Efficient Electromechanical Network Models for Wireless Acoustic-Electric Feed-throughs

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Outline

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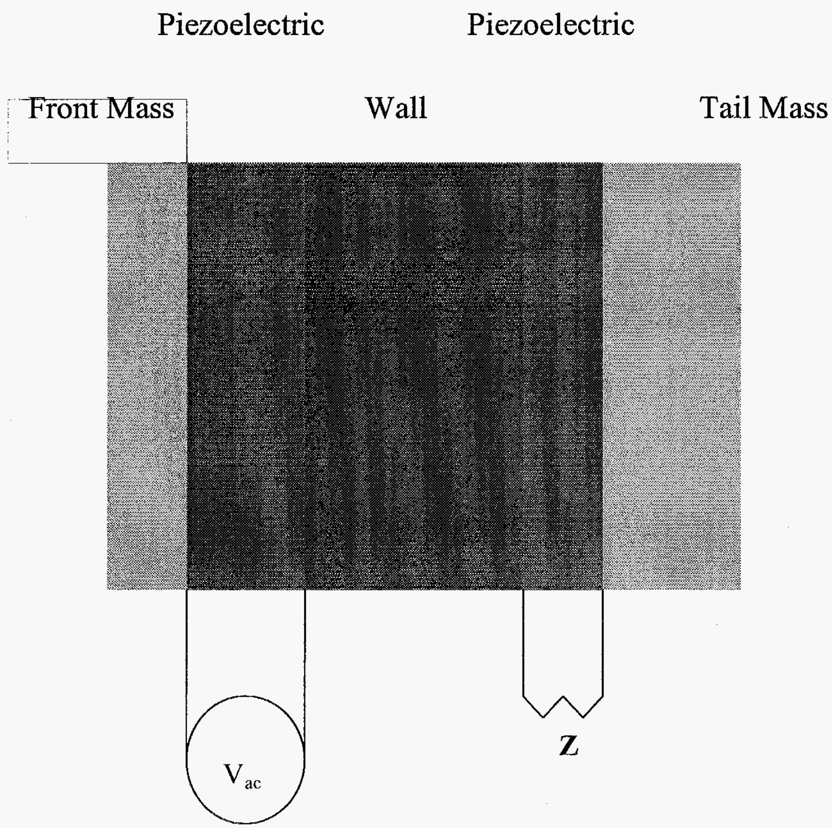
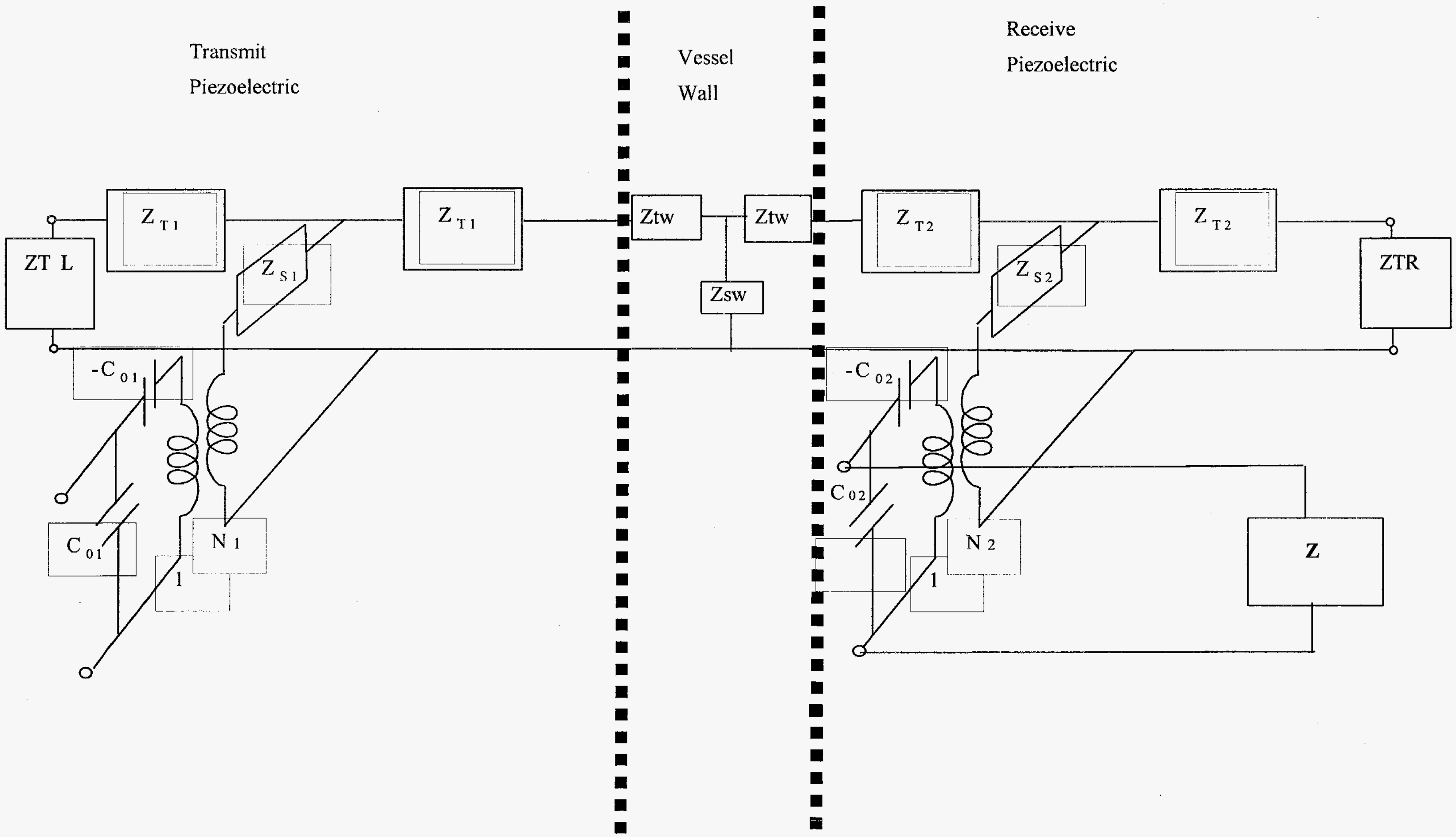
- Impetus for an acoustic-electric feed through
- Presentation of a network model that is exact in 1D
- Compare this model to model derived from Wave equation and linear equation of piezoelectricity
- Look at changes to the efficiency when dielectric and piezoelectric losses are included
- Look effects of using hard rather than soft PZ T

