Piezoelectric motor for cryogenic applications

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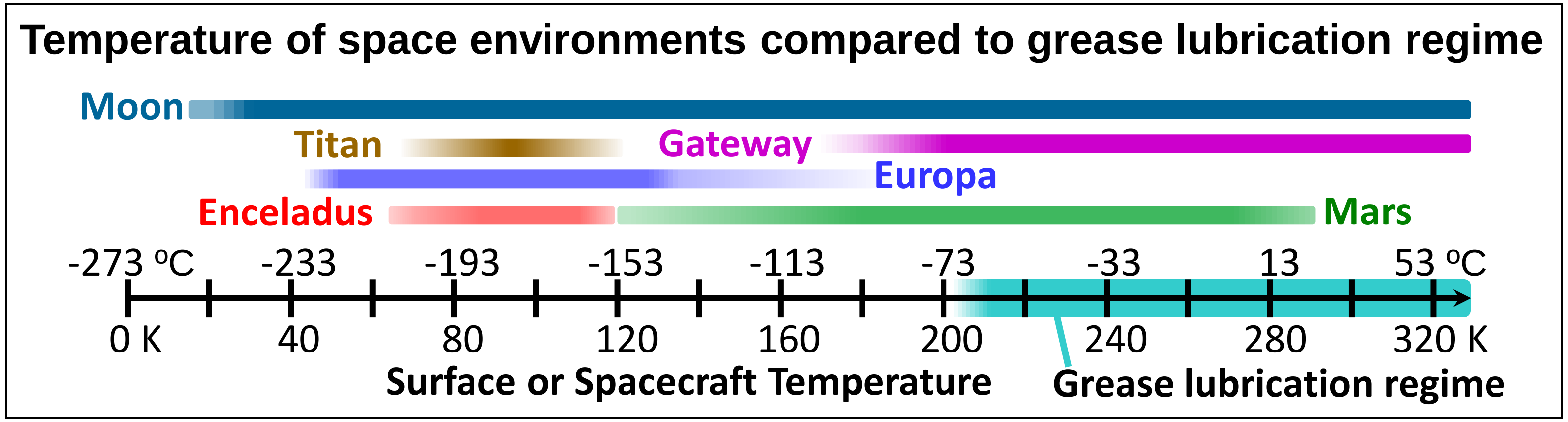
Outline

- Introduction
- Design requirements
- Configurations
- Inchworm actuator
- Linear inchworm proof of concept
- V-shaped PZT fixture configuration
- V-shaped fixture analysis
- Conclusions and future work
- Acknowledgements

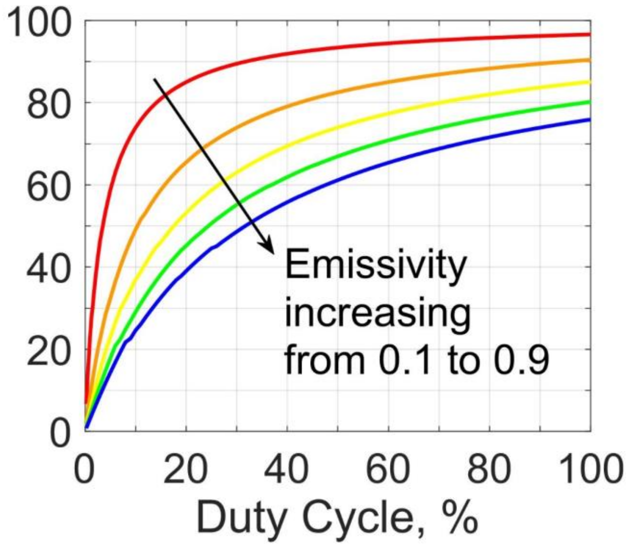
Motivation

- Rotational actuators almost always require a mechanical gearbox to meet mass, volume requirements
- Challenging to lubricate a gearbox operating in cold environments
  - Pervasive problem – *potential for big impact*



- Objective: enable operation in cold to extremely cold environments…
  - Without the mass, complexity, & energy/efficiency penalties of heating actuators
  - Without the strict design constraints & life limitations of solid lubricated gears

Theoretical limit on average total efficiency (%) of heated actuator for indefinite operation [1]

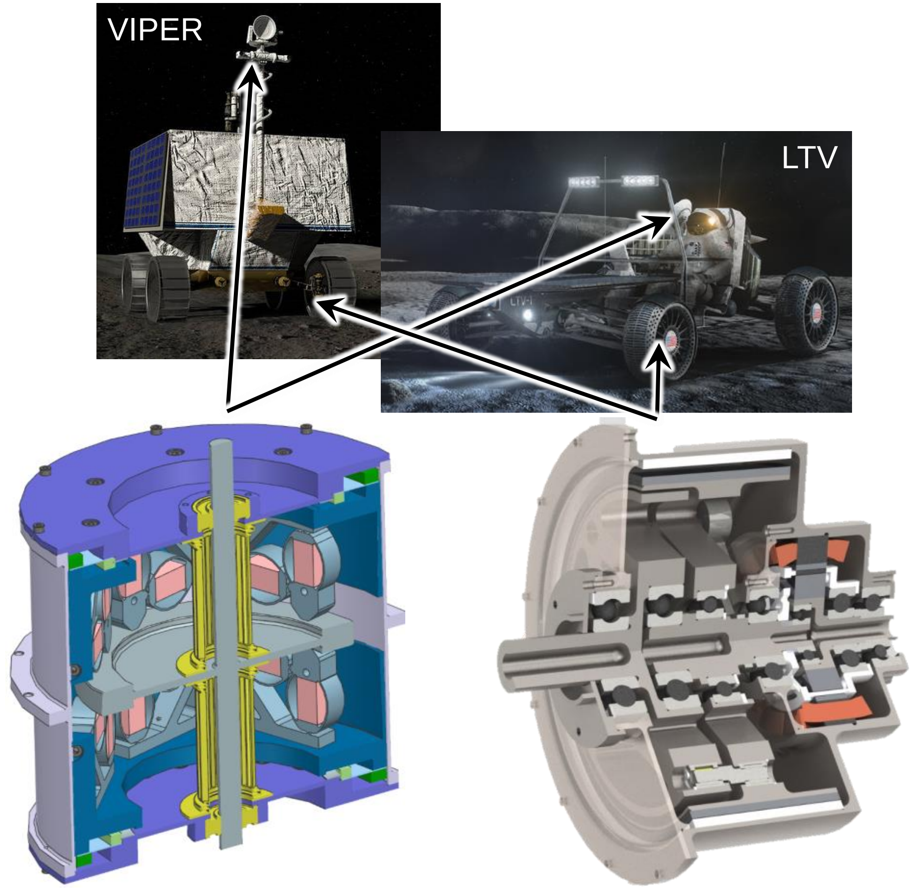


1. Scheidler, J.J. et al., in. *Proc. IEEE Aerospace Conference*, 2022.

Motors for Dusty & Extremely Cold Environments (MDECE) Project

- **R&D & ground test project, Oct 2020 – Sep 2024**
- **Goal:** Develop 2 unheated rotational actuators that can operate for a long duration in extreme cold (ambient temperature of -243 ºC (30 K))
  - Evaluate life in controlled, representative lunar dust environment with and without lunar simulant
- **Approach:** Eliminate gear lubrication – 1 actuator with non-contact gearing, 1 actuator with no gears
- **Key Performance Parameters:** Min. operating temperature ▪ dust-free life ▪ efficiency of magnetic actuator ▪ output resolution of piezoelectric actuator
- **Relevant environment:** Broadly applicable; focusing on lunar PSR
- **Promising applications:**
  - Magnetic actuator: rover mobility ▪ in-situ resource utilization ▪ robotic arm joints ▪ rotors for powered flight
  - Piezoelectric actuator: precision pointing (e.g., laser communication) ▪ low power robotic arm joints

Example mechanisms for demonstrating prototypes (NASA KSC)



Piezoelectric actuator preliminary design (JPL)
[graphic courtesy of NDEAA team / JPL / Caltech / NASA (Patent pending)]

Magnetically-geared actuator preliminary design (NASA GRC & GSFC)

Design Requirements for Piezoelectric Actuator

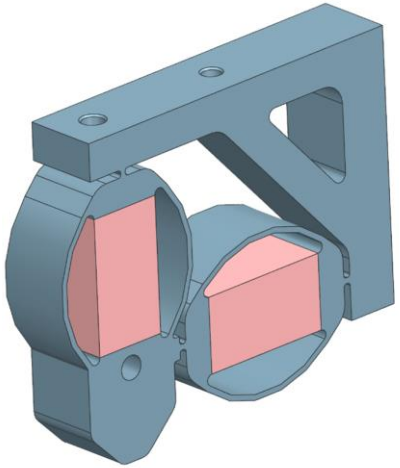
TPM	Unit	KPP	Threshold / Required Value	Goal Value	Current Estimated Value (based on modeling)
Operation temperature	°C	X	-165	-243	-243
Pointing Resolution	°	X	0.003	0.001	0.003/0.001
Actuator output cycle life (dust-free)	cycles	X	240	48,300	>240
Actuator output cycle life (dusty)	cycles		24	4,830	>24
Torque output	Nm		7	14	14
Rotation rate/speed output	rpm		0.15	0.3	0.3
Mass	kg		≤ 7.5	≤ 2.0	7.17
Physical size – diameter	cm		≤ 18	≤ 12	14.4
Physical size – axial length	cm		≤ 19.2	≤ 12.8	14.5

Thermal specifications for operation

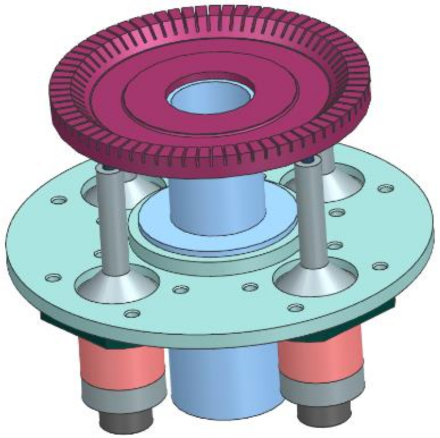
Parameter	Minimum		Maximum	
	Goal	Required	Required	Goal
Lunar surface temperature	30 K (-243 °C)	108 K (-165 °C)	293 K (20 °C)	313 K (40 °C)
Solar heating environment	Shadowed		–	Lunar 85° S

JPL Conceived Three Configurations

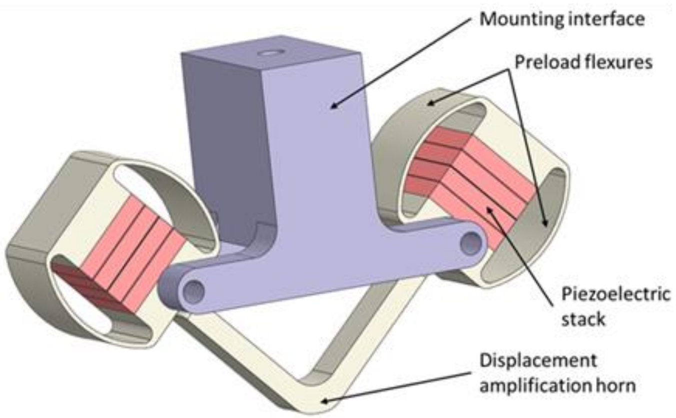
- Three configurations were conceived
- Preliminary design was created for each configuration
- Analysis for simplified models was performed



