Design Limitations of Langeven Transducers With PZT8, PZT4, and PMN-PZT Stacks

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Ultrasonic Industry Association

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Agenda

- Nonlinear Behavior of Langeven Transducers
    - Overview of Mathieson (Glasgow University Paper)
        - The Influence of Piezoceramic Stack Location
- Material Properties & Analysis Tools
    - PZT4, PZT8, PMN-PZT (Single Crystal)
    - Computer Model Using PiezoTran : Acoustic Transmission Line Theory
- Designs Limited by Reserve Power
    - Coupling Coefficient,
    - Voltage
- Designs Limited by Heat
    - Piezo Stack Cyclic Stress

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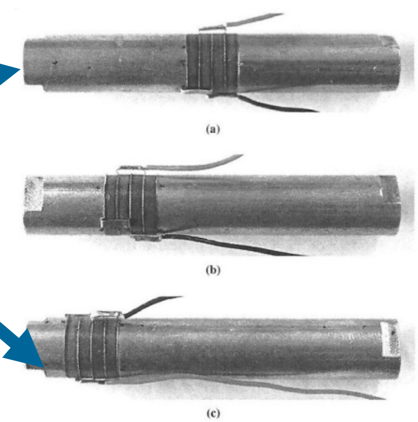
Scope

- Mathieson
  - Three Stack Geometries
  - Four 10mm PZT4 Rings
  - Longitudinal Bending and Torsion Modes of Vibration
  - Jump / Hysteresis amplitude plots Vs Volts 1 to 50 VRMS
- Reduced Scope of this Presentation
  - First Longitudinal Mode of Vibration
  - Two Design Geometries



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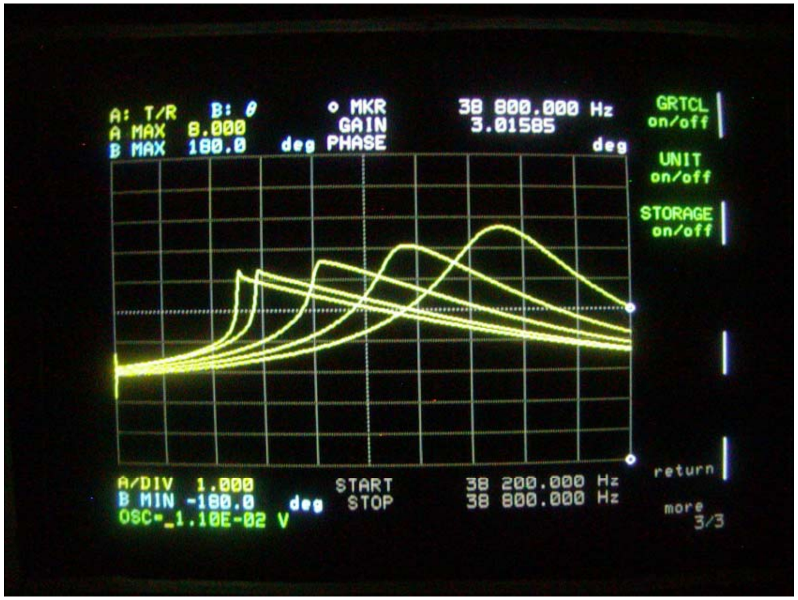
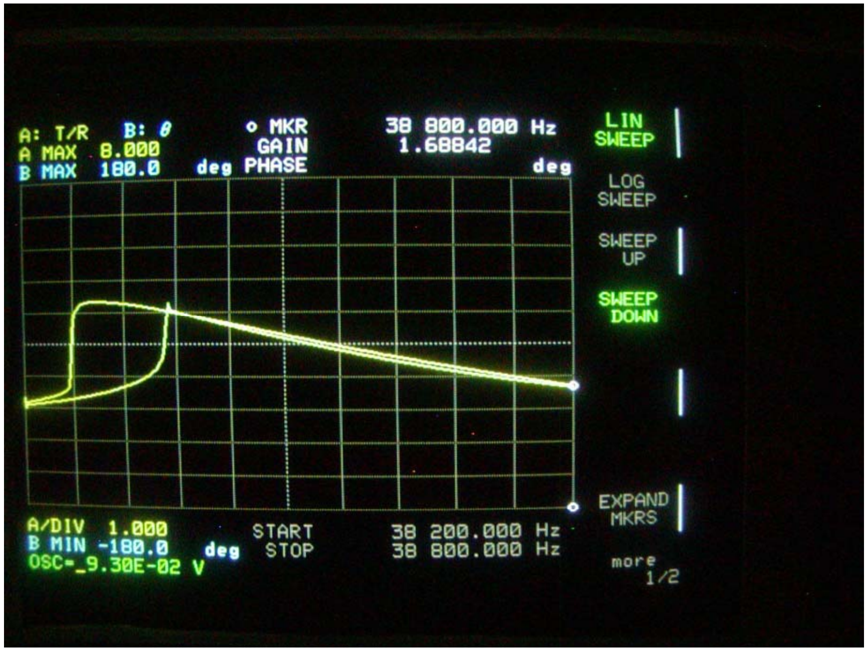
Non Linear Behavior

40 kHz Dumbbell Transducer with 20 MPa bias-stress

- Piezo Innovations Measurement Method
  - HP Impedance/Gain Phase Analyzer 4194A
    - Transfer Function Mode
    - Instruments Inc.L6 or Krohn-Hite 7500 Constant Voltage Amplifier





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Material Properties

Inputs For PiezoTran Transducer Analysis Software

Material	k_{33}	Q	E^T_{33}	g_{33}	T_c
PZT 4	0.71	500	1300	24.5	328
PZT 8	0.64	1000	1000	25	300
PMN-PZT	0.93	100	4850	35.6	211

Note: Usage temperature range is typically limited to ½ Tc

k_{33} is the measure of the ability of thickness mode piezo ceramic stacks to convert electrical energy into mechanical energy

Material	Young's Mod 10^3 MPa	Q*	Density Kg/m^3	Sound Velocity m/s
Titanium 6 al4v	117	20,000	4500	4916
Aluminum2014A-T6	74	10,000	2800	5141
Stainless Steel 316	210	7,000	7750	5200
Beryllium Copper	127		8300	3911
Brass	95		8500	3343
Alumina	240		3300	8528
Tungsten	400		17100	4836

* Typical Q values can be determined from Wuchinich paper entitled :A practical evaluation of harmonic elastic power loss in substantially strained structures

