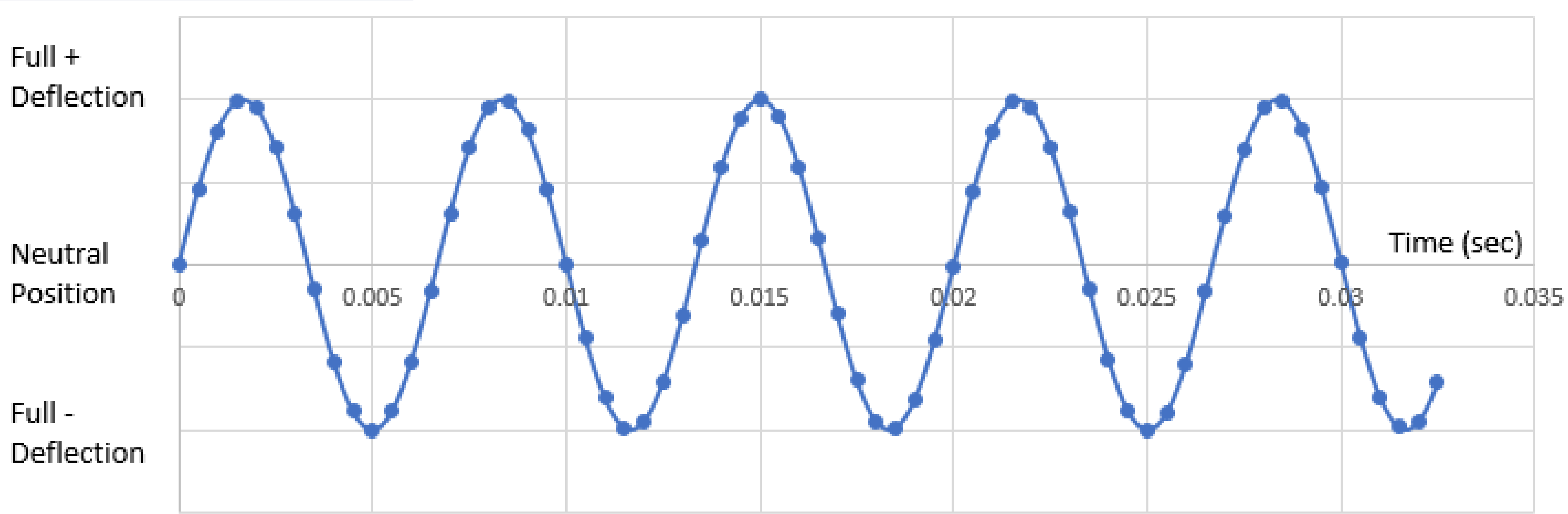


Drive eccentric exerts force on a single surface due to constant side load

Clearances exaggerated for clarity

Trajectory for Constant Side Load Case



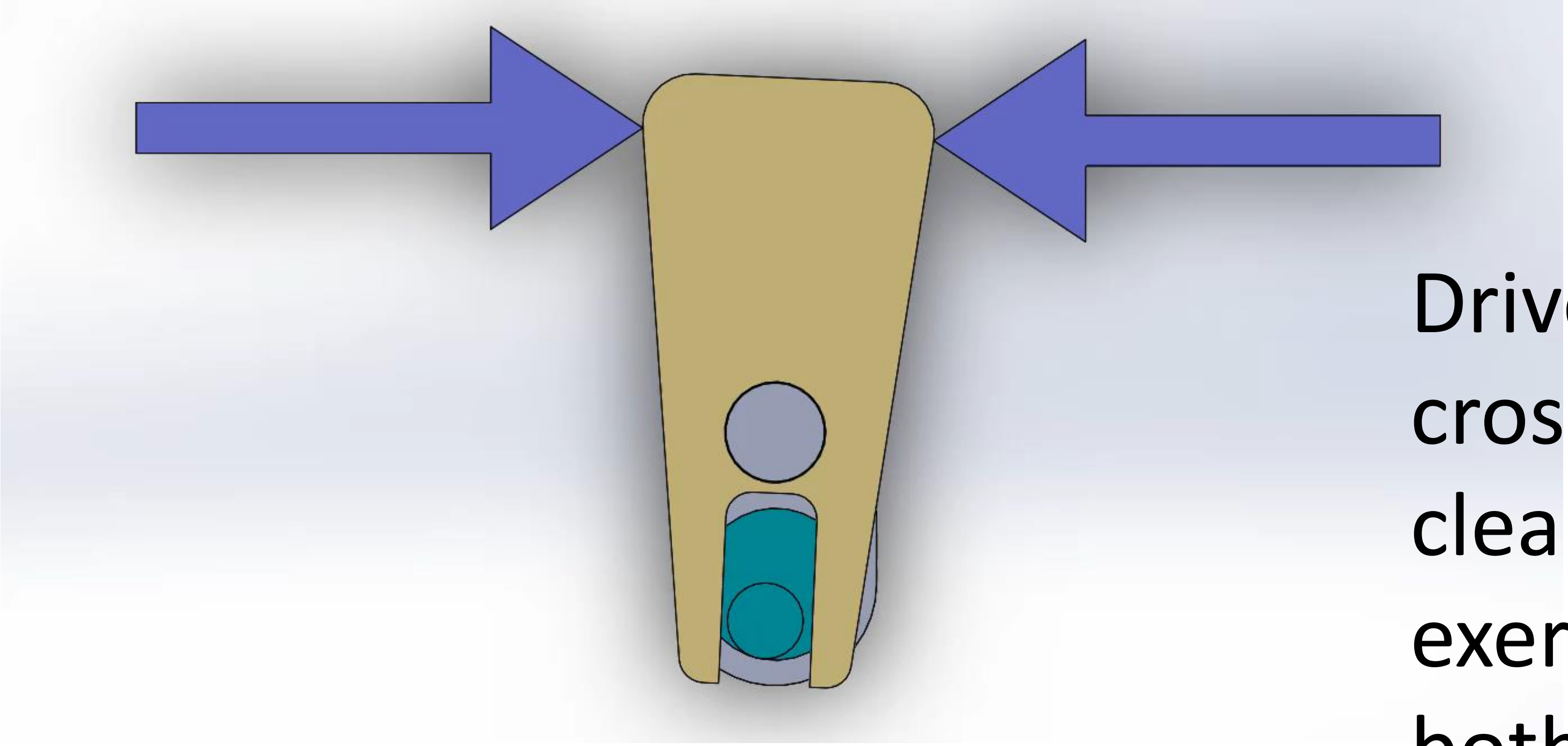


Position as a function of time s(t), is purely sinusoidal and continuous $s(t) = \sin(\omega t)$

Where ω = Frequency (Hz) converted to rad/sec

Investigate Prototypes:

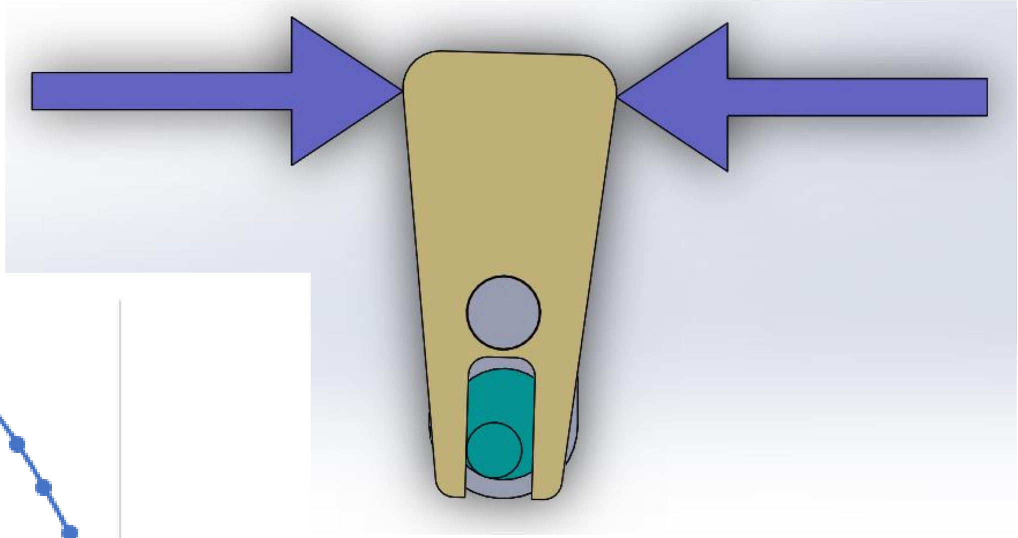
Captured by resisting loads exerted from both sides:

