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Low-Frequency Energy Transmission across Material Interfaces using Incident Evanescent Waves

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Low-Frequency Energy Transmission across Material Interfaces using Incident Evanescent Waves

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West Lafayette, Indiana, USA

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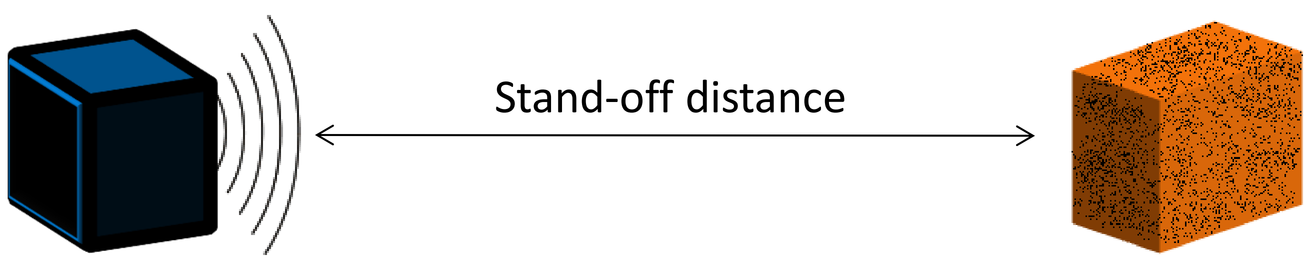
Premise and Motivation

- Detection of improvised explosive devices (IEDs)
- Strong dependence of vapor pressure on temperature
  - May improve detection capabilities by selective heating



Low-frequency source

Energetic material

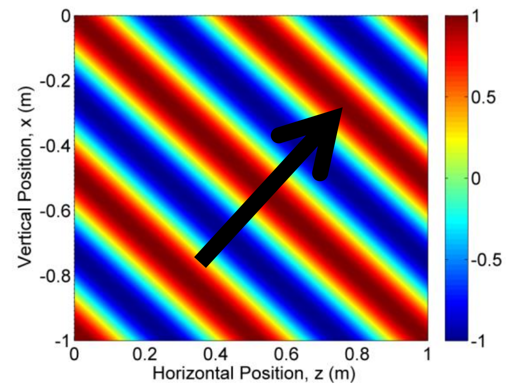
- Increase in temperature
- Increase in vapor pressure

Premise and Motivation

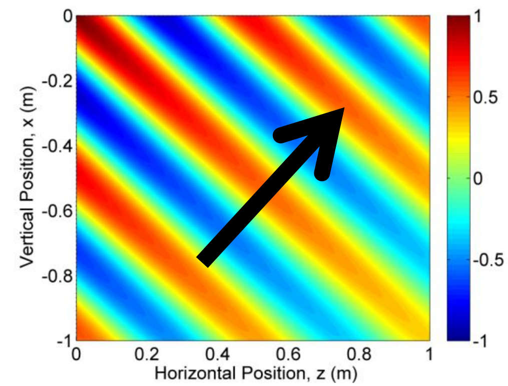
- High impedance-difference interfaces
- Methods for increased stand-off stress and energy transmission

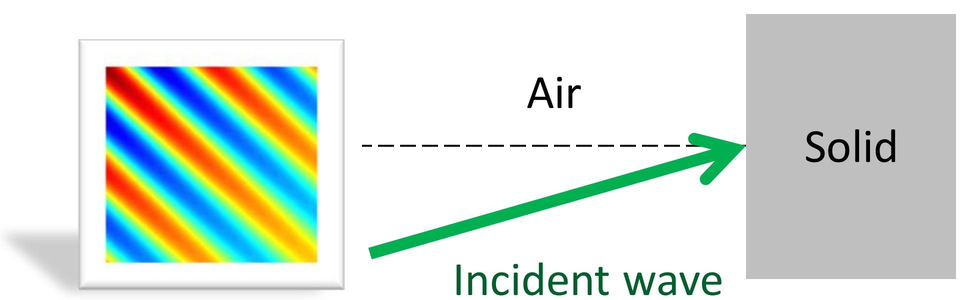
Pressure field (Pa)
1-Pa, 1000-Hz wave in air

