COMSOL CONFERENCE BOSTON 2012

Simulation of Acoustic Energy Harvesting Using Piezoelectric Plates in a Quarter-wavelength Straight-tube Resonator

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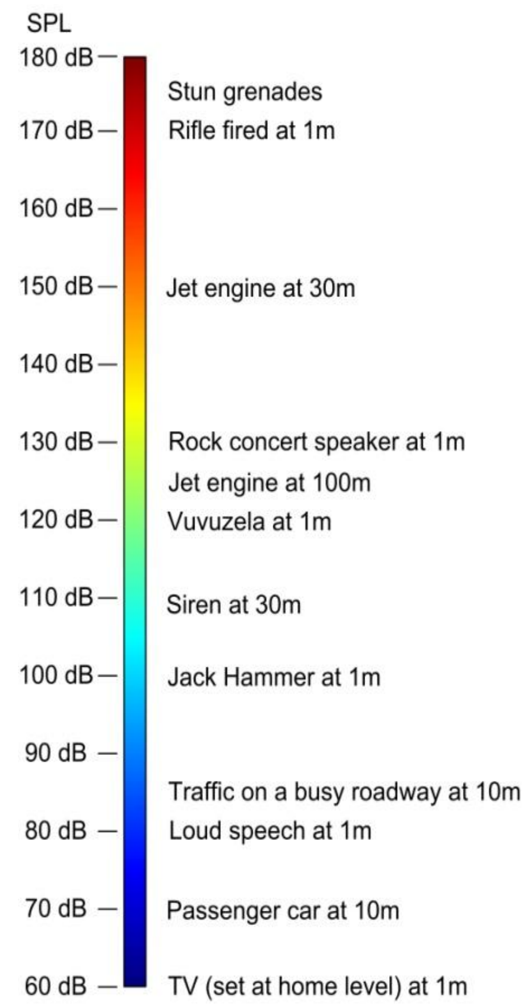
1. Acoustic energy

(1)Low energy density;

(2)Clean, renewable and abundant in our life;

(3)Currently wasted.

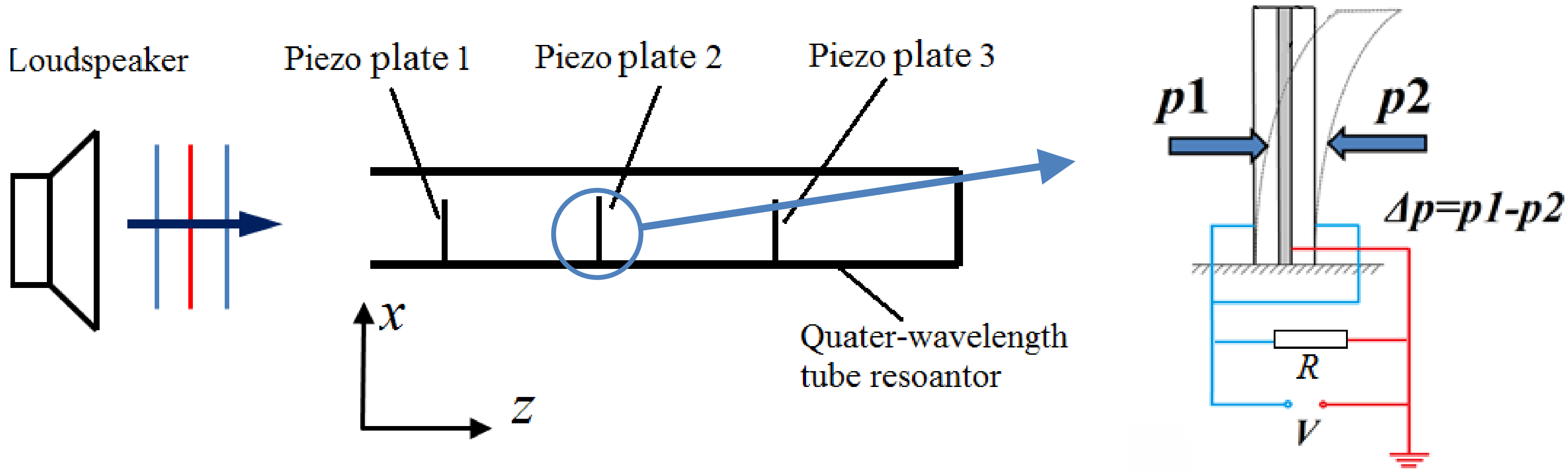
<u>Various sound sources</u>



2. Objective

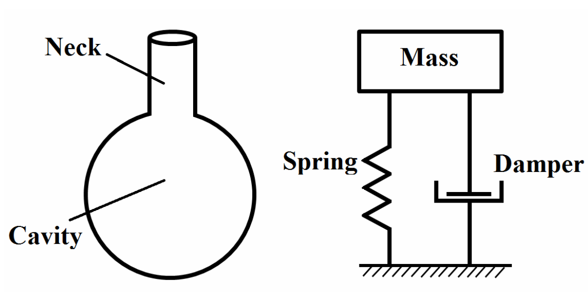
Develop an acoustic energy harvester:

- Low operating frequency(~190Hz)
- High efficiency



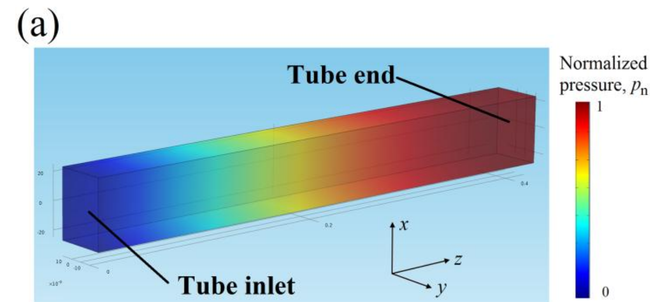
3. Acoustic resonator

Helmholtz resonator

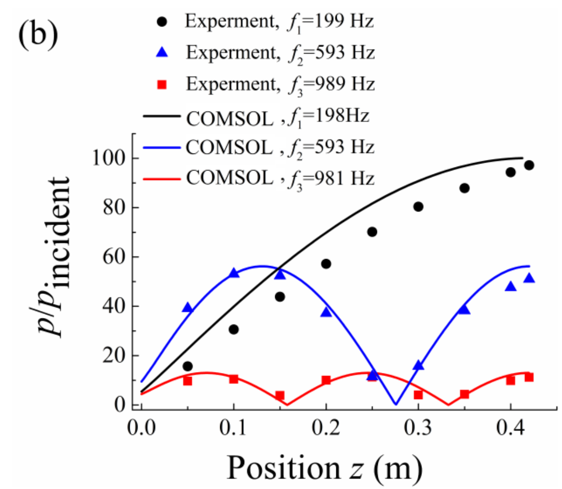


Reduce noise (architectural acoustics, aircraft engines)