Configuration 1:
L-shape fixture inchworm



Configuration 2:
Traveling wave

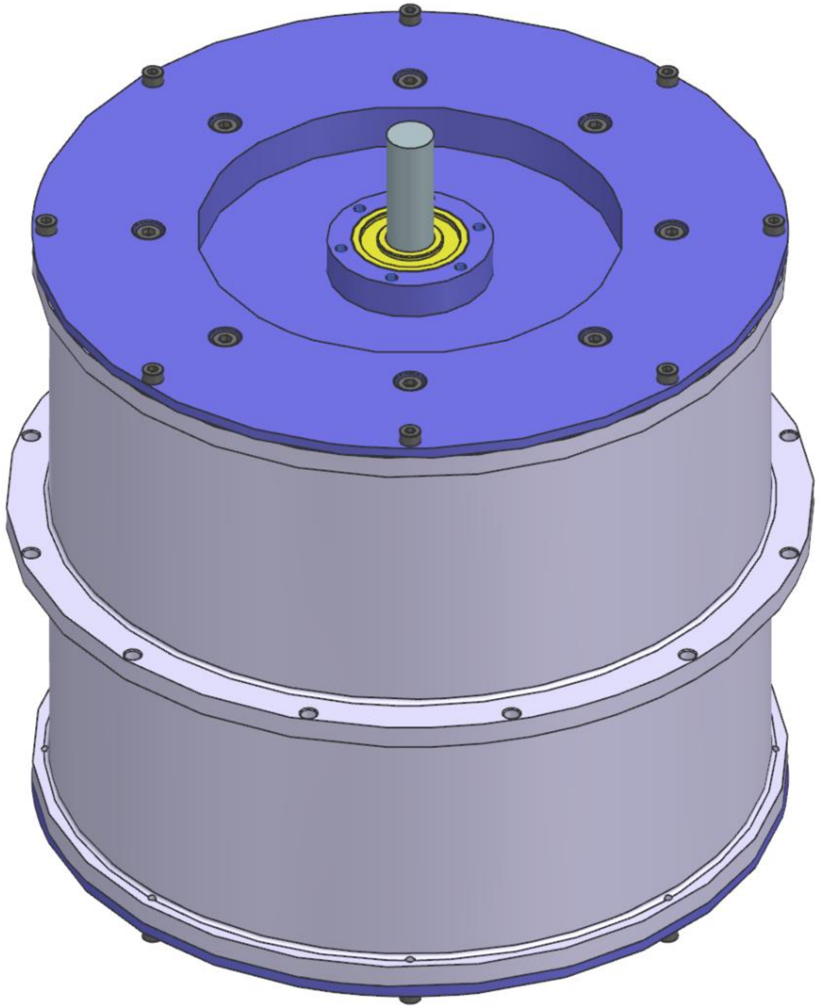


Configuration 3:
V-shaped resonant fixture

Configuration 1 (Baseline): L-Shape Inchworm

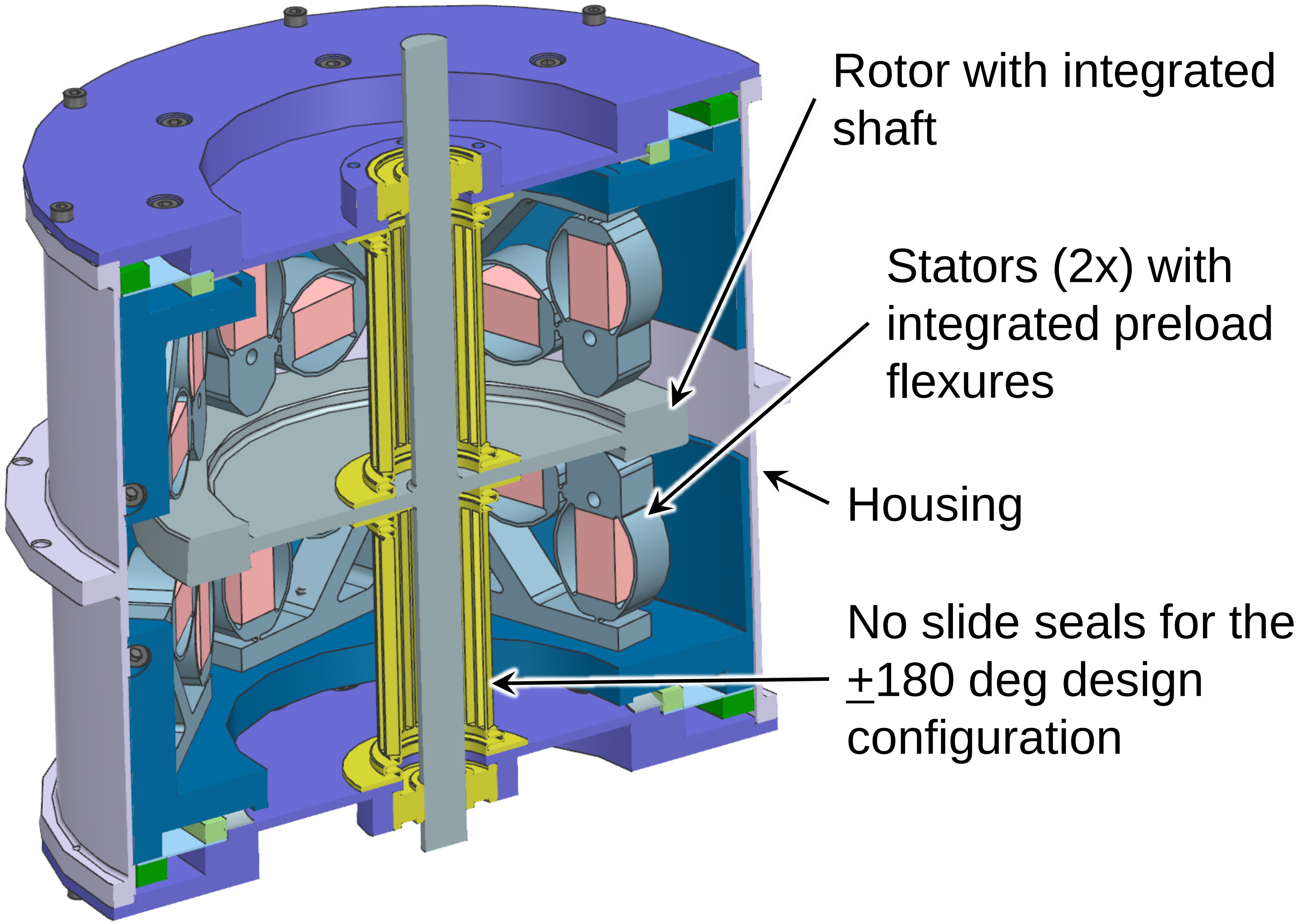
- Based on actuators that have L-shape incorporating 2 extensional PZT stacks for preload and tangential rotor motion control
- 6 actuators are mounted on a stator mounting plate “floating” with respect to a base element
- 2 stators preloaded against a rotor disk
- The housing provides interfaces to the stators, the driven mechanism and mounting

- Size envelope: 170mm diameter, 145mm height



Configuration 1 (Baseline): Piece Part Overviews

- Main subassemblies and components:
  - Rotor with shaft (integrated part or assembly)
  - Stators (2x) on each side of the rotor disk
  - Housing with ground and stators interfaces
  - No sliding seals for the ±180º design configuration
  - Bearings (1 radial and 1 matched pair angular contact FF)



Configuration 1 (Baseline): Design Details

Interfaces

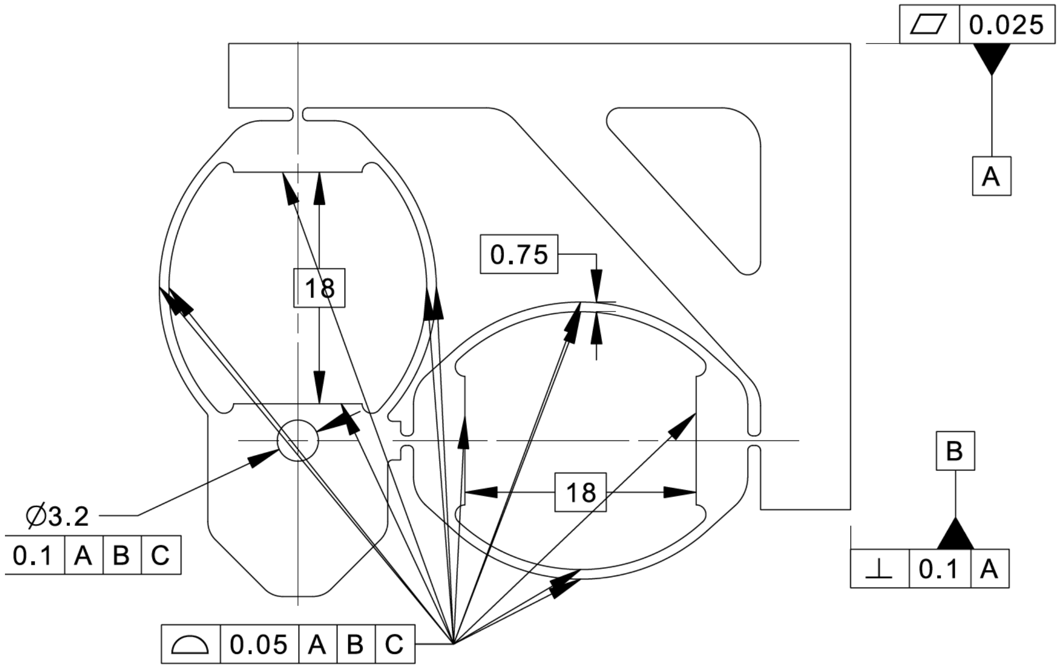
- Housing to ground – flange with bolt holes pattern
- Shaft to shaft – flexible coupling

Mandatory Inspection Points (MIPs)

- Fixtures mounting on the rigidized plate using epoxy shims and preloading against the rotor disk

Critical clearances and tolerances

- PZT flexures and interface surfaces – surface profiles of 50 µm
- Planar stator faces – located within 50 µm with respect to the shaft axis
- Planar stator faces – 10 µm flatness overall and 5 µm flatness within a 35º arc sector
- PZT flexures mounting face of the stator disk – 25 µm flatness



Potential Electro-Mechanical Materials

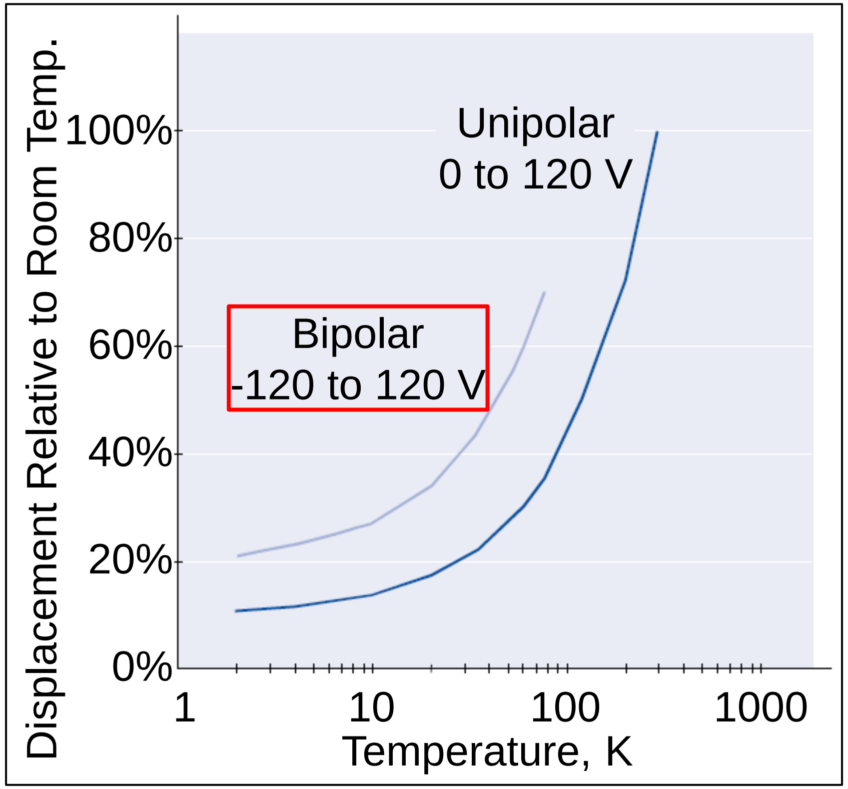
1. Newer piezoelectric single crystals
   - Many compositions [(PZN, PMN, PIN, PSN, PIT)-PT] - PIN-PT Pb(In1/2Nb1/2)O3 [PIN] PbTiO3 [PT] have been identified as suitable cryogenic actuator materials with higher performances. Unfortunately stacks of these materials are not available off-the-shelf and the thicker layer requires higher drive voltages.

