Design and Evaluation of a Piezoelectric Actuator for Turning

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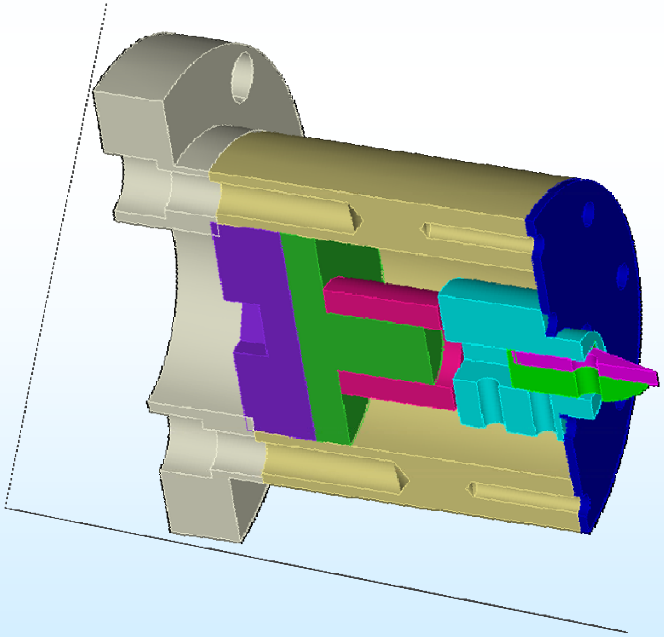

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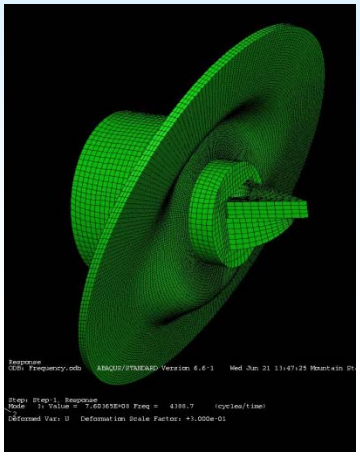
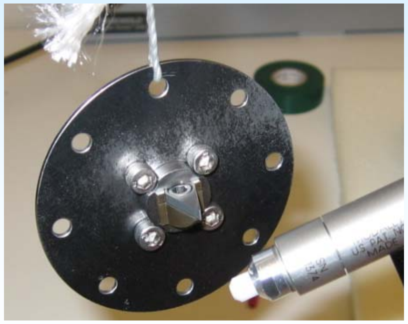
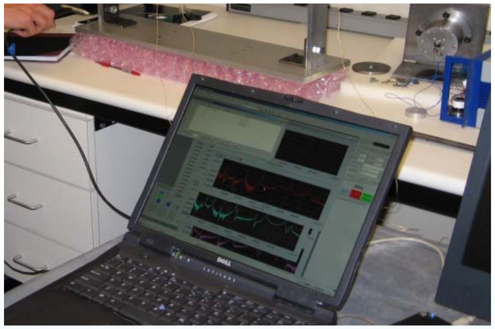
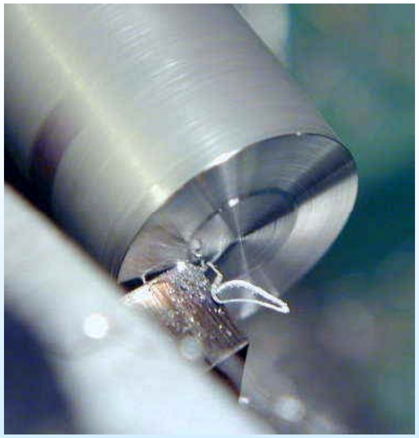
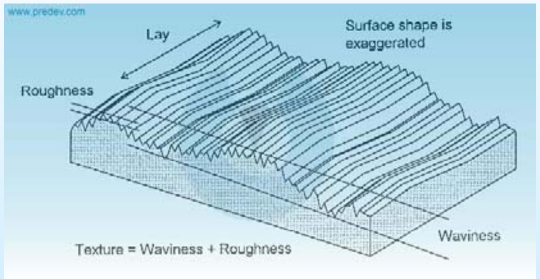








http://www.mini-lathe.com



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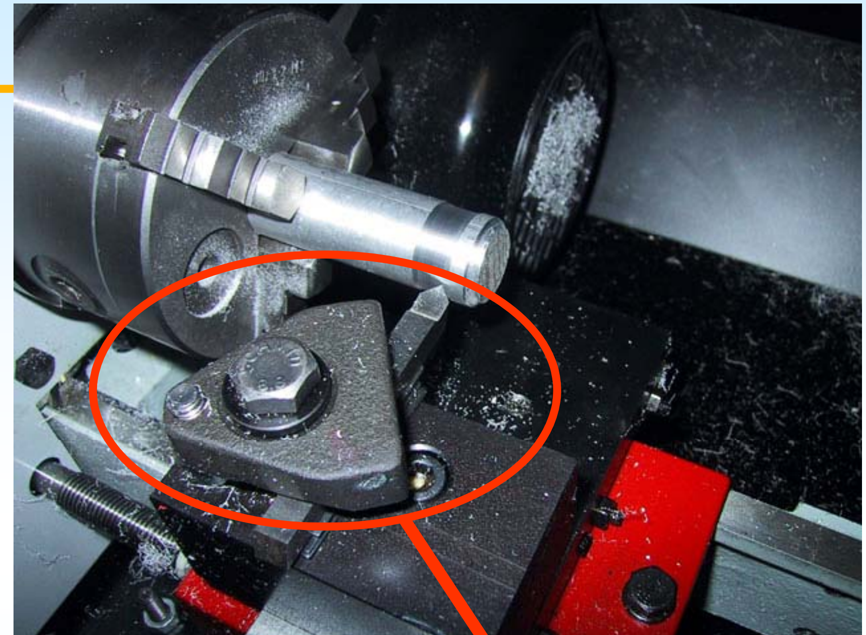
Introduction

- Design a Piezoelectric (PZT) fast tool servo (FTS) concept to attach to a conventional CNC lathe in order to improve surface finish
- Analytically and experimentally evaluate the baseline and cutting performance of the FTS
- Determine FTS effects on surface finish



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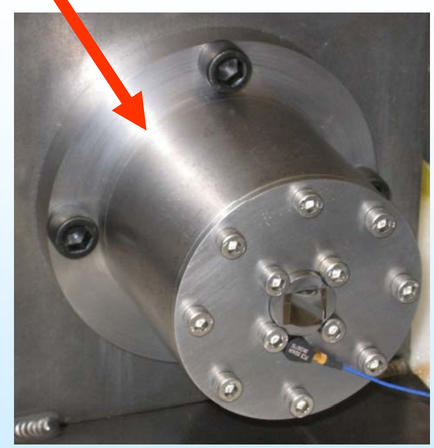