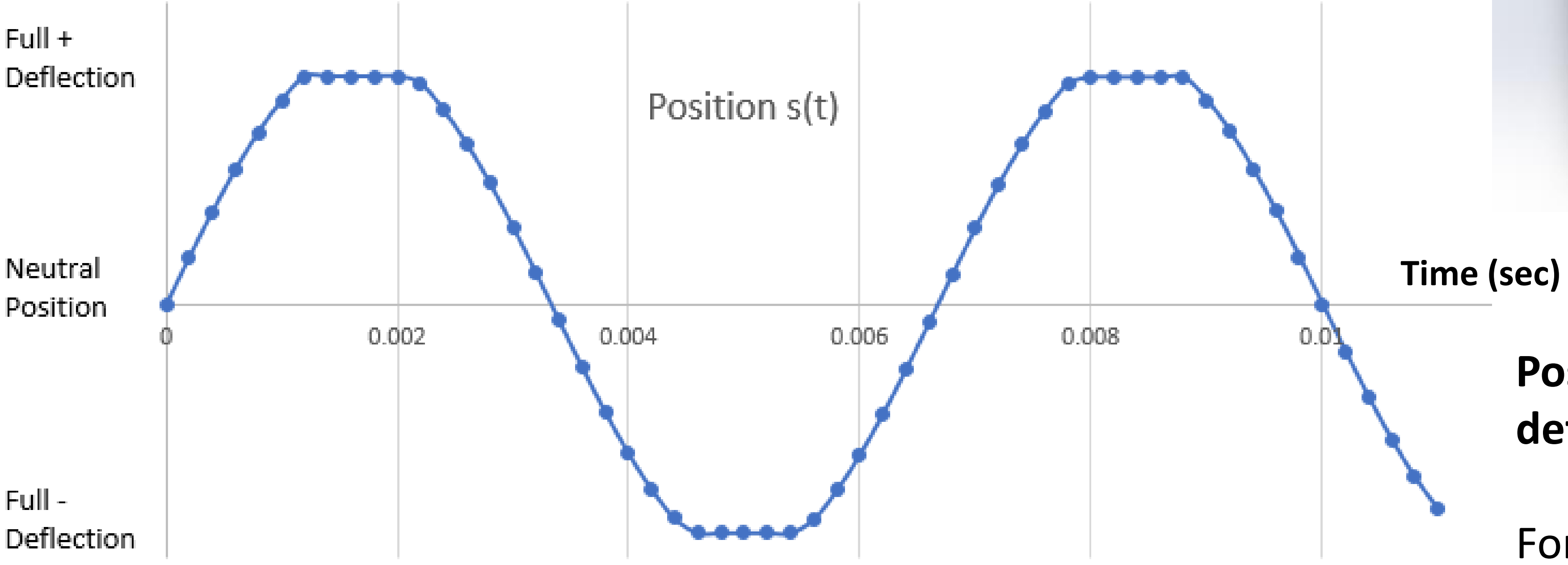


Drive eccentric crosses the clearance gap and exerts forces on both sides.

Clearances exaggerated for clarity

Trajectory When Captured by Resisting Loads from Both Sides





Position s(t) is now a piecewise defined function:

For time = 0..0.001sec,
s(t) = sin(ωt)

For time = 0.001sec..0.0022sec
s(t) = constant value

Etc.

Position as a function of time s(t), is truncated and discontinuous… Is this a problem? We lost a bit of amplitude, probably not a big deal…

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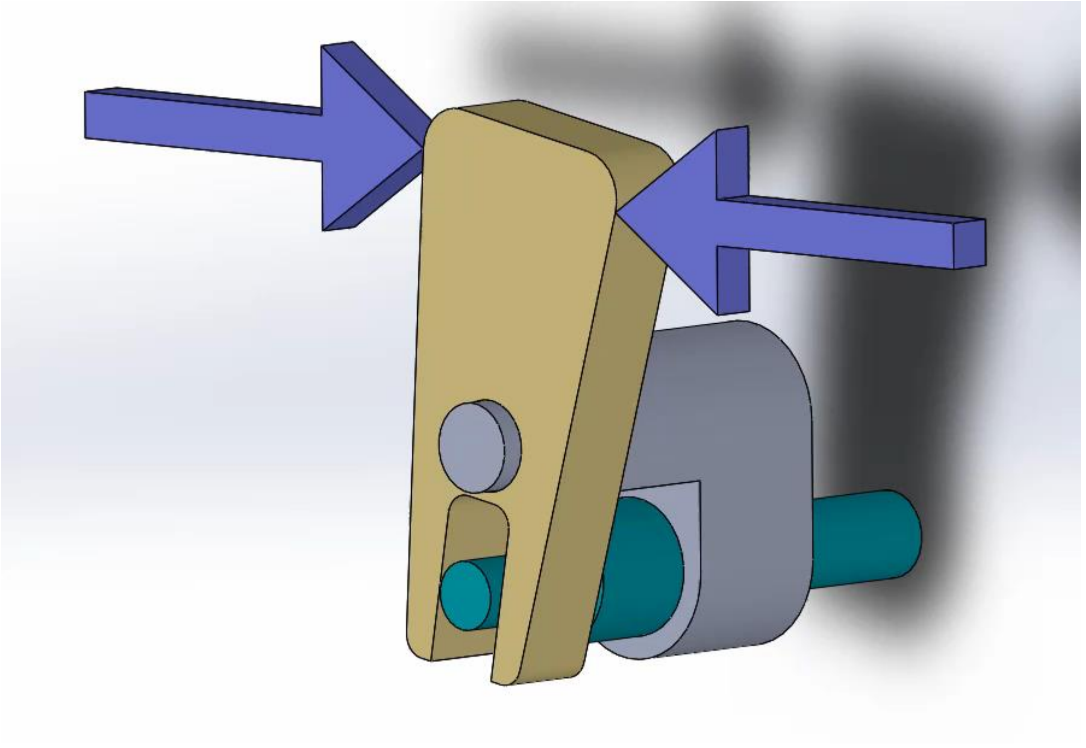
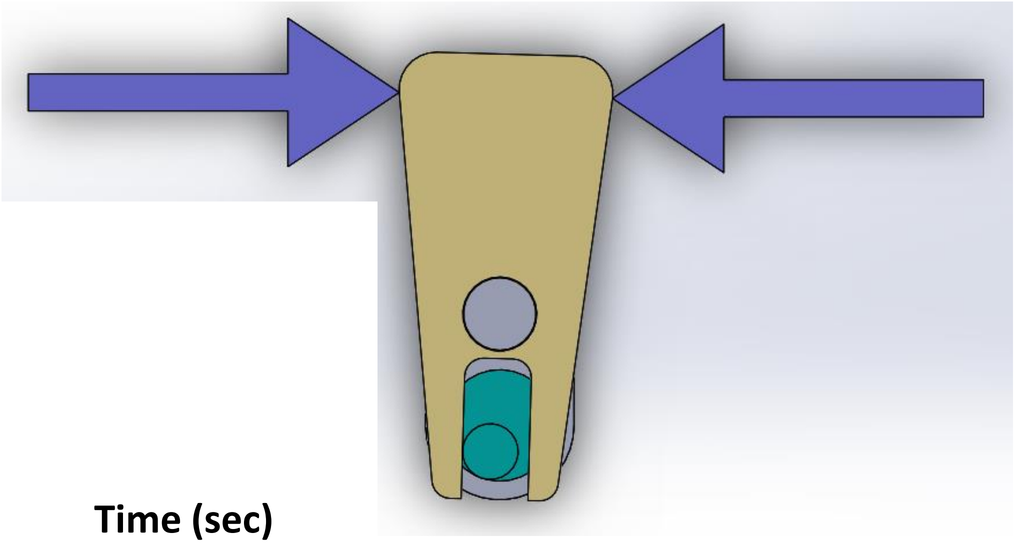
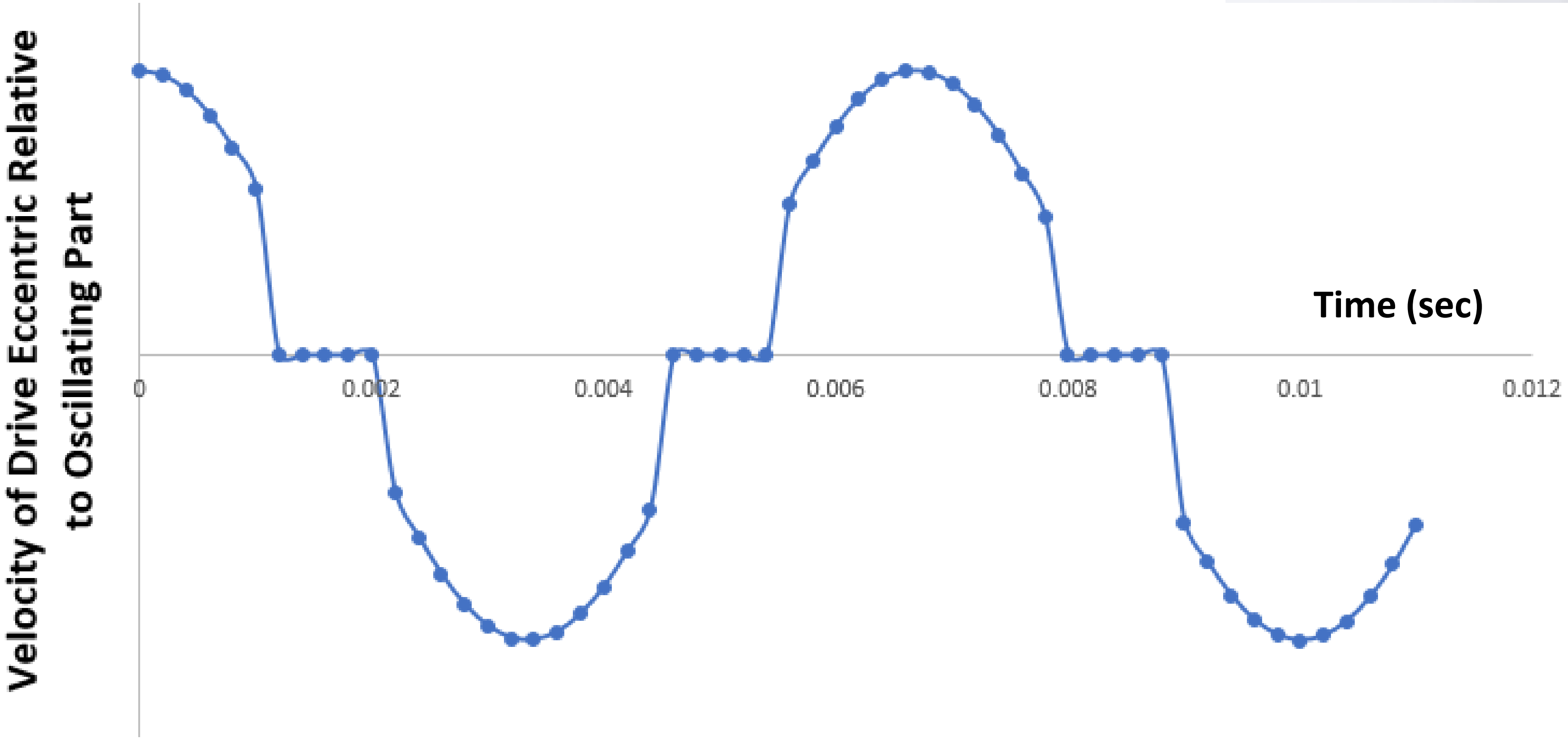
Observations in Context

- Mechanism was wearing and shedding particles -> Why?
    - Possibly very large compressive and / or tensile forces
- Prototypes would not survive force of application -> Drive eccentric was breaking off
    - Possibly very large cyclic bending forces
- Mechanism required the use of higher risk more expensive components -> What, Why, What next?