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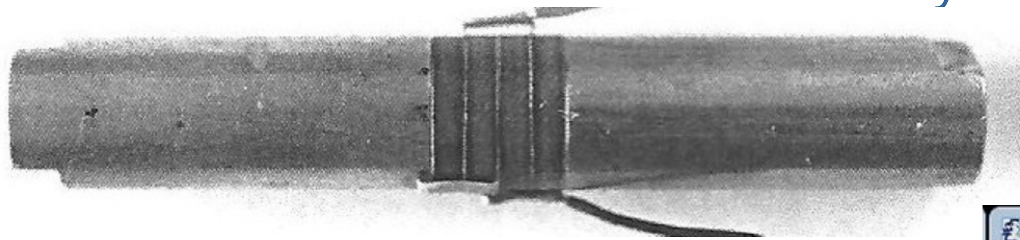
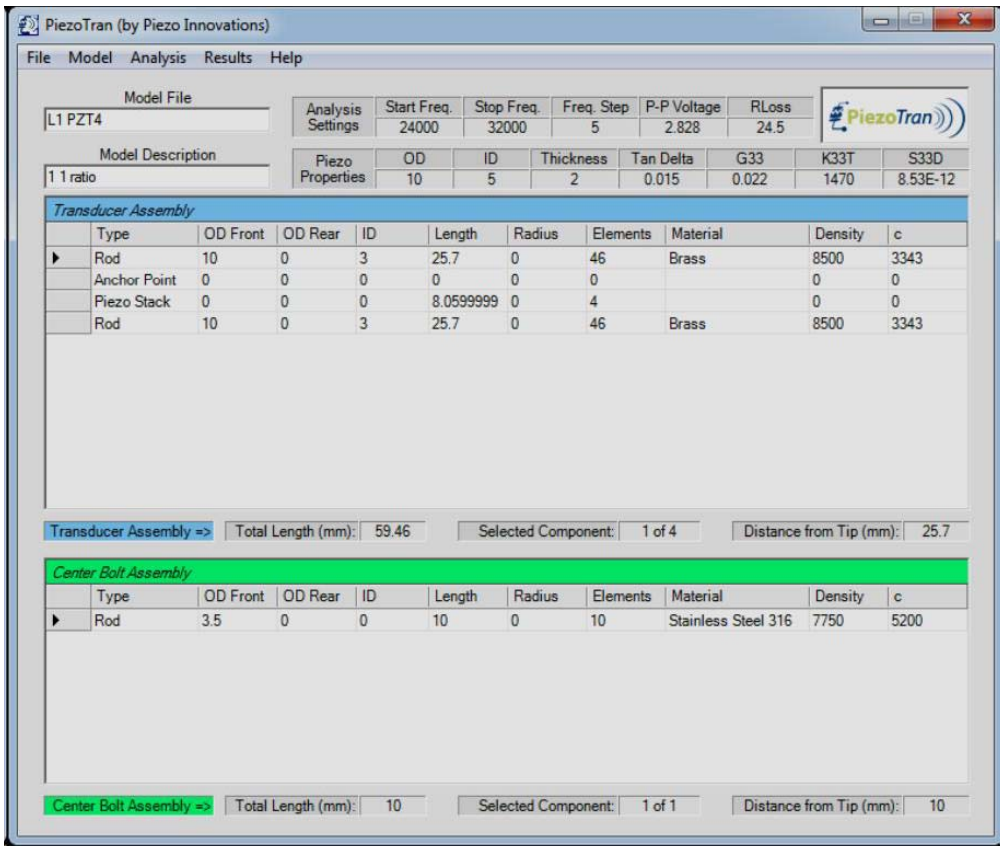
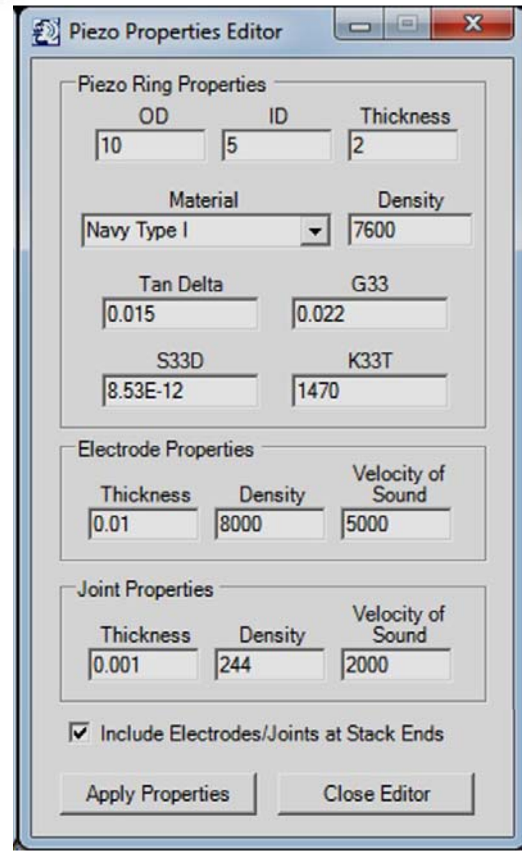
PiezoTran Transducer Analysis

- Acoustic Transmission Line Theory







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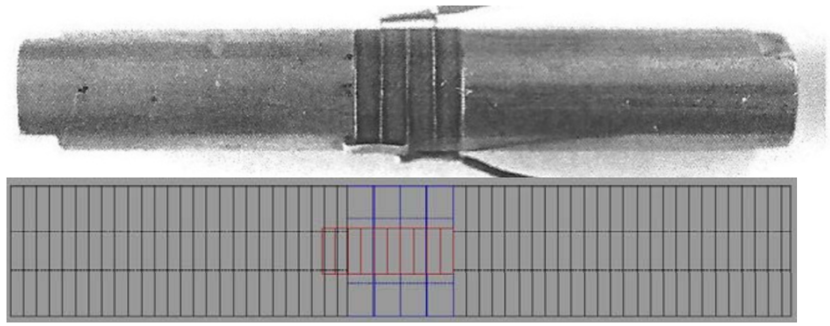
PiezoTran Output



L1 PZT4.ptr_results - Notepad

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Description 1 1 ratio

Resonant Frequency = 26390.0
Maximum Conductance = 0.003797

Anti-Resonant Frequency = 28170.0
Maximum Resistance = 60802

Q = 129.5056

RLoss = 24.50

Coupling Coefficient (K) = 0.3497

Low Frequency (1000 Hz) Capacitance = 1.4214E-009

Maximum Tip Displacement = 2.1227E-007

Applied Voltage (P-P) = 2.8280

Applied Voltage (RMS) = 1.0000

Power (Watts) = 0.0038

Real Current (amps) = 0.0038

Mathieson Measured Values

Resonant Frequency = 26576

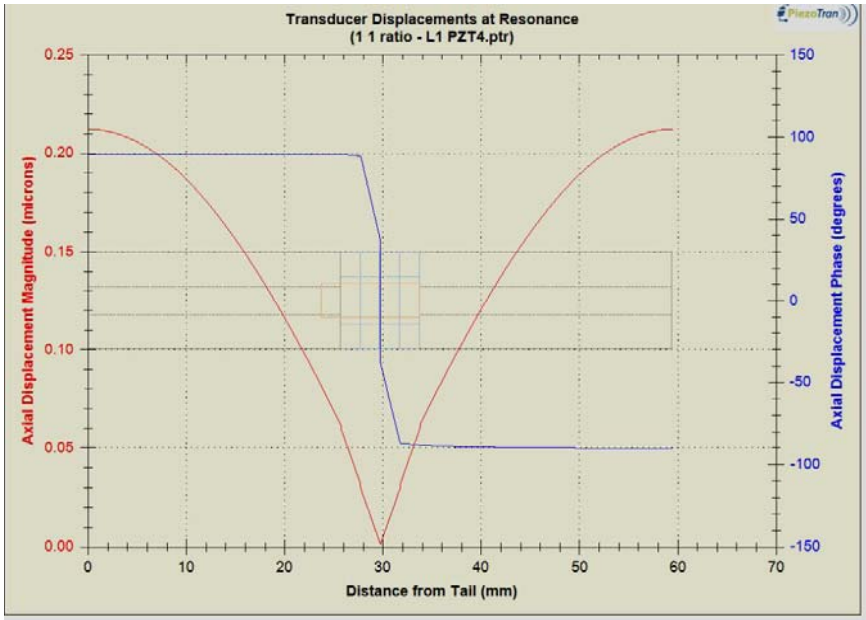
Q = 255

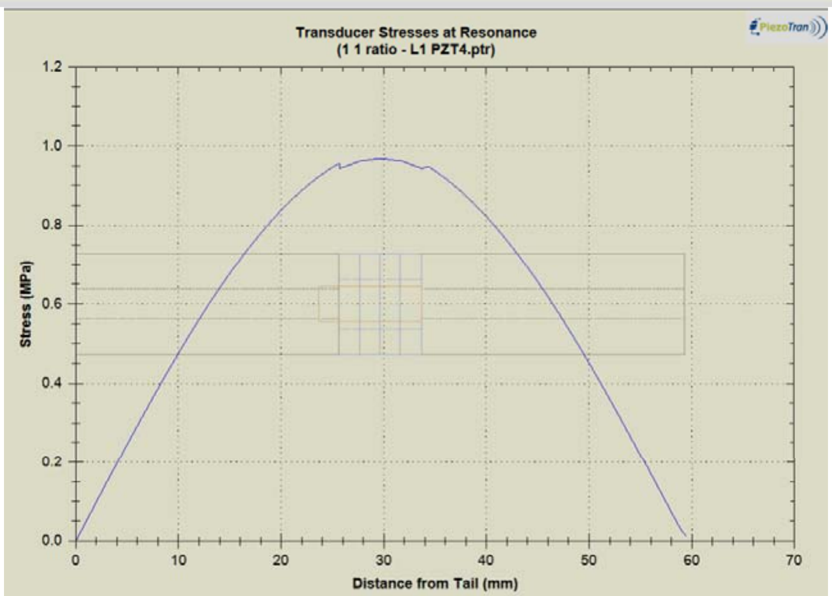
k eff = 0.351

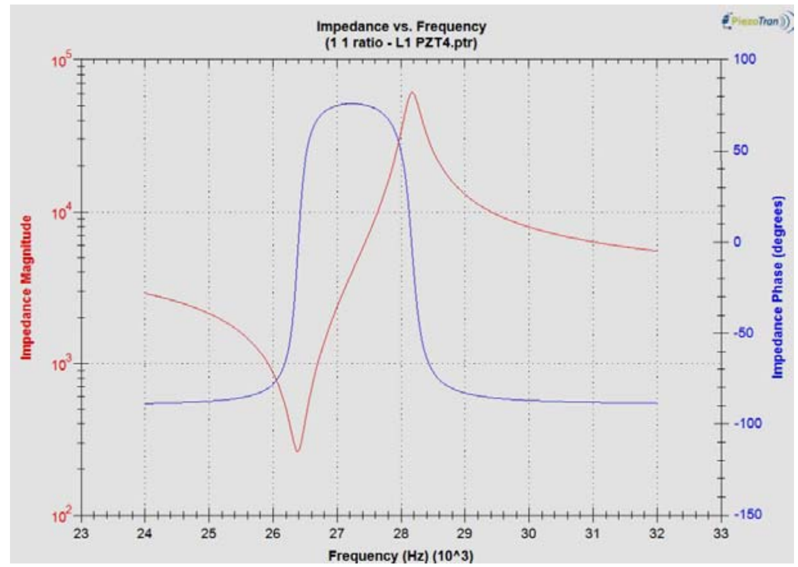
Tip Displacement = 0.2 microns

Applied Voltage 1.0 RMS

Piezotran Outputs







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Reserve Power Index (IEC 6147)