Homogeneous plane wave

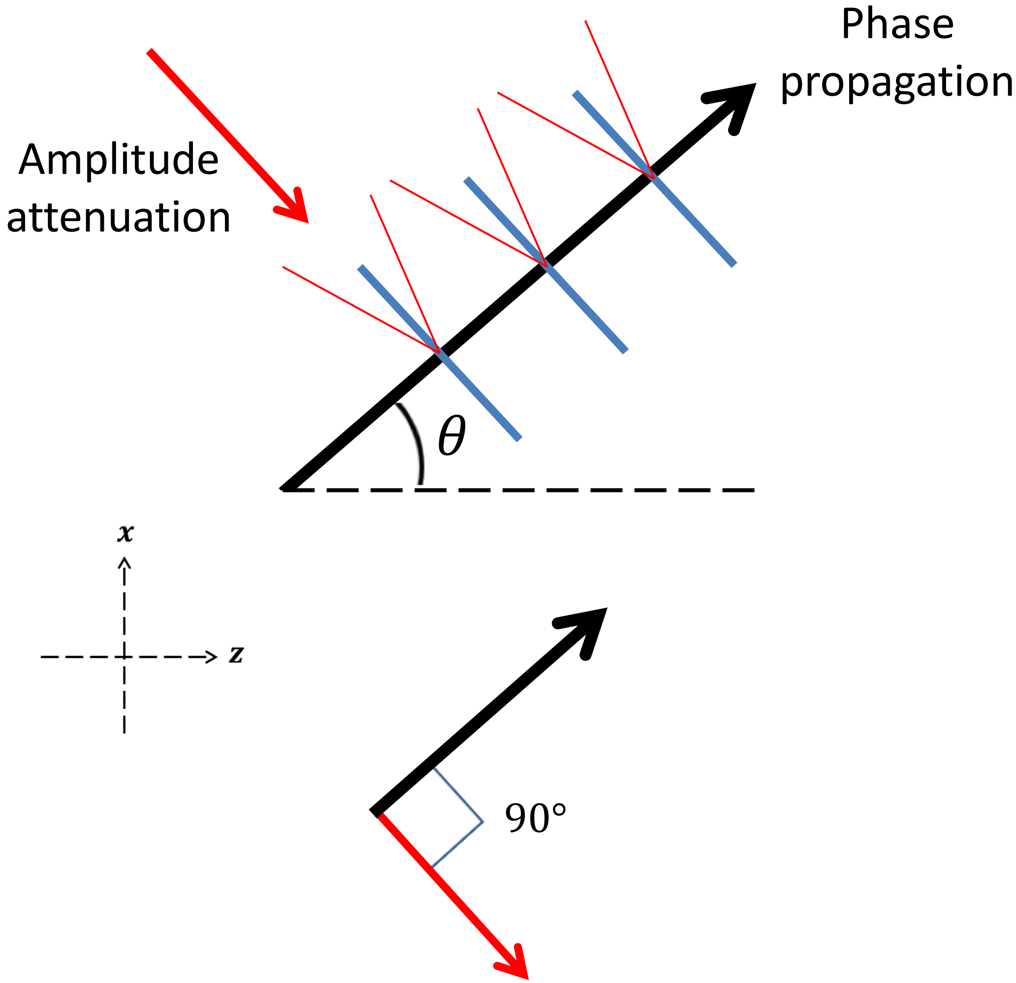


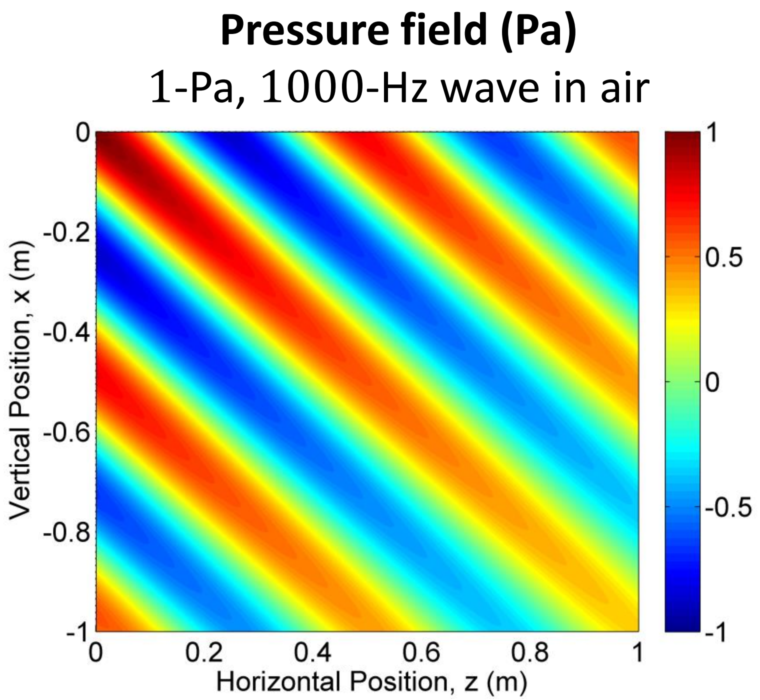
Evanescent plane wave





Evanescent Plane Waves





Evanescent Plane Waves

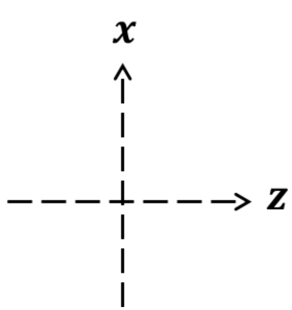
- Complex angle representation

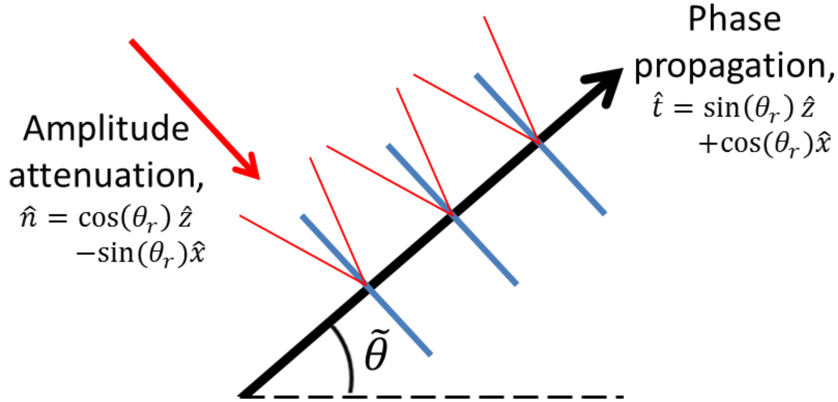
$$\tilde{\theta} = \theta_r + j\theta_i$$