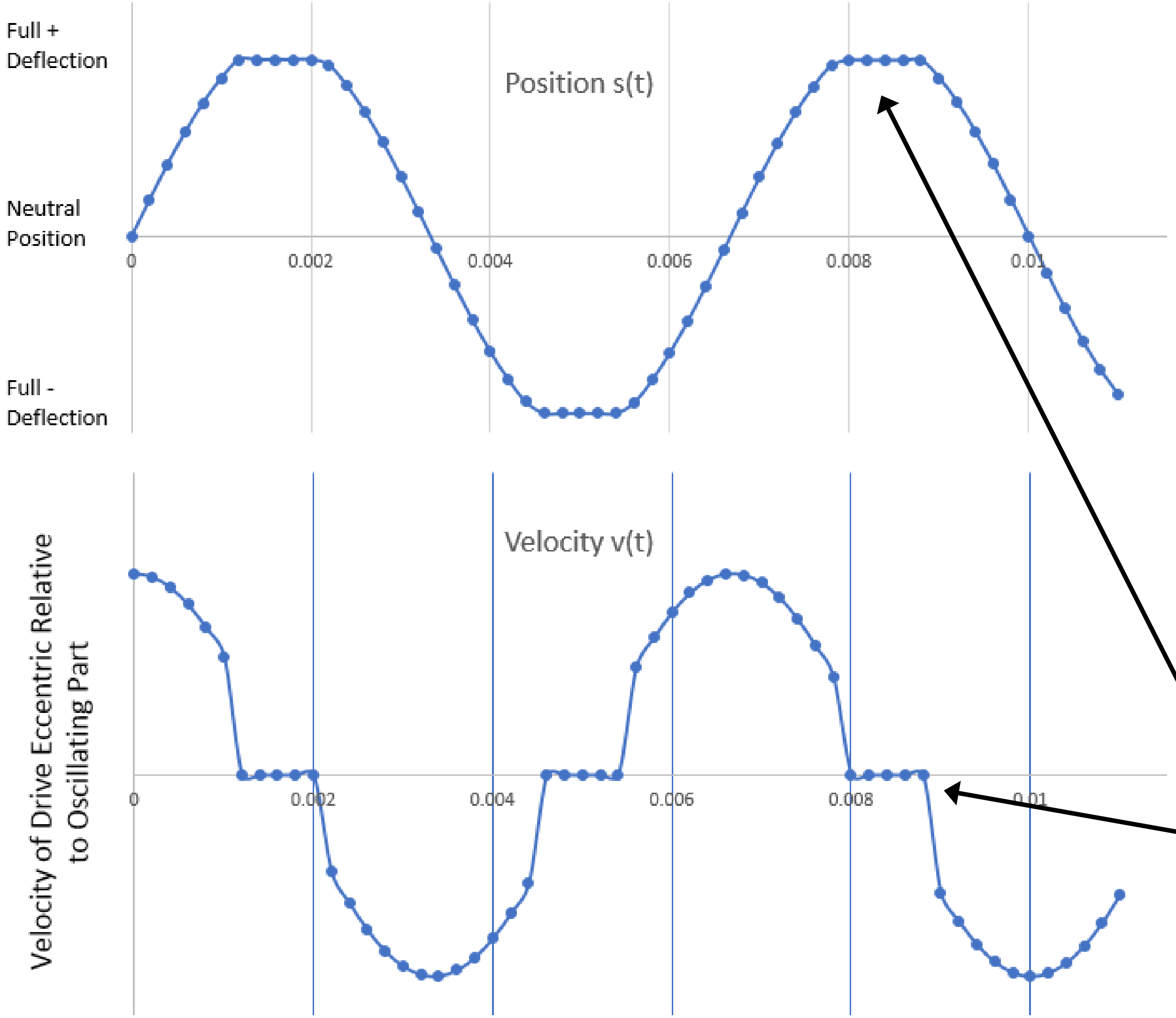
What about Velocity?

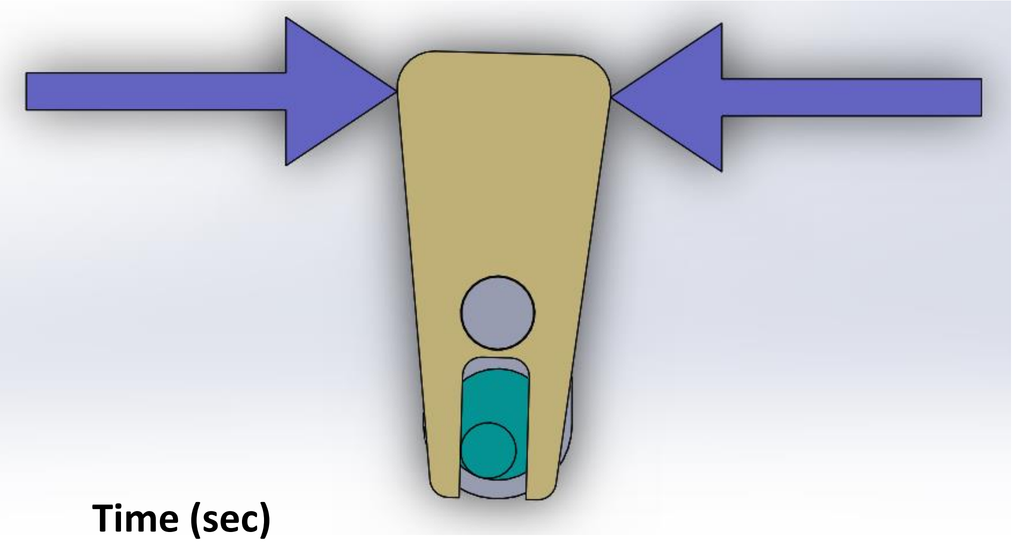




Velocity v(t) is the first derivative of position s(t) with respect to time   v(t) = ds(t) / dt   v(t) = cos(ωt)

What about Velocity?