- Scope
  - Ultrasonic Systems Operating in 20 kHz to 60 kHz
  - Typically Used to Fragment tissue and bone
  - Symmetrical ½ wave transducer with 5 Variable Gain Horns
- Definition
  - Ratio Of Maximum Electrical Power to Quiescent Electrical Power
    - A measure of How Much “Extra” Power is Available to Maintain a Constant Tip Excursion Amplitude Under Various Load Conditions
- Illustrative Example (Using PiezoTran)
  - Assumptions
    - Control System is Voltage Limited to 800 Vp-p
    - Tip Displacement = 62 μm p-p
    - Power = 13 watts
    - Rloss =1 Tip loading condition
  - Output
    - Impedance Plots that Illustrate the Importance of Coupling Coefficient

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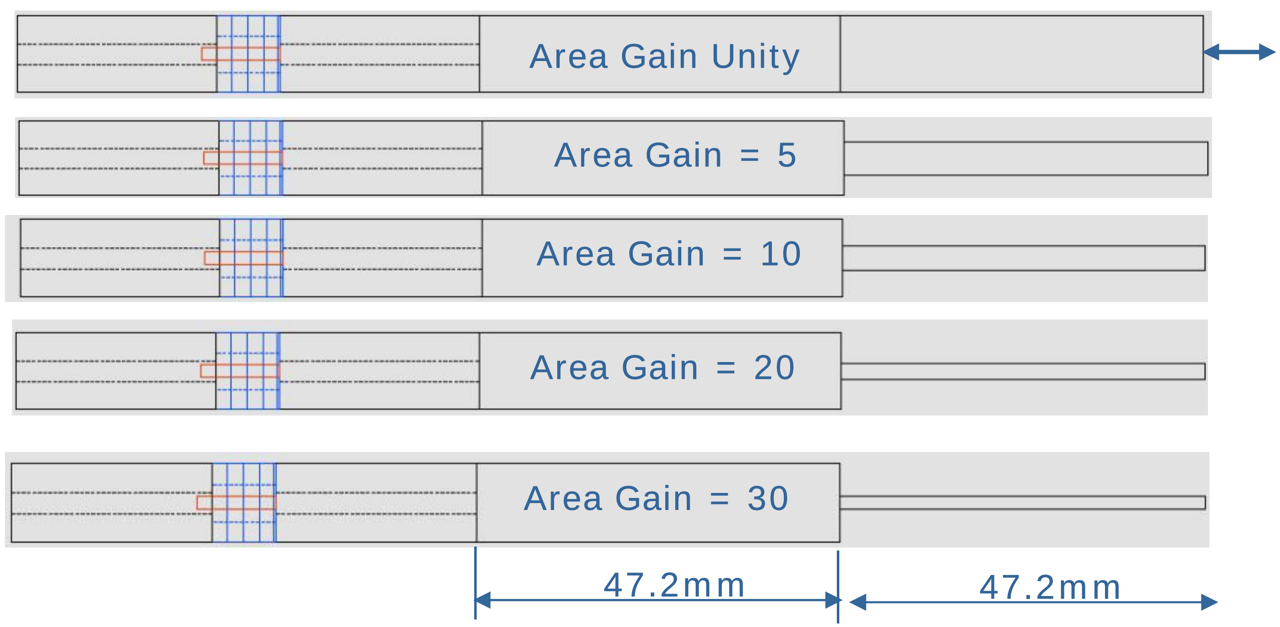
Illustrative Examples

5 Horn Geometries

- Resonant Frequency Constant at 26 kHz
- Tip Displacements Constant at 62 μm p-p
- Constant Tip Load Rloss =1
- Power Constant at 13 Watts



k_{eff} = .322 Q = 3884

k_{eff} = .235 Q = 446

K_{eff} = .187 Q = 180

K_{eff} = .142 Q = 79

K_{eff} = .118 Q = 50

Titanium horns Velocity c = 4916 m/s

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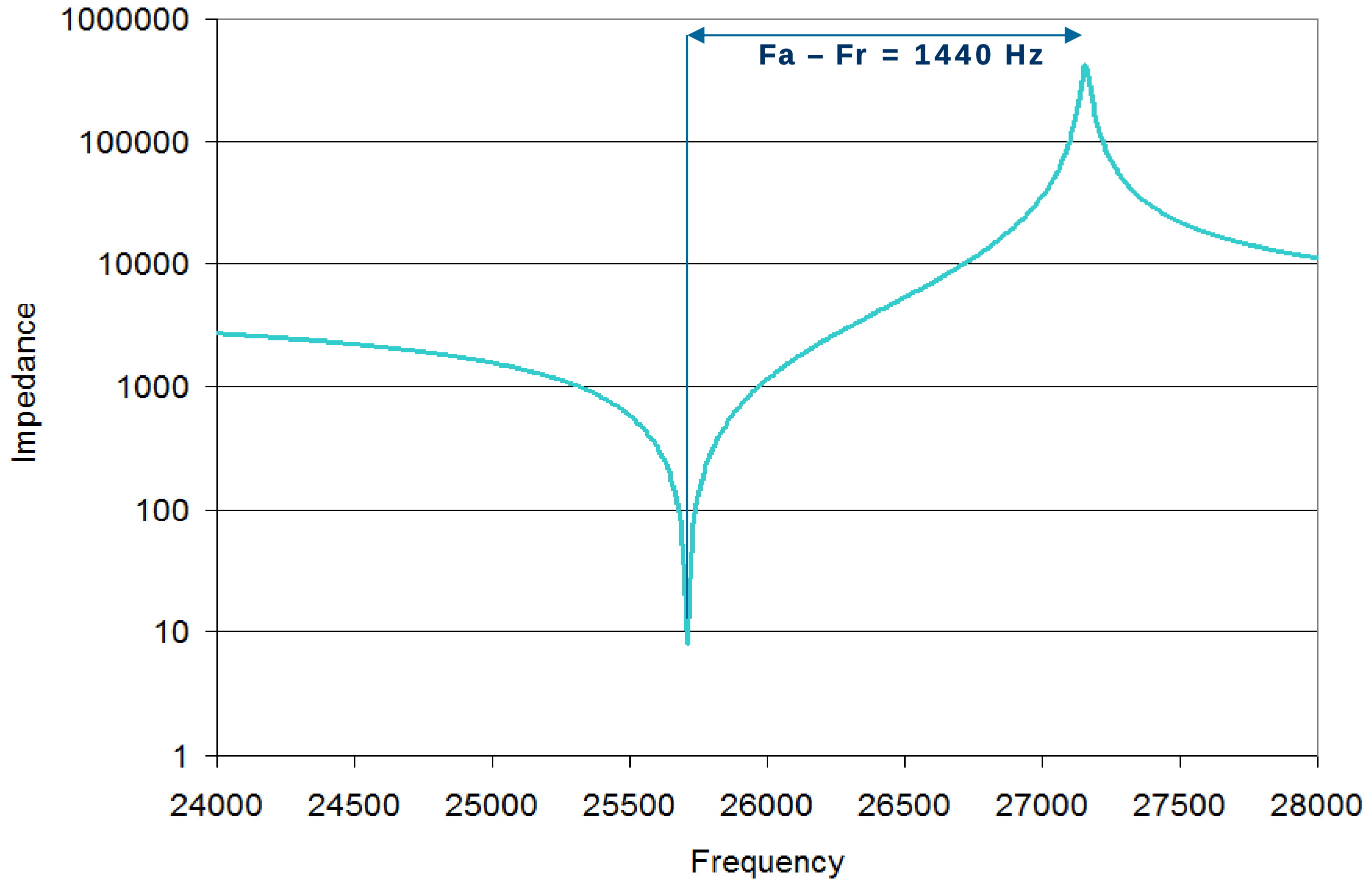
Unity Gain Horn