$$\tilde{k}_x = k\cosh(\theta_i)\sin(\theta_r) + jk\sinh(\theta_i)\cos(\theta_r)$$
$$\tilde{k}_z = k\cosh(\theta_i)\cos(\theta_r) - j\boxed{k\sinh(\theta_i)}\sin(\theta_r)$$

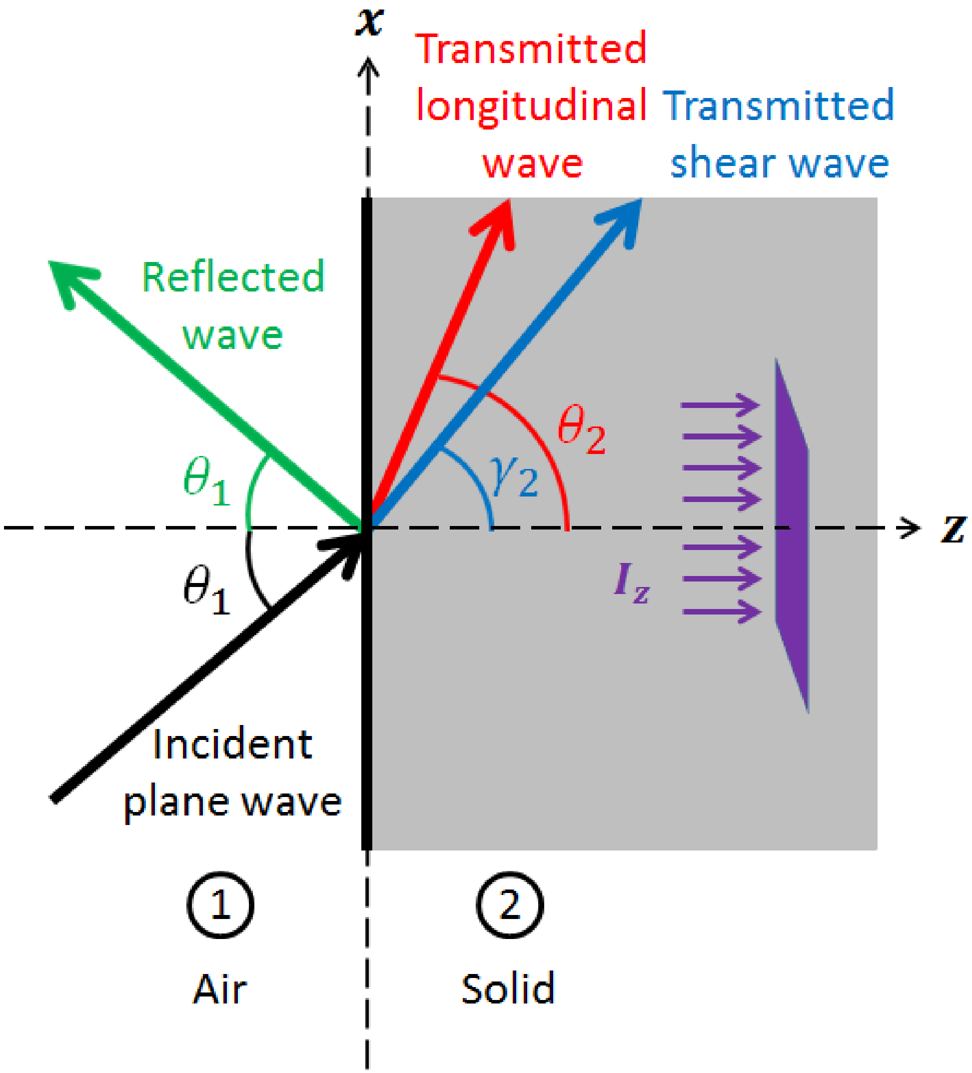
Evanescent decay parameter, β

$$\tilde{p} = \tilde{A}e^{-\beta\hat{n}\cdot\vec{r}}e^{-jk\cosh(\theta_i)\hat{t}\cdot\vec{r}}$$