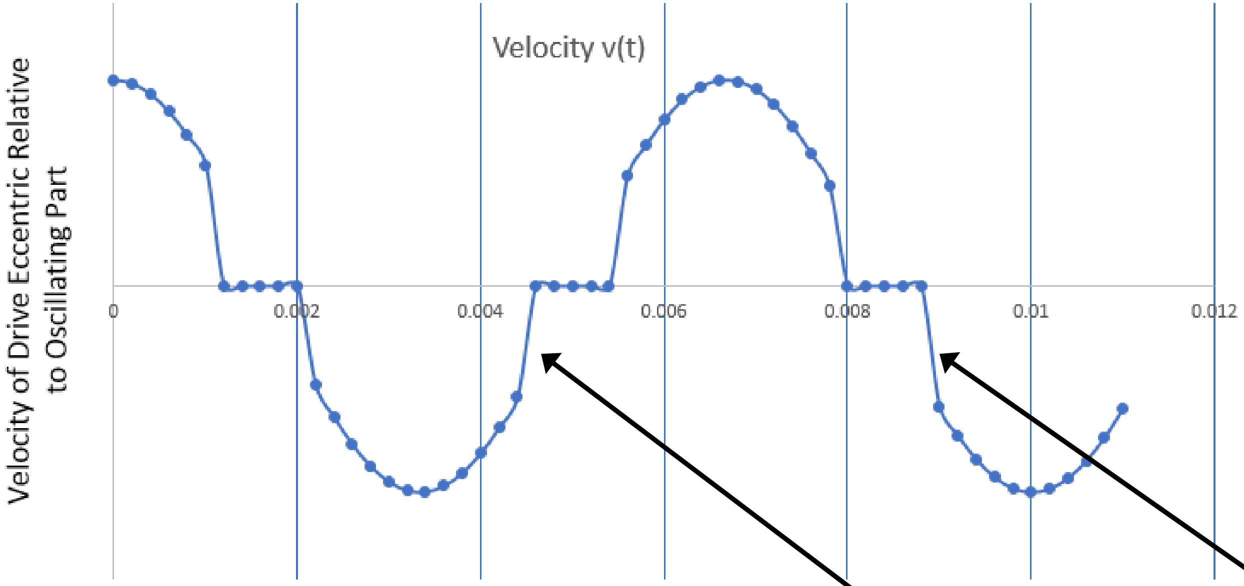


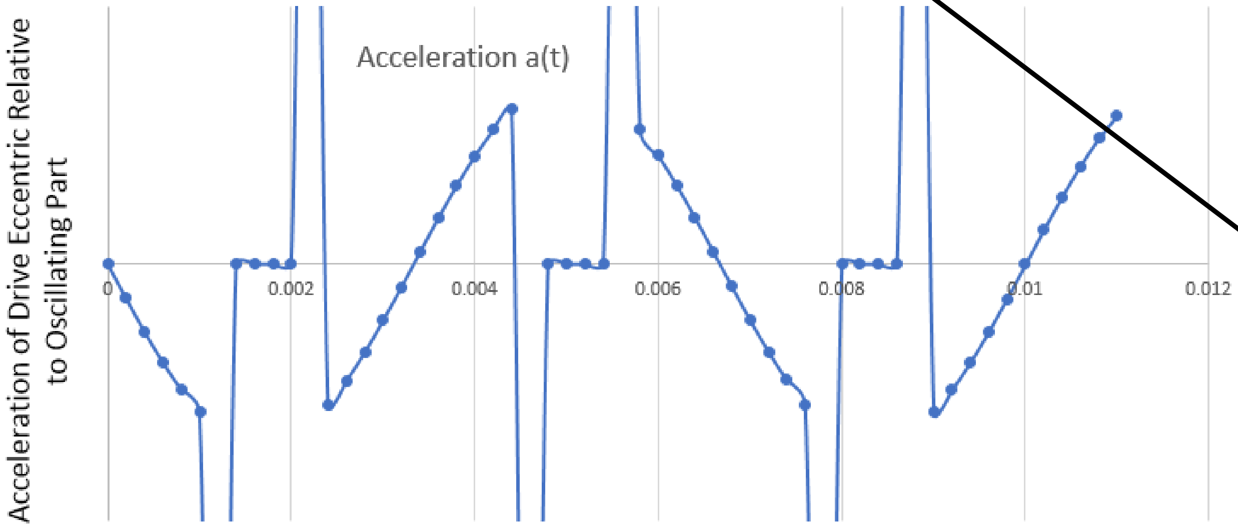
The derivative of a function is the instantaneous slope of that function.

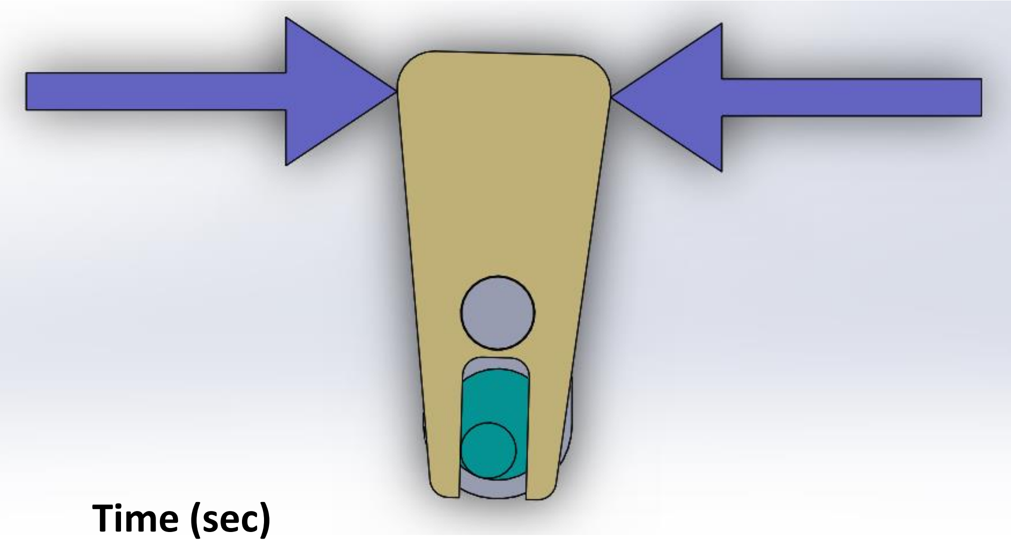
What is the slope of these flat tops?

0…

What About Acceleration?







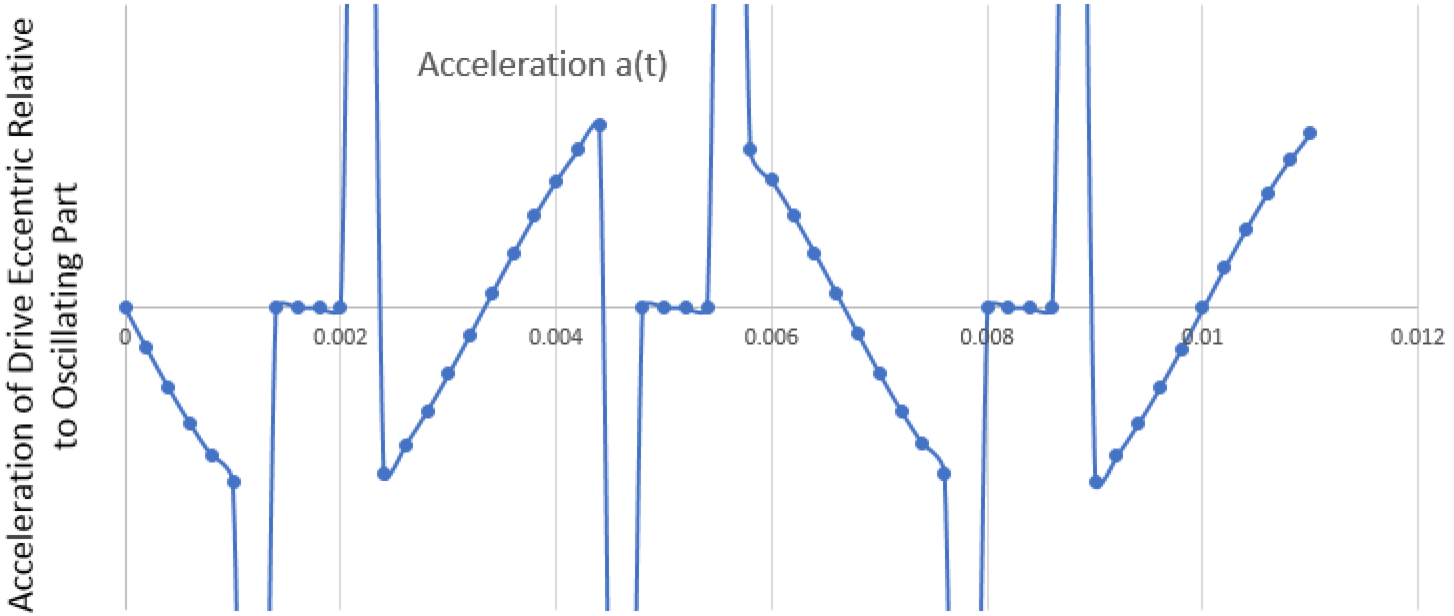
$a(t) = dv(t) / dt$ $a(t) = -\sin(\omega t)$

What acceleration is required to go from some velocity to zero velocity near instantaneously?

What is the slope of these instantaneous velocity changes?

Near infinite acceleration…

Repercussions of Near Infinite Acceleration?



F = m * a

Finite mass components * near infinite accelerations = Very Large Forces

Large Forces produce large stresses and deformations in the components and eventually produce component failures

Therefore, shedding particles and breaking components

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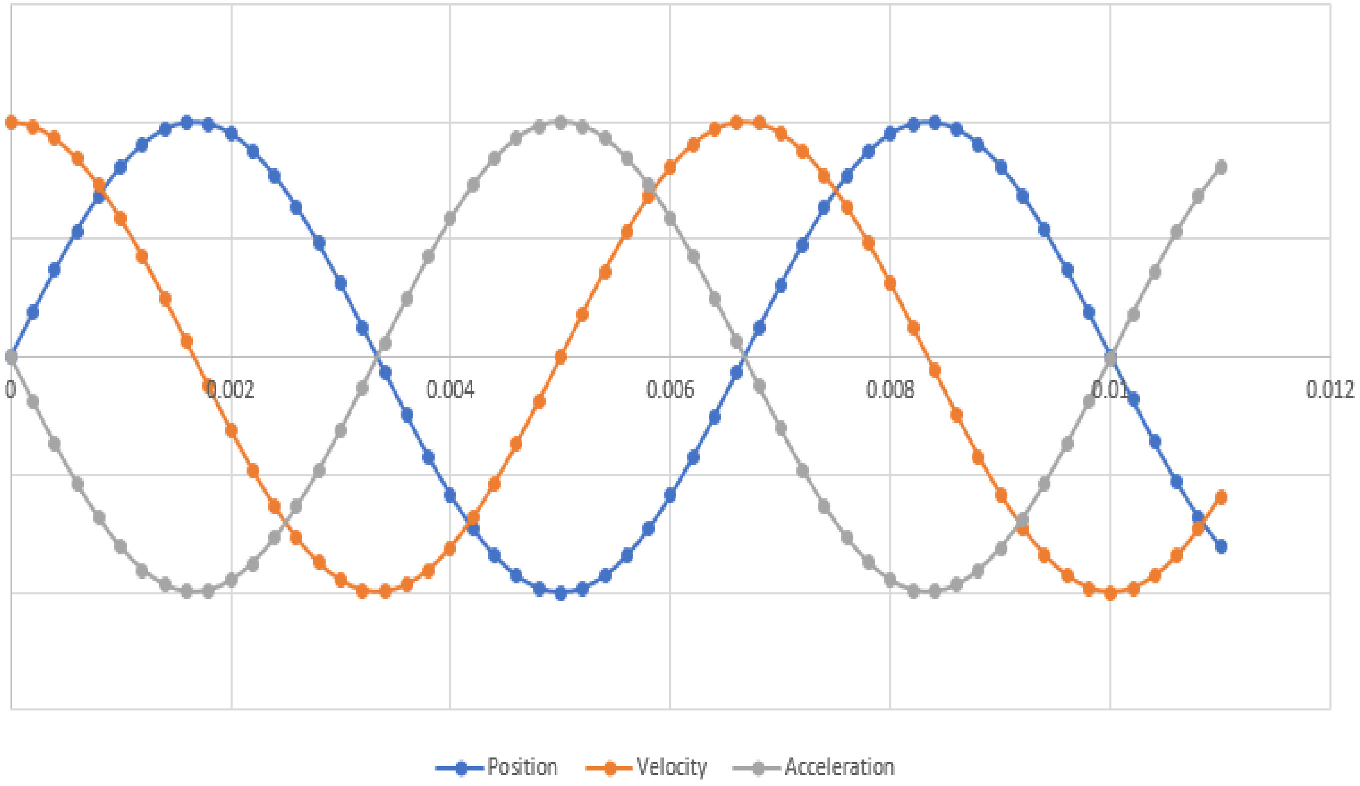
Benefit of Maintaining Sinusoidal Trajectory?