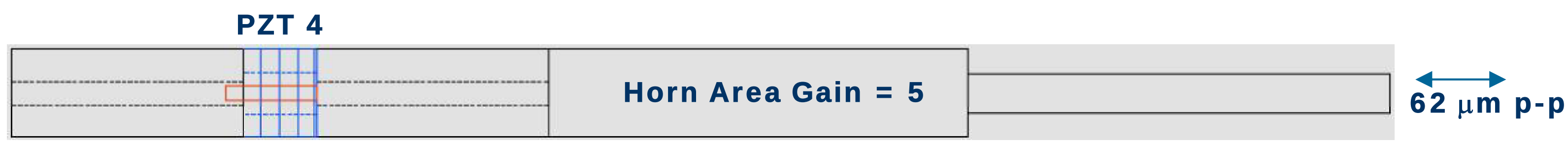
k $_{eff}$ = 0.322

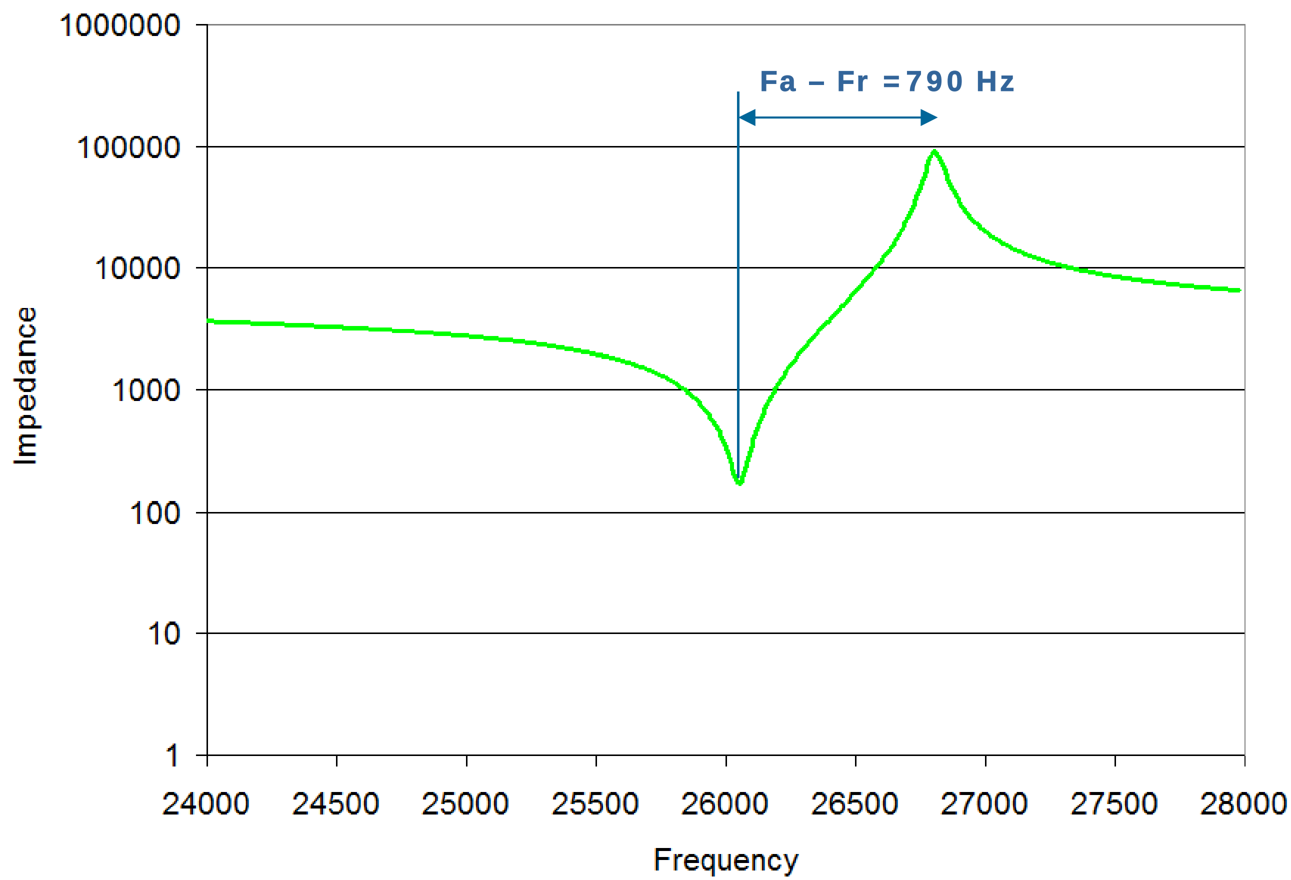


Zmn = 9 Ohms
Phase = + 2.8 °
Volts p-p = 30

Horn Area Gain = 5

$k_{eff} = 0.235$





Zmn = 171 Ohms
Phase =– 7.6 °
Volts p-p = 133

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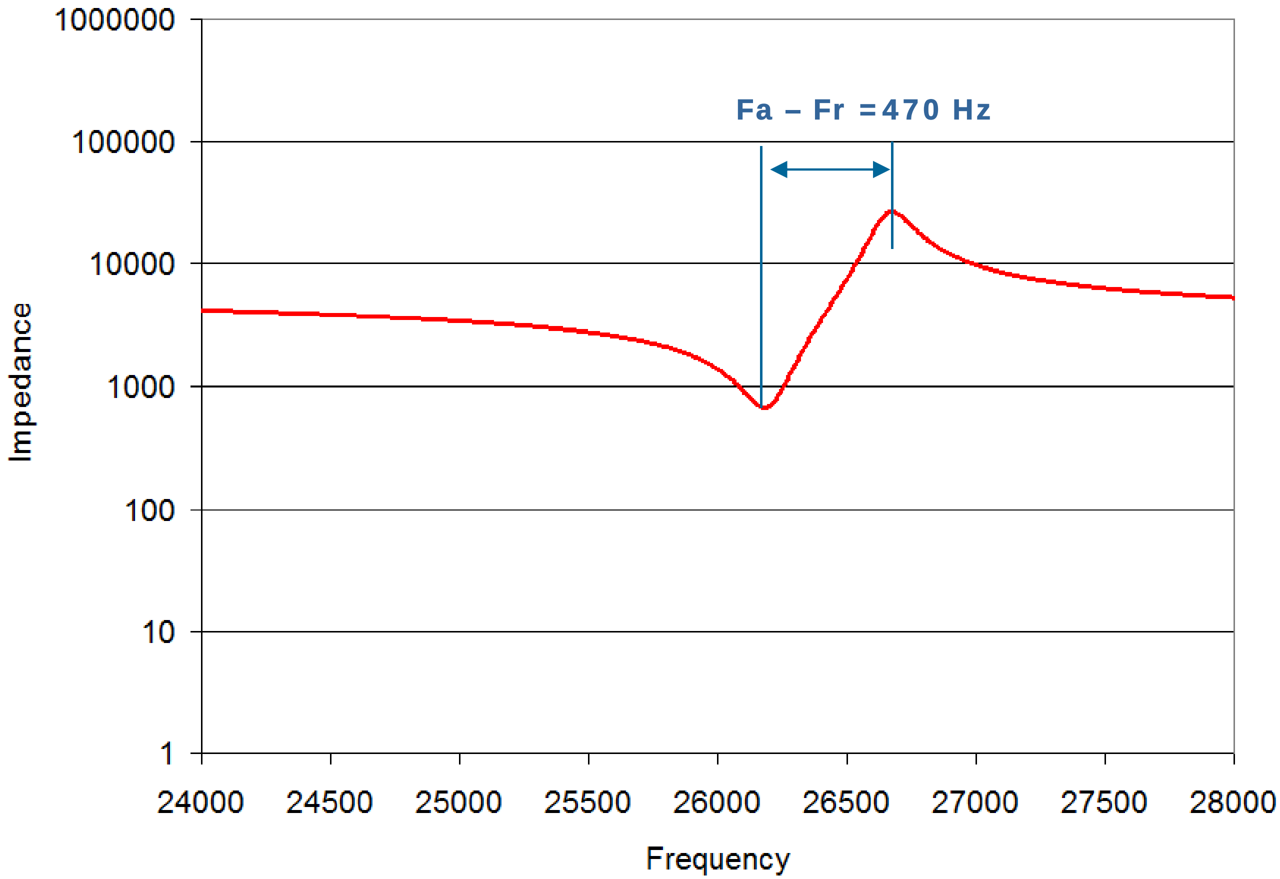
Horn Area Gain = 10