Motivation

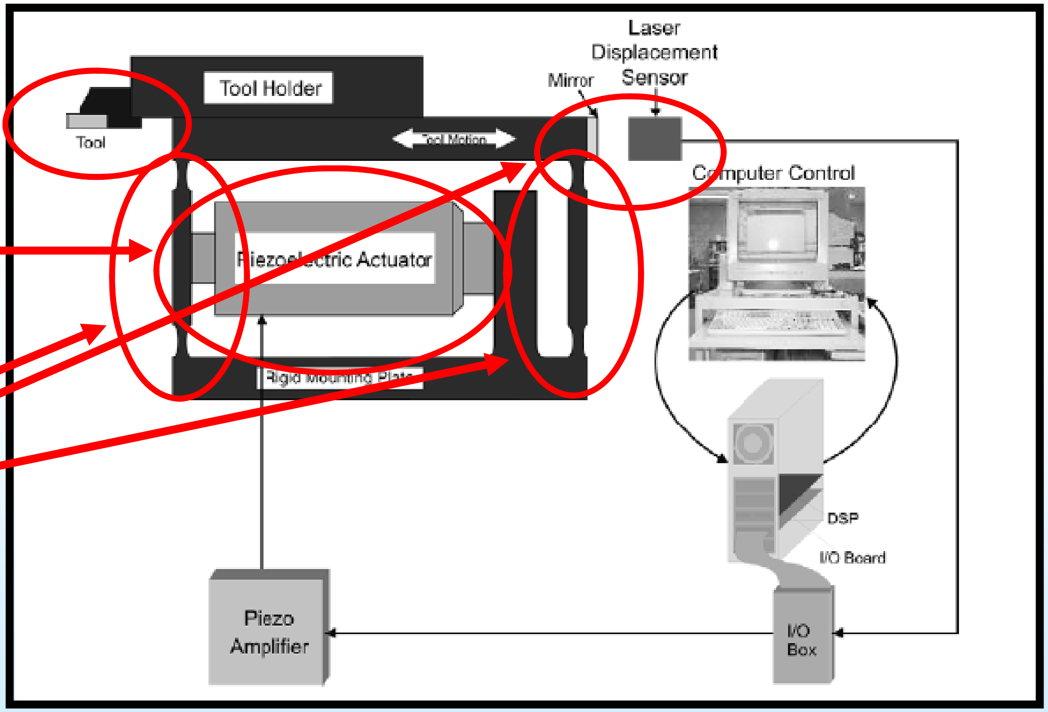
- High-precision turning is a two step process:
  - Turning and Grinding/Ultra-Precision Lathe
- Conditions between the part surface and cutting tool change rapidly
  - Non-uniformities have a negative effect on surface finish
- An actively controlled tool can react quickly to undesired vibrations
  - High Bandwidth
  - High Force
  - Low Displacement

Previous Work

Precision Shaft Cutting:

Zhu et al (2000) utilized a conventional CNC lathe and a piezoelectric actuator to produce a maximum surface roughness of 2 µm on SAE 4340 heat treated steel alloy shafts.

- **Cutting Tool**
- **Piezoelectric actuator (PI Inc.)**
- **Mirror and Laser nano sensor**
- **Flexures**

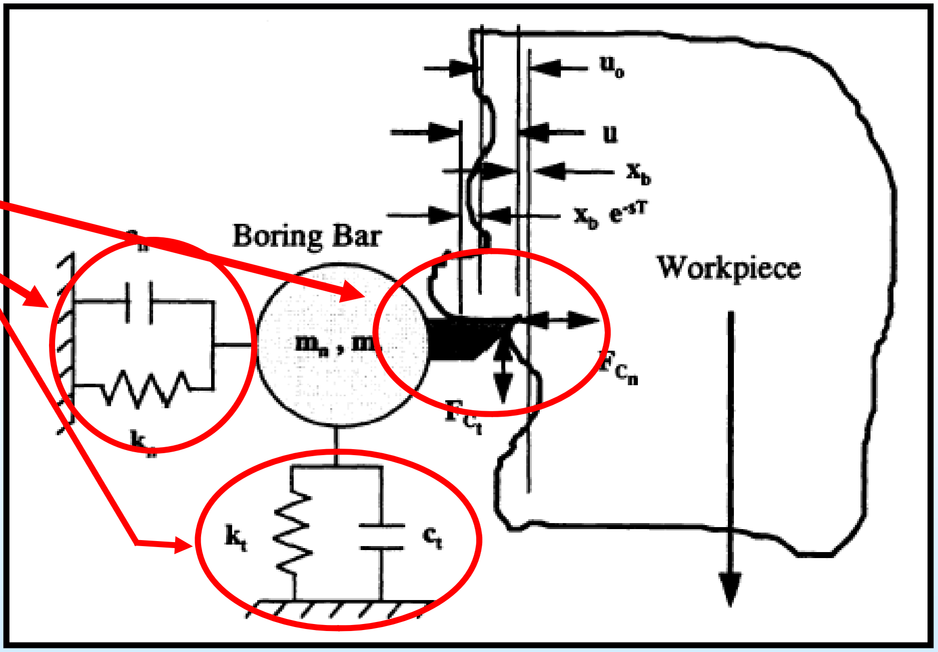


Previous Work

Depth Boring:

Browning et al (1997) implemented an active clamp for boring bars. Within it, actuators directed in tangential and normal directions actively damped the bar from the data received from the accelerometers at the tool tip.

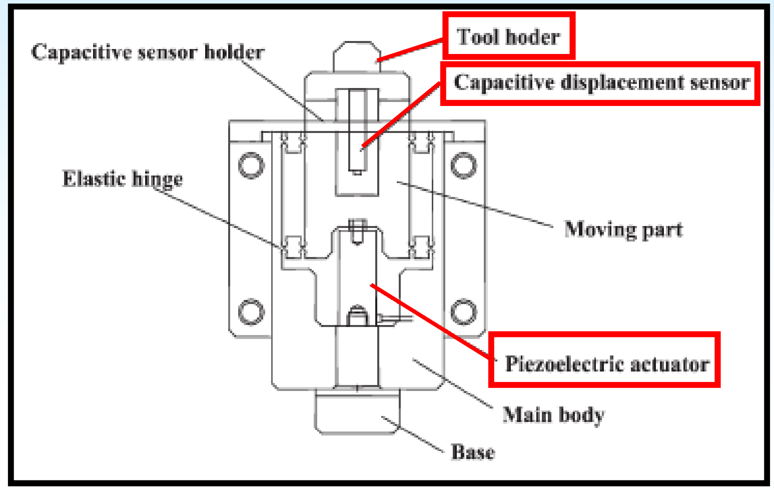
- Chatter limits bore depth
- Two accelerometers at tip
- Four piezoelectric actuators
- Result: 400% depth increase (High Temperature Nickel)



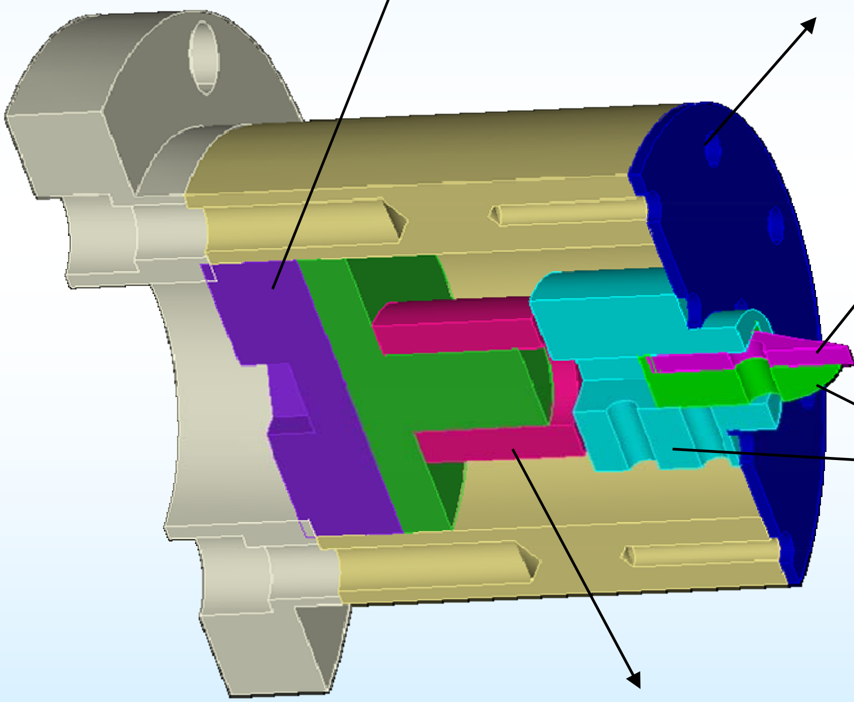
Previous Work

Fast Tool Servo in diamond turning

- Design: Kim et al (2003)
  - Piezoelectric actuator within lathe head
  - Diamond tipped tool
  - Capacitive displacement sensor
    - Measures tool to part distance
- Capabilities:
  - Can Machine up to 100 mm diameter specimens
  - Peak to valley accuracy of 0.10 µm