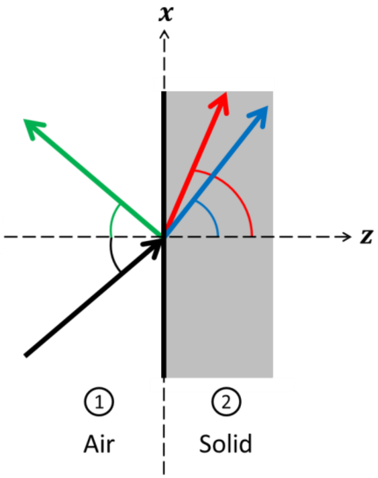
Air-Solid Interface



- Boundary conditions at interface ($z = 0$)
  - Generalized Snell's Law
- Mean energy flux in solid (normal component):

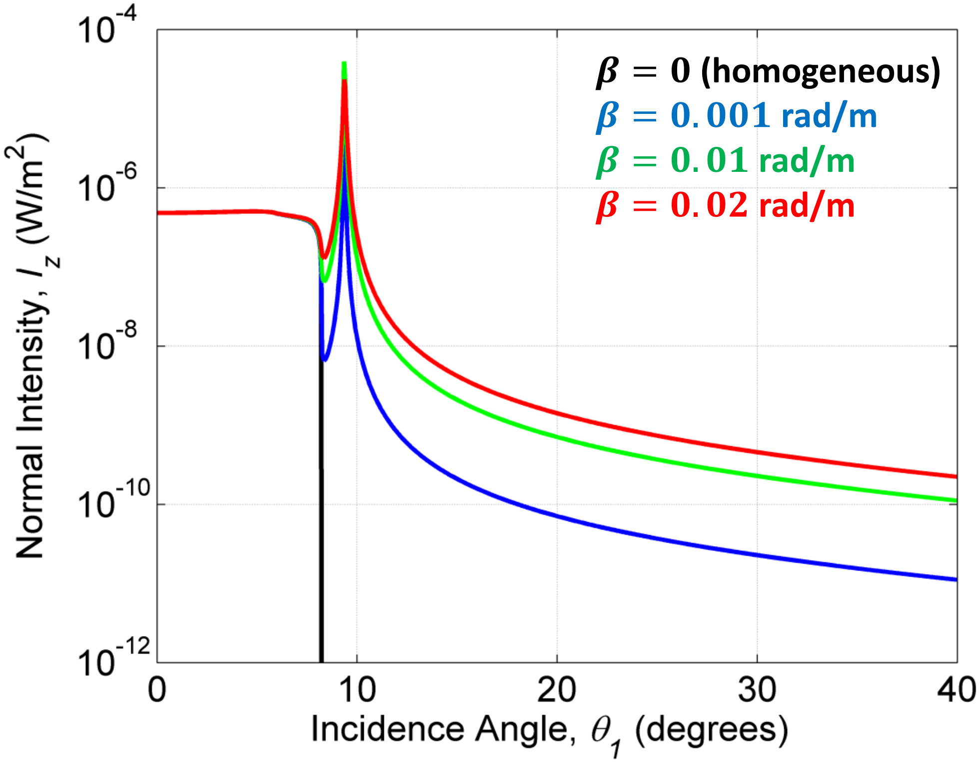
$$I_z = \frac{1}{T}\int_0^T -(\sigma_z v_z + \sigma_{xz} v_x)dt$$

Numerical Results: Air-Solid



Transmitted Normal Intensity (W/m²)