Acoustic Electric Feed-throughs

Use piezoelectric to generate stress wave through
A mechanical barrier - Stress wave generates voltage
on a secondary piezoelectric- Transfer of energy and
Information using stress waves



Model



Transmit
Piezoelectric
Vessel
Wall
Receive
Piezoelectric
ZT L
Z T1
Z T1
Z S1
-C 01
C 01
N 1
1
Ztw
Ztw
Zsw
Z T2
Z T2
Z S2
ZTR
-C 02
C 02
N 2
1
Z

Model Parameters

Material Properties

$\boldsymbol{\varepsilon}_{33}^{S}$ clamped complex permittivity

$\mathbf{c}_{33}^{D}$ open circuit complex elastic stiffness

$\boldsymbol{k}_{t}$ complex electromechanical coupling

$$\boldsymbol{k}_t^2 = \boldsymbol{e}_{33}^2 / \mathbf{c}_{33}^D \boldsymbol{\varepsilon}_{33}^S = \boldsymbol{h}_{33}^2 \boldsymbol{\varepsilon}_{33}^S / \mathbf{c}_{33}^D$$

$$\boldsymbol{h}_{33} = \boldsymbol{k}_t \sqrt{\mathbf{c}_{33}^D / \boldsymbol{\varepsilon}_{33}^S}$$

Mason's Model (Generator) ρ=density, t= thickness, A=area

$$\mathbf{C}_{01} = \frac{\boldsymbol{\varepsilon}_{33_1}^S A_1}{t_1} \qquad \mathbf{N}_1 = \mathbf{C}_{01} \boldsymbol{h}_{33_1}$$

$$\boldsymbol{Z}_{01} = \rho_1 A_1 \mathbf{v}_1^{\mathbf{D}} = A_1 \sqrt{\rho_1 \mathbf{c}_{33_1}^D} \qquad \Gamma_1 = \frac{\omega}{\mathbf{v}_1^{\mathbf{D}}} = \omega \sqrt{\frac{\rho_1}{c_{33_1}^D}}$$

$$Z_{T1} = i\mathbf{Z}_{01} \tan(\Gamma_1 t_1 / 2) \qquad Z_{S1} = -i\mathbf{Z}_{01} \csc(\Gamma_1 t_1)$$

Mason's Model (Reciever) ρ=density, t= thickness, A=area

$$\mathbf{C}_{02} = \frac{\boldsymbol{\varepsilon}_{33_2}^S A_2}{t_2} \qquad \mathbf{N}_2 = \mathbf{C}_{02} \boldsymbol{h}_{33_2}$$

$$\boldsymbol{Z}_{02} = \rho_2 A_2 \mathbf{v}_2^{\mathbf{D}} = A_2 \sqrt{\rho_2 \mathbf{c}_{33_2}^D} \qquad \Gamma_2 = \frac{\omega}{\mathbf{v}_2^{\mathbf{D}}} = \omega \sqrt{\frac{\rho_2}{c_{33_2}^D}}$$

$$Z_{T2} = i\mathbf{Z}_{02} \tan(\Gamma_2 t_2 / 2) \qquad Z_{S2} = -i\mathbf{Z}_{02} \csc(\Gamma_2 t_2)$$

Wall Properties ρ=density, t= thickness, A=area

$$Z_{tw} = i\mathbf{Z}_w \tan(\Gamma_w t_w / 2) \qquad Z_{sw} = -i\mathbf{Z}_w \csc(\Gamma_w t_w)$$

$$\boldsymbol{Z}_w = \rho_w A_w \mathbf{v}_{\mathbf{w}}^{\mathbf{D}} = A_w \sqrt{\rho_w \mathbf{c}_w^D} \qquad \Gamma_w = \frac{\omega}{\mathbf{v}_{\mathbf{w}}^{\mathbf{D}}} = \omega \sqrt{\frac{\rho_w}{c_w^D}}$$

Tail mass properties ρ=density, t= thickness, A=area

$Z_{TR} = i\mathbf{Z}_R \tan(\Gamma_R t_R)$ termination impedance

$$\boldsymbol{Z}_R = \rho_R A_R \mathbf{v}_{\mathbf{R}}^{\mathbf{D}} = A_R \sqrt{\rho_R \mathbf{c}_R^D} \qquad \Gamma_R = \frac{\omega}{\mathbf{v}_{\mathbf{R}}^{\mathbf{D}}} = \omega \sqrt{\frac{\rho_R}{c_R^D}}$$

Head Mass properties ρ=density, t= thickness, A=area

$Z_{TL} = i\mathbf{Z}_L \tan(\Gamma_L t_L)$ termination impedance

$$\boldsymbol{Z}_L = \rho_L A_L \mathbf{v}_{\mathbf{L}}^{\mathbf{D}} = A_L \sqrt{\rho_L \mathbf{c}_L^D} \qquad \Gamma_L = \frac{\omega}{\mathbf{v}_{\mathbf{L}}^{\mathbf{D}}} = \omega \sqrt{\frac{\rho_L}{c_L^D}}$$

Load Impedance = $\mathbf{Z}$

Input Impedance Calculation

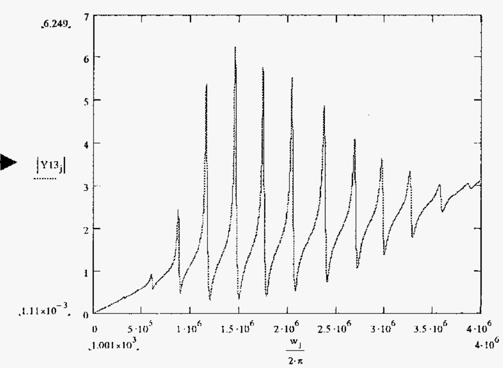
$$Zx1 = \mathbf{Z}\frac{Z02}{\mathbf{Z}+Z02} \qquad Zx2 = Zx1 - Z02 \qquad Zx3 = N_2^2 Zx2 \qquad Zx4 = Zs2 + Zx3$$

$$Zx5 = Zx4\frac{(Zt2+ZtR)}{(Zt2+ZtR+Zx4)} \qquad Zx6 = Zx5 + Zt2 + Ztw \qquad Zx7 = Zx6\frac{Zsw}{Zx6+Zsw}$$

$$Zx8 = Zx7 + Ztw + Zt1 \qquad Zx9 = Zx8\frac{(Zt1+ZtL)}{(Zx8+Zt1+ZtL)} \qquad Zx10 = Zs1 + Zx9$$

$$Zx11 = \frac{Zx10}{N_1^2} \qquad Zx12 = Zx11 - Z01 \qquad Zx13 = Zx12\frac{Z01}{(Zx12+Z01)}$$

$$Y13 = 1/Zx13 \longrightarrow$$



Voltage and Current Across Receive Piezoelectric

The current through the electrical port of the transmit piezoelectric is therefore