Position: $s(t) = \sin(\omega t)$

Velocity: $v(t) = ds(t)/dt$

$v(t) = \cos(\omega t)$

Acceleration: $a(t) = dv(t) / dt$

$a(t) = -\sin(\omega t)$

Acceleration stays bounded, and we can design for the resulting Forces and Stresses.

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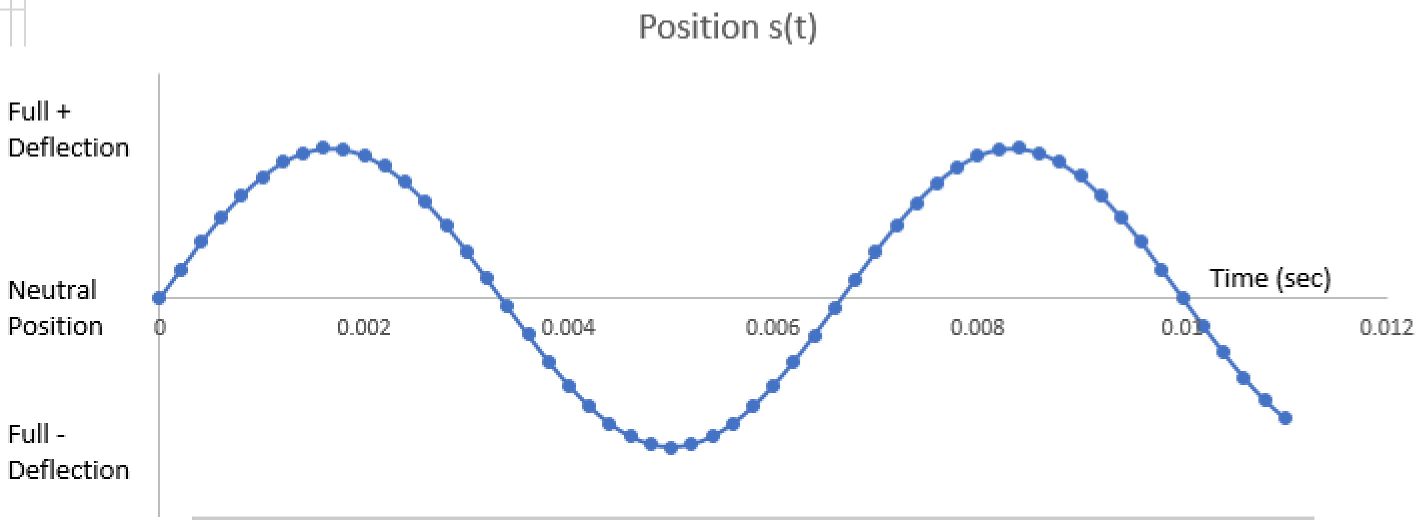
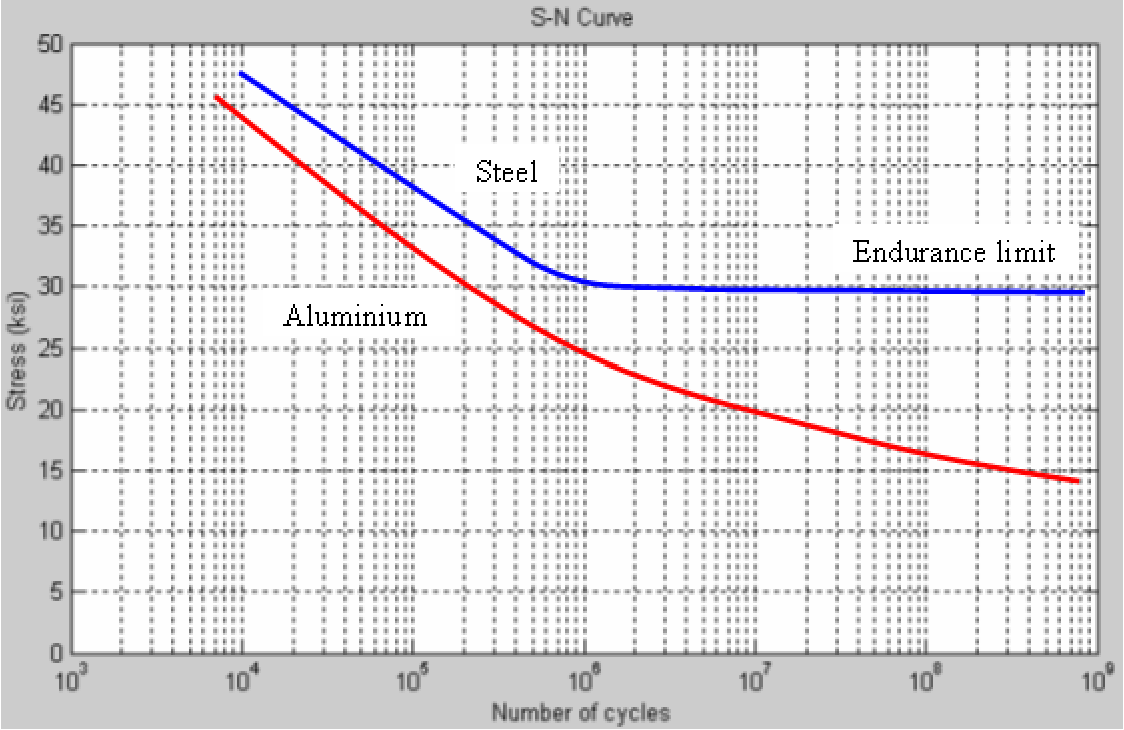
Lessons Learned?

- The design must strictly adhere to sinusoidal trajectory.
- More generally, the design must provide a continuous trajectory to the 3rd derivative of position. (polynomial?)
- The components must be designed for maximum stress levels below the endurance limits of their respective materials.





https://en.wikipedia.org/wiki/Fatigue_limit#/media/File:S-N_curves.PNG

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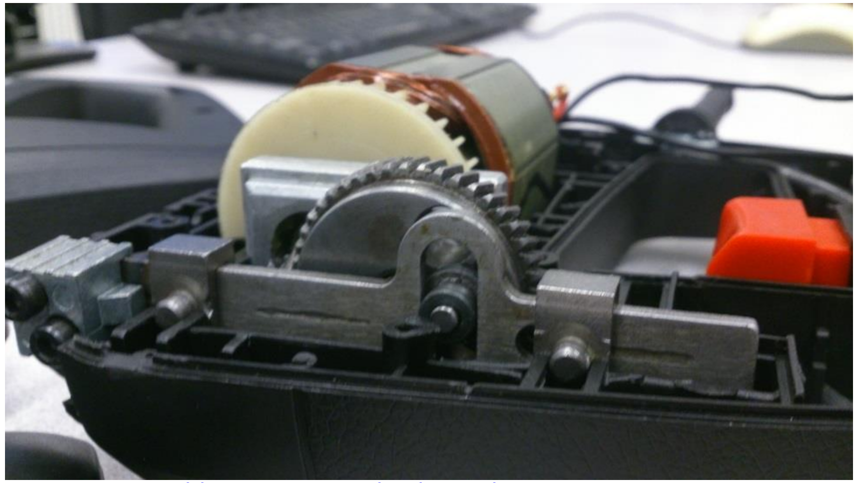
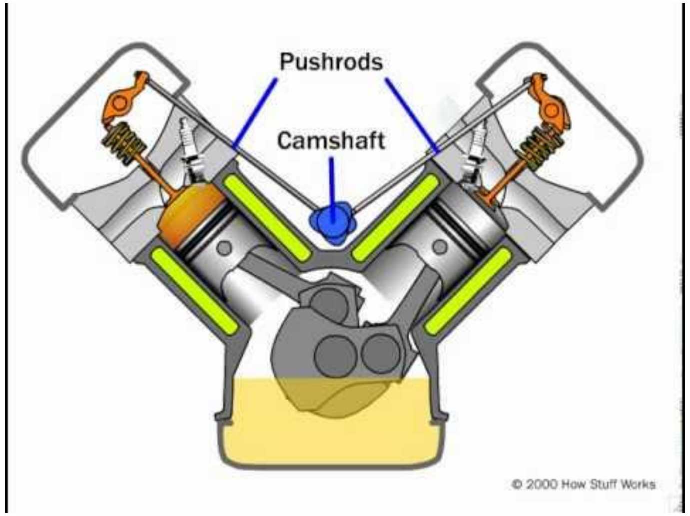
What Machine Designs Produce Sinusoidal Motion?