1-Pa, 1000-Hz incident wave



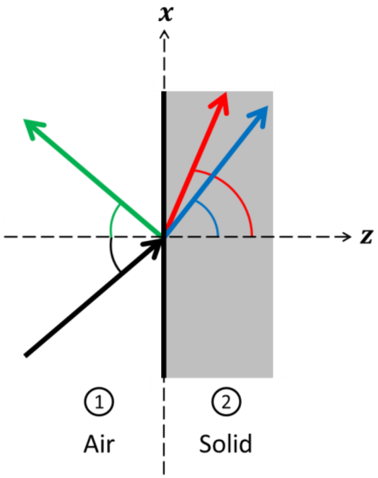
<u>Sample solid</u>

$\rho = 1000\rho_{air}$

$c = 10c_{air}$

$b = 7c_{air}$

Numerical Results: Air-Solid



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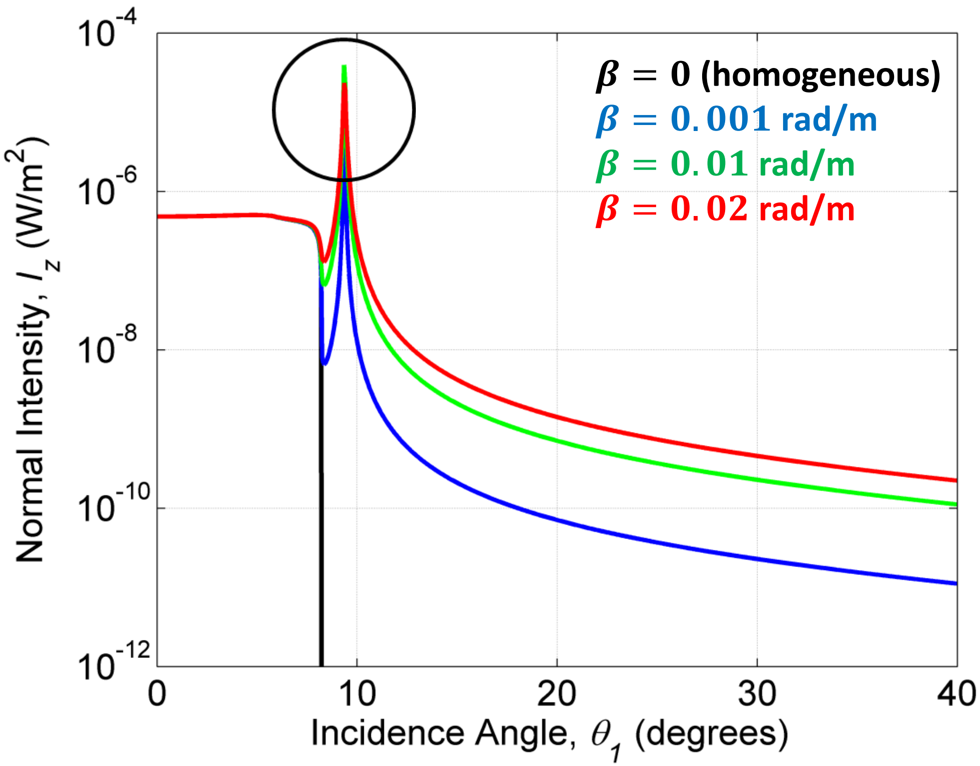
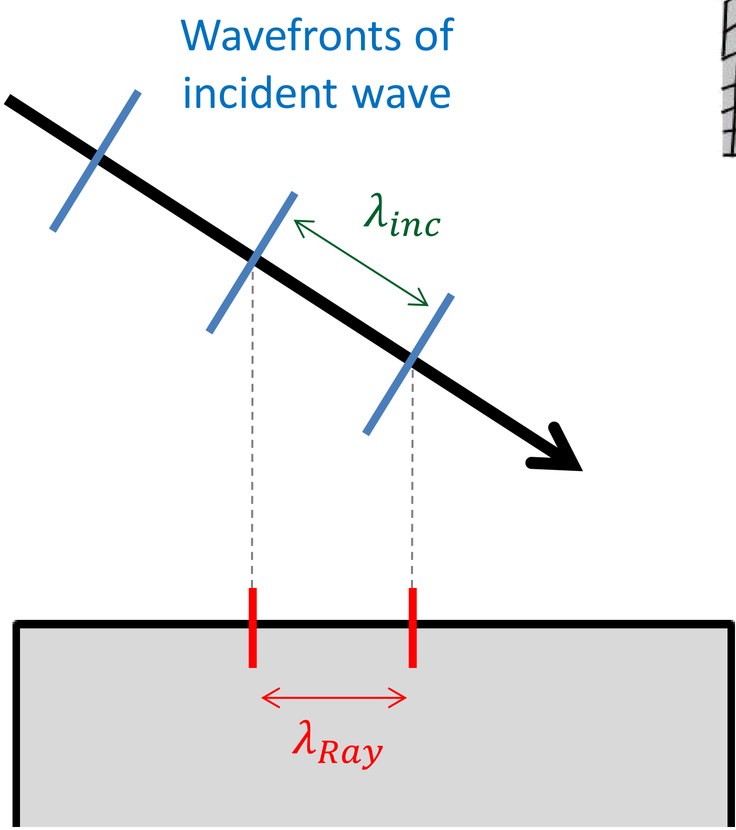
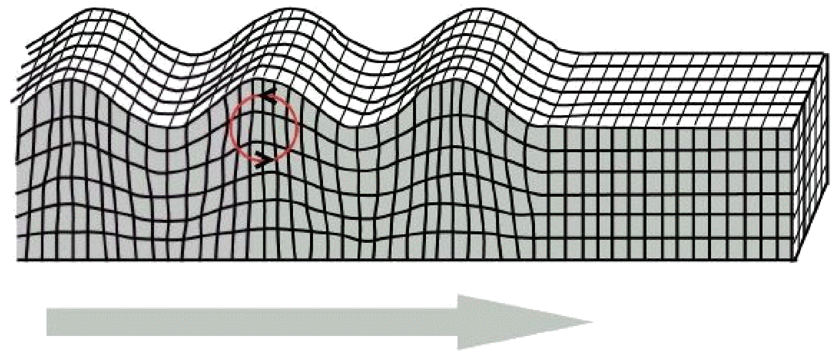
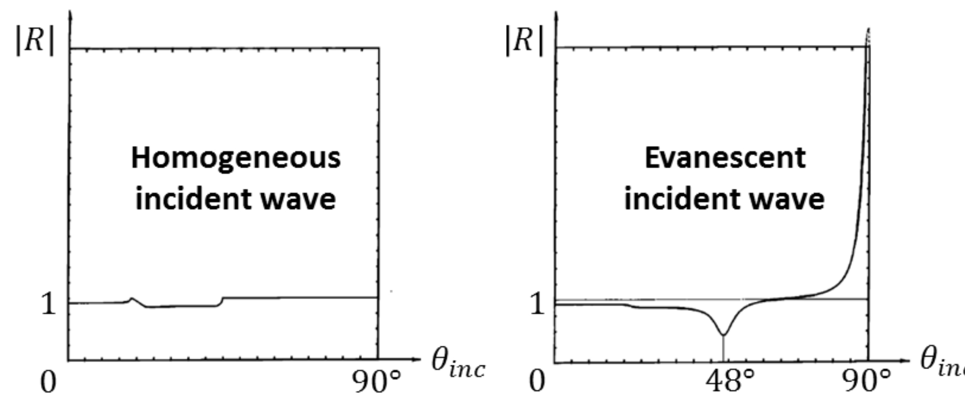