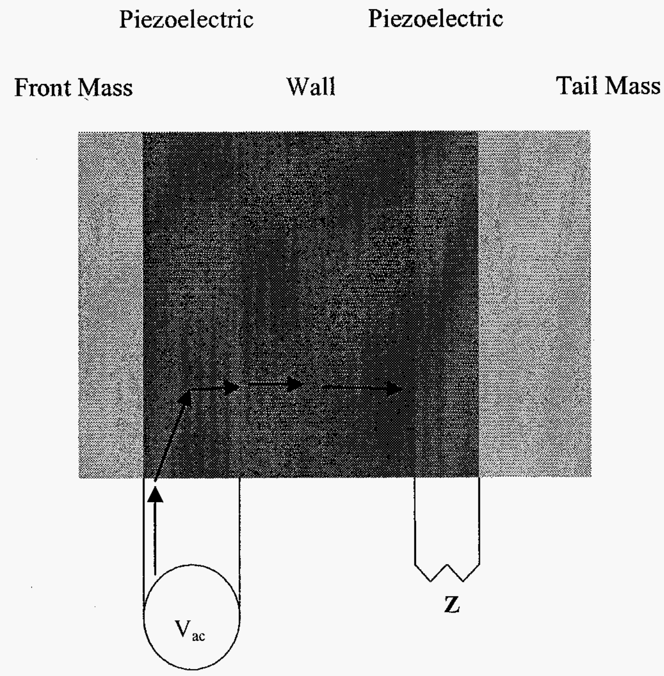
$$I = V / Zx13$$

The current through the transformer on the electrical side of the transmit piezoelectric is

$$I2 = I\frac{Z01}{(Z01 + Zx2)}$$

The velocity (current) through the transformer on the mechanical side is

$$v3 = \frac{I2}{N1}$$



The velocity (current) of the left face of the wall is

$$v4 = v3\frac{Zt1 + ZtL}{Zt1 + ZtL + Zx8}$$

The velocity (current) at the right face of the wall is

$$v5 = v4\frac{Zs0}{Zs0 + Zx6}$$

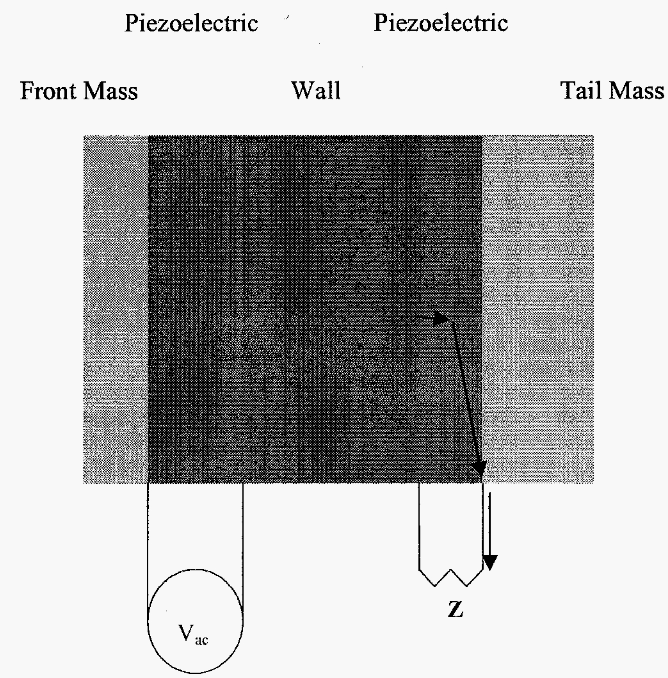
Voltage and Current Across Receive Piezoelectric

The velocity (current) into the mechanical side of the receive transformer of the piezoelectric is

$$v6 = v5\frac{Zt2 + ZtR}{Zt2 + ZtR + Zx4}$$

The current through the electrical side of the transformer for the receive piezoelectric is