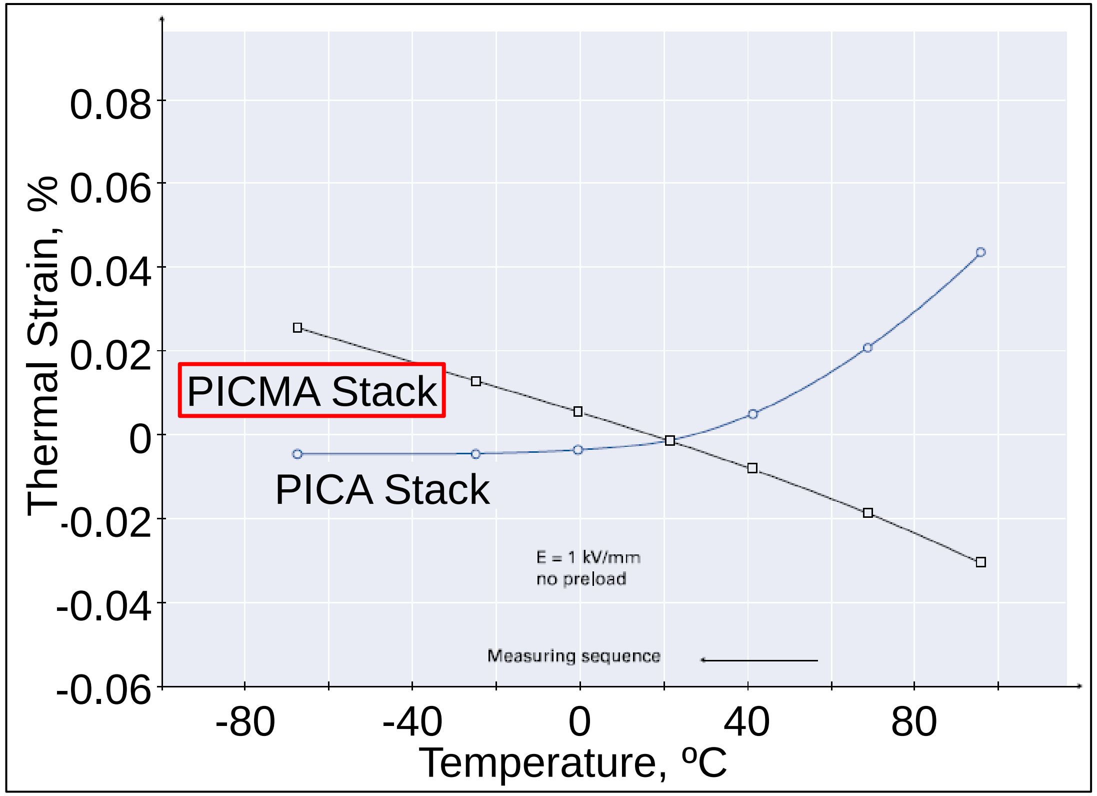
2. Typical commercial piezoelectric PZT (Lead Zirconate, Lead Titanate)
   - Most commercial PZT multilayer stacks specified for operation at –40 to 150 ºC, but use of alternative solders expands range to –271 to 200 ºC

3. PMN-PT electrostrictive ceramic
   - Multilayer cofired stacks are produced commercially for large optical devices but not sold publicly

Temperature Dependent Properties

- The displacement of commercial PZT multilayer stacks degrades as temperature is decreased
  - 36% reduction at 65 K, 58% reduction at 30 K (±120 V operation)
- Coefficient of thermal expansion is also negative (approx. -2.5 µm/m/K)
- The design also considered temperature-dependent properties for structures





Friction Coefficient Table

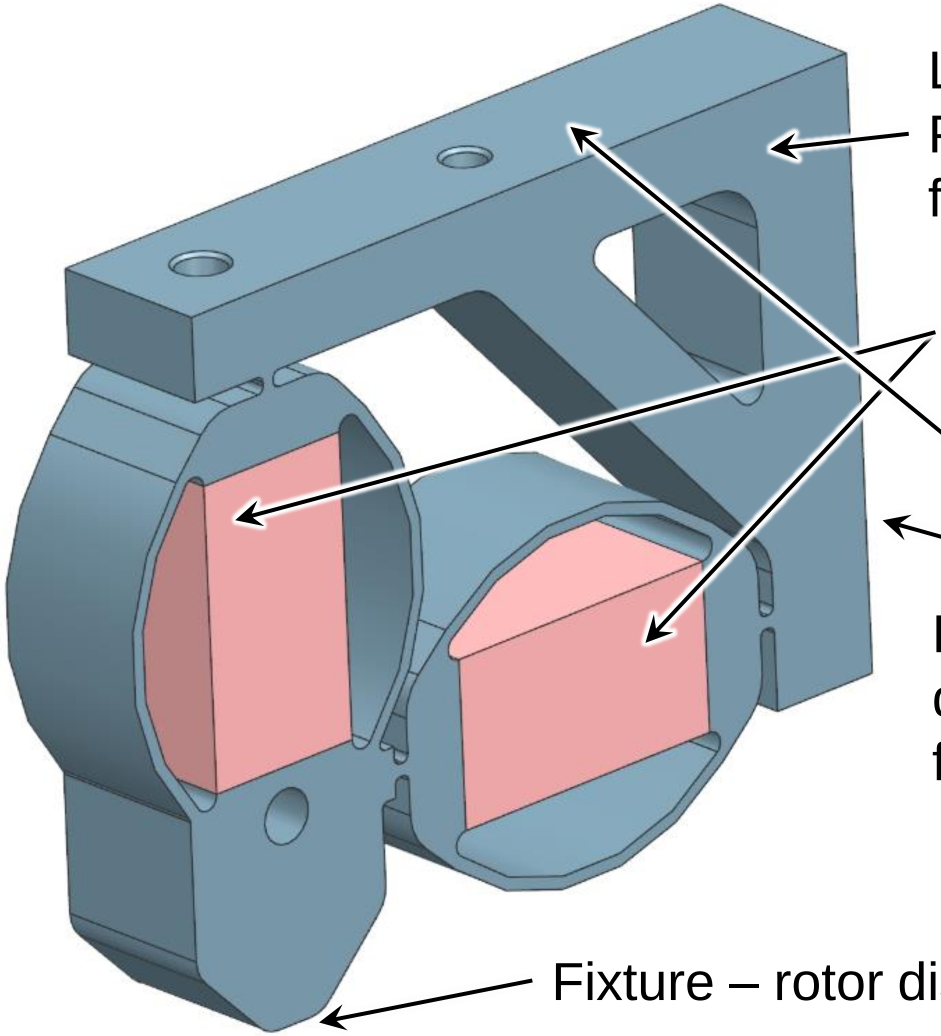
- No friction coefficient data for Invar – SS304 was found
- The coefficients are sensitive to various surface conditions with only few pairs with <0.3 friction coefficient
- Therefore, in design and analysis we had conservatively set the coefficient to 0.3

Material Combination	Friction coefficient in vacuum
Fe-Fe	1.9
Fe-Mg	0.6
Fe-Cd	0.4
Fe-Pb	0.4
Stainless Steel - Stainless Steel	2.9
Stainless Steel – Cu	0.3
Stainless Steel-Al	0.3
Stainless Steel-Mo	0.8
Stainless Steel-Ni	0.8
Stainless Steel-Teflon	0.2
Stainless Steel-Si	0.2
Stainless Steel-Ge	0.2
Stainless Steel-Glass	0.5
Chromium Steel – Chromium Steel	0.5
Cu-Cu	4.8-21.0
Cu-Ni	1.5-2.0
Al-Al	1.6-2.2
Al-Ni	2.4
Al-Cu	1.5
Al-Ag	2.2
Brass-Brass	0.7
Ni-Ni	4.9
Ag-Ag	3.9
Cr-Cr	3
Au-Au	4.5
Zn-Zn	3
Zr-Zr	1.5

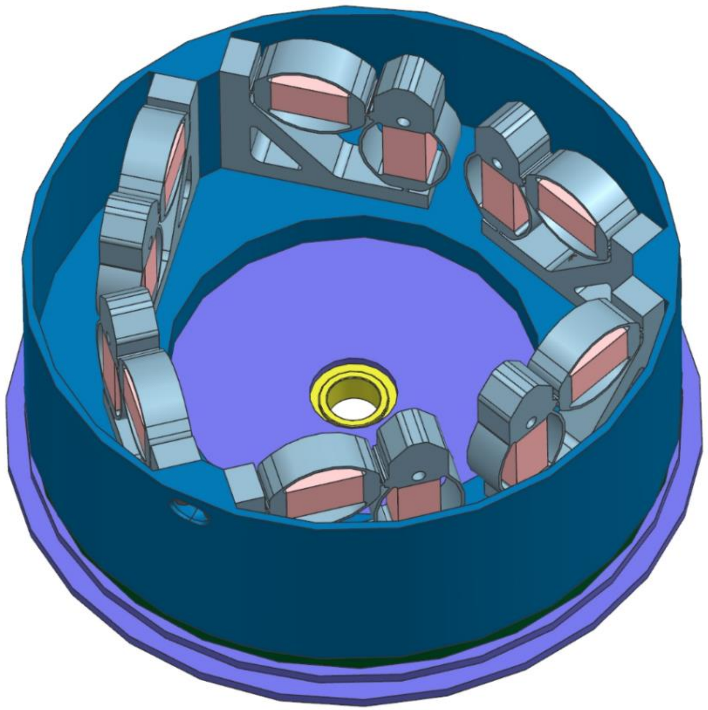
Configuration 1 (Baseline): Design Details – PZT Fixtures

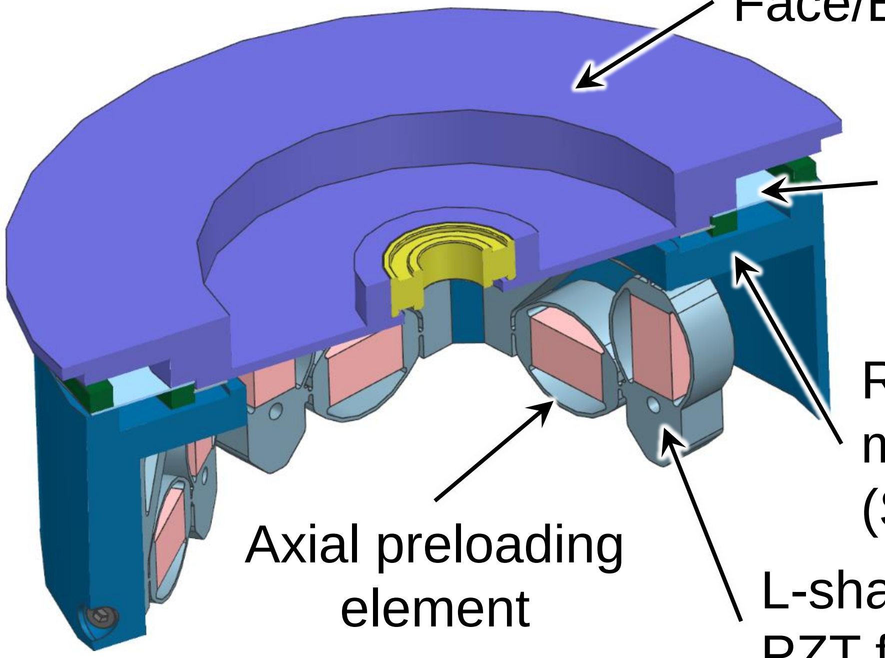
- L-shaped inchworm configuration
- Based on an L-shaped actuator fixture that incorporates 2 extensional PZT stacks for preload and tangential rotor motion control
- PZT stacks (10 x 10 x 18 mm) preloaded by flexures
- Additional flexures to allow relative rotation of the stacks during the operation