Rayleigh Angle Phenomenon



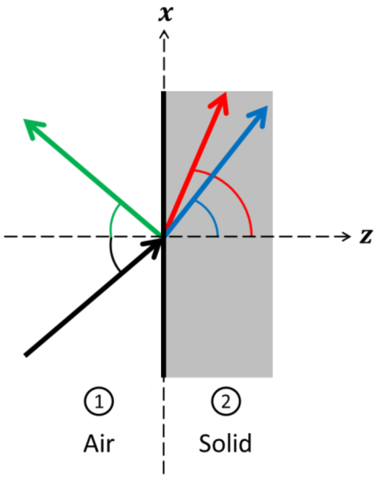


Spatial resonance of induced
longitudinal and shear particle motions
(*image: http://www.sjvgeology.org/oil/Rayleigh_surface_waves2.gif*)

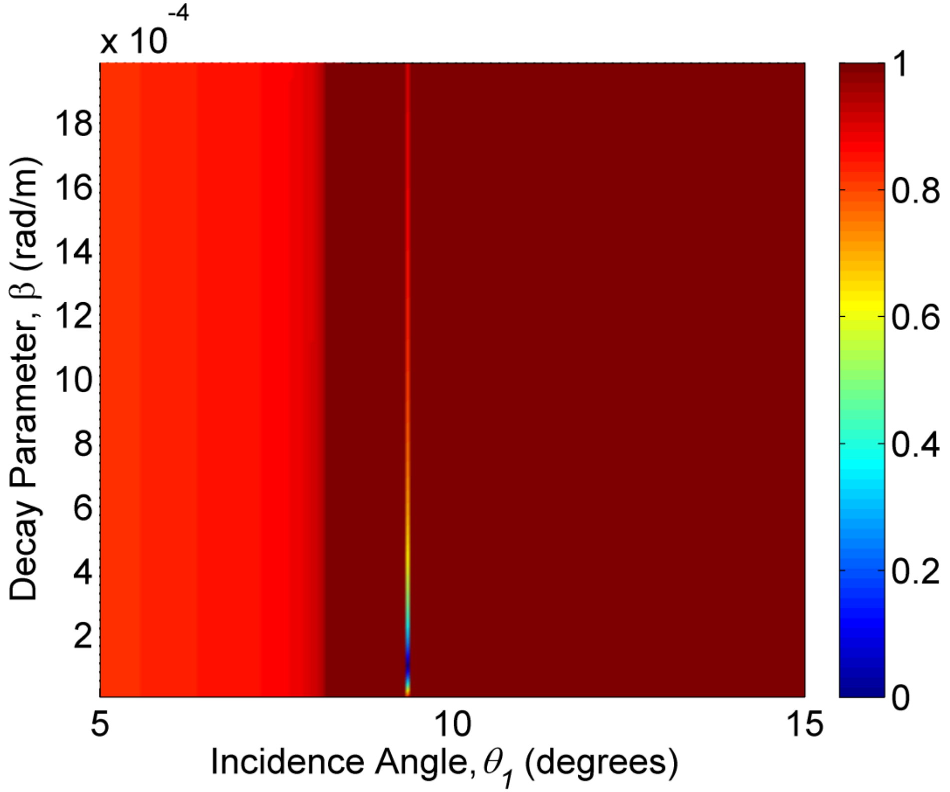


Magnitude of reflection coefficient
(adapted from *Leroy et al., 1988*)