$$I7 = v6N2$$



The current through the load resistor is

$$I_L = I7\frac{Z02}{Z02 + \mathbf{Z}}$$

The Voltage across the load resistor is

$$V_L = I_L\mathbf{Z}$$

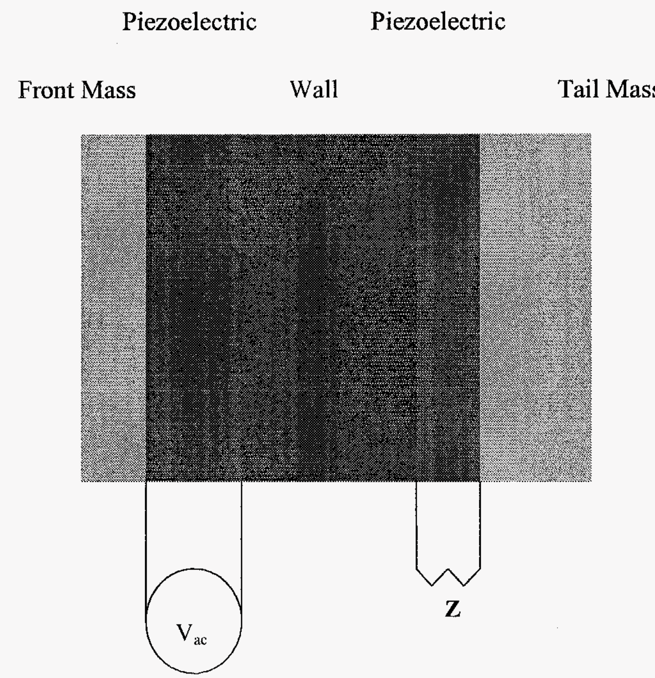
Power, Efficiency, Voltage Gain

The power delivered to the load resistor is

$$P_L = \mathrm{Re}(V_L I_L)$$

Power efficiency of the acoustic electrical feed-through is therefore

$$\eta_L = \frac{\mathrm{Re}(V_L I_L)}{\mathrm{Re}(VI)}$$



The voltage gain is

$$\alpha_V = |V_L| / |V|$$

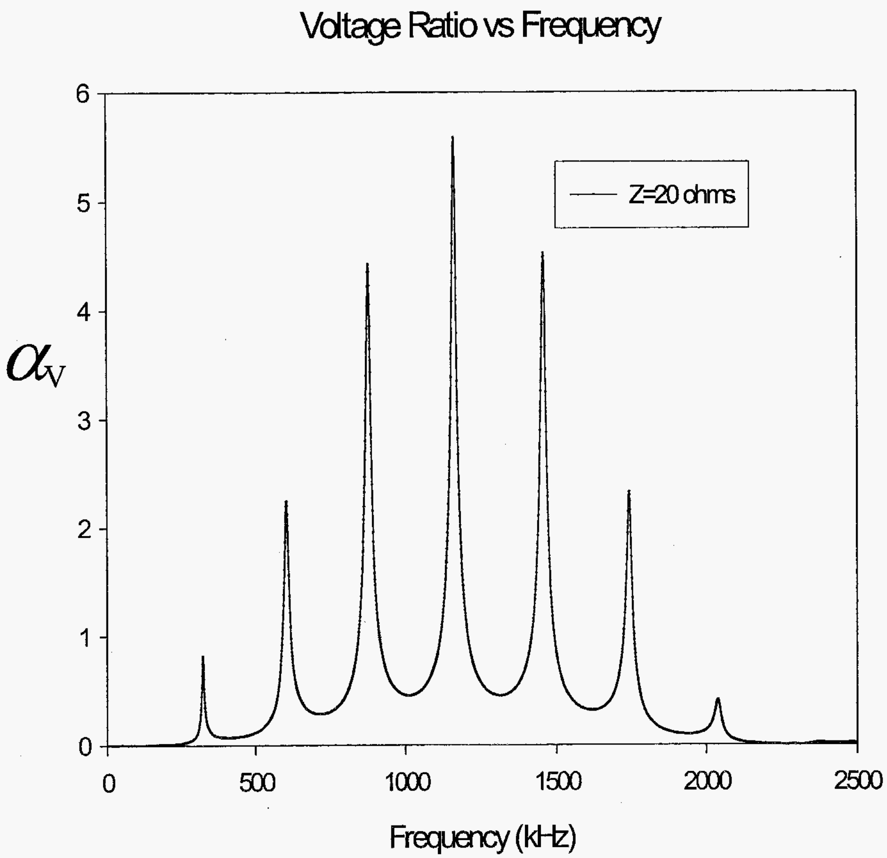
Example 1, Comparison to Hu et al. Calculation

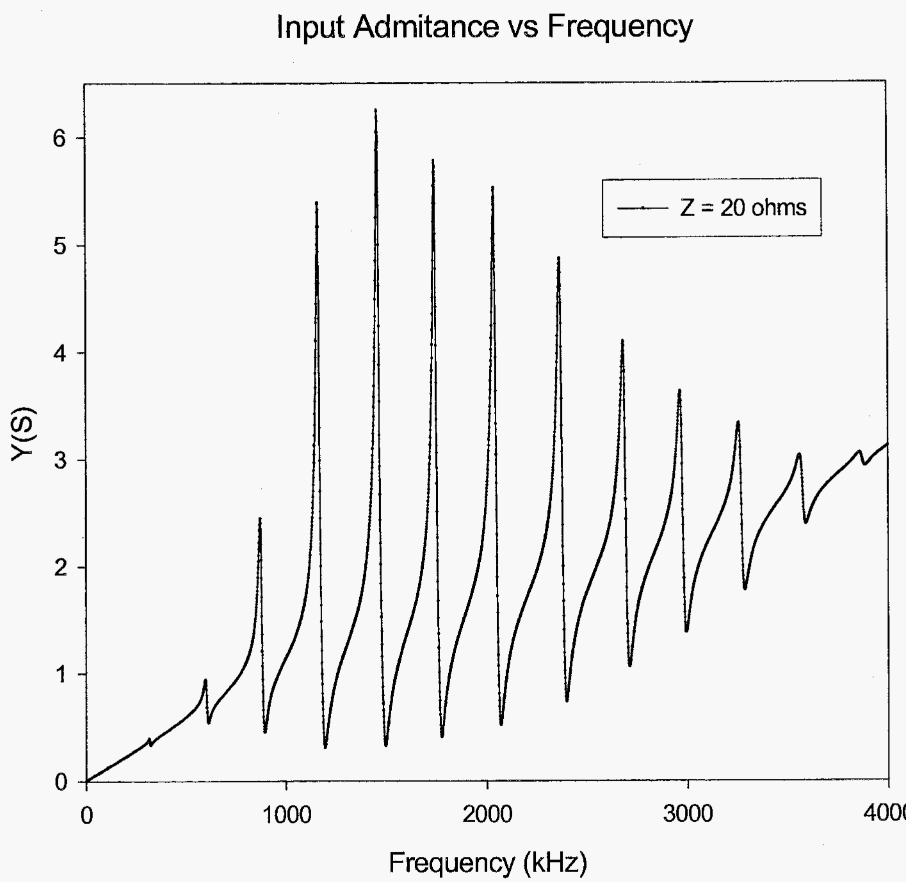
Table 2. Data used by Hu et al.[1] to calculate response of the power transfer efficiency. The transmit and receive piezoelectric transducers were of the same material and head and tail masses were not used.