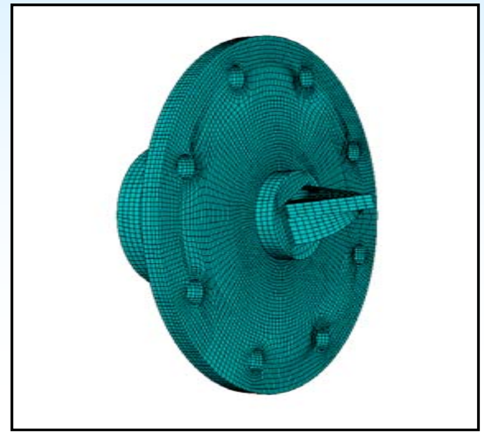


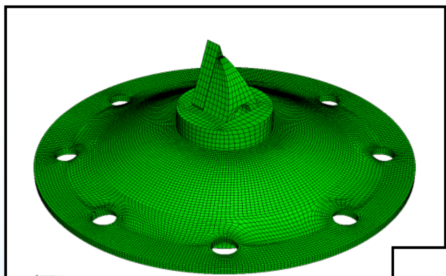
Our Project Design…

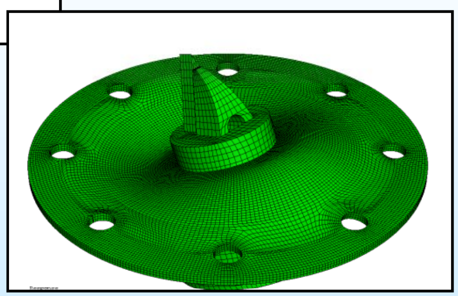


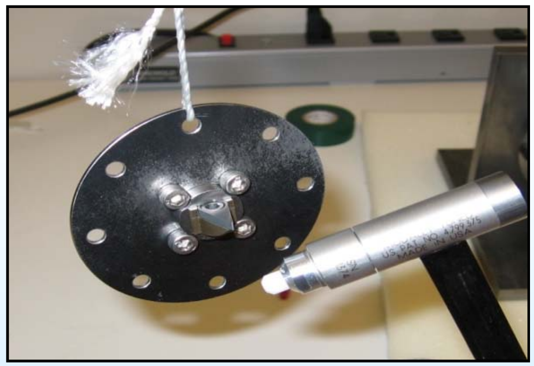
Non-Cutting, Un-powered

- **Modal Analysis**
  - Create finite element model of the FTS
  - Experimentally determine the frequency response
  - Correlate the analytical to the experimental results