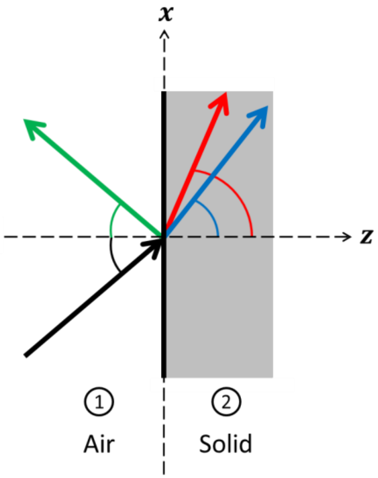
Numerical Results: Air-Solid



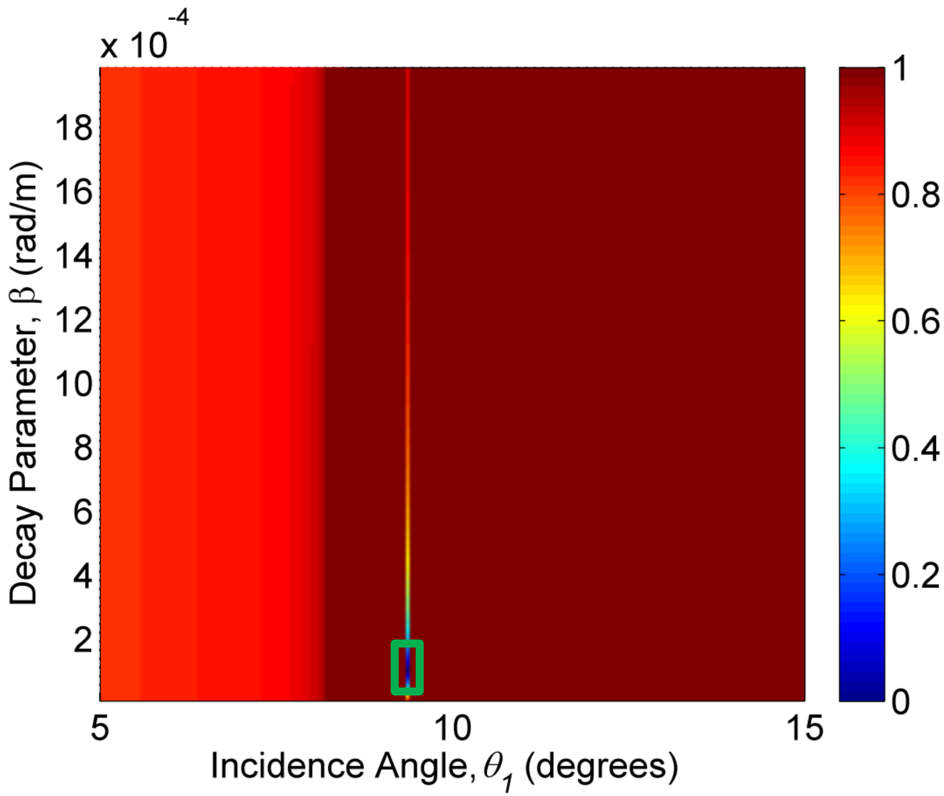
Magnitude of Reflection Coefficient
(1000 Hz)



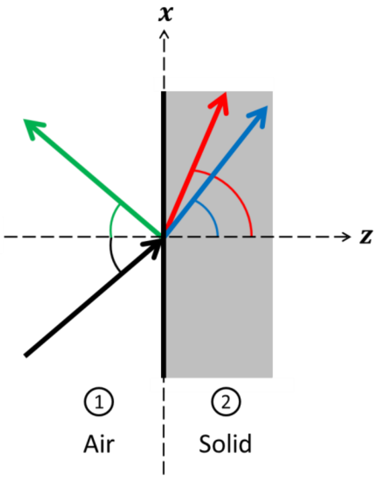
Numerical Results: Air-Solid



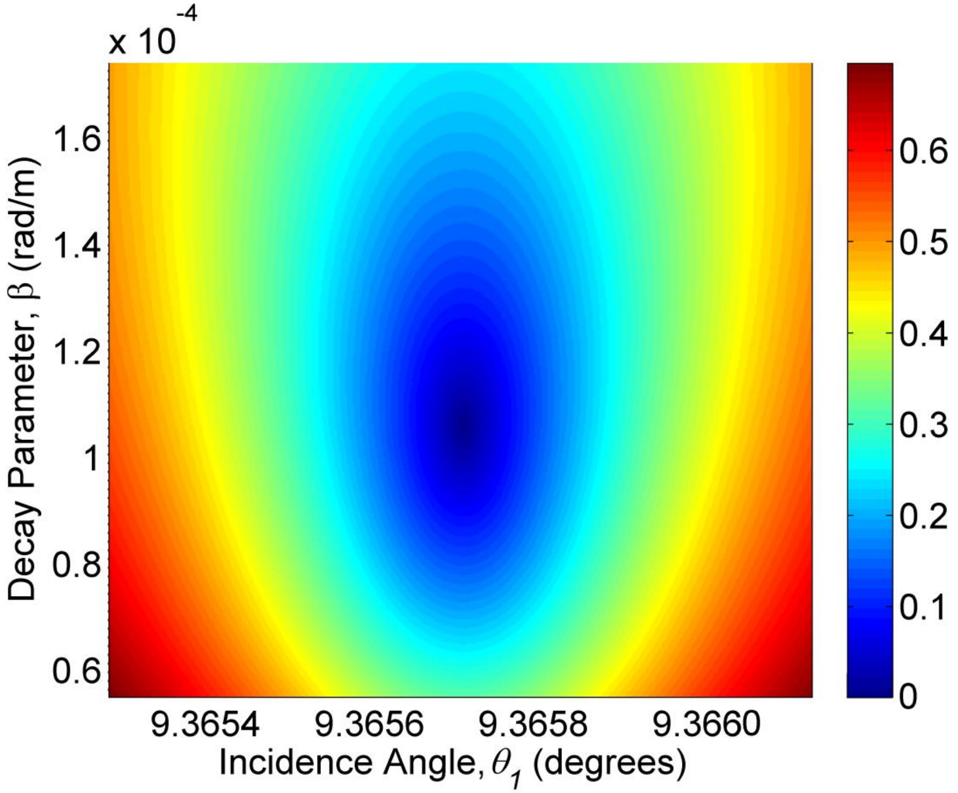
Magnitude of Reflection Coefficient
(1000 Hz)