Property	Value
Density of Piezoelectric (kg/m^3)	7500
Density of wall (kg/m^3)	7850
Area of piezoelectric on wall (m^2)	0.01
Wall thickness (m)	0.006
Transmit Piezoelectric thickness (m)	0.002
Receive Piezoelectric thickness (m)	0.001
Piezoelectric Coefficient e_{33} (C/m^2)	23.3
Permittivity (F/m) ε^S_{33}	1.302×10^{-8}
Elastic stiffness at constant Field c^E_{33} (N/m^2)	$11.7\times10^{10}(1+0.01i)$
Thickness Coupling	0.513(1-0.00368i)
Elastic stiffness at constant Displacement c^D_{33} (N/m^2)	$15.87\times10^{10}(1+0.00737i)$
Elastic stiffness of wall c_w (N/m^2)	$26.9\times10^{10}(1+0.01i)$

[1] Y. Hu, X. Zhang, J. Yang, Q. Jiang, " Transmitting Electric Energy Through a Metal Wall by Acoustic Waves Using Piezoelectric Transducers, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, **50**, 7, pp. 773-781, 2003

Example 1, Comparison to Hu et al. Calculation





Input admittance and voltage gain identical to Hu et al. Curves

Example 1, Comparison to Hu et al. Calculation

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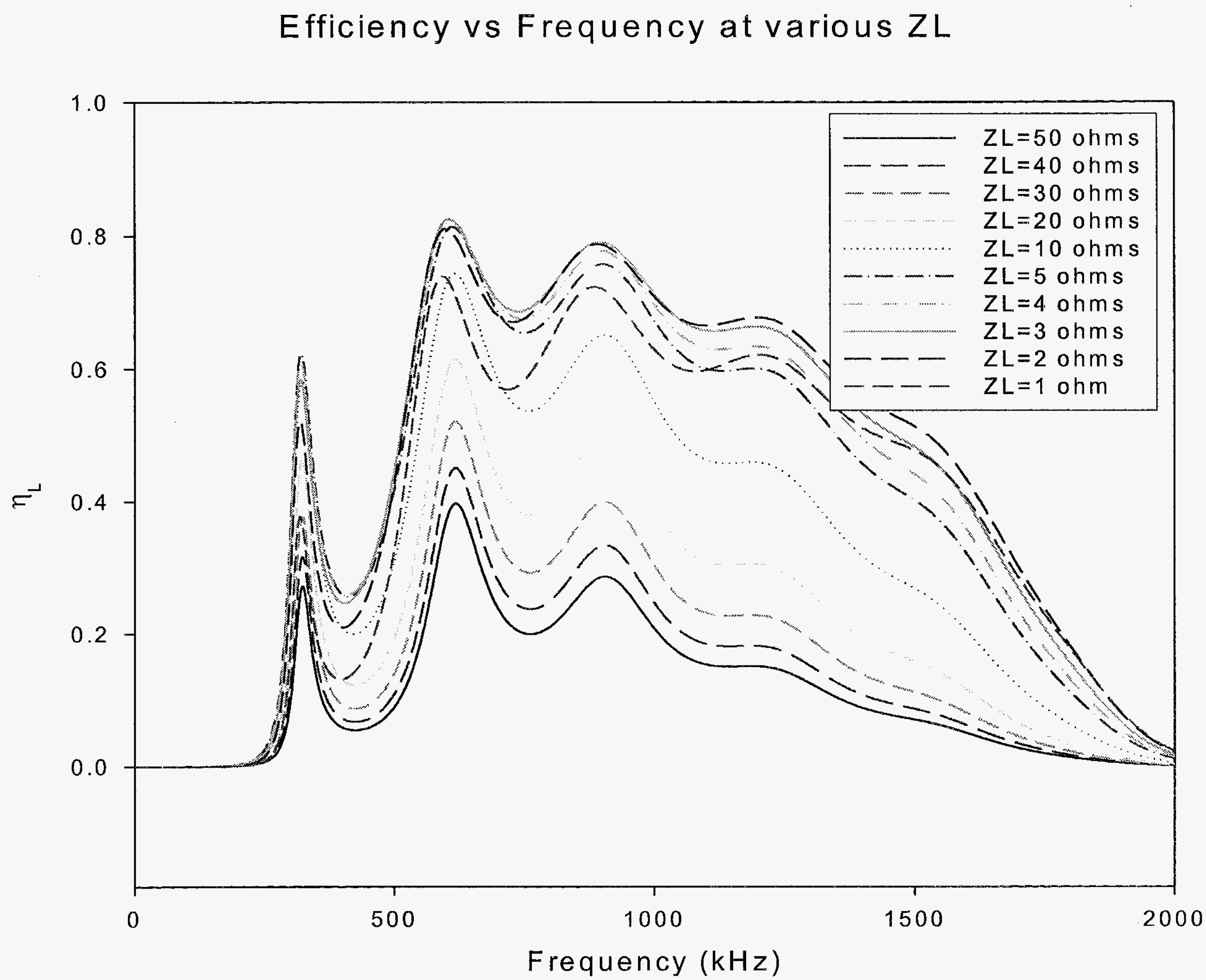


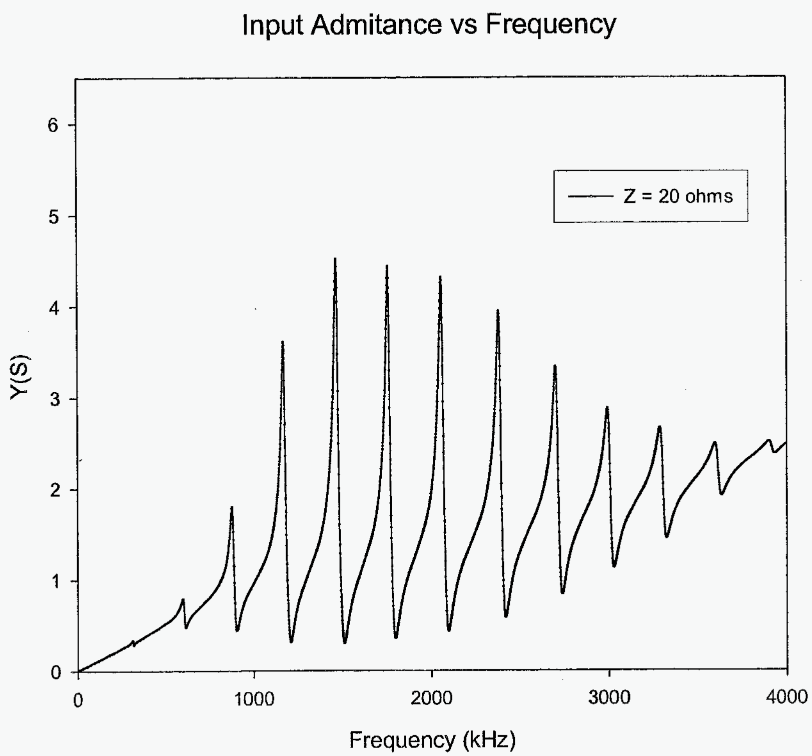
Power Efficiency identical to Hu et al. Curves