- Size: W54 x H43 x T10
- Material: Invar 36



Configuration 1 (Baseline): Design Details – Stators



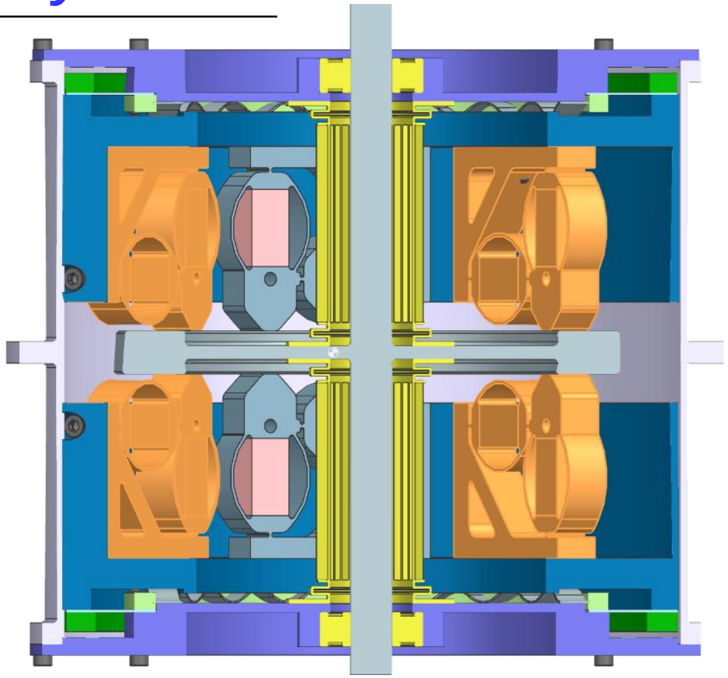


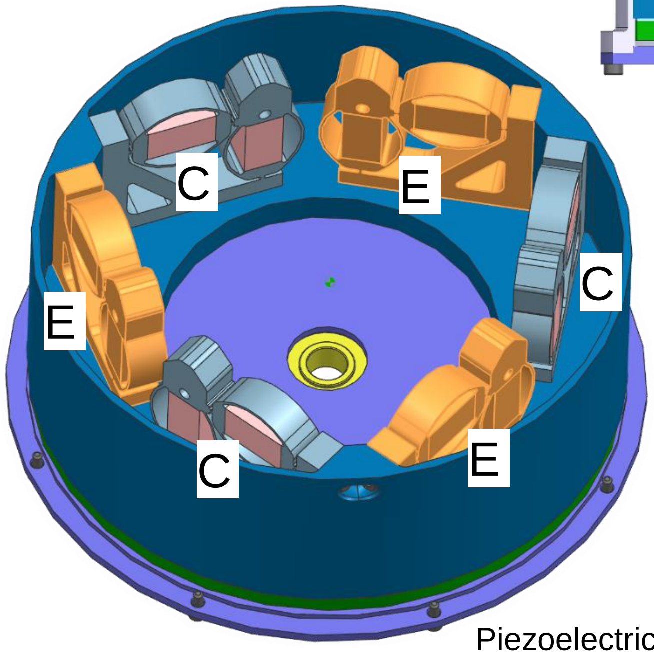
- Asymmetric placement of the L-shaped fixtures
- 6 fixtures mounted on a stator
- Base element mounted on the housing; rigidized mounting plate floats axially with respect to the base element and “follows” the rotor profile
- Fixture, stator disk and base, membrane – Invar 36 selection

Configuration 1 (Baseline): Design Details – Motor Assembly

- In operation, 3 PZT fixtures make contact with the rotor face and define the contact plane
- The other 3 PZT fixtures are retracted and reposition for the next drive step
- Preload springs allow the stator disk to follow the rotor profile and maintain preload of the PZT fixtures against the rotor
- The stroke of the PZT stacks dictate the rotor planar face profile tolerances
- The asymmetric mounting of the PZT fixtures on the stator disk help ease the rotor tolerances

Size:
170 mm diameter
x 145 mm height





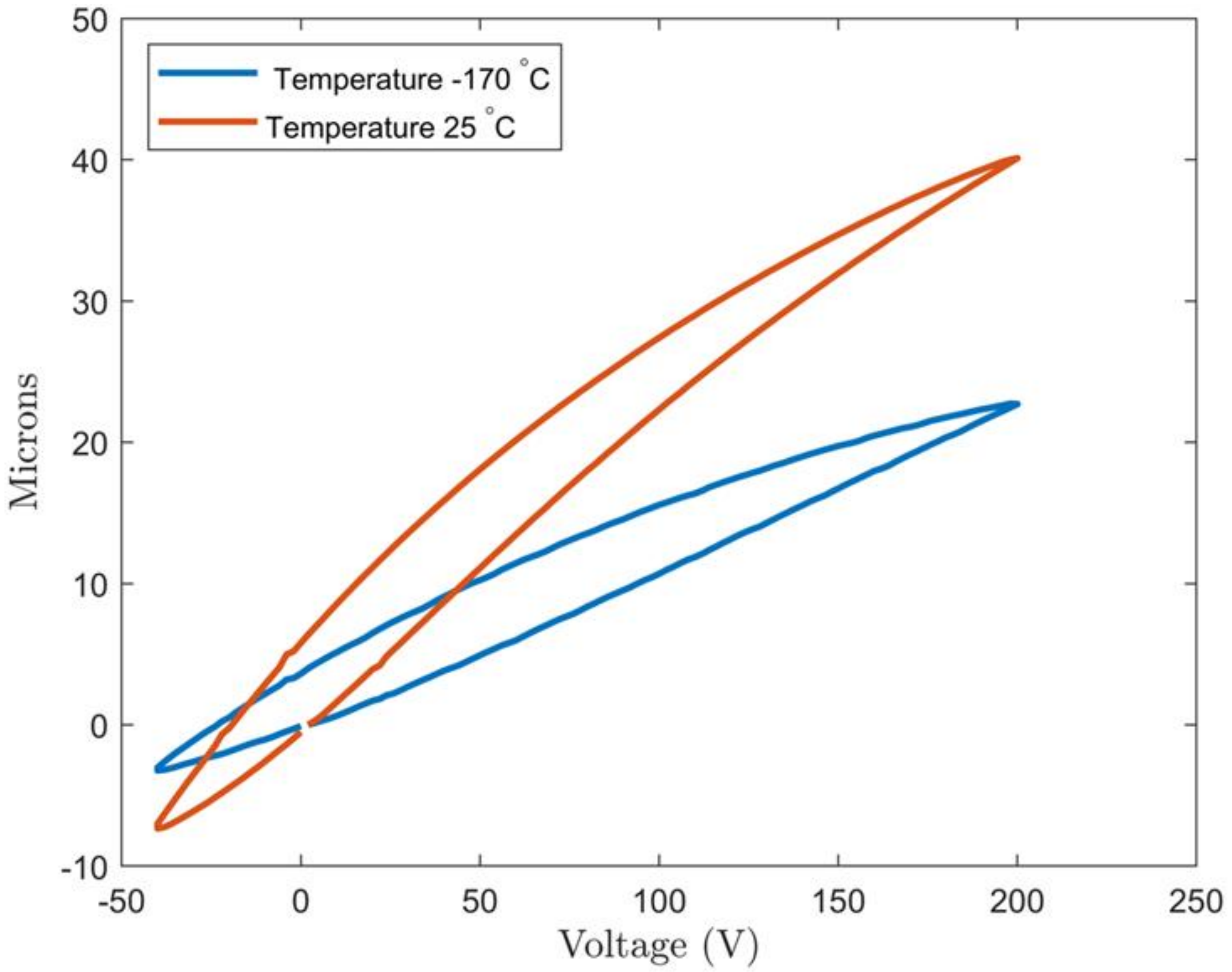
E: extended PZT stacks (fixture contacts rotor)

C: retracted PZT stacks (fixture does not contact rotor)

Configuration 1 (Baseline): PZT Stack Performance

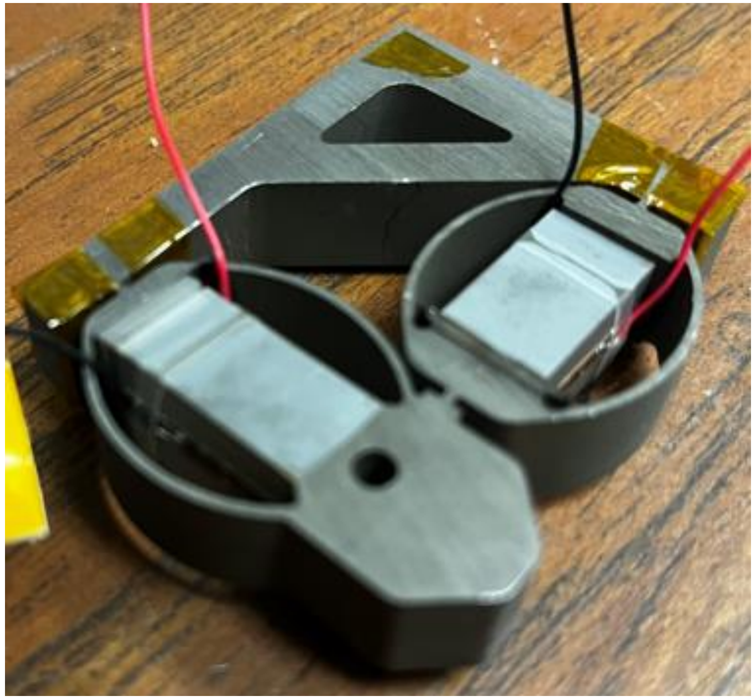
- Example of the stroke decrease for ΔT = 195 K temperature drop for a PI stack (PI-888.51 10 x 10 x 18 mm)