42 cm quarter-wavelength tube resonator

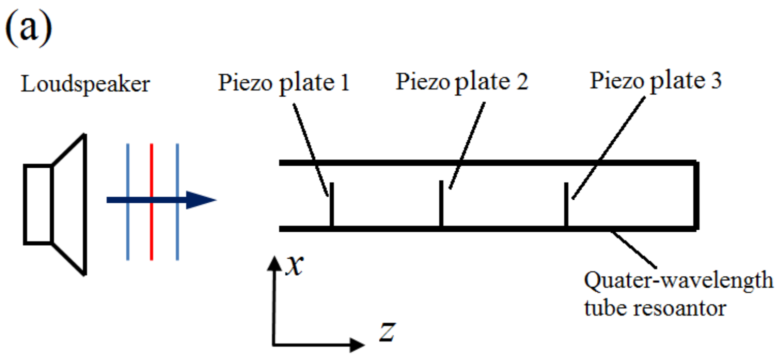


1st eigemode shape

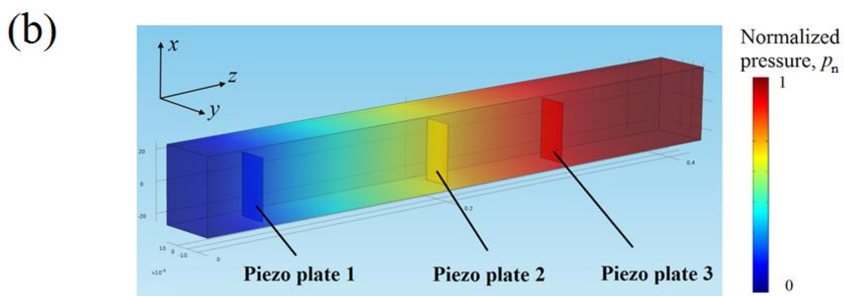


Magnitudes of normalized first three acoustic pressure eigenmodes

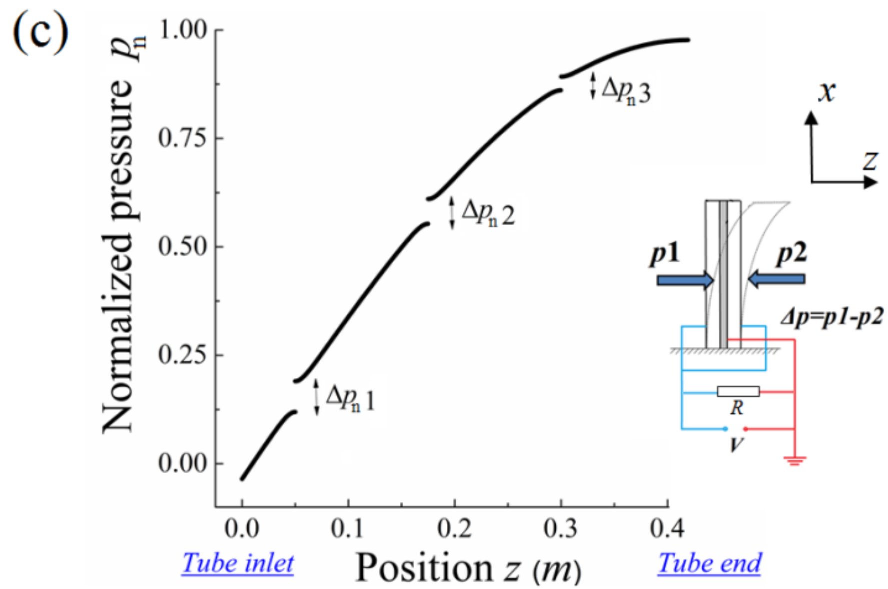
4. Acoustic energy harvesting mechanism



Piezo cantilever plates in a 42 cm long quarter-wavelength tube resonator (operating frequency is ~190 Hz)

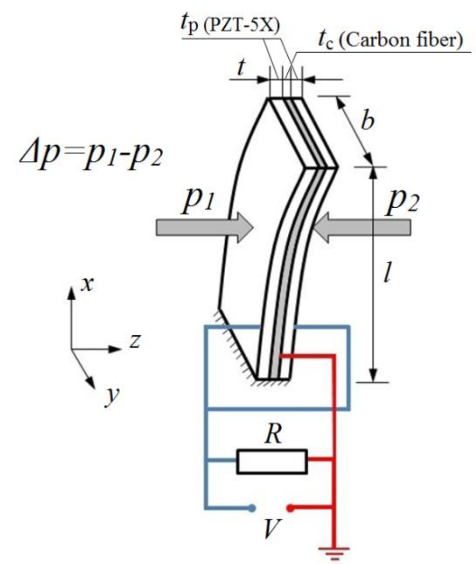


Eigenmode shape with 3 piezo plates



Normalized pressure with 3 piezo plates

5. Piezo energy conversion (PZT)



Kirchoff's Voltage Law:

$$\sigma_{\text{in}} = \sigma_i + \sigma_d + \sigma_s + \sigma_p,$$

Output power:

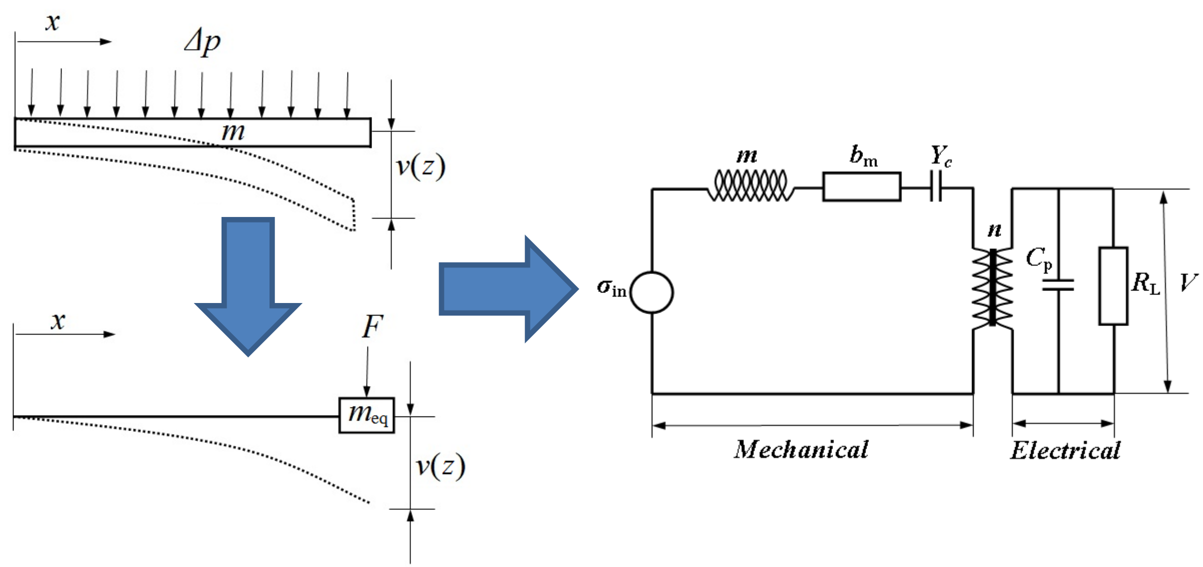
$$P = \frac{(\omega_n d t_p / \varepsilon)^2 R C_p{}^2}{(\omega_n R^2 C_p{}^2 (4\zeta^2 + k^4) + 4\zeta^2 + 4k^2 \zeta \omega_n R C_p} \times$$

$$(\frac{t_c l^2 b}{6I} \Delta p)^2,$$

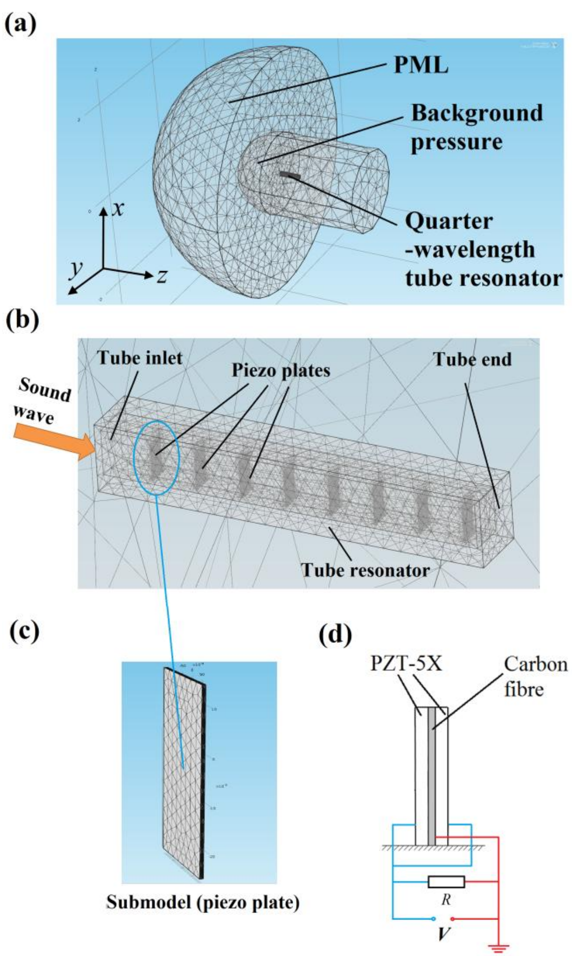
$$\frac{\partial P}{\partial R} = 0,$$

Optimized loading resistance:

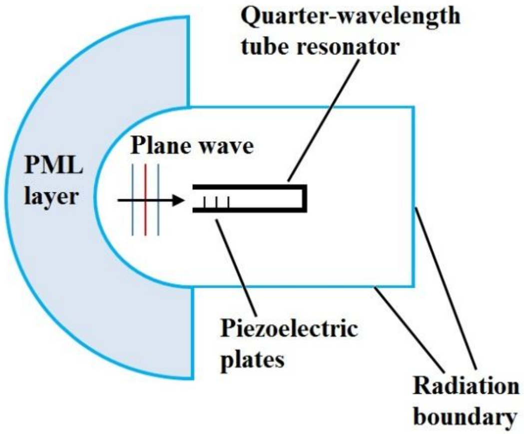
$$R_{opt} = \frac{1}{\omega_n C_p} \frac{2\zeta}{\sqrt{4\zeta^2 + k^4}}.$$



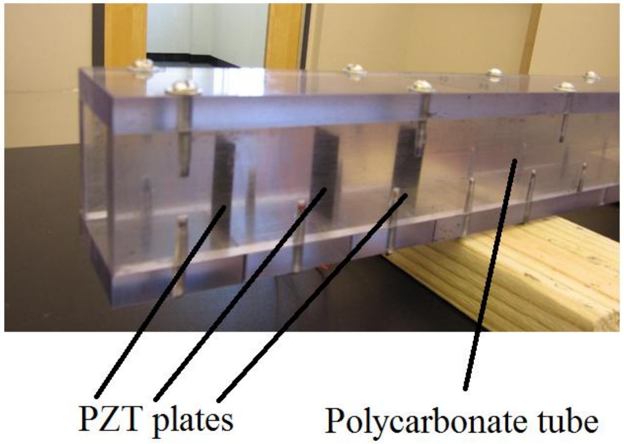
6. Use of COMSOL Multiphysics and experiment apparatus