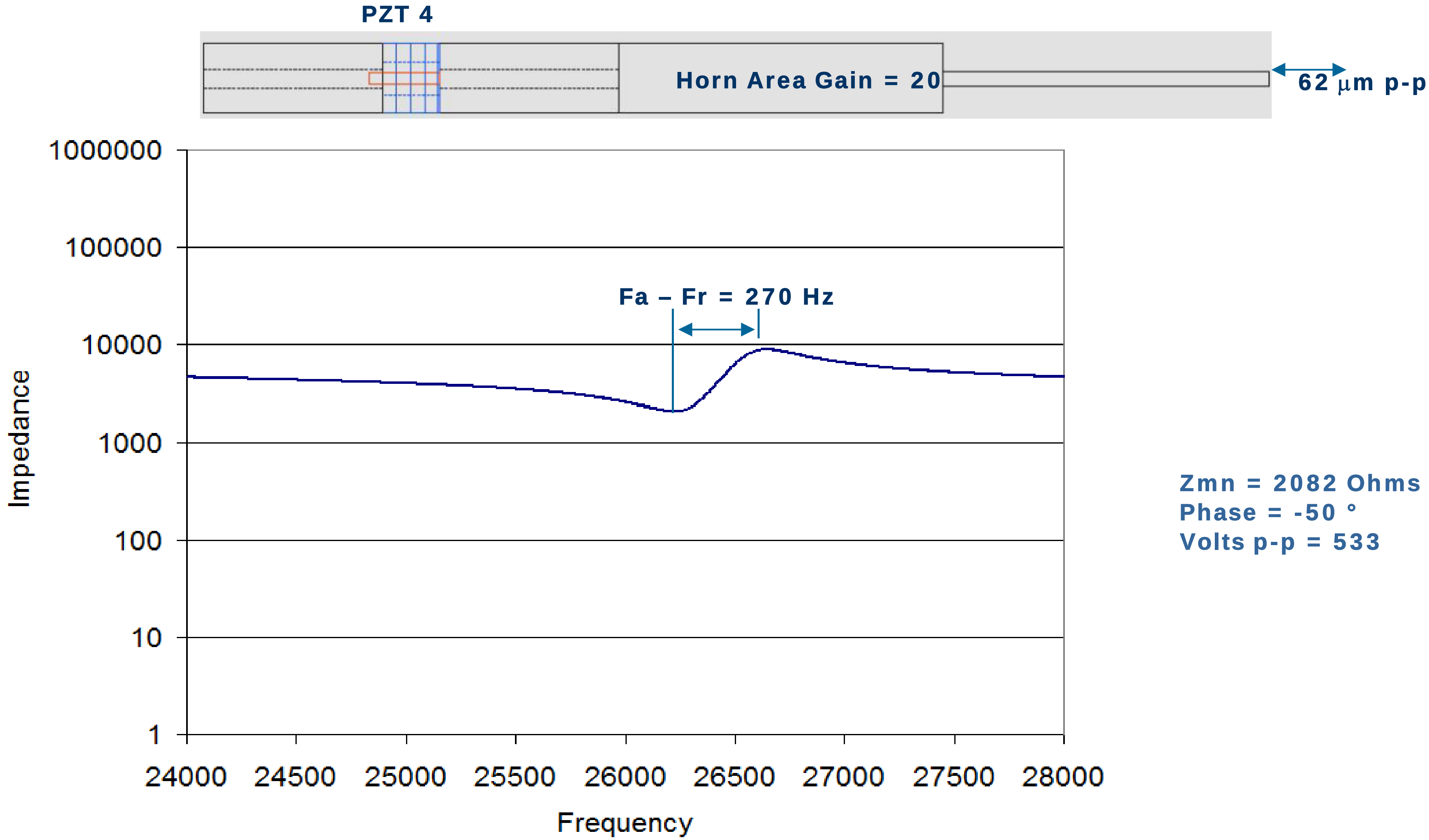
$k_{eff} = 0.187$



Zmn = 664 Ohms
Phase =– 19 °
Volts p-p = 266

Horn Area Gain = 20

k eff = 0.142



Zmn = 2082 Ohms
Phase = -50 °
Volts p-p = 533

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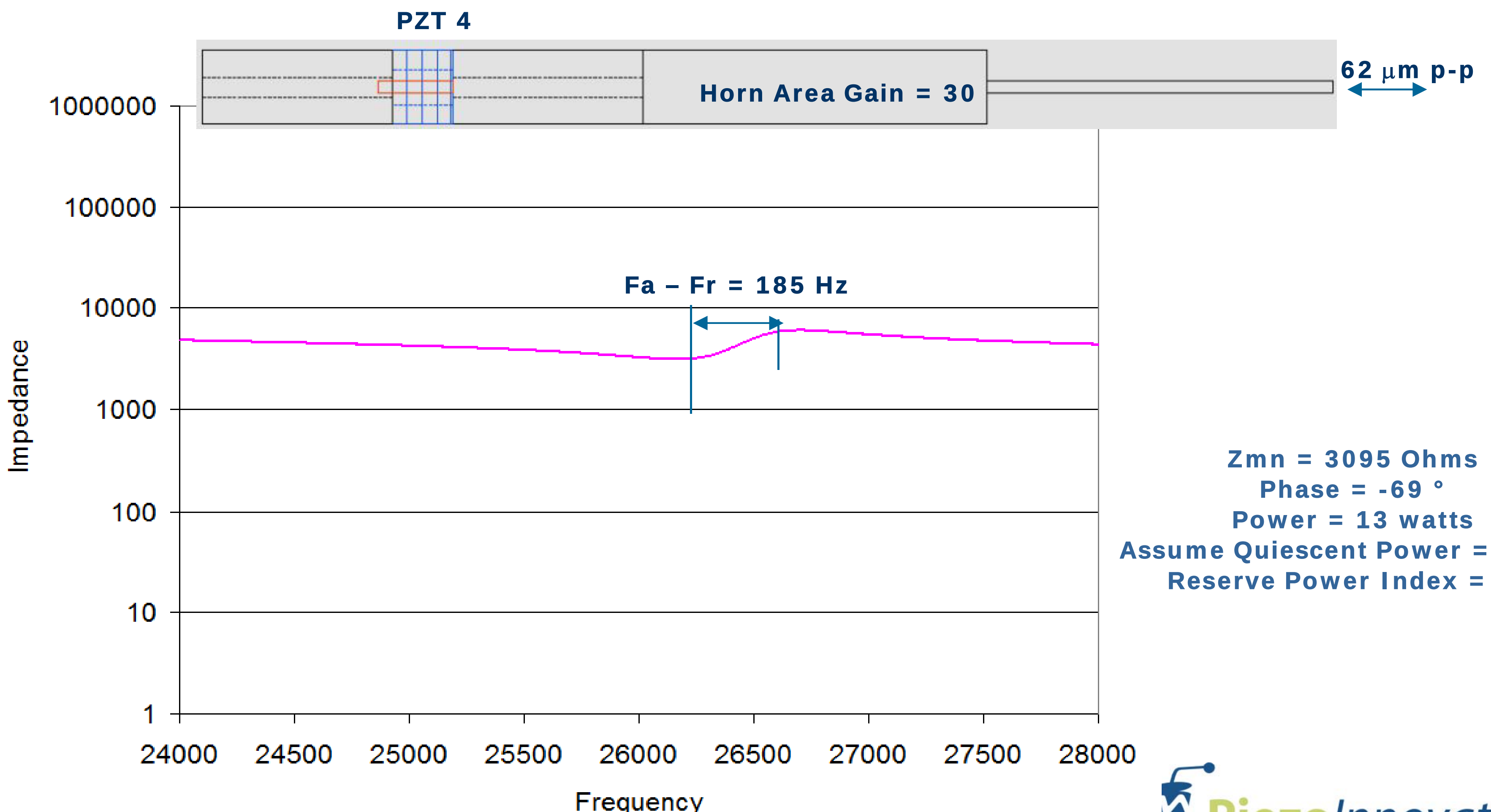
Horn Area Gain = 30

k eff = 0.118

Voltage Limited by Control System 800 Vp-p



Zmn = 3095 Ohms
Phase = -69 °
Power = 13 watts
Assume Quiescent Power = 1 watt
Reserve Power Index = 13