- Stroke is 47% lower than at room temperature



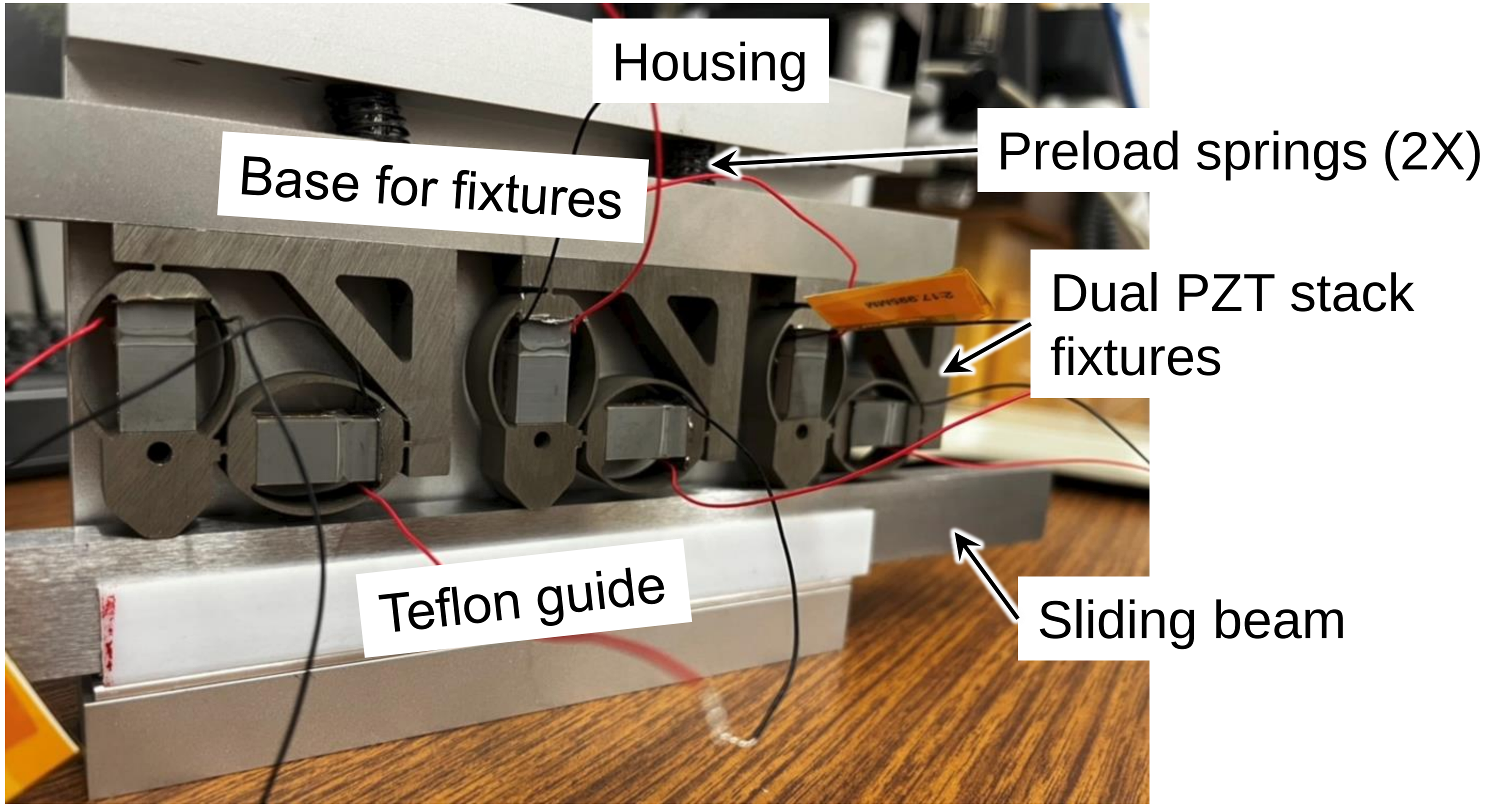
Configuration 1 (Baseline): Manufacturability and Procurement

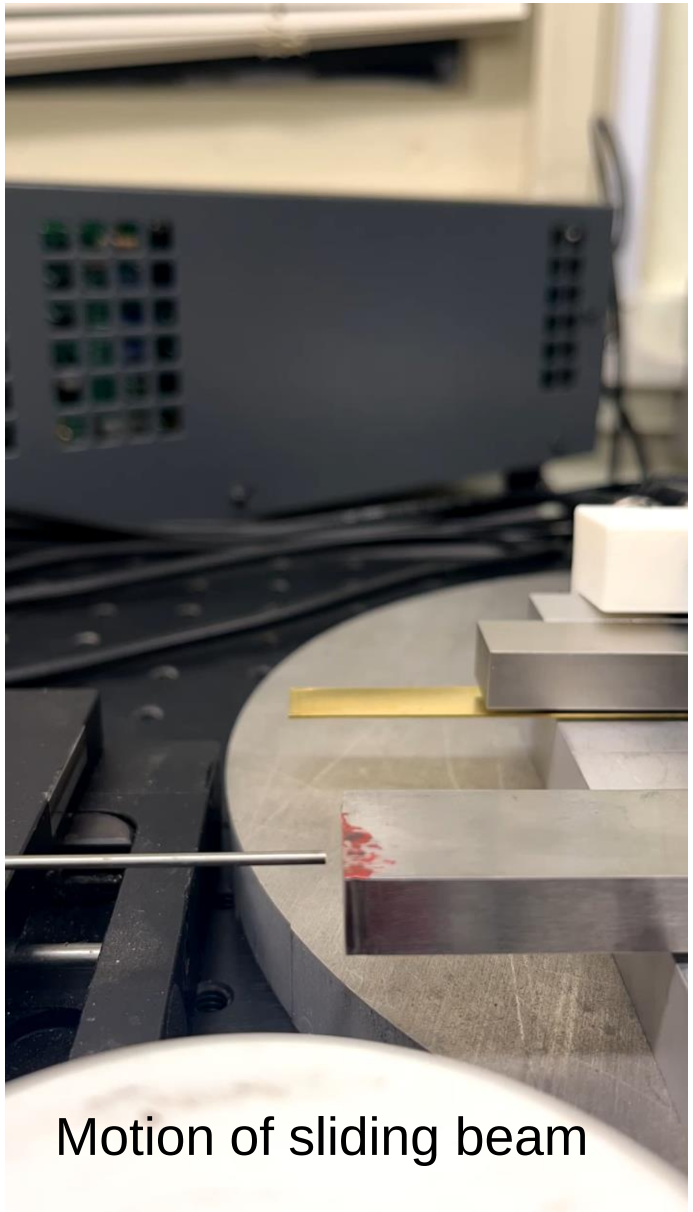
- The stacks are purchased from PI actuators. If not in stock, they have 12 week delivery time but they are working to shorten it
- The actuators require assembly under preload which requires verification and we are currently testing methods to accomplish this using the direct piezoelectric effect in the stack
- Fixtures in direct contact with PZT stacks, shims, mounting plate, membrane and face plate are made from Invar
- The assembly is done at room temperature but needs to operate at cryogenic and we need to address the thermal strain mismatch. This requires understanding the CTE of the stacks as a function of different boundary conditions including preload, electrical connection status (e.g. short, open circuit) and with applied voltage



Proof of Concept Development

- 3 L-shape actuators were incorporated into a linear motor configuration towards demonstrating proof of concept





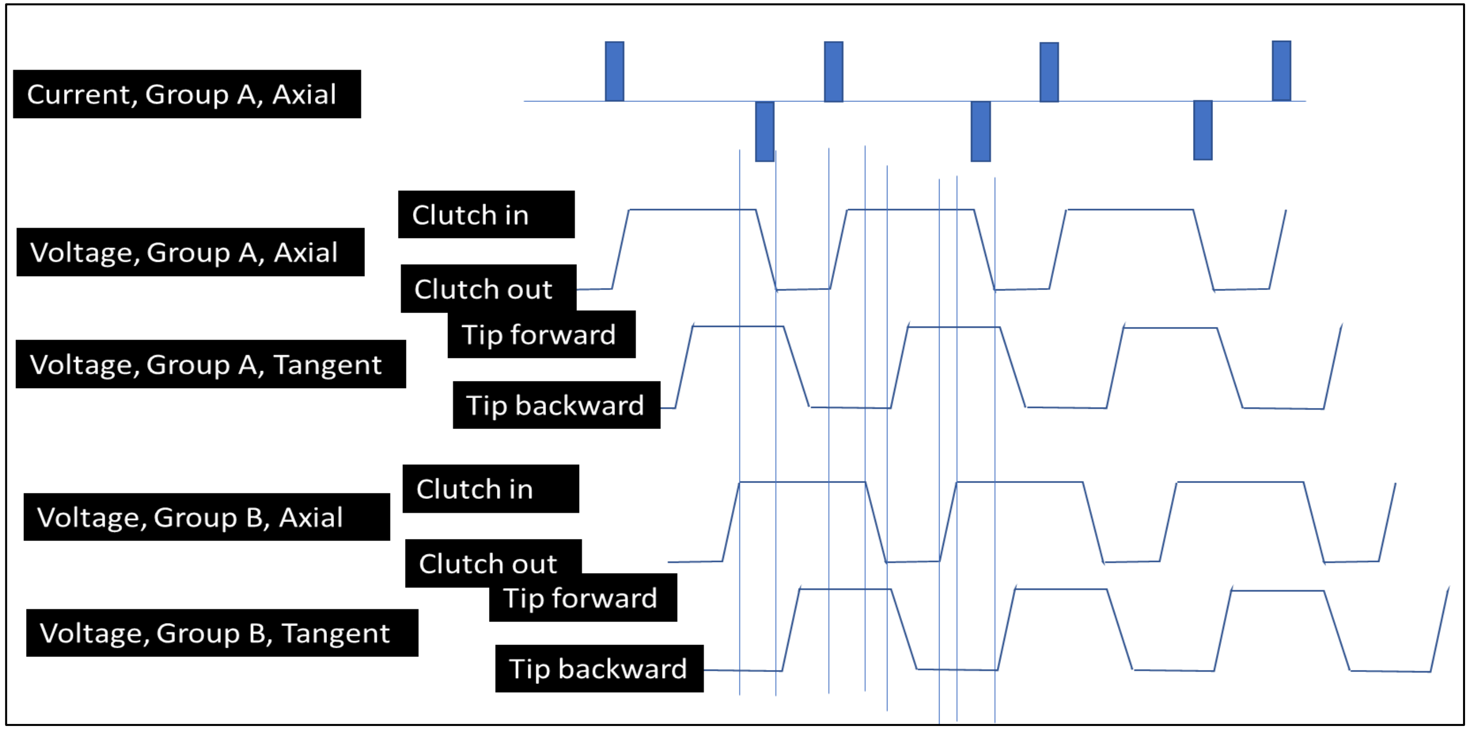
Software / Drive Electronics

- To meet the Key Performance Parameters (KPP) electrical requirements, pulse frequency and duration, and the current requirements were identified.
- For debugging, testing and validation of the prototype, benchtop testing was performed using off-the-shelf drive electronics, amplifiers and power supply.

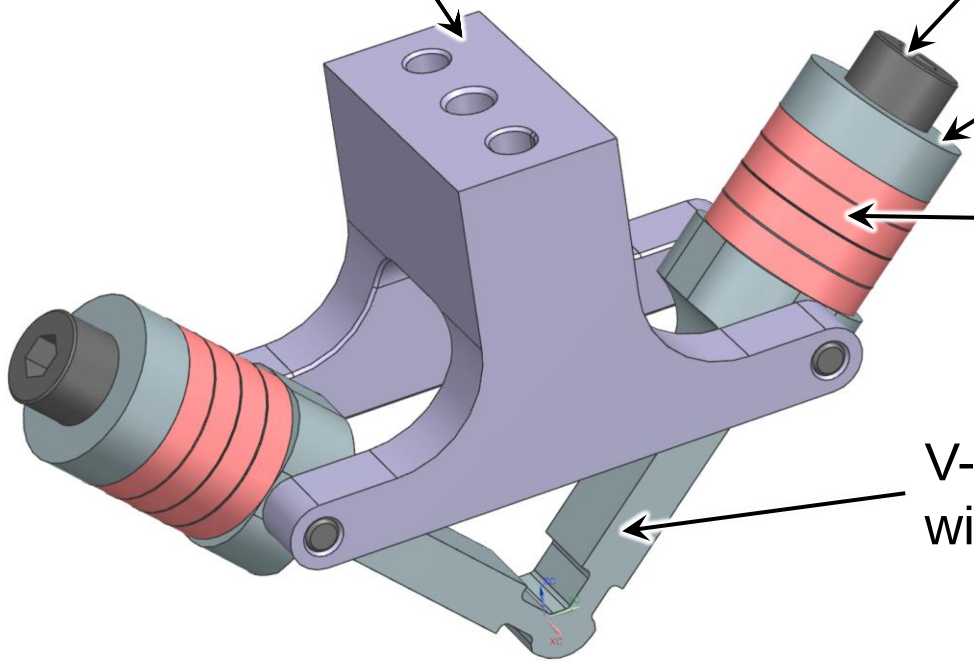
Electric driver requirements

Phase		4
Voltage, Vdc	Max	120
	Min	-120
Freq., Hz		220
Charge / discharge time, ms		0.38
Charge / discharge current, A		5.90