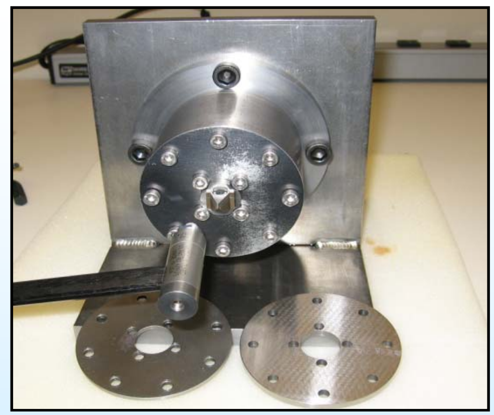








Free-Free

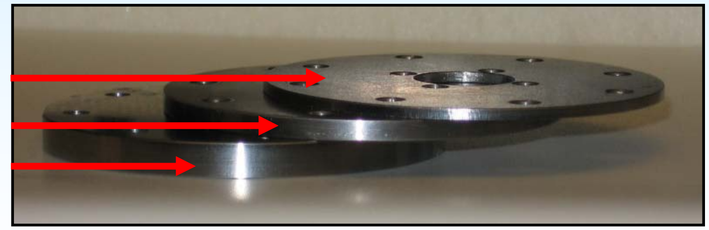


Constrained

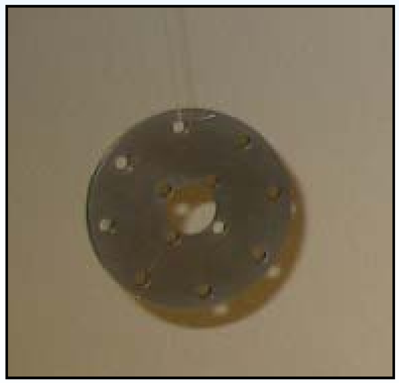
The modal experiments…

- **Three modal experiments for each diaphragm thickness**

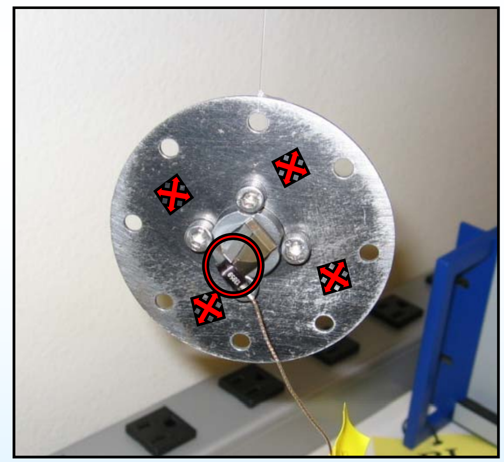
1.5875 mm
3.1750 mm
4.7625 mm



  - Free Diaphragm

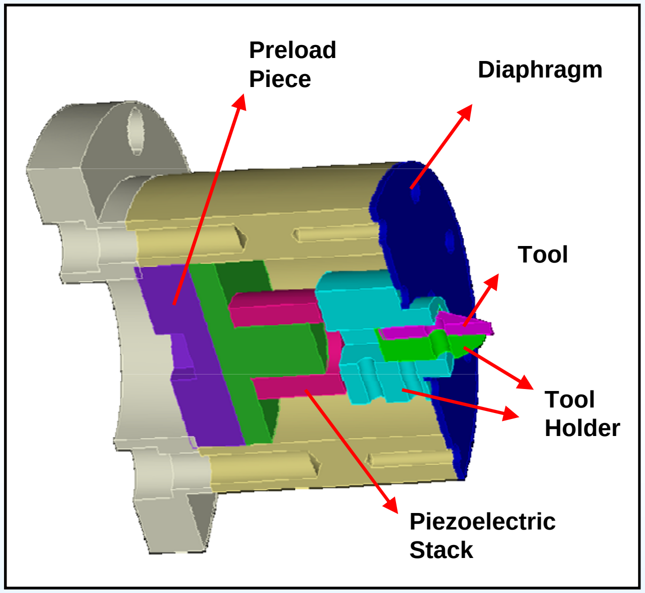


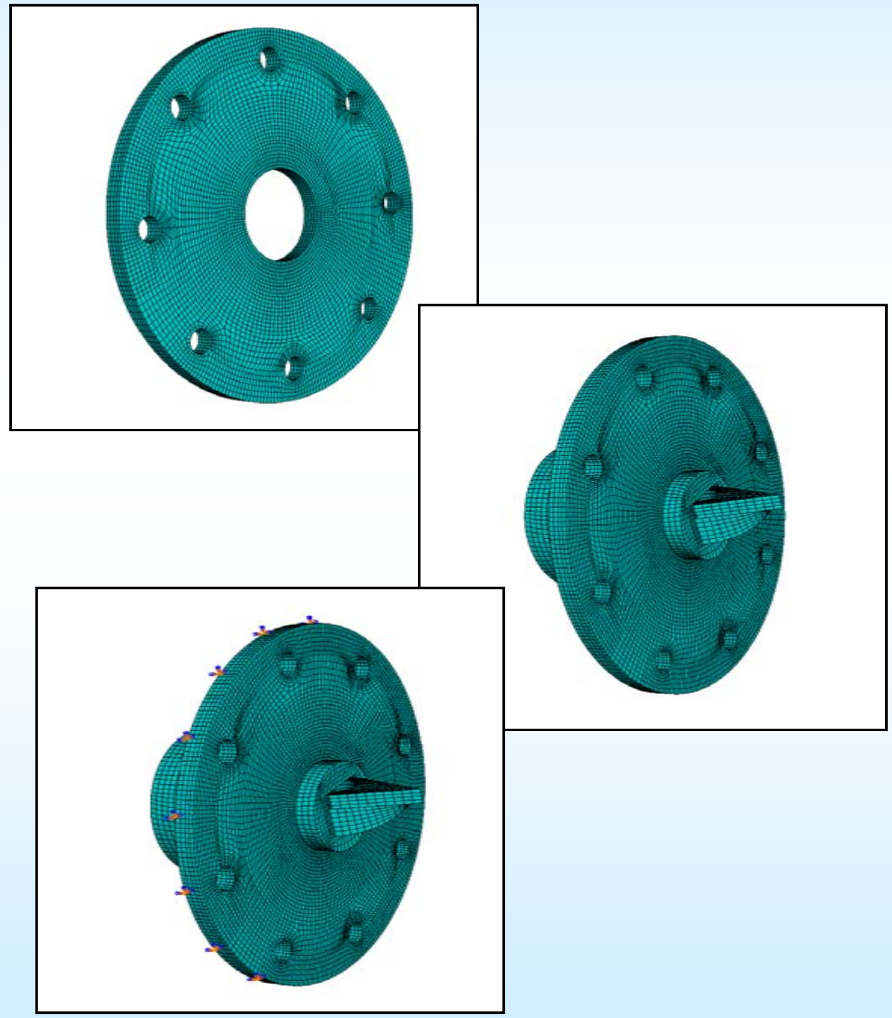
  - Free Tool Holder Assembly



  - Fixed Tool Holder Assembly

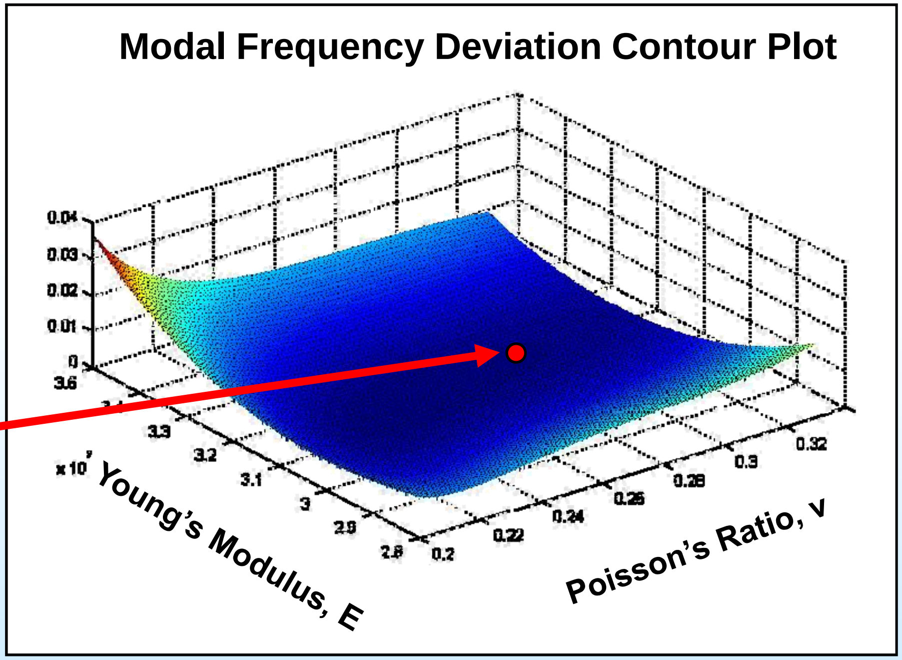
The Finite Element model…



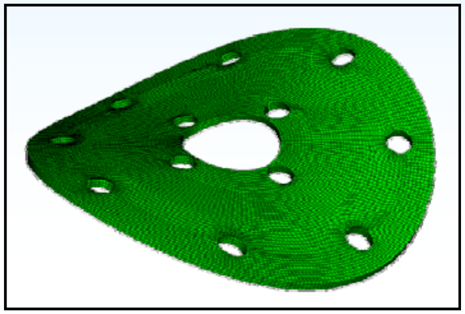


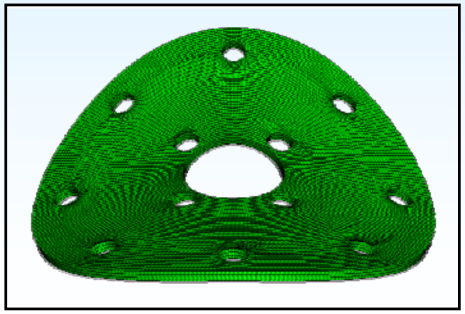
FE Model Refinement and Optimization

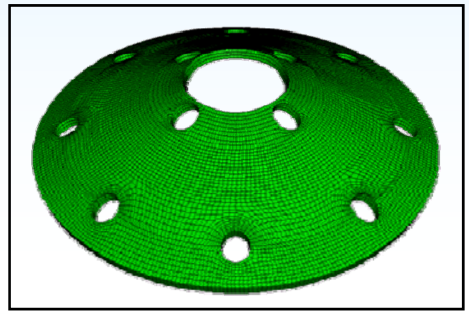
- **Mesh Refinement**
- **Improve model dimensions**
- **Parameter Variation**
  - Young's Modulus
  - Poisson's Ratio
  - Optimal Parameters
    - **E = 222 GPa (3.22e7 psi)**
    - **v = 0.28**

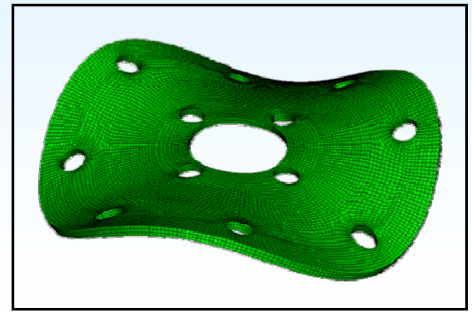


Finite Element model results for diaphragm


Mode 1


Mode 2


Mode 3

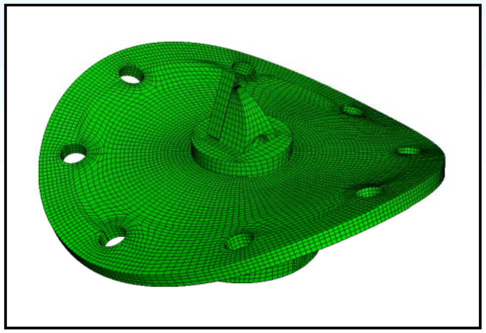

Mode 4

1.5875 mm (1/16") Diaphragm	
Mode	Frequency (Hz)
1	1.27E+03
2	1.28E+03
3	2.08E+03
4	3.15E+03