Finite element model

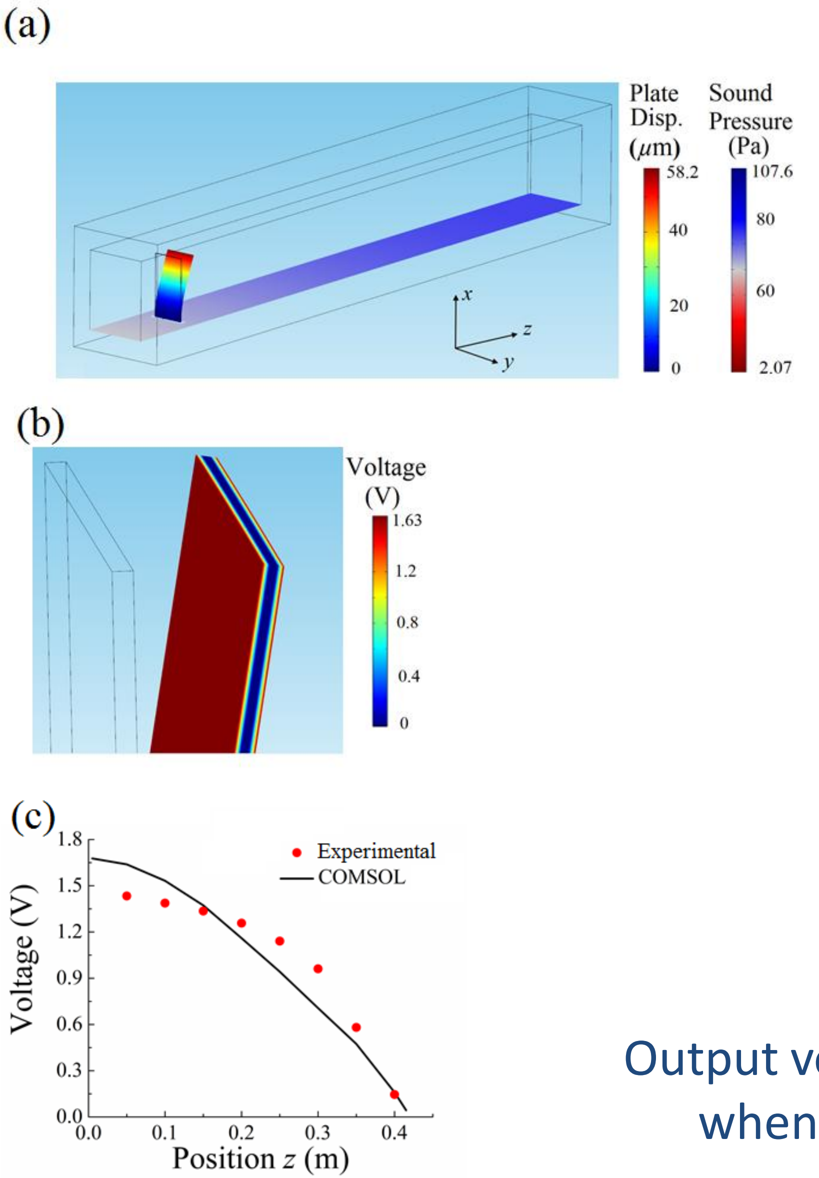


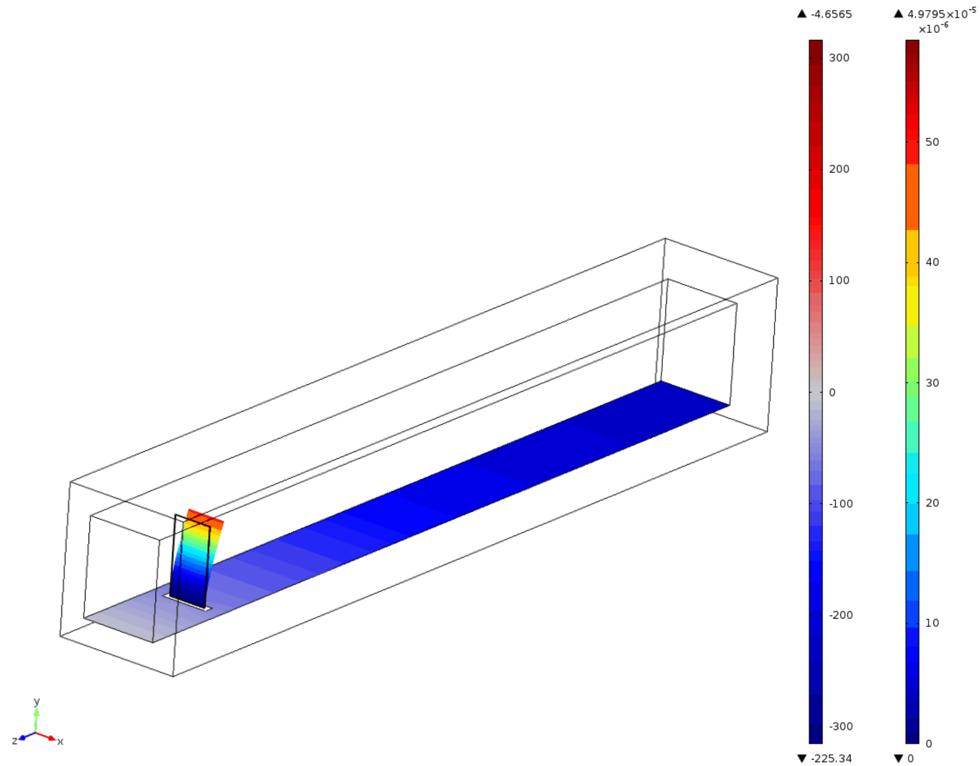
Boundary conditions



Experimental apparatus

7. 1 piezo plate placed inside the tube resonator