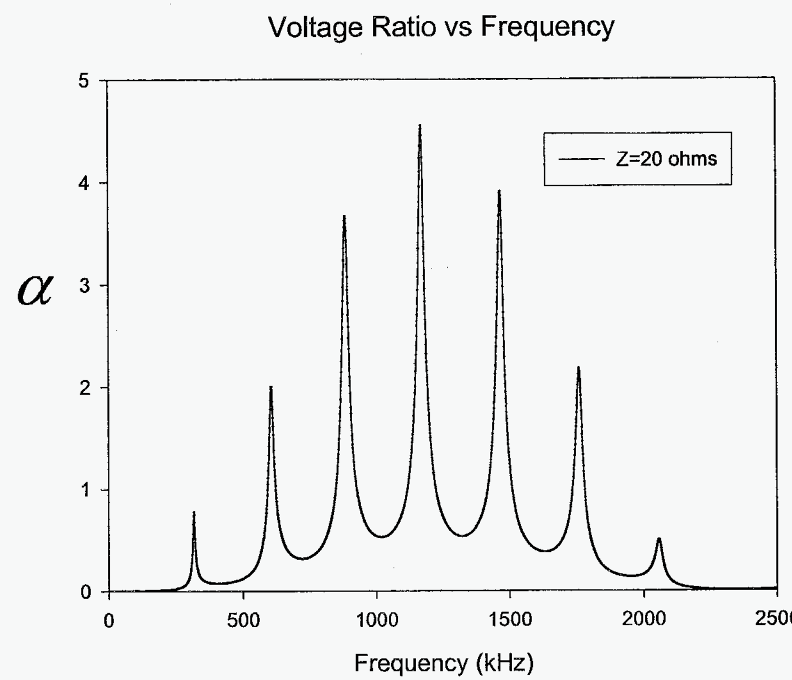
Example 2, Application of Real loss

Table 3. Data used to study the acoustic-electric feedthrough with measured coefficients for the piezoelectric (Motorola 3203HD – now CTS Wireless Products). This material is a soft PZT with similar nominal properties to 5H. The transmit and receive piezoelectric transducers were of the same material and head and tail masses were not used.

Property	Value
Density of Piezoelectric (kg/m^3)	7850
Density of wall (kg/m^3)	7850
Area of piezoelectric on wall (m^2)	0.01
Wall thickness (m)	0.006
Transmit Piezoelectric thickness (m)	0.002
Receive Piezoelectric thickness (m)	0.001
Piezoelectric Coefficient e_{33} (C/m^2)	23.38(1-0.03495i)
Permittivity (F/m) ε^S_{33}	1.061×10^{-8}(1-0.0485i)
Elastic stiffness at constant Field c^E_{33} (N/m^2)	12.28×10^{10} (1+0.0253i)
Thickness Coupling	0.5435(1-0.01649i)
Elastic stiffness at constant Displacement c^D_{33} (N/m^2)	17.43×10^{10}(1+0.0115i)
Elastic stiffness of wall c_w (N/m^2)	26.9×10^{10}(1+0.01i)