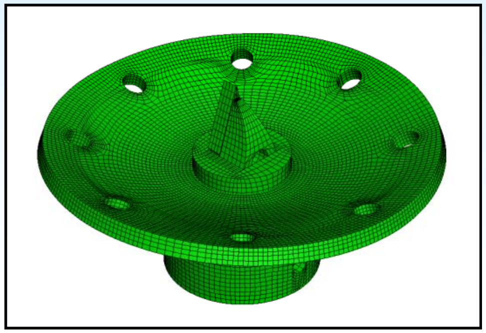
3.1750 mm (1/8") Diaphragm	
Mode	Frequency (Hz)
1	2.44E+03
2	2.46E+03
3	4.00E+03
4	6.02E+03

4.7625 mm (3/16") Diaphragm	
Mode	Frequency (Hz)
1	3.80E+03
2	3.83E+03
3	6.26E+03
4	9.26E+03

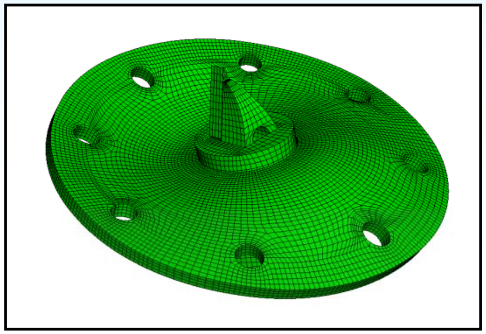
Finite Element results for free-free assembly…



Mode 1



Mode 2



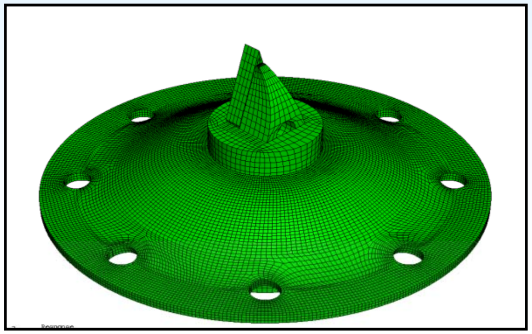
Mode 3

1.5875 mm (1/16") Diaphragm	
Mode	Frequency (Hz)
1	2.17E+03
2	2.27E+03
3	2.74E+03

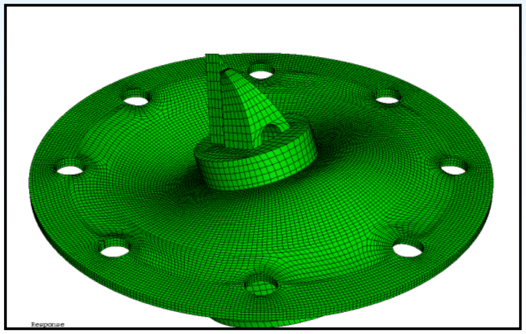
3.1750 mm (1/8") Diaphragm	
Mode	Frequency (Hz)
1	4.12E+03
2	4.12E+03
3	4.25E+03

4.7625 mm (3/16") Diaphragm	
Mode	Frequency (Hz)
1	5.10E+03
2	5.11E+03
3	5.71E+03

Finite Element results for fixed assembly…



Mode 1



Mode 2

1.5875 mm (1/16") Diaphragm	
Mode	Frequency (Hz)
1	2.24E+03
2	2.63E+03

3.1750 mm (1/8") Diaphragm	
Mode	Frequency (Hz)
1	5.00E+03
2	5.82E+03

4.7625 mm (3/16") Diaphragm	
Mode	Frequency (Hz)
1	5.00E+03
2	5.18E+03

The 3.1750 mm (1/8”) thick diaphragm seems to be close to optimal for increasing the first mode frequency

1.5875 mm (1/16") Diaphragm	
Fixed Diaphragm Assembly - Unmounted	
Mode	Frequency (Hz)
1	2.24E+03
2	2.89E+03
3	5.66E+03
4	7.09E+03
Free Diaphragm Assembly	
Mode	Frequency (Hz)
1	2.19E+03
2	2.50E+03
3	2.73E+03
4	2.98E+03
Diaphragm	
Mode	Frequency (Hz)
1	1.28E+03
2	2.04E+03
3	3.17E+03
4	4.58E+03

3.1750 mm (1/8") Diaphragm	
Fixed Diaphragm Assembly - Unmounted	
Mode	Frequency (Hz)
1	4.88E+03
2	5.57E+03
3	6.04E+03
4	7.25E+03
Free Diaphragm Assembly	
Mode	Frequency (Hz)
1	4.12E+03
2	4.22E+03
3	4.44E+03
4	5.53E+03
Diaphragm	
Mode	Frequency (Hz)
1	2.46E+03
2	3.91E+03
3	5.93E+03
4	8.55E+03

4.7625 mm (3/16") Diaphragm	
Fixed Diaphragm Assembly - Unmounted	
Mode	Frequency (Hz)
1	5.00E+03
2	6.56E+03
3	8.29E+03
4	9.92E+03
Free Diaphragm Assembly	
Mode	Frequency (Hz)
1	4.70E+03
2	5.50E+03
3	5.63E+03
4	6.12E+03
Diaphragm	
Mode	Frequency (Hz)
1	3.83E+03
2	6.21E+03
3	7.65E+03
4	9.31E+03

FE Model/Modal Test Comparison for Diaphragm Tests…

FE Model

1.5875 mm (1/16") Diaphragm	
Mode	Frequency (Hz)
1	1.27E+03
2	1.28E+03
3	2.08E+03
4	3.15E+03

3.1750 mm (1/8") Diaphragm	
Mode	Frequency (Hz)
1	2.44E+03
2	2.46E+03
3	4.00E+03
4	6.02E+03

4.7625 mm (3/16") Diaphragm	
Mode	Frequency (Hz)
1	3.80E+03
2	3.83E+03
3	6.26E+03
4	9.26E+03

Modal Tests

1.5875 mm (1/16") Diaphragm	
Mode	Frequency (Hz)
1	1.28E+03
2	2.04E+03
3	3.17E+03
4	4.58E+03

3.1750 mm (1/8") Diaphragm	
Mode	Frequency (Hz)
1	2.46E+03
2	3.91E+03
3	5.93E+03
4	8.55E+03

4.7625 mm (3/16") Diaphragm	
Mode	Frequency (Hz)
1	3.83E+03
2	6.21E+03
3	7.65E+03
4	9.31E+03

FE Model/Modal Test Comparison for Free-Free Assembly Tests…

FE Model

1.5875 mm (1/16") Diaphragm	
Mode	Frequency (Hz)
1	2.17E+03
2	2.27E+03
3	2.74E+03
4	

3.1750 mm (1/8") Diaphragm	
Mode	Frequency (Hz)
1	4.12E+03
2	4.12E+03
3	4.25E+03
4	

4.7625 mm (3/16") Diaphragm	
Mode	Frequency (Hz)
1	5.10E+03
2	5.11E+03
3	5.71E+03
4	