Output voltage of the piezo plate decreases when moving to the tube closed end

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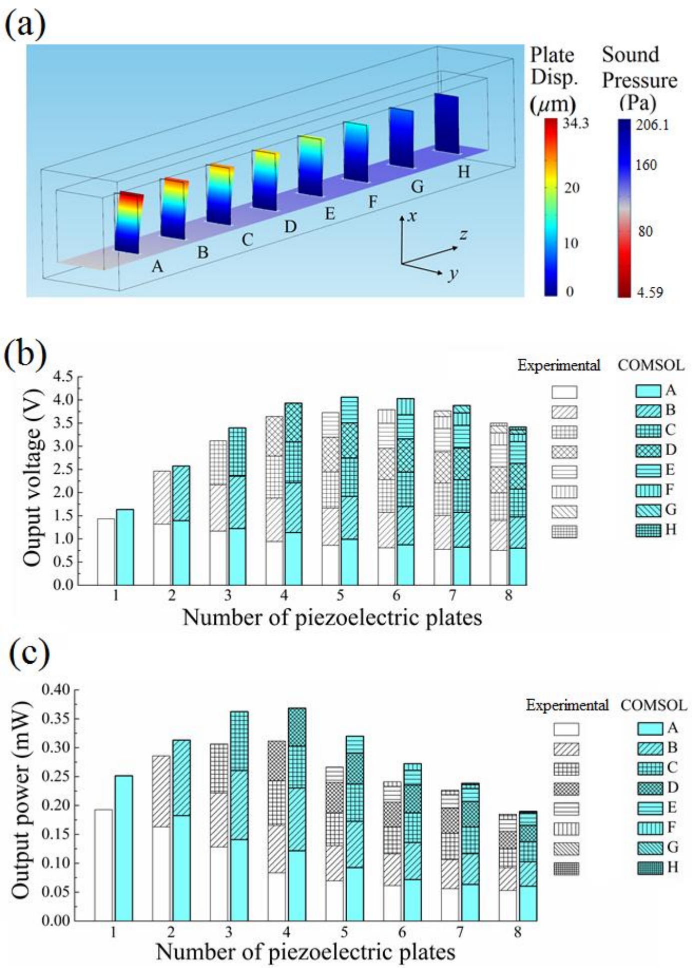
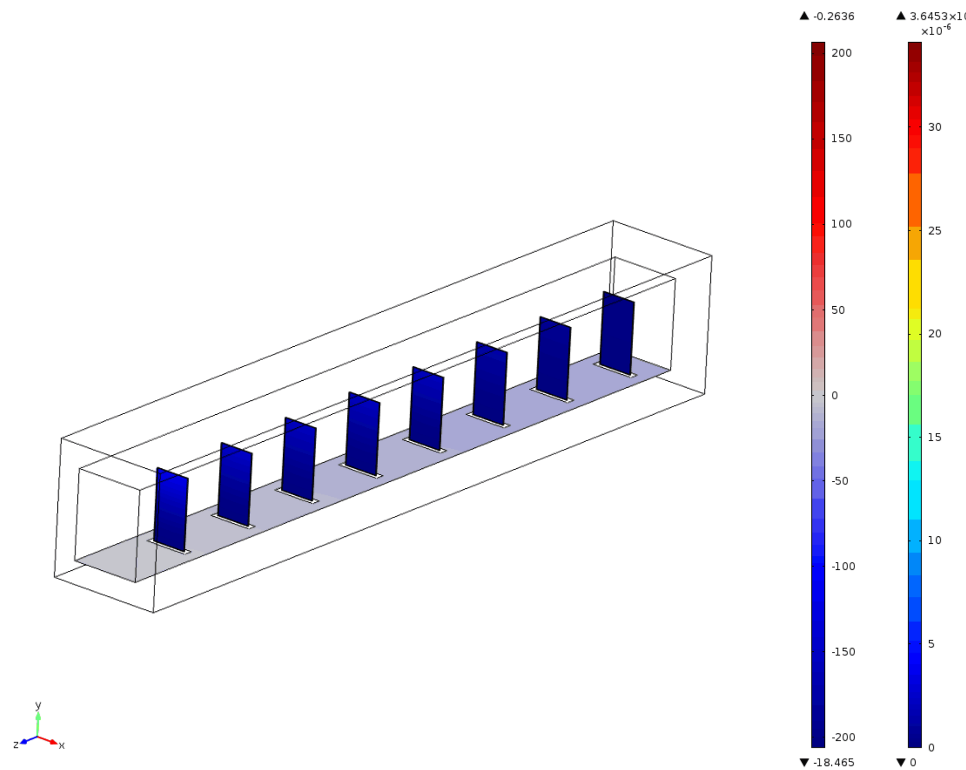
7. 8 piezo plates placed along the whole tube