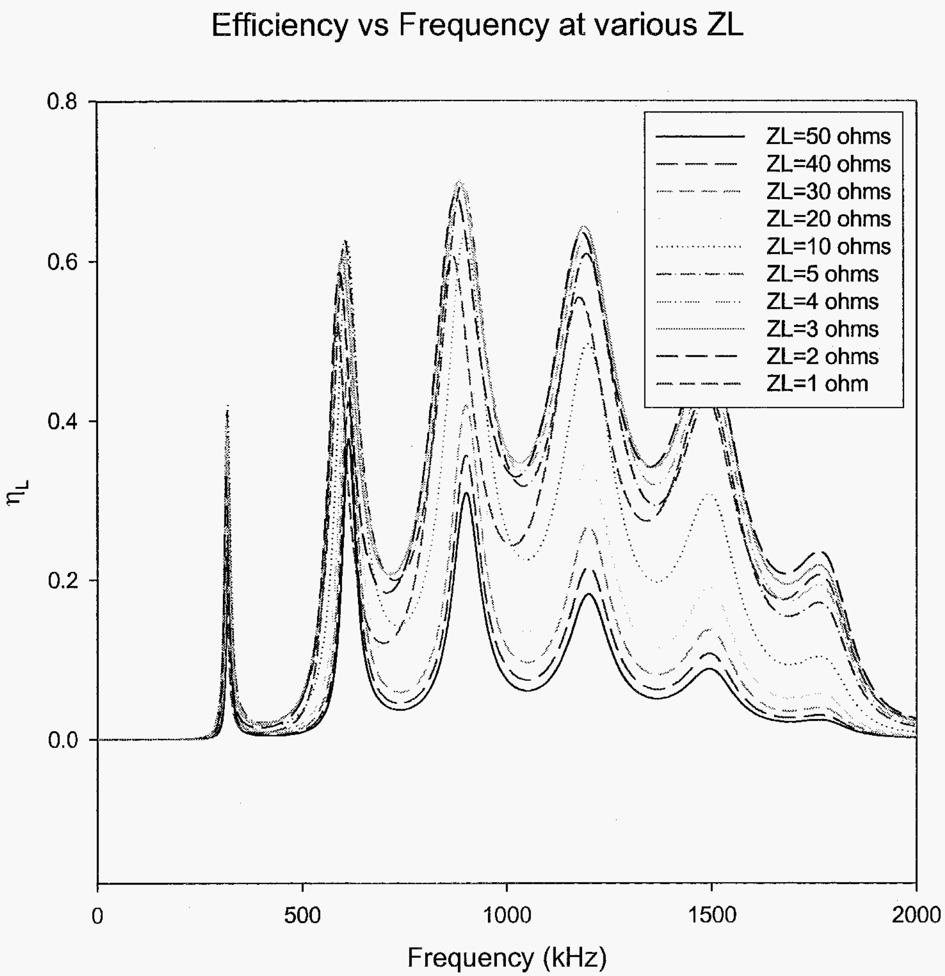
Example 2, Application of Real loss

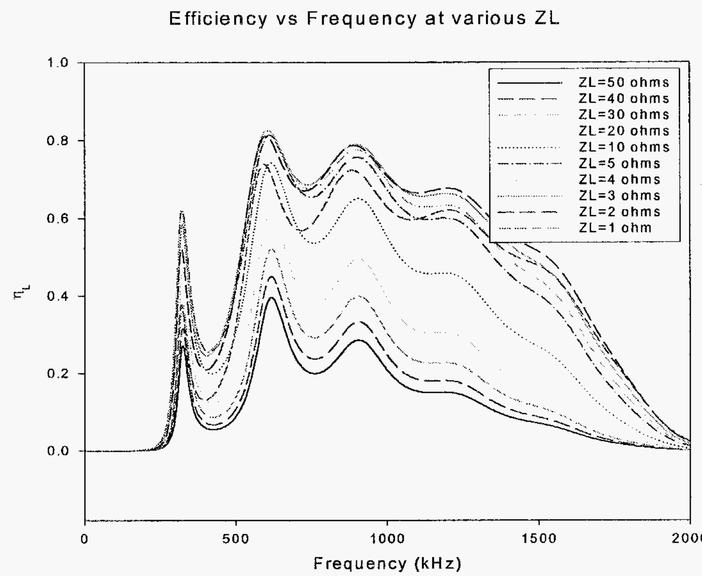




Accounting for dielectric and piezoelectric loss lowers the Input admittance maximum and the maximum of the voltage gain

Example 2, Application of Real loss





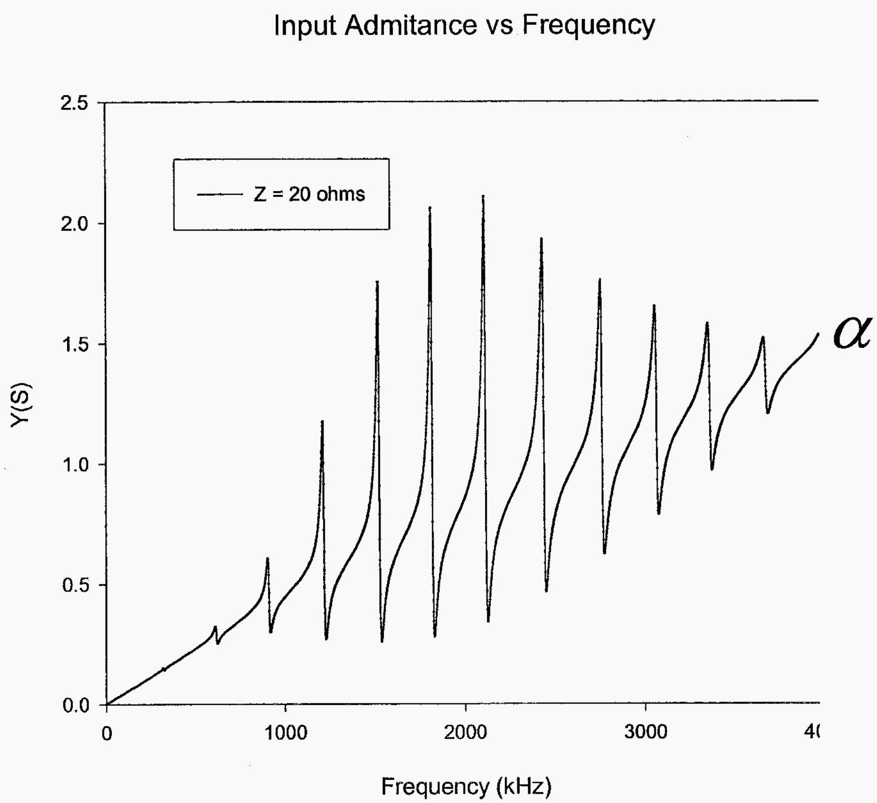
Maximum of Power Efficiency reduced slightly at resonance and drastically away from peaks

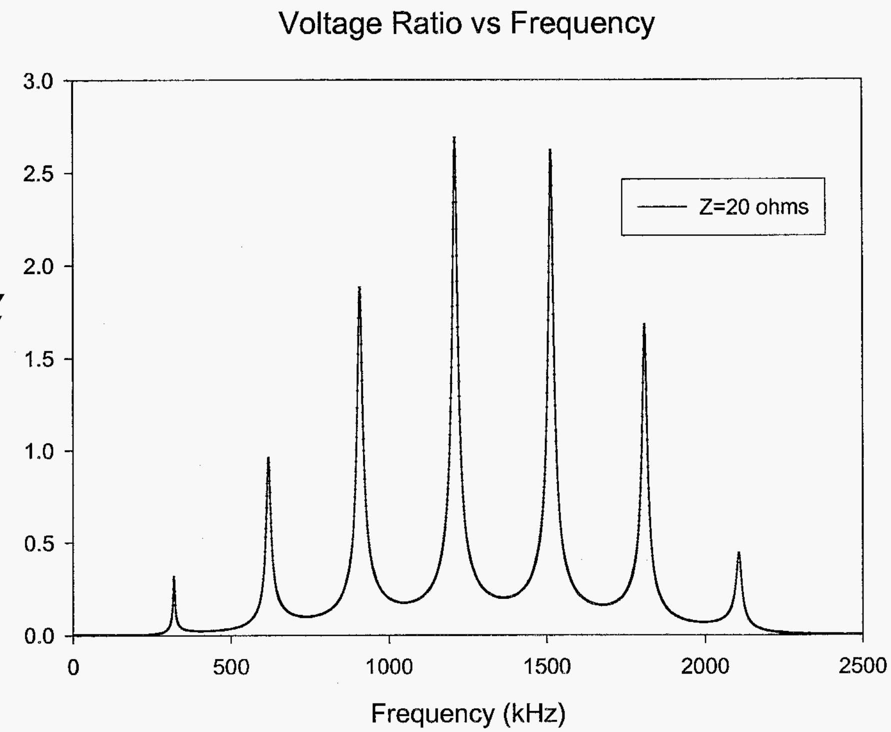
Example 3, Application of Hard PZT with loss

Table 4. Data used to study the acoustic-electric feedthrough with measured coefficients for the piezoelectric (Morgan Matroc PZT-8). This material is a hard PZT with similar nominal properties to Navy III. The transmit and receive piezoelectric transducers were of the same material and head and tail masses were not used.