Modal Tests

1.5875 mm (1/16") Diaphragm	
Mode	Frequency (Hz)
1	2.19E+03
2	2.50E+03
3	2.73E+03
4	2.98E+03

3.1750 mm (1/8") Diaphragm	
Mode	Frequency (Hz)
1	4.12E+03
2	4.22E+03
3	4.44E+03
4	5.53E+03

4.7625 mm (3/16") Diaphragm	
Mode	Frequency (Hz)
1	4.70E+03
2	5.50E+03
3	5.63E+03
4	6.12E+03

FE Model/Modal Test Comparison for Fixed Assembly Tests…

FE Model

1.5875 mm (1/16") Diaphragm	
Mode	Frequency (Hz)
1	2.24E+03
2	2.63E+03
3	
4	

3.1750 mm (1/8") Diaphragm	
Mode	Frequency (Hz)
1	5.00E+03
2	5.82E+03
3	
4	

4.7625 mm (3/16") Diaphragm	
Mode	Frequency (Hz)
1	5.00E+03
2	5.18E+03
3	
4	

Modal Tests

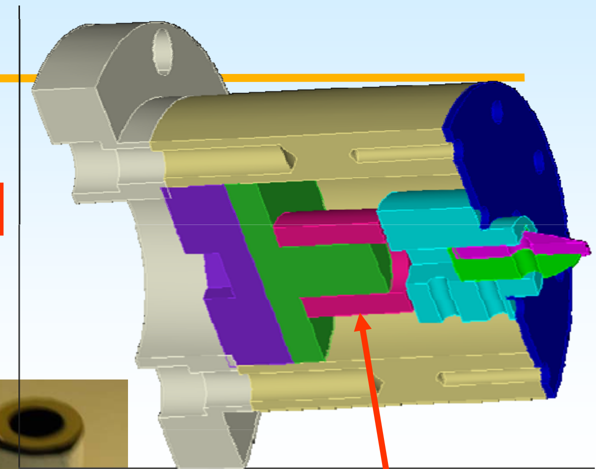
1.5875 mm (1/16") Diaphragm	
Mode	Frequency (Hz)
1	2.24E+03
2	2.89E+03
3	5.66E+03
4	7.09E+03

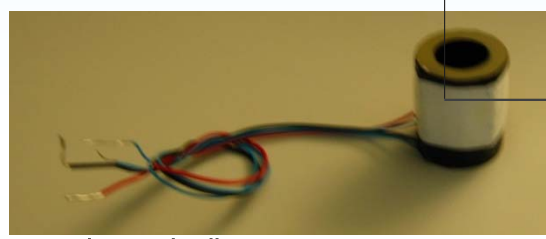
3.1750 mm (1/8") Diaphragm	
Mode	Frequency (Hz)
1	4.88E+03
2	5.57E+03
3	6.04E+03
4	7.25E+03

4.7625 mm (3/16") Diaphragm	
Mode	Frequency (Hz)
1	5.00E+03
2	6.56E+03
3	8.29E+03
4	9.92E+03

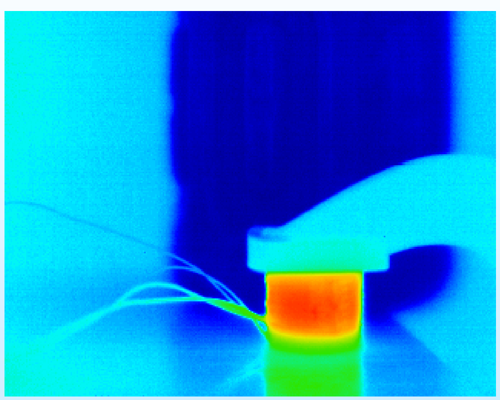
Non-Cutting, Powered FTS Tests

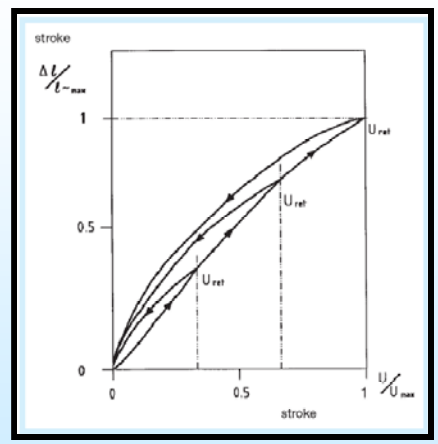
- **Static**
  - Tool Tip Displacement vs. Voltage
- **Dynamic**
  - FTS Frequency Response
  - Effects of Preloading
- **PZT Thermal Characteristics**





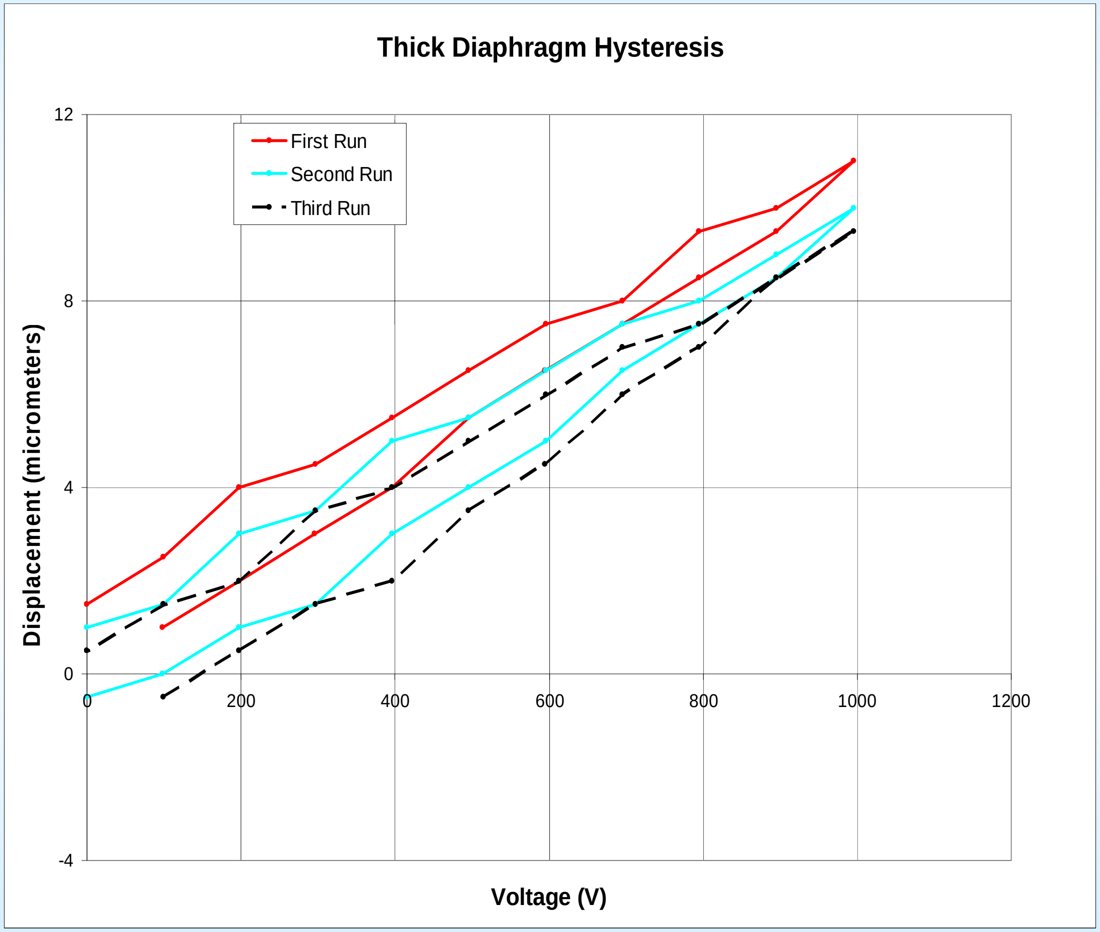
www.piezomechanik.com





The static displacement tests show the hysteresis effects of the PZT

- **Excitation:**
  - 0 – 1000 V DC @ 100 V intervals
  - Cycled 3 times
- **Output:**
  - Displacement at tool tip using displacement sensor