- Many are susceptible to the issue we've just encountered
- Some crankshaft / pushrod machines solve the problem through tribology
- Many lessons to be learned, but none directly address what we're trying to do.



https://seelio.com/w/1srt/jigsaw-dissection



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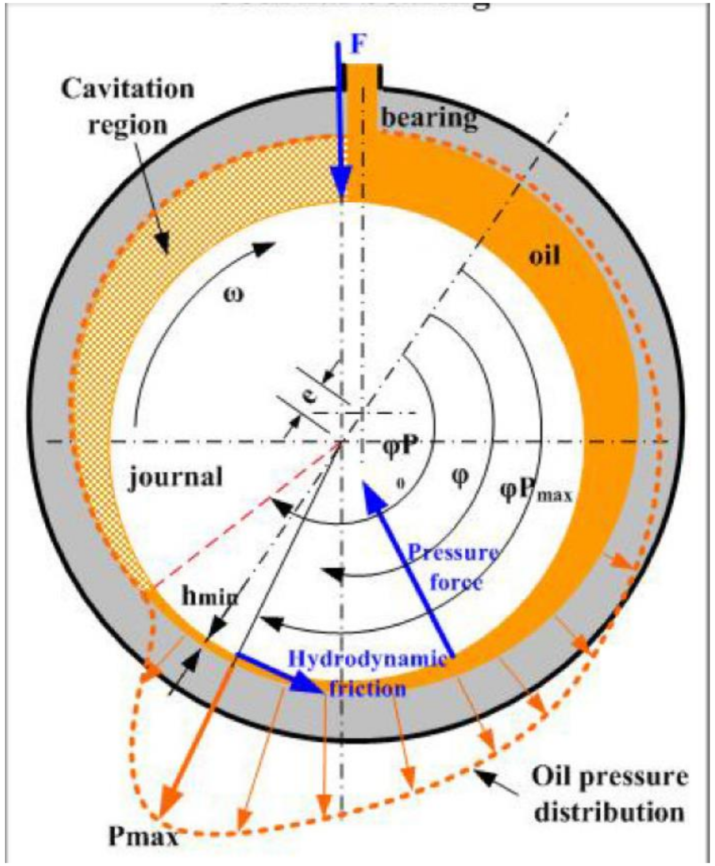

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Design Directions

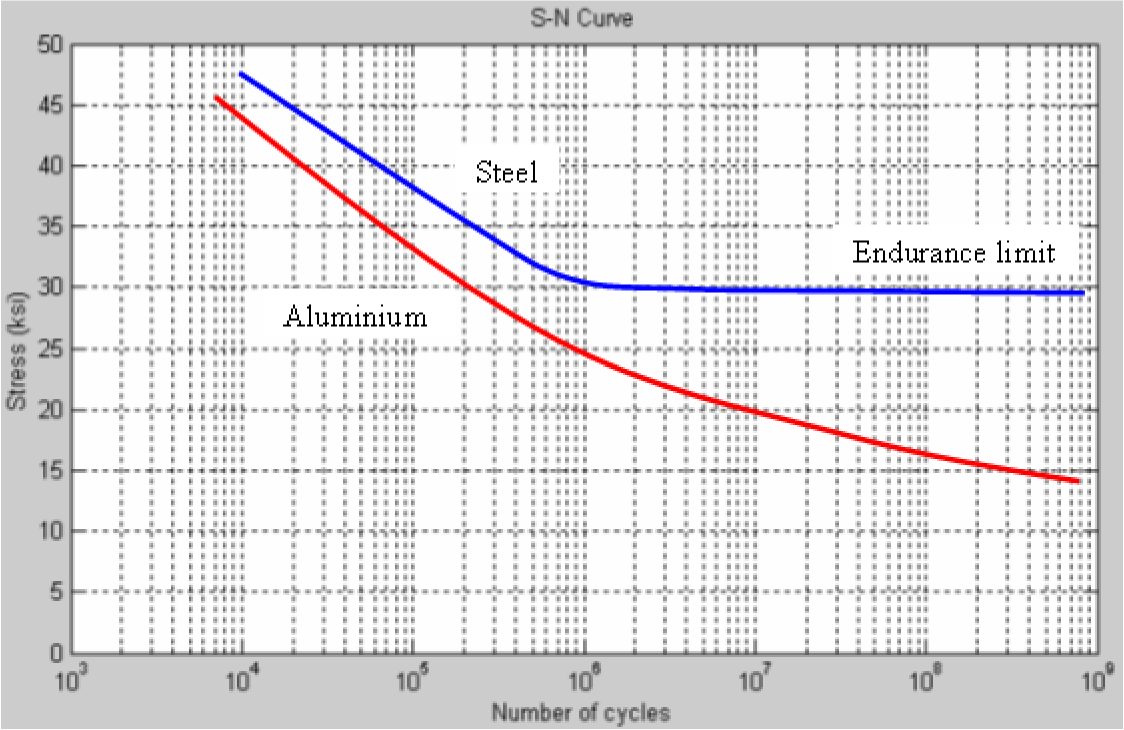
- Drive mechanism must be compatible with a long slender shaft
- Pushrods would be susceptible to beam buckling in compression
- Pressurized lubrication is totally impractical
- Pushrods are heavy
- Drive system must have very low inertia given the frequency of operation
- Design might incorporate a bent shaft or the ability to operate through an articulated joint
- Must never break or allow pieces to fall out
- Must tolerate large loads from any direction
- Must adhere to sinusoidal trajectory

Wire Rope, Benefits of Helical Construction

- Lightweight, Strong, Flexible, Inexpensive, Accommodates long shaft lengths and operation through articulated joints.
- Multi-strand construction enables operation around small radii.
- Helical construction keeps it all together and manageable
- Helical construction allows relative motion of individual strands and accommodates tensile and compressive length changes of individual strands as they operate through small radii.
- Helical construction enables relative motion of individual strands to remain local to the area of deformation. Relative motion does not have to propagate from the point of deformation to the ends.
- Visual inspection can catch imminent failures

Wire Rope Design Principles

- Design must allow wire rope to operate at stress levels below the endurance limit of the steel that it's made from.
- For stainless steel, the endurance limit for cyclical loads is 172 Mpa (25 ksi)
- At stresses below this, the wire rope material will survive for the expected duration.



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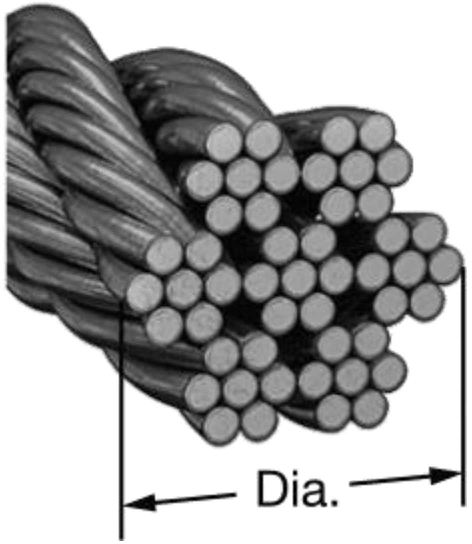
Which is Better for this Application

- For a given wire rope, what is the equivalent solid rod diameter?
- Tensile area of wire rope:
  - Diameter of individual wires, Øw
  - Number of individual strands, N
- $A = N*\pi*(Øw/2)^2$

- Diameter of equivalent solid rod, Øs
- $Øs = 2*\sqrt{(A/ \pi)}$



Wire Rope

or

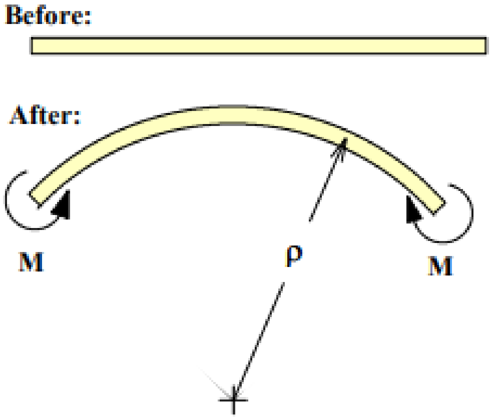
Solid element of equivalent tensile area

Objectives:

- Support Loads
- Enable Cyclical movement
- Operate below the endurance limit of the material

Bending Stress Equation Based on Known Radius of Curvature of Bend, ρ.

The beam is assumed to be initially straight. The applied moment, **M**, causes the beam to assume a radius of curvature, ρ.



$$\sigma = E \cdot \frac{y}{\rho}$$

E = Modulus of elasticity of the beam material

y = Perpendicular distance from the centroidal axis to the point of interest (same **y** as with bending of a straight beam with $\mathbf{M_x}$).

ρ = radius of curvature to centroid of cross section

- For operation below the endurance limit of Stainless Steel,
  σ + tensile stress due to cable load ≤ 172MPa (25ksi).
- We're interested in the stress at the outer most fiber, so y = Øw/2 for multi strand or y = Øs/2 for solid rod
- E = Modulus of Elasticity for Stainless Steel = 200MPa (29ksi)

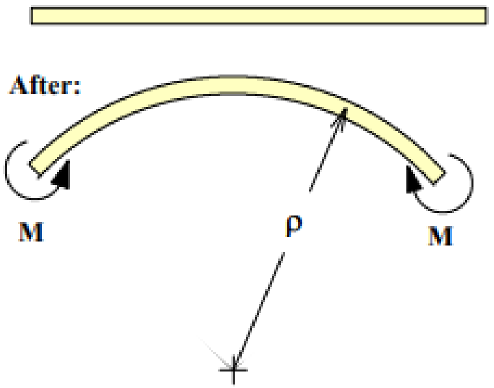
Solve for ρ:

Bending Stress Equation Based on Known Radius of Curvature of Bend, ρ.

The beam is assumed to be initially straight. The applied moment, **M**, causes the beam to assume a radius of curvature, ρ.

Before:

After:



$$\sigma = E \cdot \frac{y}{\rho}$$

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ρ = radius of curvature to centroid of cross section

$$\rho = (E * y) / \sigma$$

- Exact pulley or feature radii can be calculated
- σ must be a small fraction of the tensile load stress
- σ + tensile load stress ≤ Endurance Limit

- Net result, wire rope works around pulleys and features that are many times smaller than would be required by a solid element of equivalent tensile cross section.