Property	Value
Density of Piezoelectric (kg/m^3)	7750
Density of wall (kg/m^3)	7850
Area of piezoelectric on wall (m^2)	0.01
Wall thickness (m)	0.006
Transmit Piezoelectric thickness (m)	0.002
Receive Piezoelectric thickness (m)	0.001
Piezoelectric Coefficient e_{33} (C/m^2)	$12.3(1+0.0015i)$
Permittivity (F/m) ε^S_{33}	$6.16x10^{-9}(1-0.003i)$
Elastic stiffness at constant Field c^E_{33} (N/m^2)	$16.1x10^{10}(1+0.002i)$
Thickness Coupling	$0.364(1+0.00063i)$
Elastic stiffness at constant Displacement c^D_{33} (N/m^2)	$18.6x10^{10}(1+0.0025i)$
Elastic stiffness of wall c_w (N/m^2)	$26.9x10^{10}(1+0.01i)$

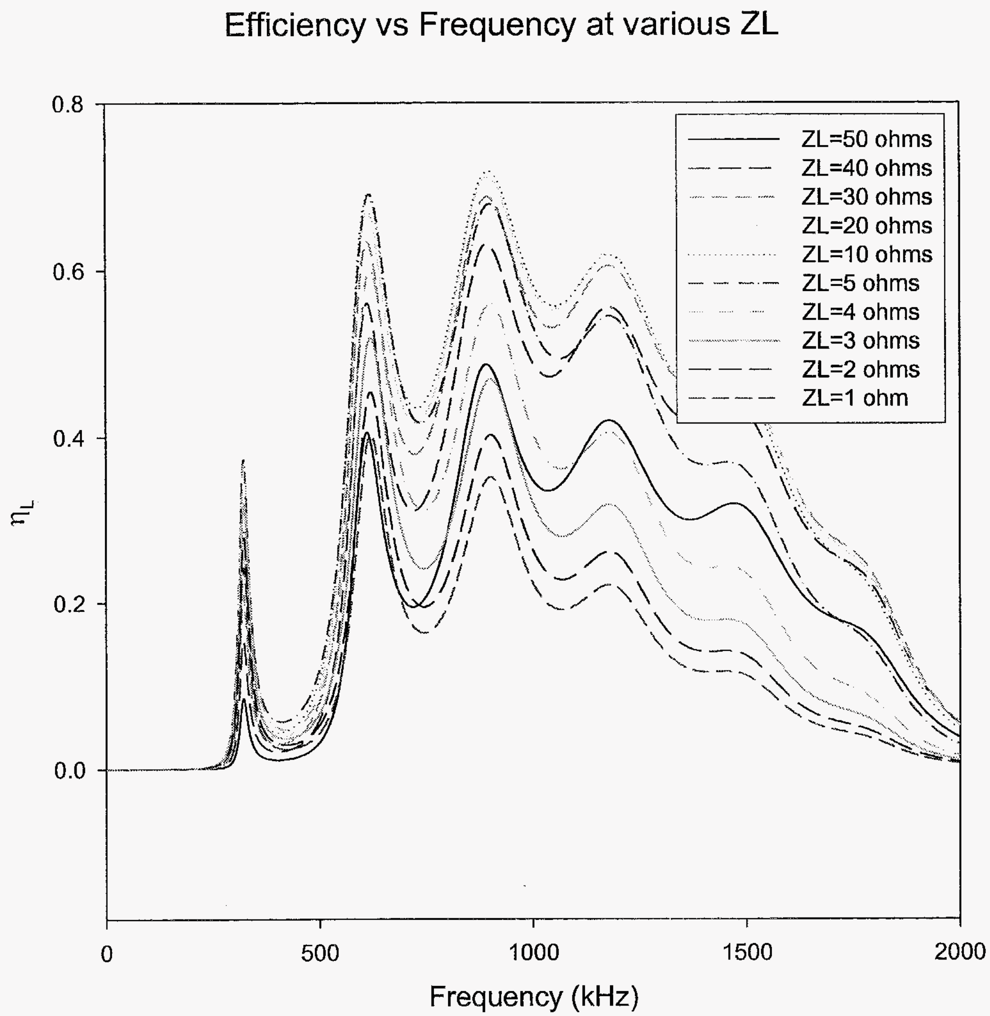
Example 3, Application of Hard PZT with loss

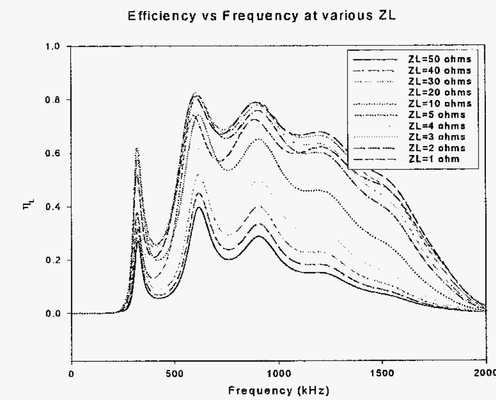




Using Hard PZT with loss lowers the Input admittance maximum and the maximum of the voltage gain further

Example 3, Application of Hard PZT with loss





Maximum of Power Efficiency reduced slightly at resonance and away from peaks with PZT- However hard PZT required for High power

Conclusions

- A equivalent network model for acoustic electric feedthrough was presented

- The model produced identical results of a more cumbersome model solved from the wave equation and linear piezoelectric Equations

- Accounting for dielectric and piezoelectric losses reduced the efficiency, voltage gain and input admittance

- Using hard PZT with loss reduced the efficiency, voltage gain and input admittance even further.

- The power efficiency is limited ultimately by the mechanical loss of the most "lossy" component