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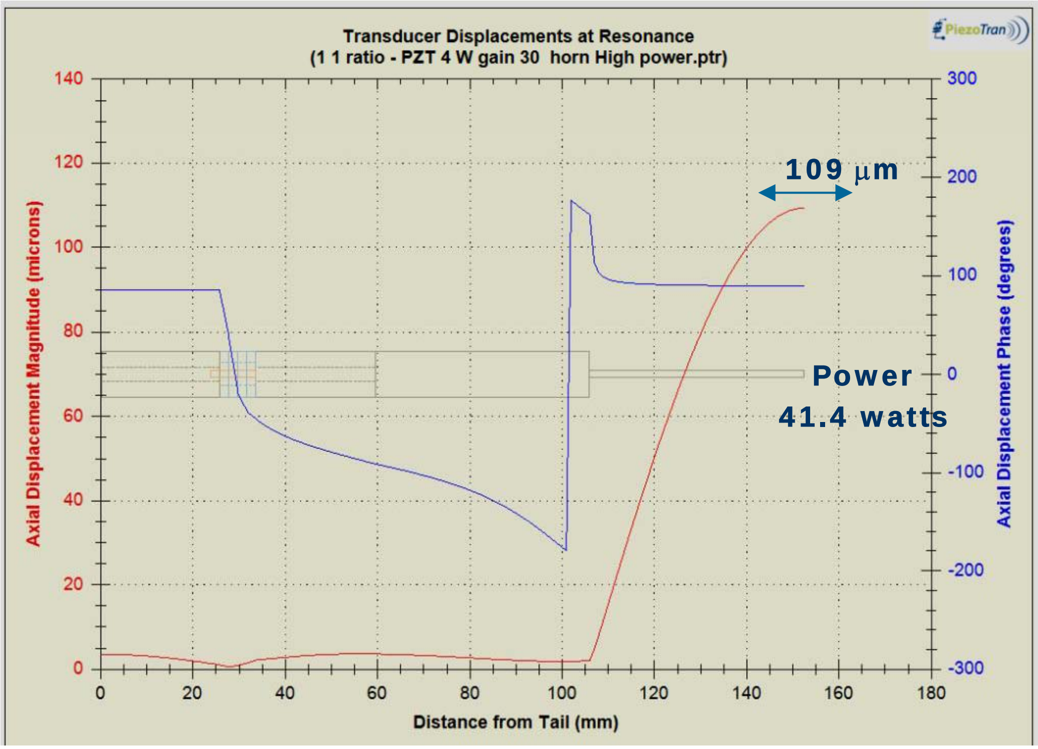
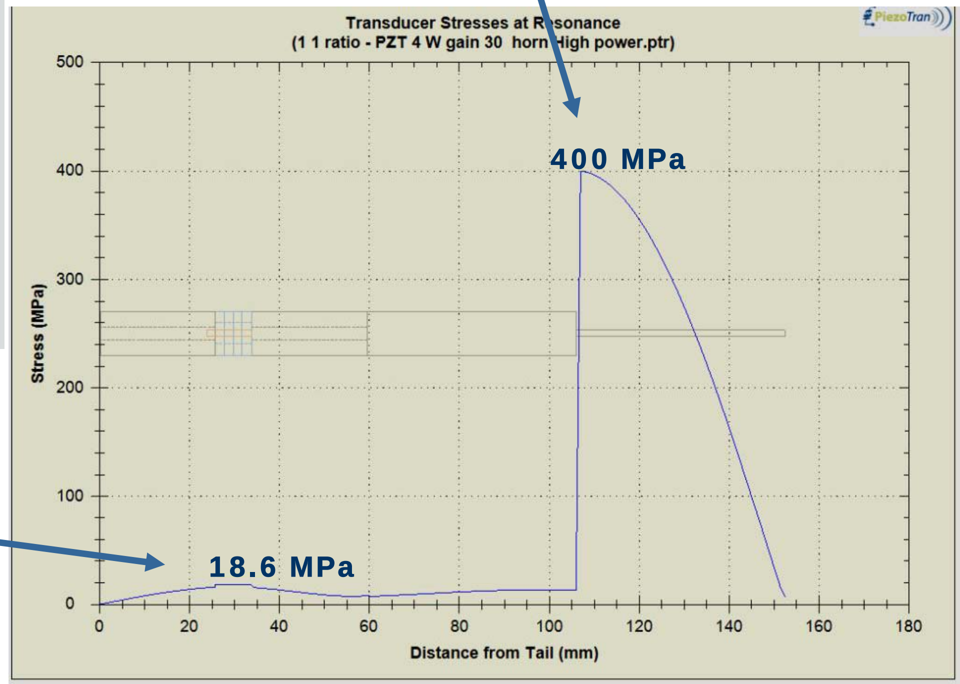
Horn Area Gain = 30

k eff = 0.118

Assume Voltage Limit Can be Increased to 500 Vrms (1414 Vp-p)



Potential Design Limitation
Fatigue Limit
Titanium 6Al-4V
390 MPa



Piezo Stack Cyclic Stress
18.6 MPa
Needs to be < 35.9 MPa to Prevent Heating

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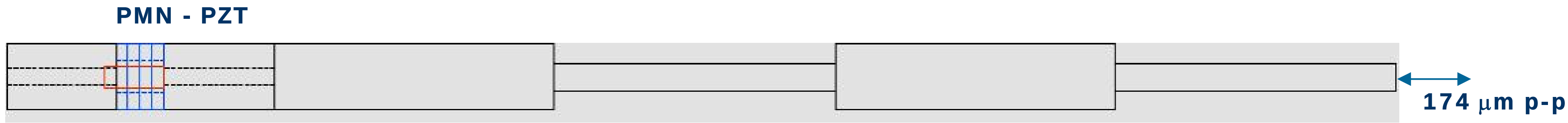
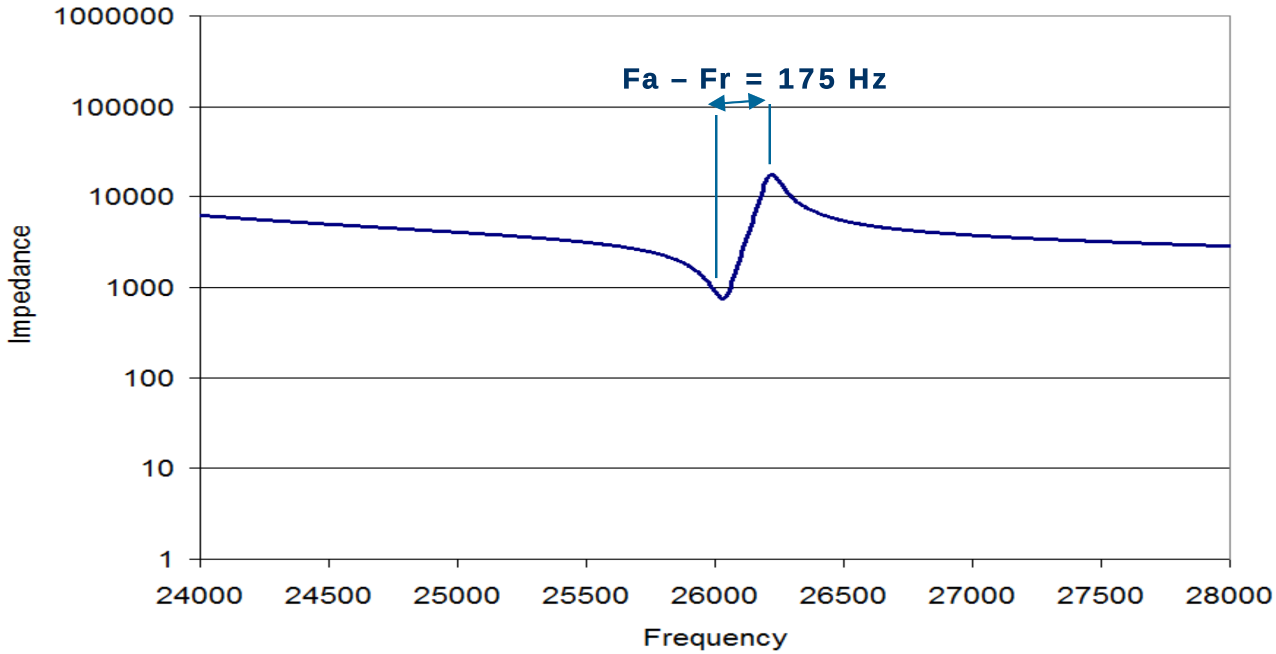
Change to PMN-PZT

$k_{eff} = 0.115$

- Single Stage Horn (Not Practical)
  - Gain = 87 Minor Diameter = 1.07 mm
- Dual Stage Horn