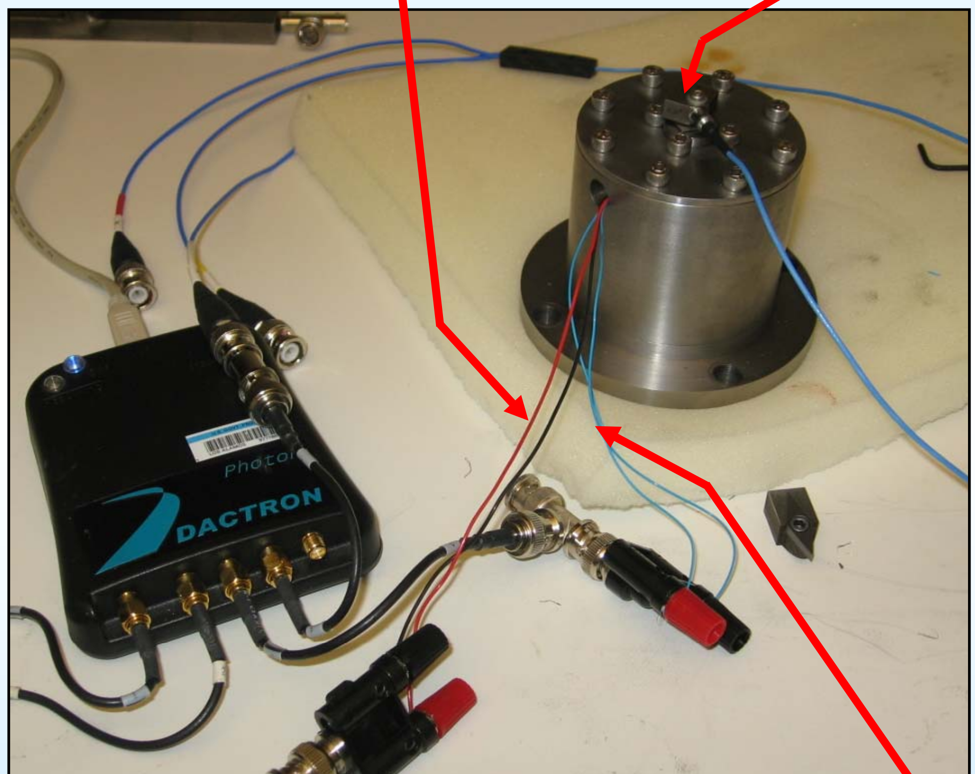


Powered FTS Frequency Response

- **Excitation:**
  - Burst Random
  - 2 V RMS (To Amplifier)
  - 12 kHz max. frequency

- **Output:**
  - PZT Sensor FRF
  - Accelerometer FRF

Amplifier Input to PZT **Tri-Axial Accelerometer**



PZT Sensor Output

Powered FTS Frequency Response

1.5875 mm (1/16") Diaphragm	
PZT Sensor	
Mode	Frequency (Hz)
1	3.57E+03
2	4.38E+03
3	6.12E+03
4	6.79E+03
Accelerometer	
Mode	Frequency (Hz)
1	3.57E+03
2	4.41E+03
3	6.16E+03
4	6.74E+03

Mode	% Difference
1	0.00
2	0.68
3	0.65
4	0.74

3.1750 mm (1/8") Diaphragm	
PZT Sensor	
Mode	Frequency (Hz)
1	4.54E+03
2	5.81E+03
3	7.47E+03
4	9.33E+03
Accelerometer	
Mode	Frequency (Hz)
1	4.55E+03
2	5.84E+03
3	7.49E+03
4	9.26E+03

Mode	% Difference
1	0.22
2	0.52
3	0.27
4	0.75

4.7625 mm (3/16") Diaphragm	
PZT Sensor	
Mode	Frequency (Hz)
1	5.38E+03
2	7.76E+03
3	Outside Freq. Range
4	Outside Freq. Range
Accelerometer	
Mode	Frequency (Hz)
1	5.73E+03
2	7.72E+03
3	Outside Freq. Range
4	Outside Freq. Range

Mode	% Difference
1	6.51
2	0.52
3	N/A
4	N/A

The Effects of Preloading…

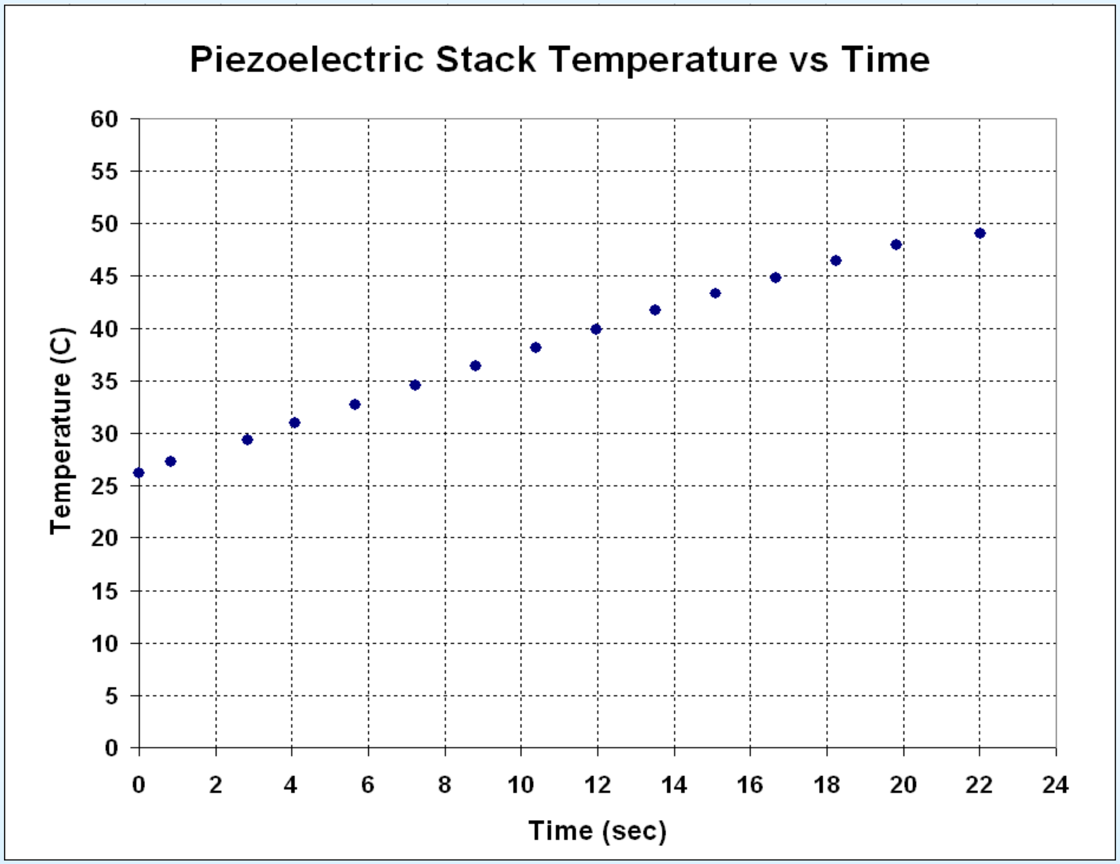
	1.5875 mm (1/16") Diaphragm				
	No Preload		Preloaded		% Change
PZT Sensor	Mode	Frequency (Hz)	Mode	Frequency (Hz)	
	1	2.57E+03	1	4.64E+03	80.54
	2	4.90E+03	2	8.40E+03	71.43
	3	6.26E+03	3	9.21E+03	47.12
	4	9.85E+03	4	9.65E+03	-2.03
Accelerometer	Mode	Frequency (Hz)	Mode	Frequency (Hz)	
	1	2.55E+03	1	4.64E+03	81.96
	2	4.36E+03	2	8.38E+03	92.20
	3	5.96E+03	3	9.21E+03	54.53
	4	9.73E+03	4	9.64E+03	-0.92