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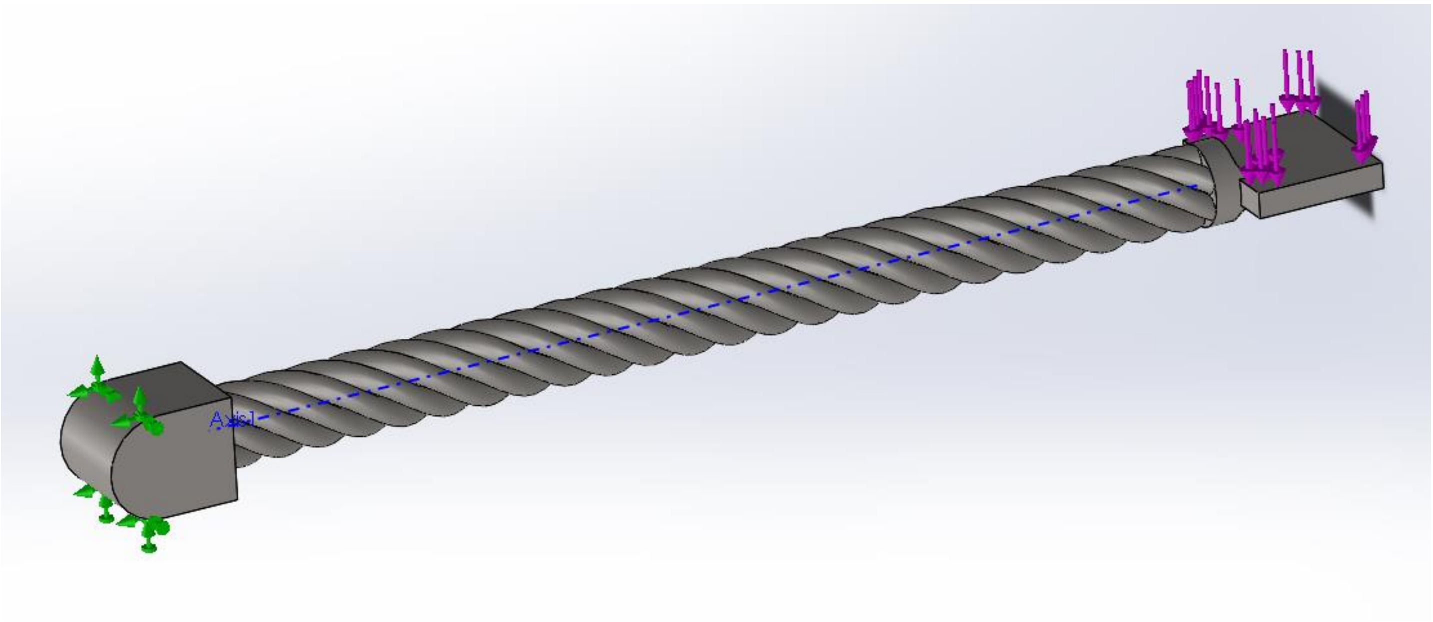
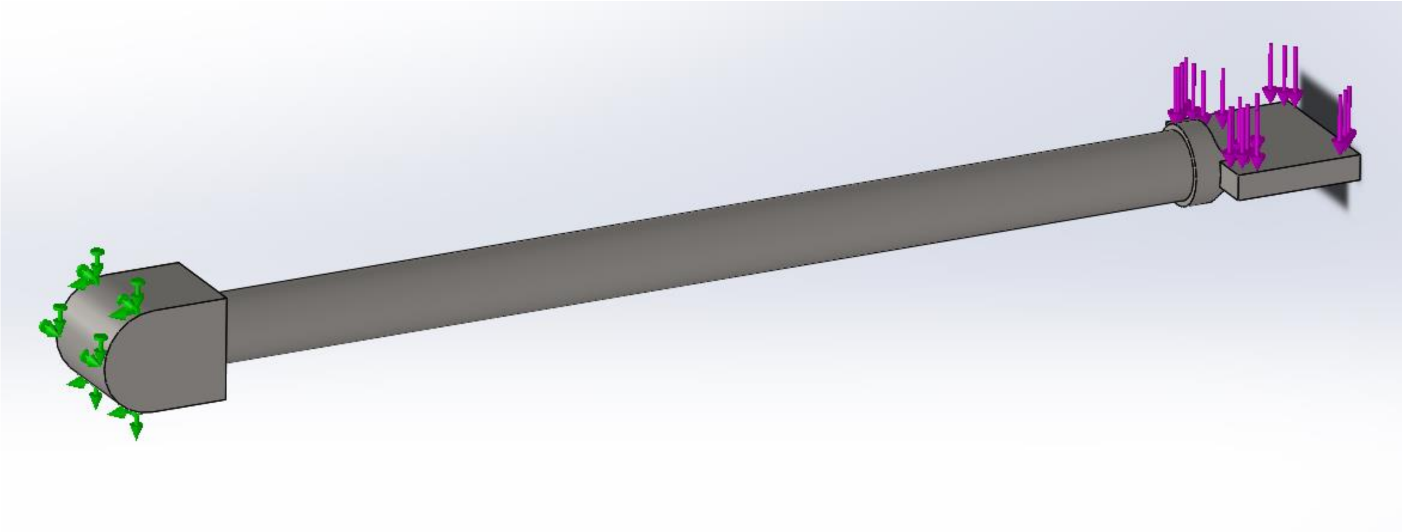
Deformation Comparison