Zmn = 751 Ohms
Phase =- 22 °
Volts p-p = 800
Power = 102 watts
Quiescent Power = 2 watts
Reserve Power Index = 102/2 = 51

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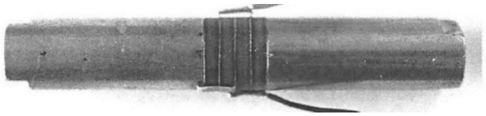
Heat Limited Performance



- Experimental Data
  - PZT 8 & PZT4 Dumbbells Like this
  - Manually Tuned for Resonance Frequency
  - Air Cooled
  - Stabilize at Approximately 41 ° C* after 10 Minutes
  - Power Manually Adjusted to 1.2 Watts
    - Each Piezo Ring Dissipates approximately 250 mWatts
    - Each End Mass Dissipates 100 mWatts (Includes Joints)

*** IEC 60601: applied parts that have localized heating exceeding 41°C must be assessed in risk management**

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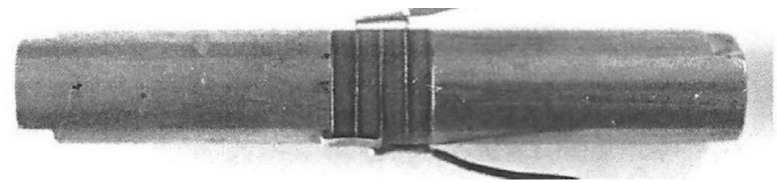
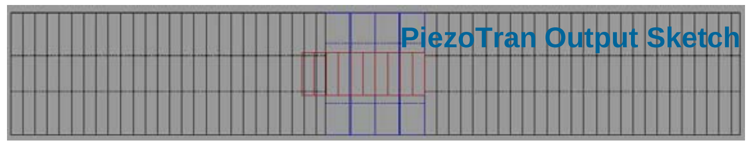
Theory

Heat Limited Designs





$$P_r(thin\ element) = \frac{\omega \sigma_M^2 lS}{2QE}$$

PMN-PZT = 80*

PZT 8 = 380*

PZT 4 = 250*

***Pr* = Power loss (heat)**

σ_M = peak cyclic stress

C = sound velocity

S = cross section area

E = Youngs modulus

l = length of thin element

Q : Defined as the ratio of the energy stored to that lost per cycle multiplied by 2 π

*Note: Published values of piezo Q relate to test samples

Actual values used based on dumbbell experimental data

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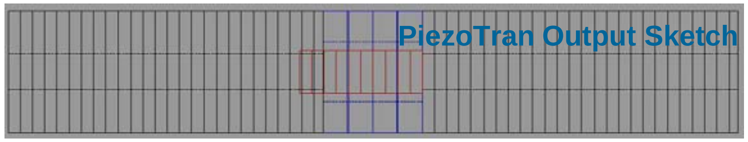
Heat Limited Designs

Power Required to Heat Transducer to 41 °C



- Four Ring Designs PZT8 & PZT4
  - Each Piezo Ring 250 mWatts
  - Each Brass End Mass 100 mWatts

- Four Ring Design 7/8 Configuration PMN-PZT
  - Ring (1) 319 mWatts Ring (2) 281 mWatts
  - Ring (3) 219 mWatts Ring (4) 145 mWatts

- Two Ring Design PMN-PZT
  - Each Ring 300 mWatts (Increased to Compensate For End Mass Conduction)

- One Ring Design PMN-PZT
  - Ring (1) 364 mWatts (Increased to Compensate For End Mass Conduction)

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Method

$$P_r(\textit{thin element}) = \frac{\omega \sigma_M^2 IS}{2QE}$$

- PiezoTran Output
  - Paste Text Output to Excel Spread Sheet
  - Adjust Accumulated P_r To Coincide With Heat Related Power
  - Determine Corresponding Max p-p Nodal Stress
- PiezoTran Input
  - Adjust PiezoTran Voltage to Corresponding Nodal Stress Value
- PiezoTran Output
  - Keff, Volts p-p, Power, Stack Stress, Horn Stress

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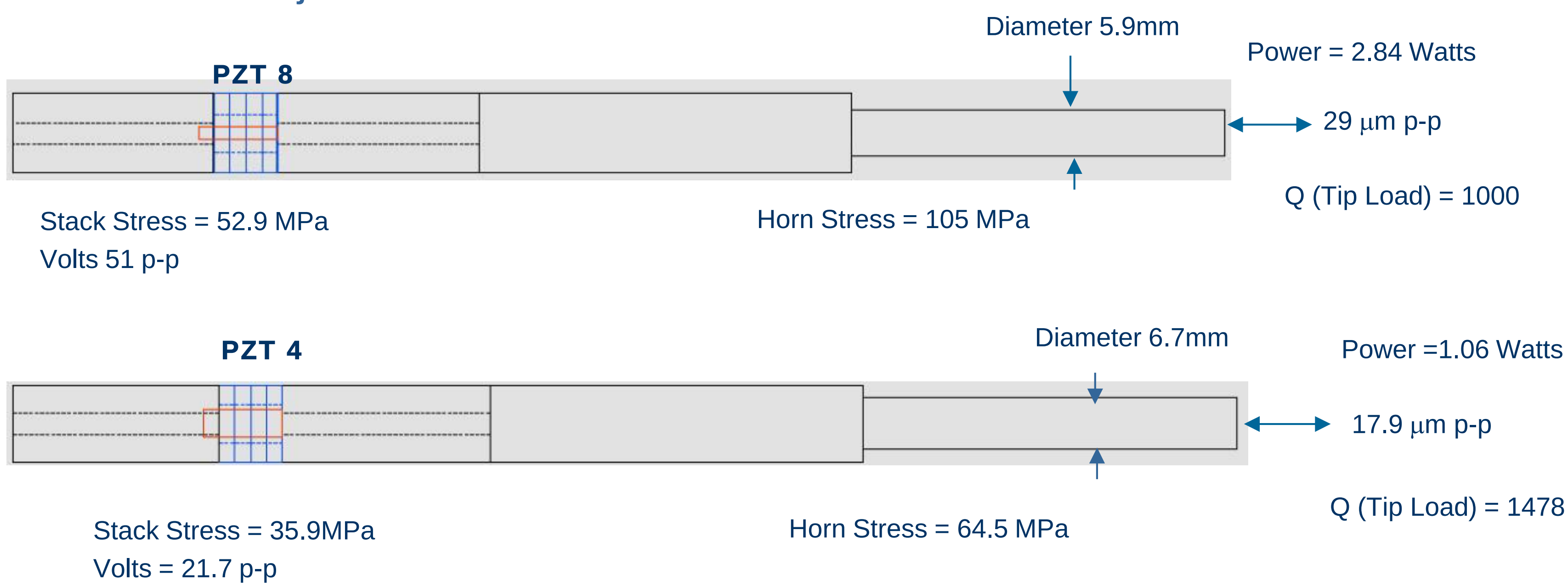
PZT8 Comparison With PZT4

Heat Limit 41° C

- 26 kHz Resonant Frequency
  - Adjust End Mass Length
- 0.230 k_{eff}
  - Adjust Horn Gain