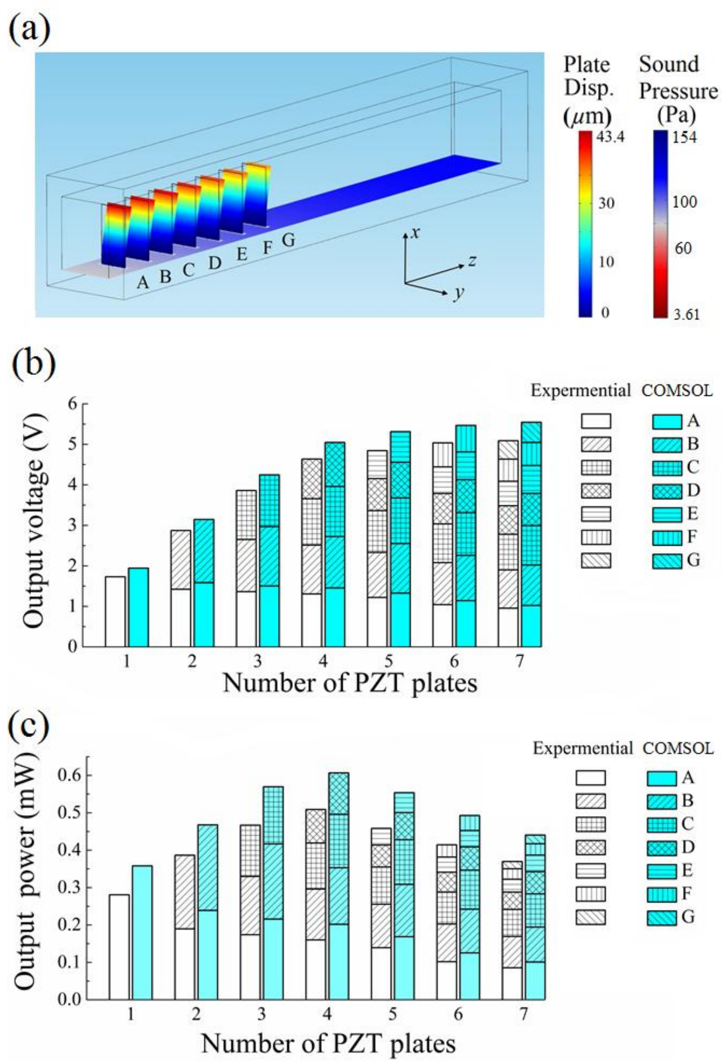


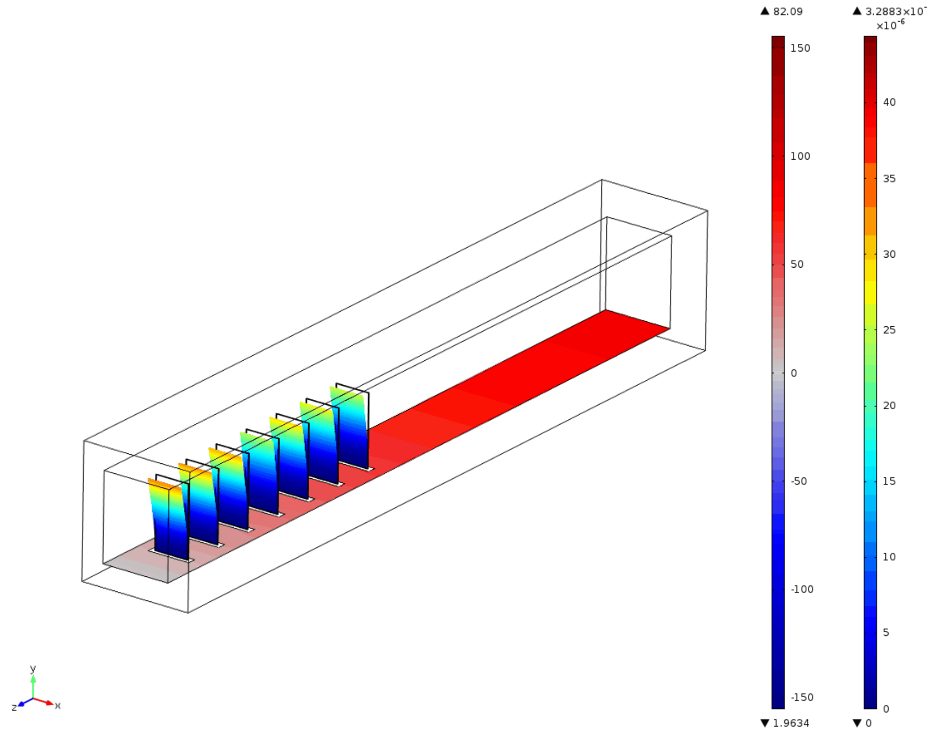
Experiment and simulation reach maximum *0.311 mW* (at 194Hz) and *0.369 mW* (at 190 Hz) for 4 PZT plates from A to D positions

The summation of power:

($\sum V_i/R_{opt}$, i=1, 2,…)

7. 7 piezo plates placed inside the first half of the tube





Experiment and simulation reach maximum *0.509 mW* (at 191Hz) and *0.605 mW* (at 188 Hz) for 4 PZT plates from A to D positions

8. Conclusion

(1) Acoustic energy harvesting mechanism is developed at low operating frequency (~190 Hz) using a quarter-wavelength straight-tube resonator with multiple piezoelectric cantilever plates;

(2) The number of plates to generate the maximum voltage and power are limited by the interruption of acoustic air particle motion caused by the presence of plates;

(3) Experiment and simulation reach maximum 0.509 mW (at 191Hz) and 0.605 mW (at 188 Hz) for 4 PZT plates placed in the first half of the tube resonator.

Backup slide

Table 1: Structure and material properties of PZT piezoelectric plate and polycarbonate.

Type	Symbol	Value
Piezo plate size		
Height	l	4 cm
Width	b	2 cm
Total thickness	t	0.7 mm
Piezo plate structure		
PZT layers	t_p	0.48 mm
Carbon fiber	t_c	0.22 mm
Piezo plate's capacitance	C_p	75 nF
PZT's Piezo constant	d31 d33	750 pC/N -320 pC/N
PZT relatively permittivity	ε/ε0	4500
PZT Young's modulus	E_p	40 GPa
PZT density	ρ_p	7400 kg/m^3
PZT damping ratio	ζ	0.025
Carbon fiber's Young's modulus	E_c	2 GPa
Polycarbonate's density	ρ_p	1175 kg/m^3
Polycarbonate's Young's modulus	E_{pc}	2.2 GPa

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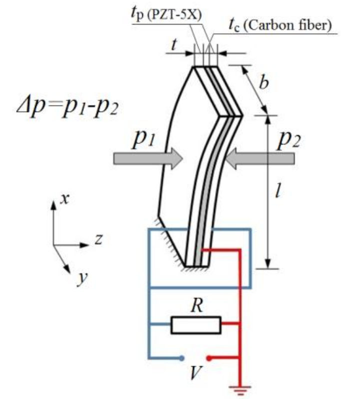

$$\sigma_{\text{in}} = \sigma_i + \sigma_d + \sigma_s + \sigma_p$$

$$\sigma_s = E\delta$$

$$\sigma_{in} = \frac{1}{l}\int_0^l \frac{M_p(x)t_c}{I}dx$$

$$\sigma_p = \frac{-dE}{t_p}V$$

$$v(\tau, x) = \frac{bx^2(6l^2 + 4lx + x^2)}{24EI}\Delta p$$

$$V_{mag.} = \frac{\omega_n RC_p dt_p / \varepsilon}{\sqrt{R^2 C_p{}^2 \omega_n{}^2 (4\zeta^2 + k^2) + 4\zeta^2 + 4\zeta k^2 \omega_n RC_p}} \left(\frac{t_c l^2 b}{6I}\right)\Delta p$$