- Wire Rope 1x7 construction

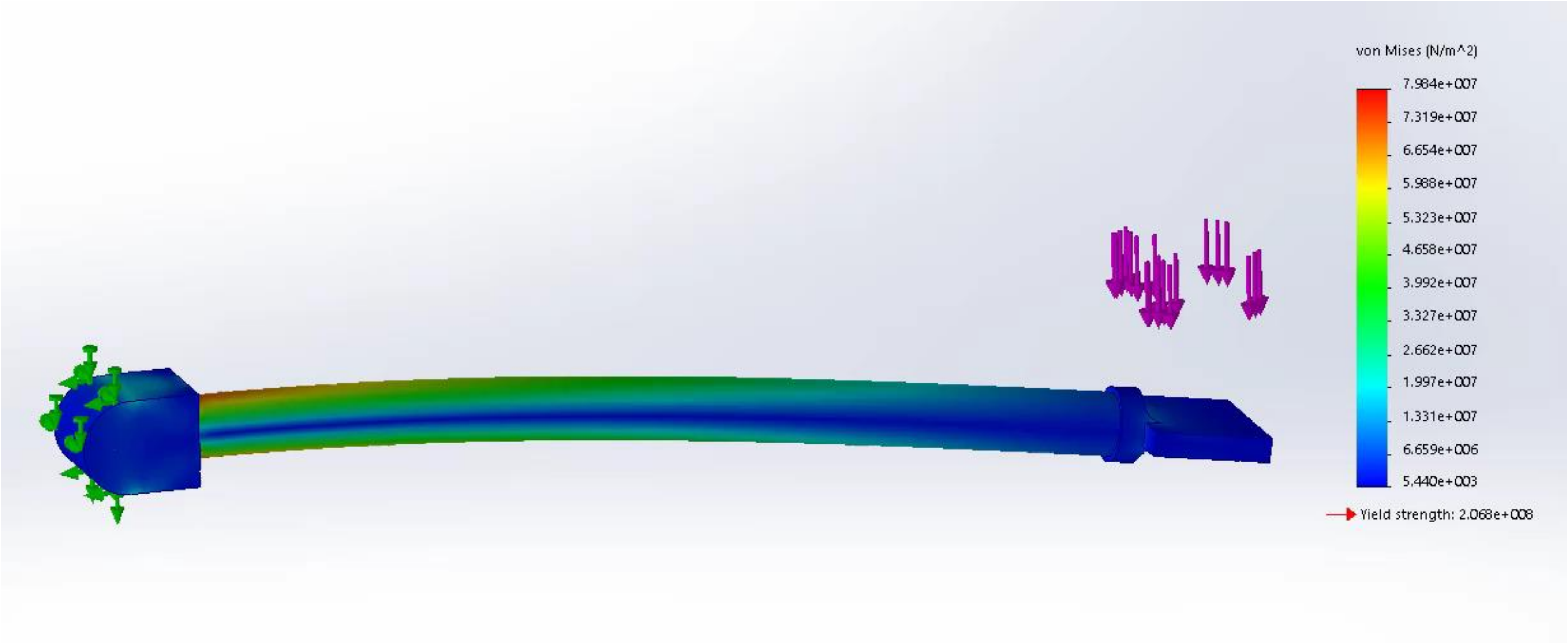


- Equivalent Tensile Area Bar

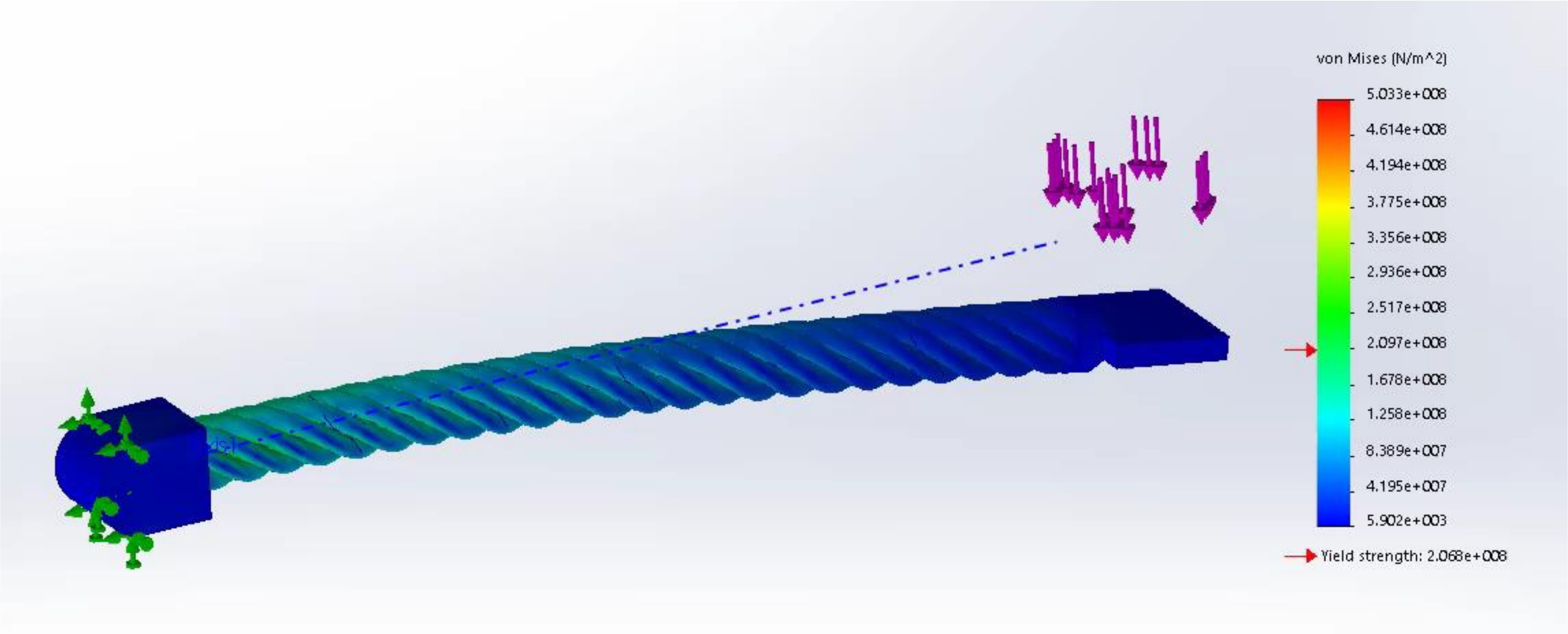


Green Arrows are Constraints
Purple Arrows are Loads

Equivalent Tensile Area Bar Deformation



Wire Rope Deformation



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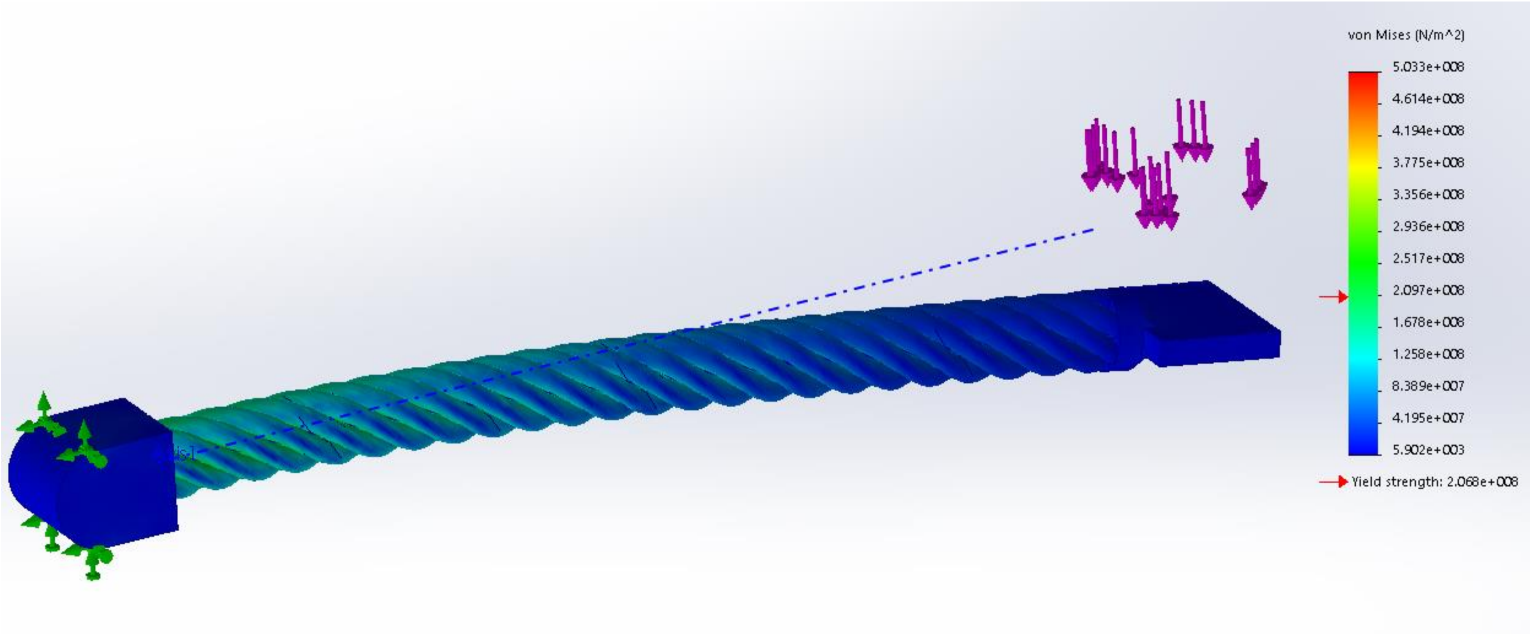
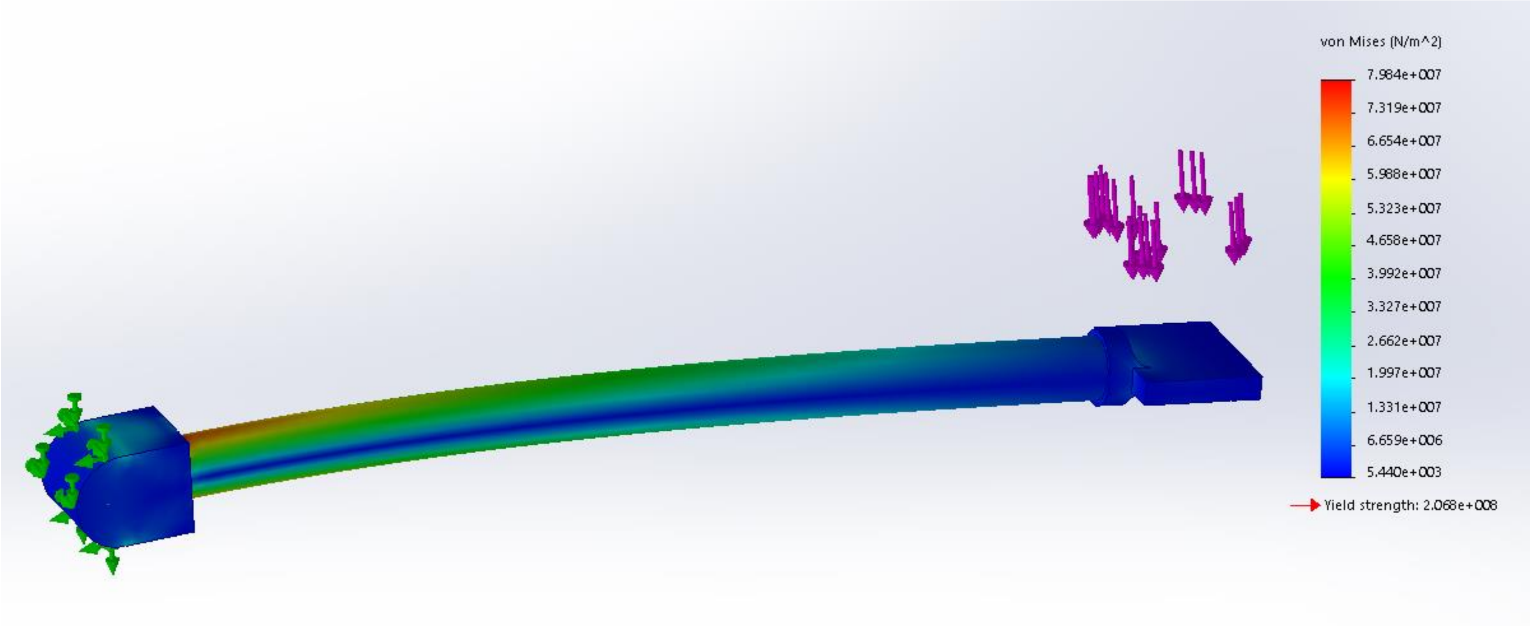
Stress Comparison

- Von Mises Stress

- Lower Stress
- More Localized





Additional Challenges:

- Terminating the wire rope
- Tensioning the wire rope
- Imparting sinusoidal motion to the wire rope
- Sealing the drive mechanism
- Recovering from force overload conditions

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The Team – 20+ Years Together

Hugh Crenshaw, Ph.D., co-founder & CEO

Director Technology Development, **GlaxoSmithKline**
Faculty **Duke University** (Biology & Engineering)

Chuck Pell, co-founder & CSO

Founder, **Nekton Research** (acquired by iRobot)
Director BioDesign Studio, **Duke University**
2018 Emmy-award winner for outstanding daytime series

Eric Espenhahn, COO

VP Engineering & Product Development, Sicel Technologies
VP Engineering Xanthon
Co-founder & VP of Engineering, Intelligent Medical Imaging

Ryan Moody, CTO

Principal investigator and Project Manager, **iRobot Inc.**
Principal investigator and Project Manager, **Nekton Research**

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Thank you.

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