Piezo Actuator Electrical Excitation



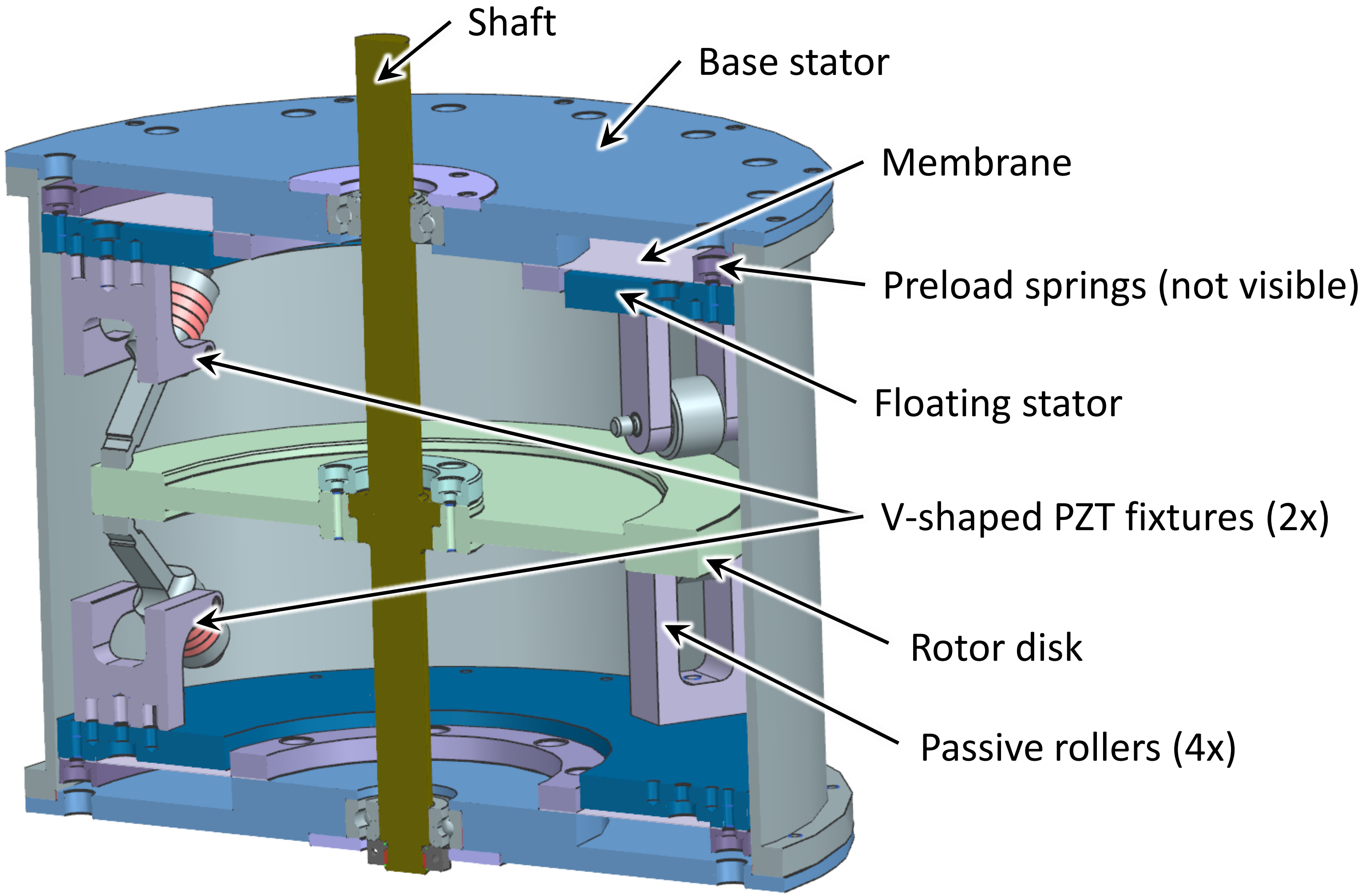
Configuration 3: V-Shape Fixture Configuration



Size envelope:
70.5 mm W x 43.5 mm H x 22.5 mm T

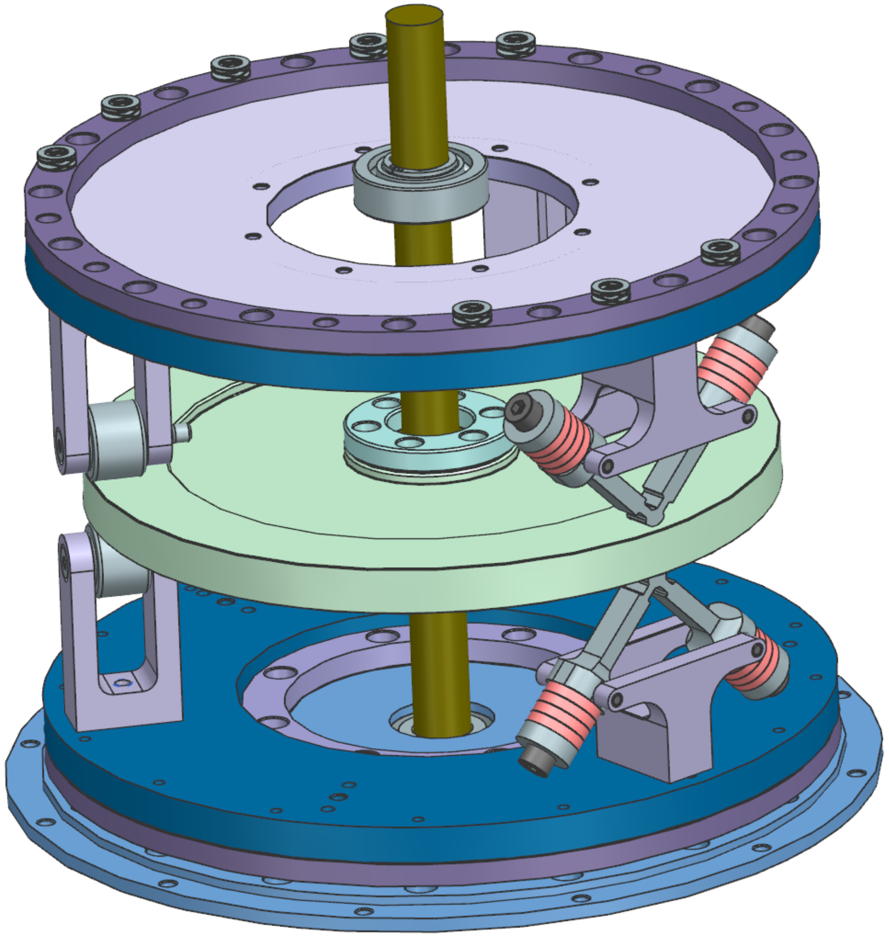
Configuration 3:
Design Configuration

Size envelope:
- Diameter 185 mm
- Shaft length 170 mm



Configuration 3: Drive Components

- PZT transducers integrated with mounting bases
- Drive fixtures integrated with the floating stators
- Rotor – rotor disk clamped onto the shaft flange
- Shaft constrained by preloaded angular contact bearings mounted in a back-to-back configuration
- Whole motor design configuration: compliant membrane, preload springs, floating stator, base stator, housing, bearings



Configuration 3: Manufacturability

Rotor flatness

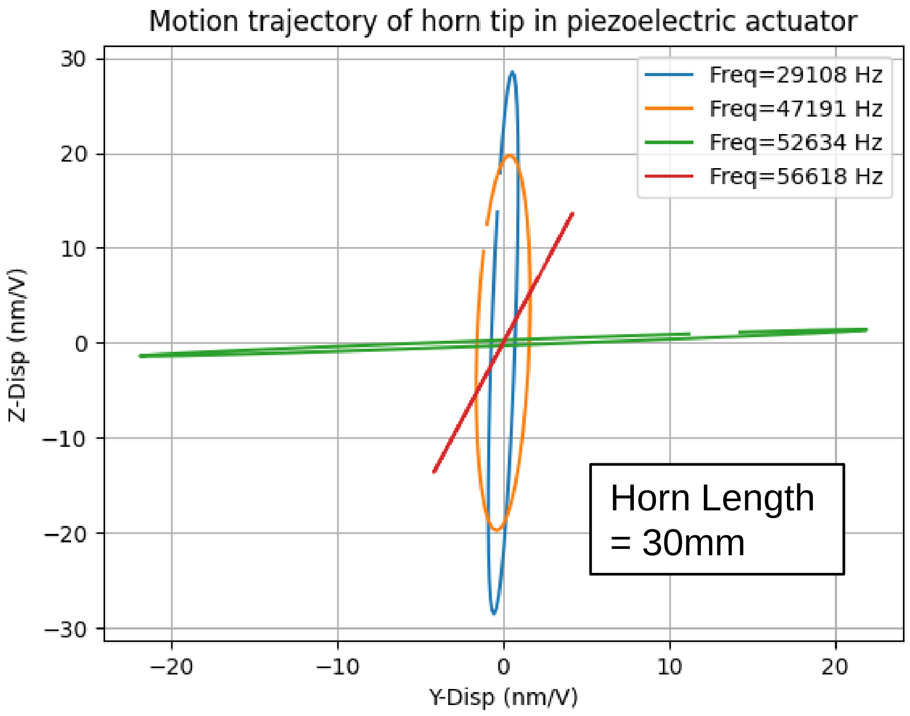
- Dictated by the stator surface profile, piezoelectric actuator displacement amplitude
- Mitigation:
  - Selected solution uses 3 point of contact per rotor side and floating stators
  - Use piezoelectric stacks to increase amplitude and keep drive voltage low
  - Use horns to increase vibration amplitude
  - Drive piezoelectric structures in resonance to increase vibration amplitude

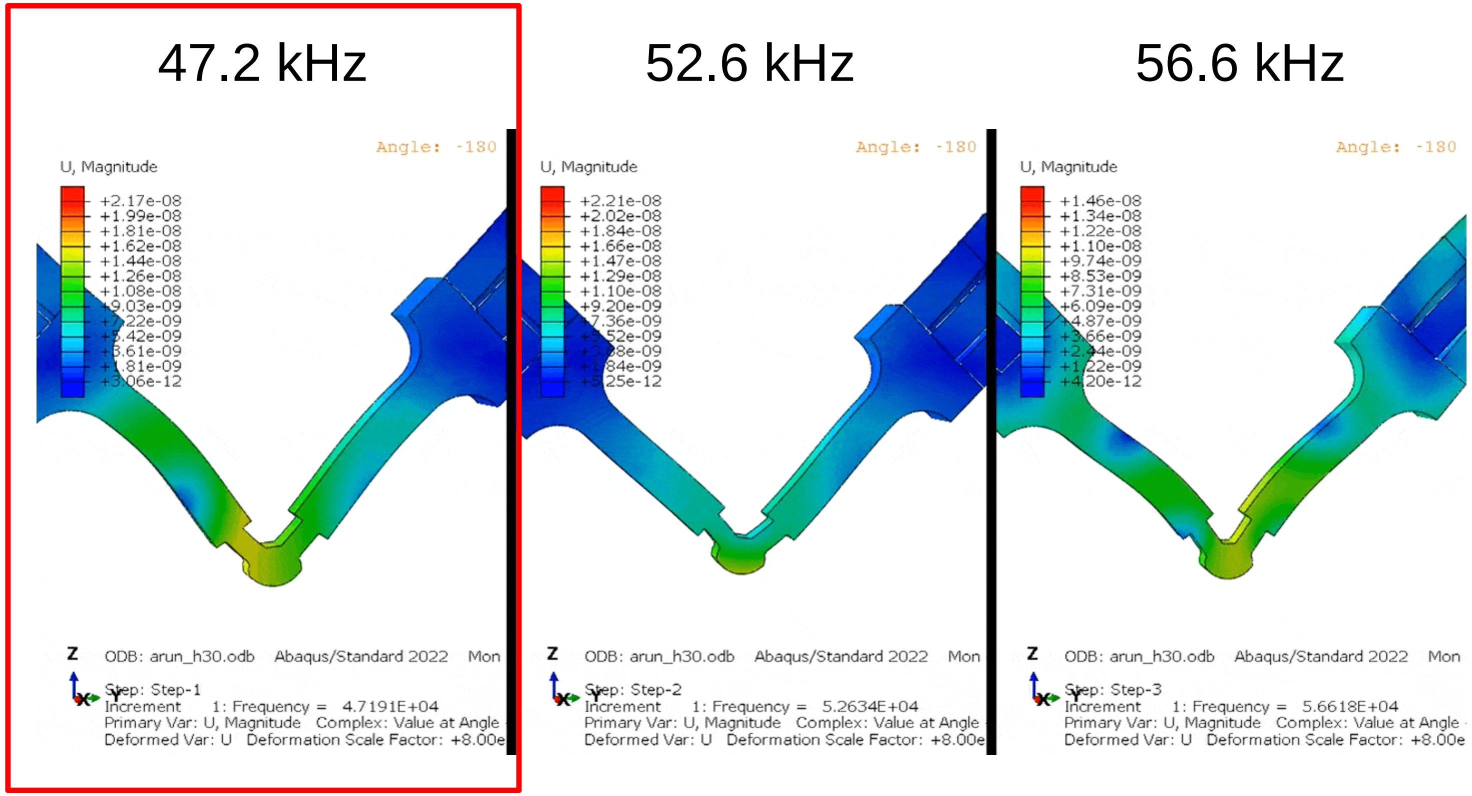
Rotor roughness – dictated by the piezoelectric actuators vibration amplitude