$$dG_k = \frac{\dot{v}(\tau, x)^2}{2}\frac{mdx}{l}$$

$$P = \frac{V_{mag.}^2}{R} = \frac{(\omega_n dt_p / \varepsilon)^2 RC_p{}^2}{\omega_n{}^2 R^2 C_p{}^2 (4\zeta^2 + k^4) + 4\zeta^2 + 4k^2\zeta\omega_n RC_p}\left(\frac{t_c l^2 b}{6I}\Delta p\right)^2$$

$$G_k = \int_0^l dG_k = \frac{\dot{v}(\tau, l)^2}{2} 0.257m$$

$$\sigma_i = \frac{m_{eq}}{c_1}\ddot{\delta}$$

$$R_{opt} = \frac{1}{\omega_n C_p}\frac{2\zeta}{\sqrt{4\zeta^2 + k^4}}$$

$$\sigma_d = \frac{\eta}{c_2}\dot{\delta}$$

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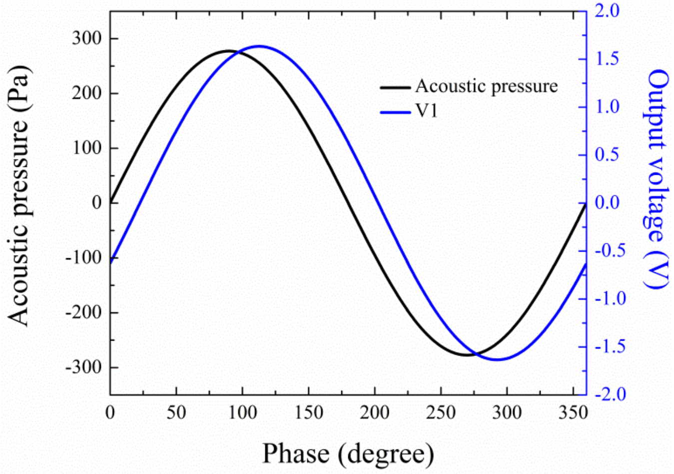

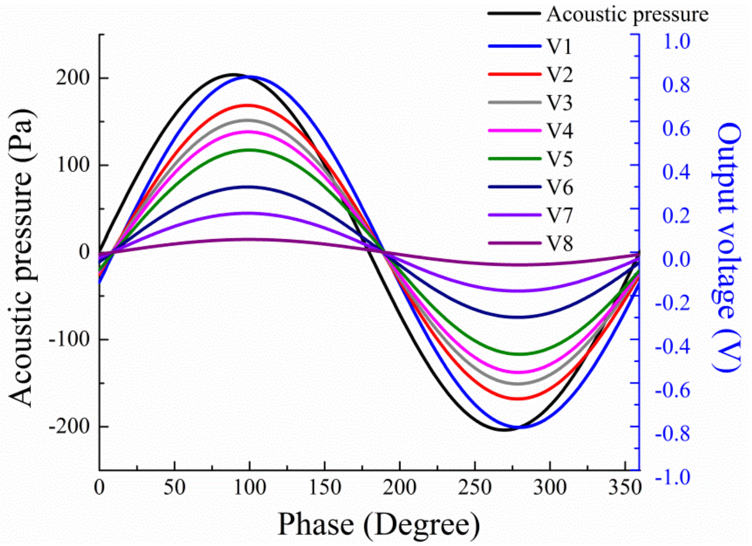

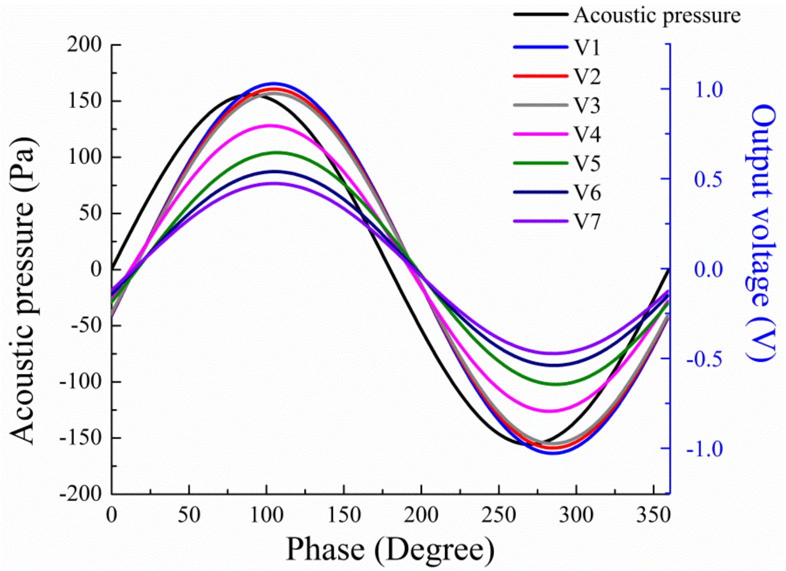

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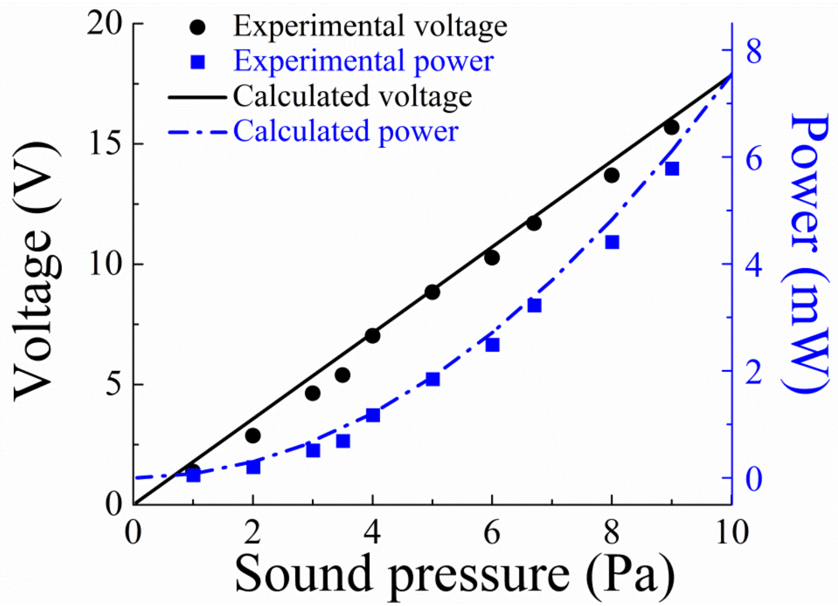