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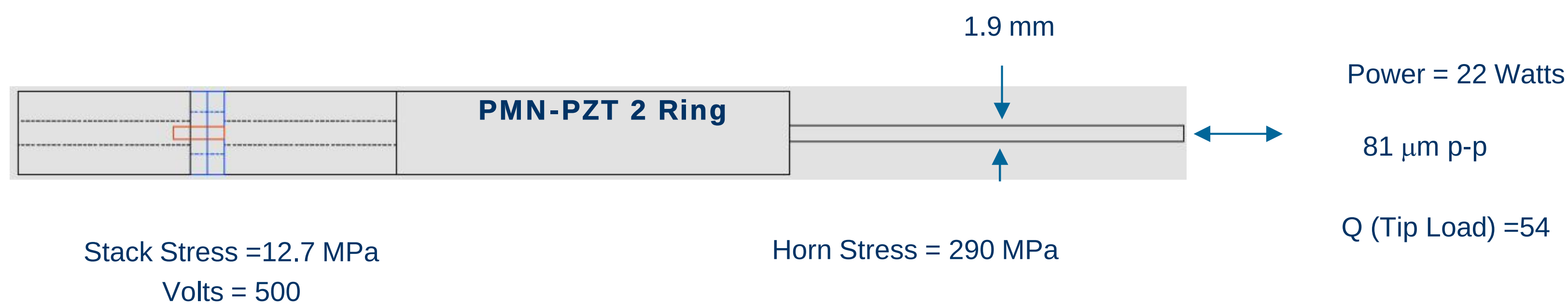
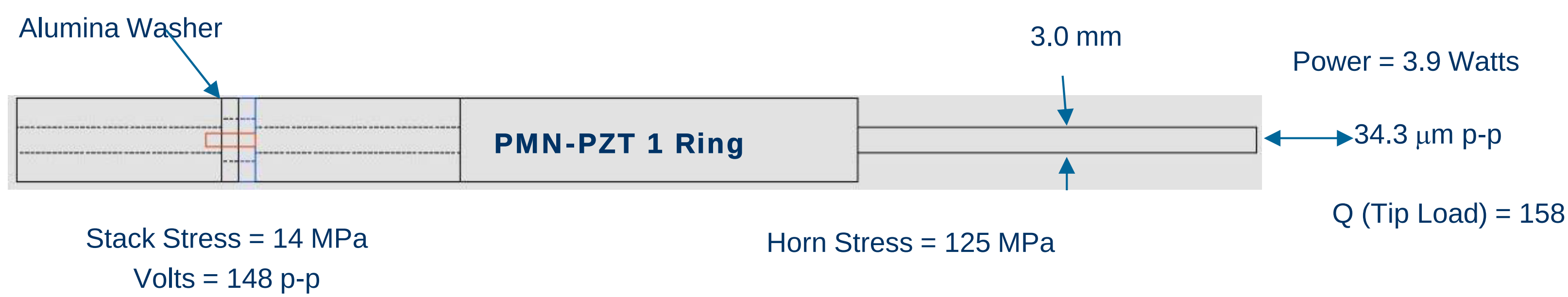
PMN-PZT 2 Ring Comparison With PMN-PZT 1 Ring

Heat Limit 40° C





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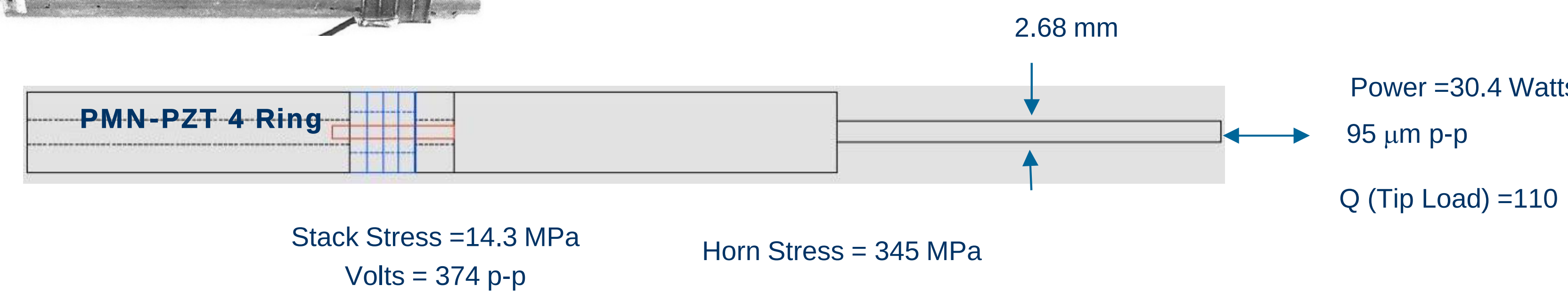
PMN-PZT 7/8 Configuration

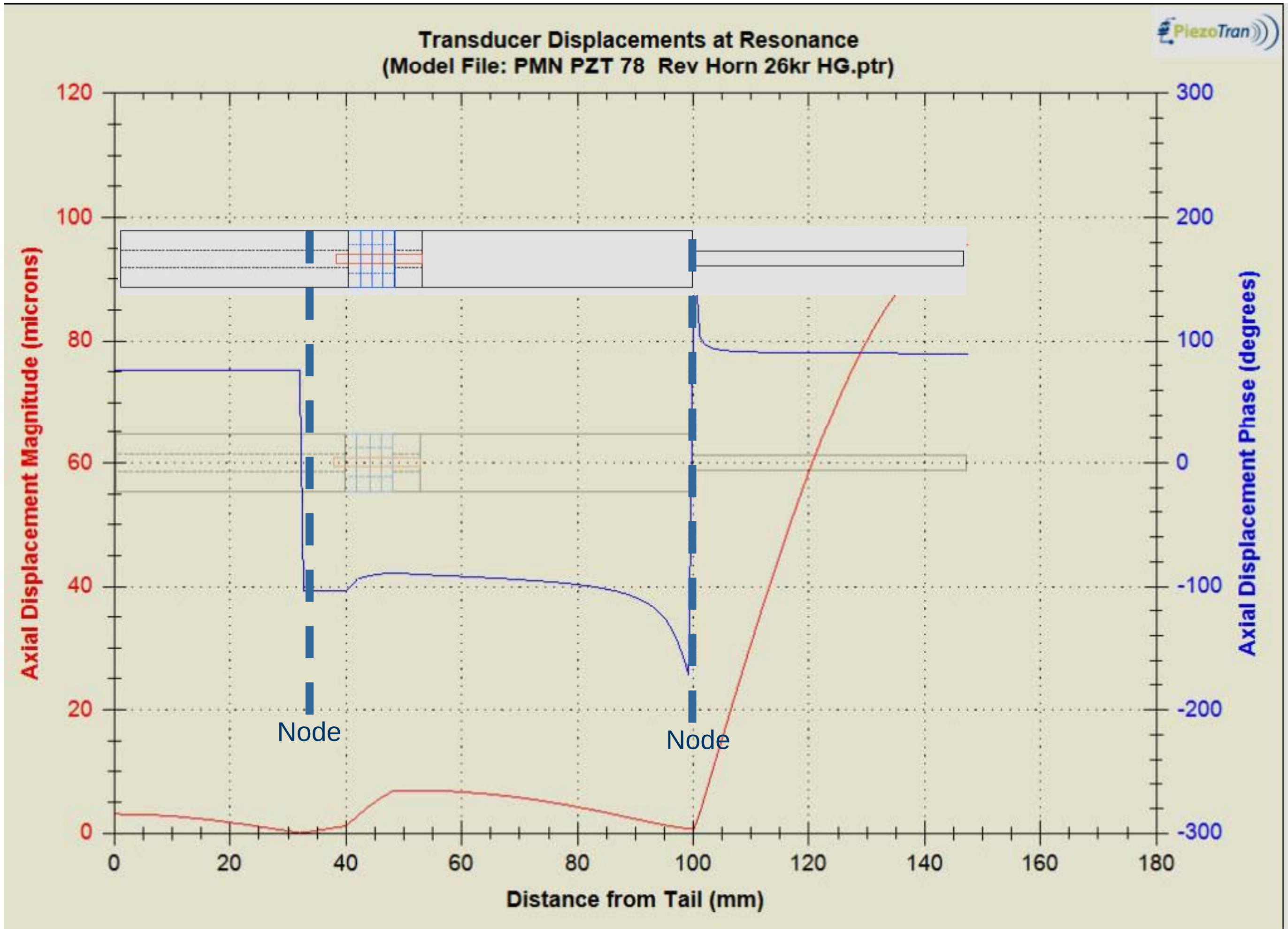
(Horn Attached to Rear Mass)



PMN-PZT 7/8 Configuration

(Horn Attached to Rear Mass)

Nodal Pattern



Tabulated Results

Resonant Frequency Tuned to 26 kHz by Adjusting End Mass Length
k_{eff} 0.230 by Adjusting Horn Diameter

Transducer	Stroke µm p-p	Power (Watts)	Volts p-p	Q	Horn Stress MPa	Stack Stress MPa
4 Ring PZT8	29	2.84	51	1000	105	52.9
4 Ring PZT4	17.9	1.06	21	1478	64.5	35.9
PMN-PZT 7/8	95	30.4	374	110	345	14.3
PMN-PZT 2 Ring	81	22	500	54	290	12.7
PMN-PZT 1 Ring	34.3	3.9	148	158	125	14

Conclusions

- Design Limitations
  - Coupling Coefficient keff Related:
    - Primary Reserve Power
    - Secondary Horn Stress
  - Stack Heat Related:
    - Mechanical Q of the Piezo Rings and Joints
    - Location in the Stack
    - PZT8 Superior to PZT4
- PMN-PZT
  - Potentially Superior Performance
    - Customized Alternate Design Configurations
    - Dual Cascaded Horns, 2 Rings and 1Ring Piezo Stacks
    - Piezo Stacks Located Away From Nodes

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Acknowledgments

Andrew Mathieson and Glasgow University

Primary Reference

" The Influence of Piezoceramic Stack Location on Nonlinear Behavior of Langevin Transducers"

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