- Mitigation:
  - Reduce rotor contact surface and specify tighter manufacturing precision
  - Use piezoelectric stacks to increase amplitude and keep drive voltage low
  - Use horns to increase vibration amplitude
  - Drive piezoelectric structures in resonance to increase vibration amplitude

Configuration 3: Piezoelectric Fixture Harmonic Performance

- Motion trajectory of the fixture's tip driven at 1 V (horn length = 30 mm)
  - Desired elliptical motion achieved with 47.2 kHz mode

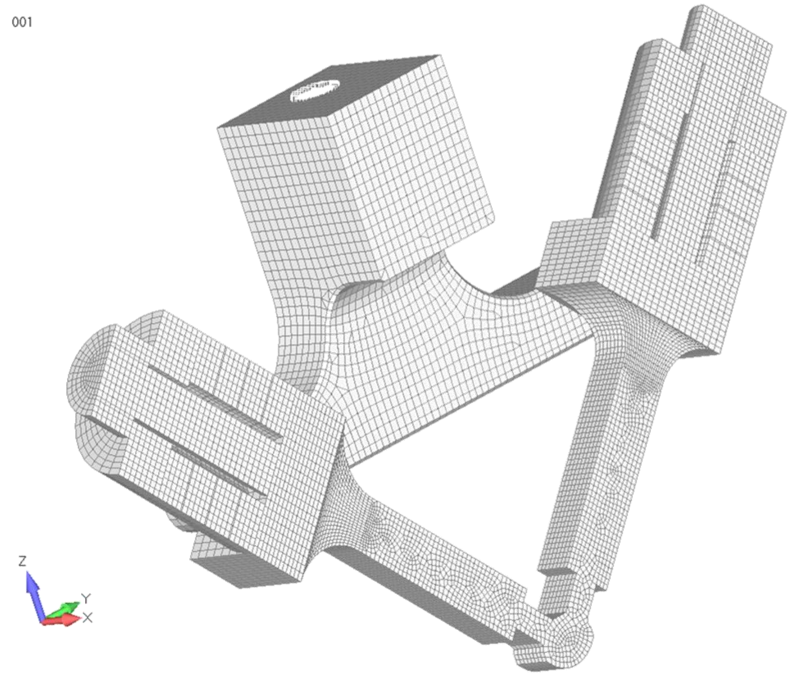


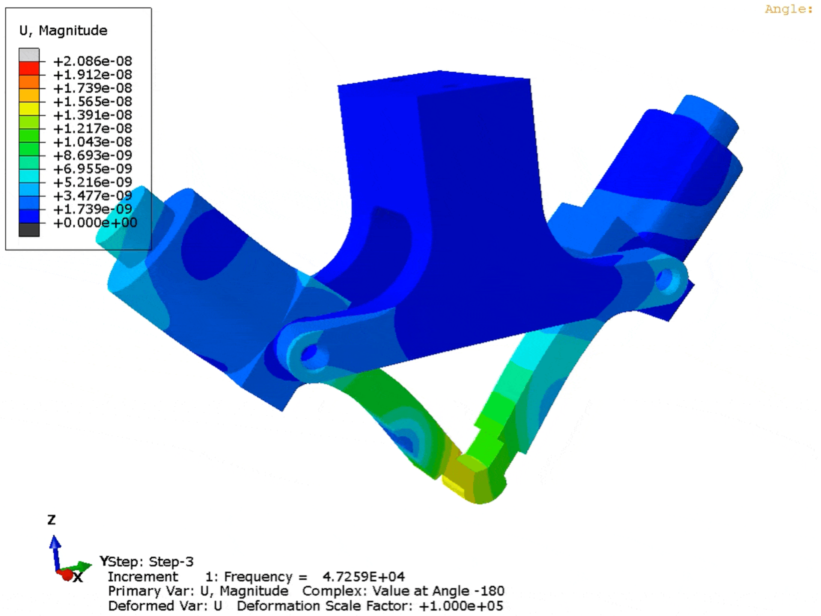


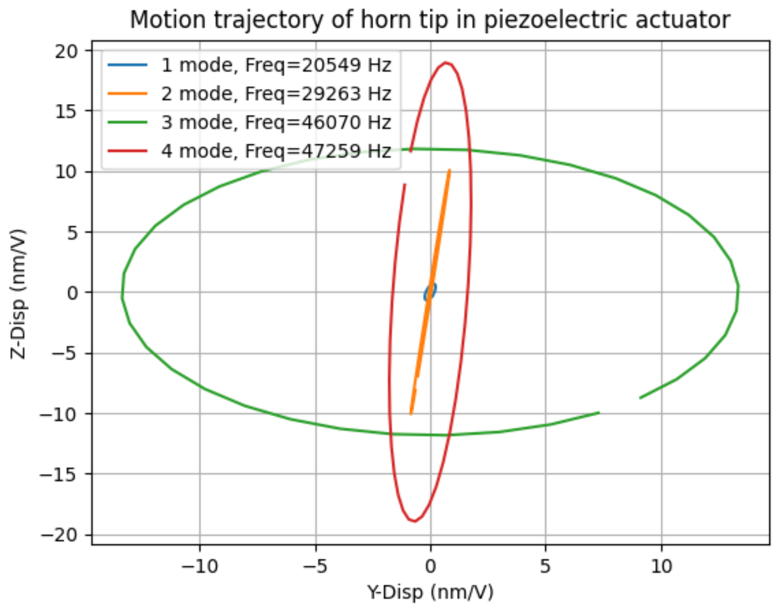
Configuration 3: Piezoelectric Fixture Harmonic Performance

- Finite Element Model was created using a mounting fixture with pin joints and it underwent harmonic analysis, revealing that the mounting fixture had minimal impact on the vibration response of the complete model

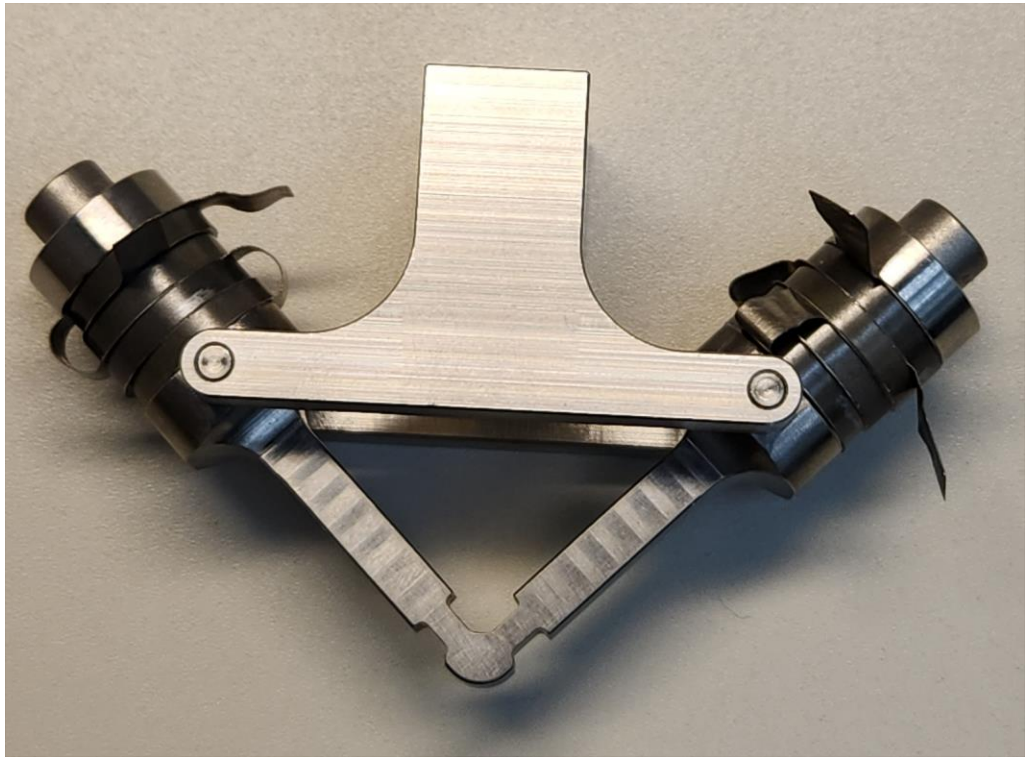
Simulated motion trajectory when driving at 1V & 47.2 kHz