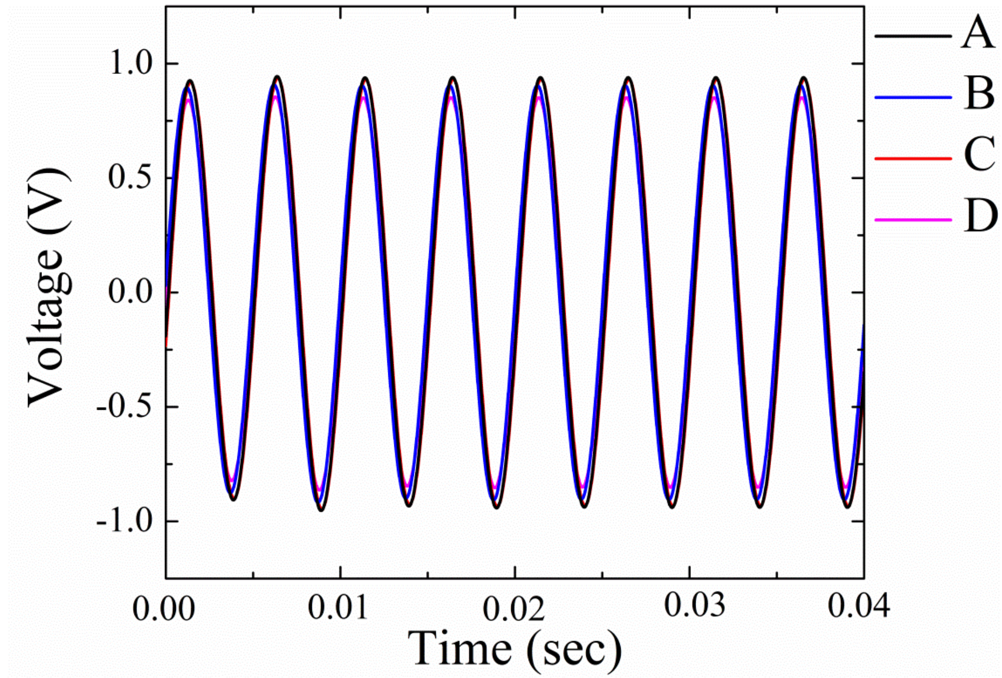

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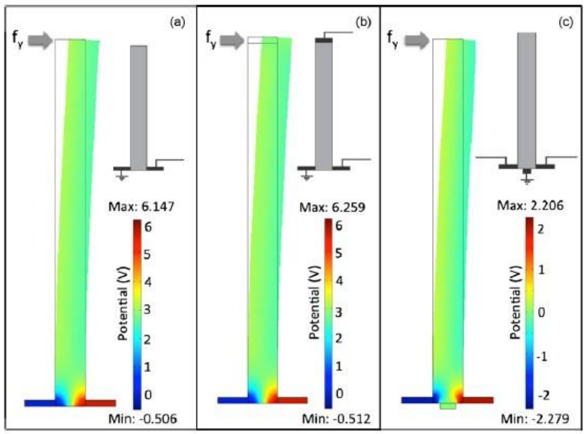
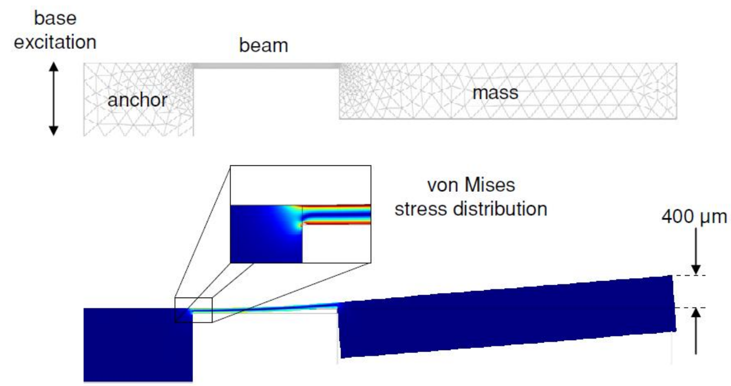
Piezoelectric nanowires



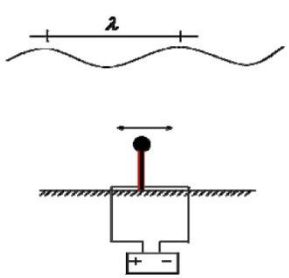
Falconi (2009)

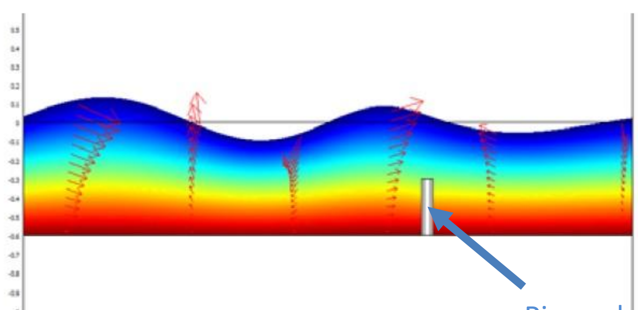
MEMS-based piezoelectric Harvesting devices



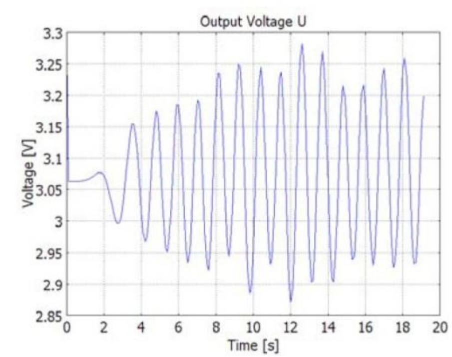
Kamel (2010)

Wave Energy Piezoelectric Converter





Piezo plate



Zurkinden (2007)