	3.1750 mm (1/8") Diaphragm				
	No Preload		Preloaded		% Change
PZT Sensor	Mode	Frequency (Hz)	Mode	Frequency (Hz)	
	1	4.39E+03	1	5.42E+03	23.46
	2	6.66E+03	2	8.80E+03	32.13
	3	8.03E+03	3	9.34E+03	16.31
	4	8.92E+03	4	9.48E+03	6.28
Accelerometer	Mode	Frequency (Hz)	Mode	Frequency (Hz)	
	1	4.35E+03	1	5.45E+03	25.29
	2	6.31E+03	2	8.79E+03	39.30
	3	8.05E+03	3	9.37E+03	16.40
	4	8.87E+03	4	9.51E+03	7.22

	4.7625 mm (3/16") Diaphragm				
	No Preload		Preloaded		% Change
PZT Sensor	Mode	Frequency (Hz)	Mode	Frequency (Hz)	
	1	4.64E+03	1	6.62E+03	42.67
	2	8.56E+03	2	9.13E+03	6.66
	3	1.03E+04	3	9.57E+03	-7.09
	4	Outside Freq. Range	4	Outside Freq. Range	
Accelerometer	Mode	Frequency (Hz)	Mode	Frequency (Hz)	
	1	4.63E+03	1	6.61E+03	42.76
	2	8.50E+03	2	9.10E+03	7.06
	3	1.01E+04	3	9.57E+03	-5.25
	4	Outside Freq. Range	4	Outside Freq. Range	

Thermal Characteristics of PZT

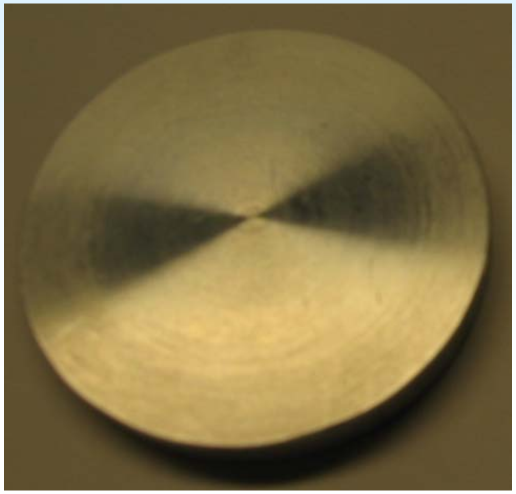
- **Input:**
  - 500 V @ 1000 Hz
- **Time Span:**
  - 22 sec.
- **Sampling:**
  - 15 sample frames
  - Peak temperature recorded



Cutting Performance Evaluation…

- **Facing Cuts:**
  - Thick Diaphragm - Unpowered
  - Thin Diaphragm - Unpowered
  - Thin Diaphragm - 2 kHz Excitation
  - Thin Diaphragm – 100 Hz to 10 kHz Sine Sweep
- **Output:**
  - Profilometry surface data in OmniPage (OPD) format

- **Unpowered FTS**

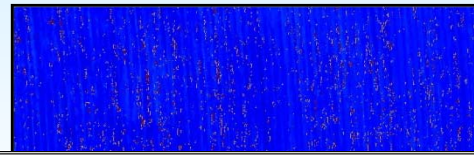


- **Constant 2 kHz Excitation**

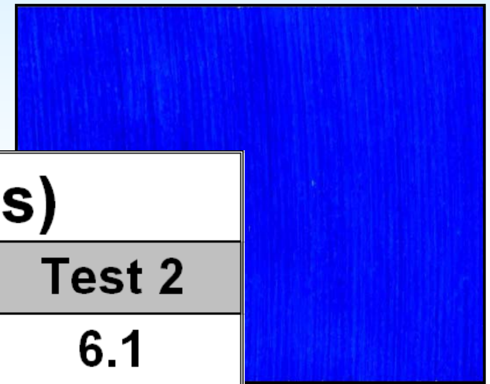
Surface profilometry shows no measurable effect on surface finish

- **Image Acquisition:**
  - Raw data contained 'holes'
- **Image**
  - Linea
  - MATL
- **Output:**
  - Filtered Surface Image
  - Cutting Direction Profile

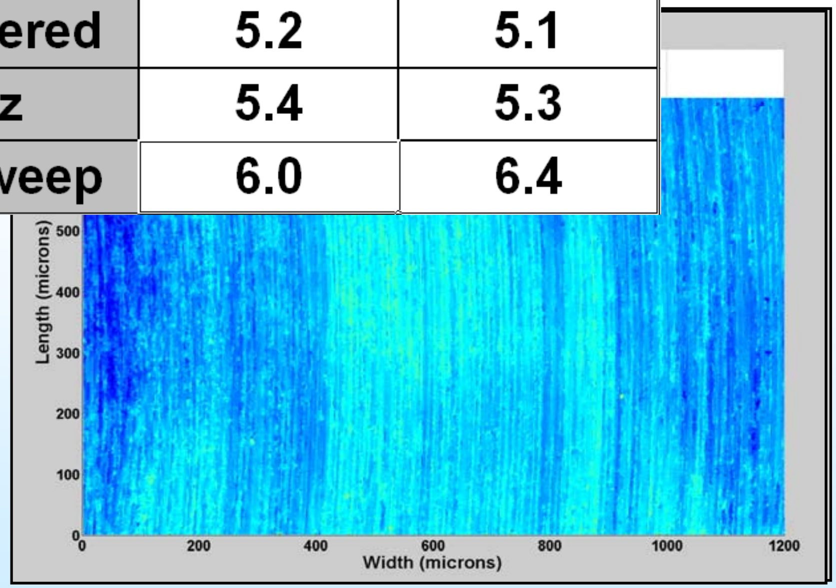
Before



After



Surface Roughness (microns)		
	Test 1	Test 2
Thick Diaphragm, Unpowered	6.3	6.1
Thin Diaphragm, Unpowered	5.2	5.1
Thin Diaphragm, 2kHz	5.4	5.3
Thin Diaphragm, Sine Sweep	6.0	6.4



Concluding Remarks…

- **Measured cutting data proved inconclusive**
  - No measurable change in surface profile
- **Further FTS Testing is promising**
  - Visual inspection suggests that surface finish was affected
- **Recommended Future Tasks**
  - Cutting tests using a more powerful amplifier
  - Include tool displacement sensing to design
  - Cutting Testing at lower RPM
  - Implementation of a control algorithm

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Questions?

References

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