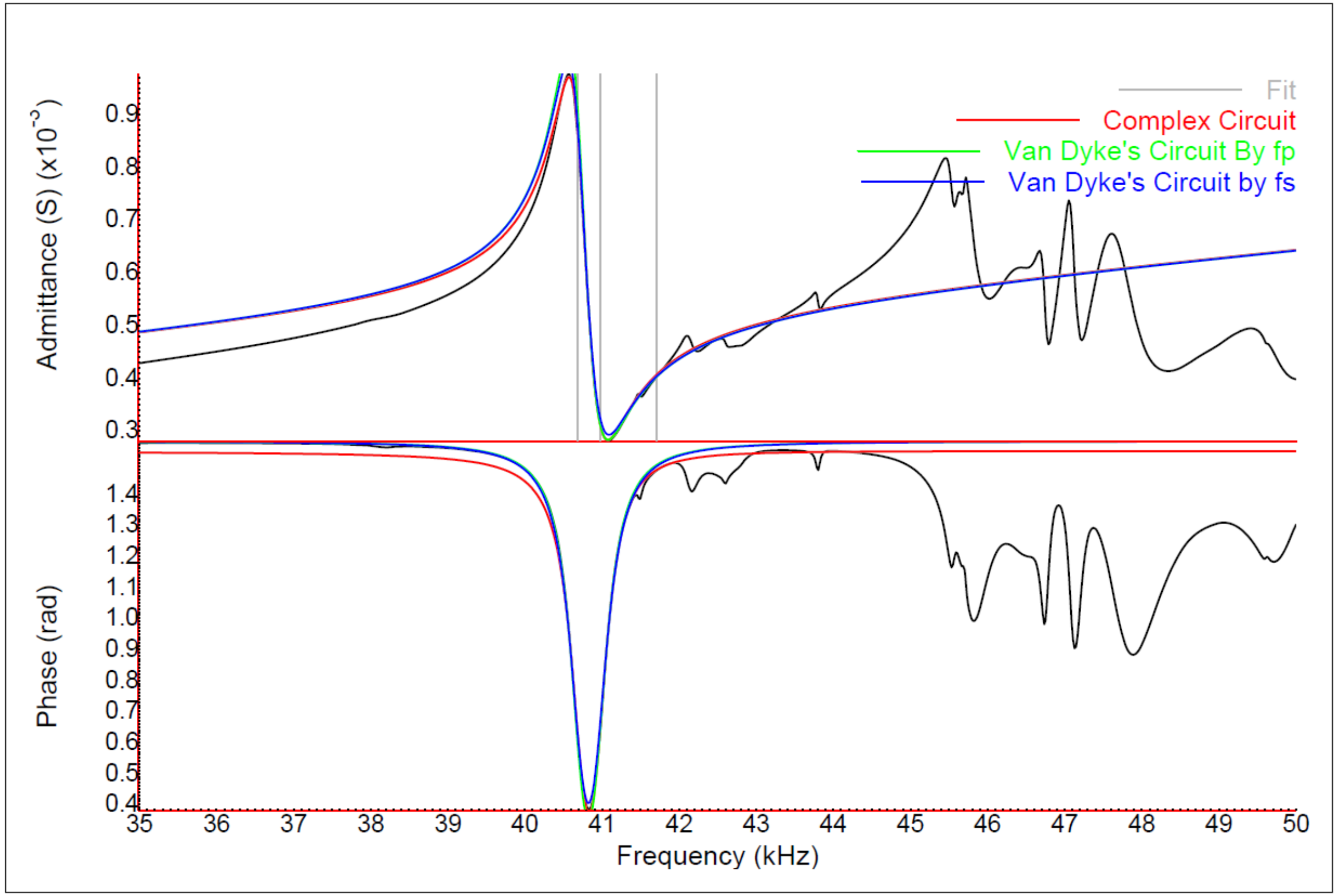




Configuration 3: Fabrication and Testing

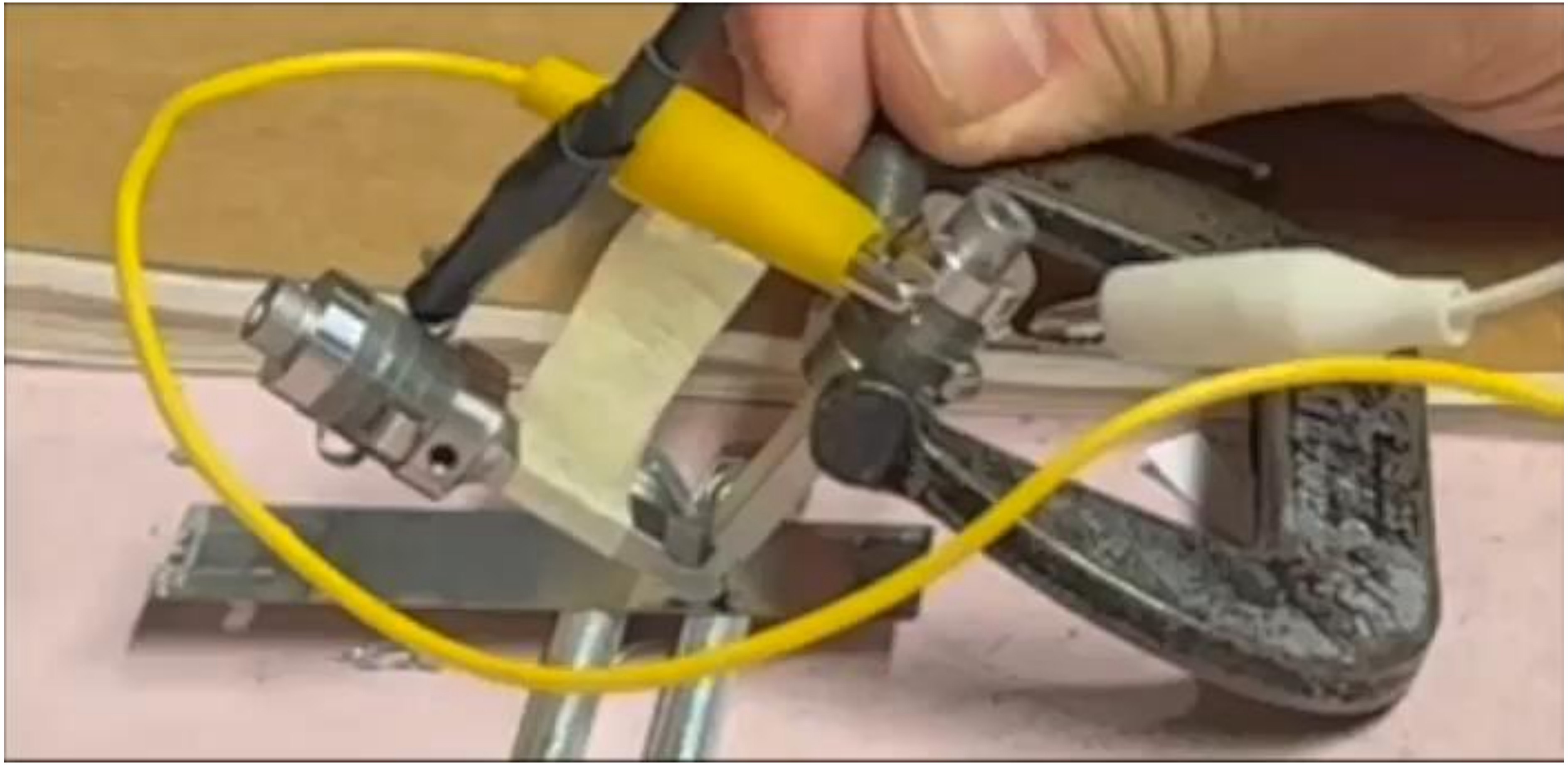


Partially assembled V-shaped fixture (Continue with epoxy bonding and preloading)



Impedance spectra of the partially assembled V-shaped fixture

Configuration 3: Fabrication and Testing



Conclusions and Future Work

- Proposed three piezoelectric motor design configurations
- Created preliminary designs for all configurations
- Performed simplified model analysis to predict behavior
- Fabricated a proof-of-concept linear inchworm configuration
- Demonstrated linear motion
- Designed a proof-of-concept V-shaped piezoelectric fixture rotary motor
- Partial testing of V-shaped fixture (other motor components still in fabrication)
- Will continue with motor integration as fabrication is completed and demonstrate rotary motion

Acknowledgement

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This work was funded by the Motors for Dusty & Extremely Cold Environments (MDECE) Project

Space Technology Mission Directorate

Game Changing Development Program

MDECE Project

JPL

NASA

Temperature Dependent Properties of Piezo Stack

Piezo stack

PICMA P-888.51	w x t mm	L mm	Stroke um (0-120C)	Blk Force N	Stiff N/um	Vmin	Vmax	C nf	Fr kHz	Operating temperature* °C	Material
RT Specs	10 x 10	18	18	3600	200	-20	120	6000	70	-40 to +150	PIC252

* Most PICMA[R] multilayer products are specified for the extended range of -40 to 150° C. With special solders, the temperature range can be increased so that the actuators can be used between -271° C and 200° C, i.e. over the range of almost 500K.

General property data at room temperature :

The following values are valid approximations for all PZT materials from PI Ceramic:

Specific heat capacity:
WK = approx. 350 J kg^{-1} K^{-1}

Specific thermal conductivity :
WL = approx. 1.1 W m^{-1} K^{-1}

Poisson's ratio (lateral contraction):
σ = approx. 0.34

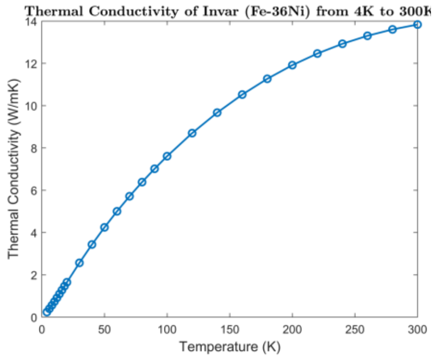
Coefficient of thermal expansion:
$\alpha 3$ = approx. -4 to -6 × 10^{-6} K^{-1}
(in the polarization direction, shorted)
$\alpha 1$ = approx. 4 to 8 × 10^{-6} K^{-1}
(perpendicular to the polarization direction, shorted)

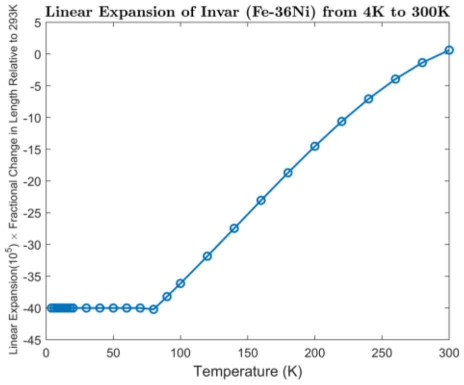
Static compressive strength:
> 600 MPa

All data provided was determined 24 h to 48 h after the time of polarization at an ambient temperature of 23 ±2 °C.

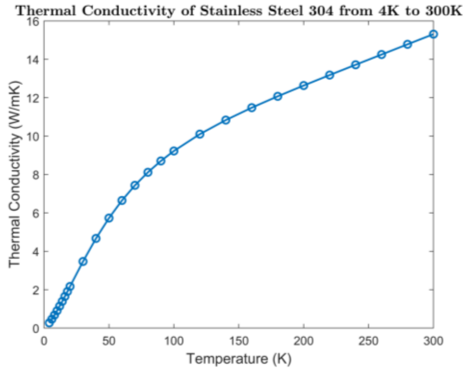
Temperature Dependent Properties

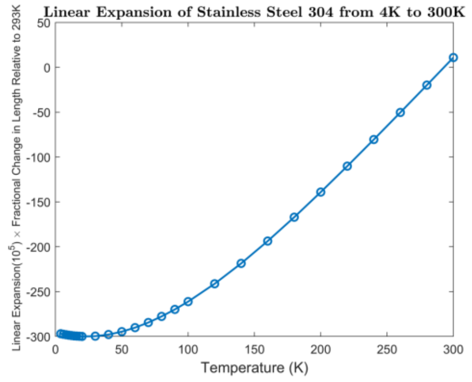
Invar





304 Stainless Steel





At -196°C

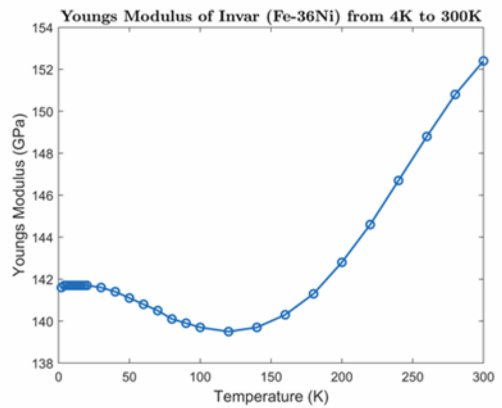
For SS 304 YS ≥ 39 ksi

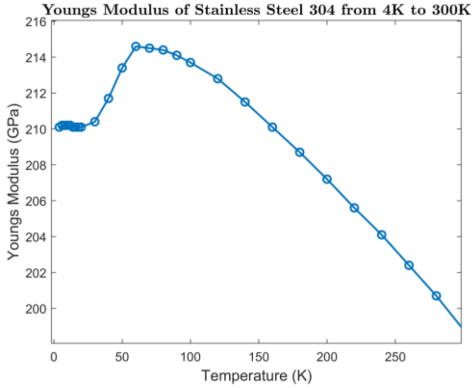
Tensile Strength ≥ 221 ksi

For Invar-36 YS ≥ 93 ksi

Tensile Strength ≥ 130 ksi

Ref. for steel: Mechanical Properties at Cryogenic Temperatures - Penflex





Ref:

J. R. Rumble (Ed), “Properties Of Selected Materials At Cryogenic Temperatures”, CRC Handbook of Chemistry and Physics, 102nd Edition (Internet Version 2021), CRC Press/Taylor & Francis, Boca Raton, FL. https://www.researchgate.net/publication/226513158_Cryogenic_Material_Properties_Database

E.D. Marquardt, J.P. Le and Ray Radebaughd, “, NIST, “Cryogenic Material Properties Database”, DOI:10.1007/0-306-47112-4_84 (2001)