Numerical Results: Air-Solid

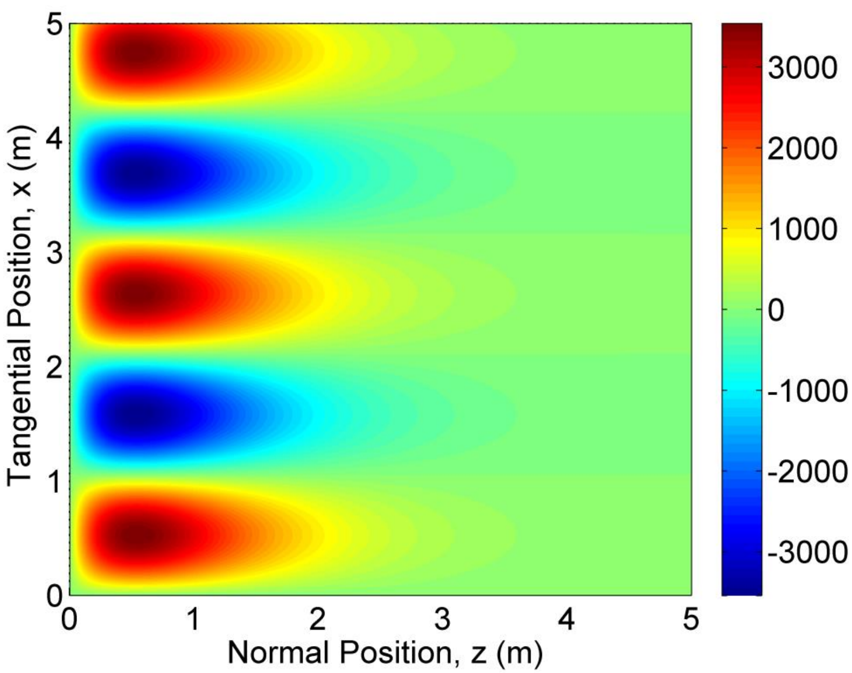


Magnitude of Reflection Coefficient Near Rayleigh Angle

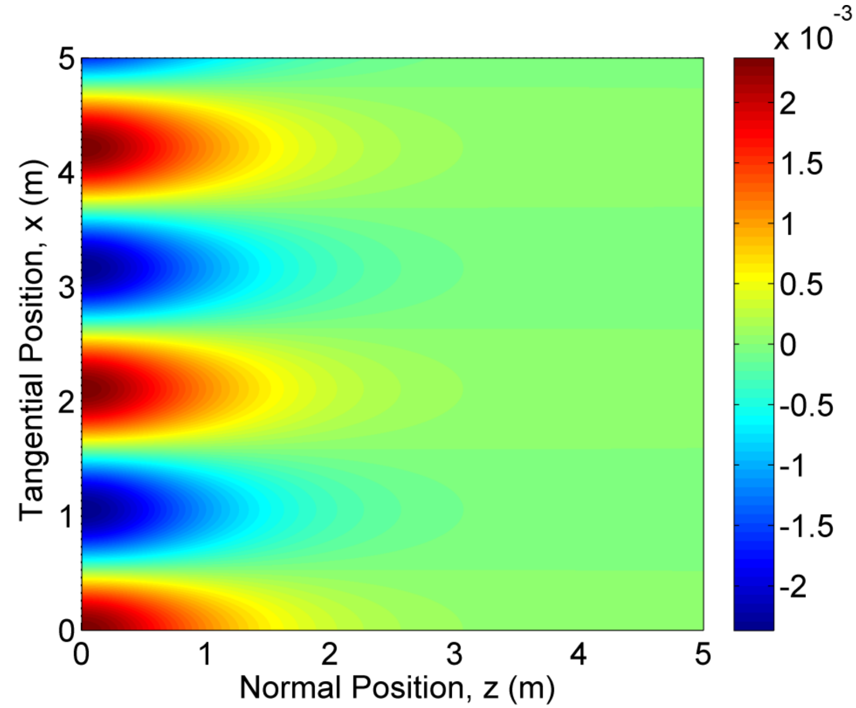


Numerical Results: Air-Solid

Transmitted Normal Stress (Pa)



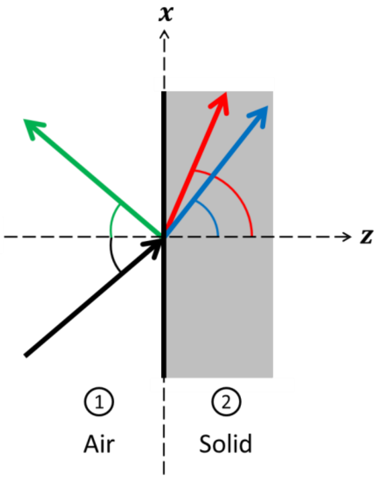
Transmitted Normal Velocity (m/s)



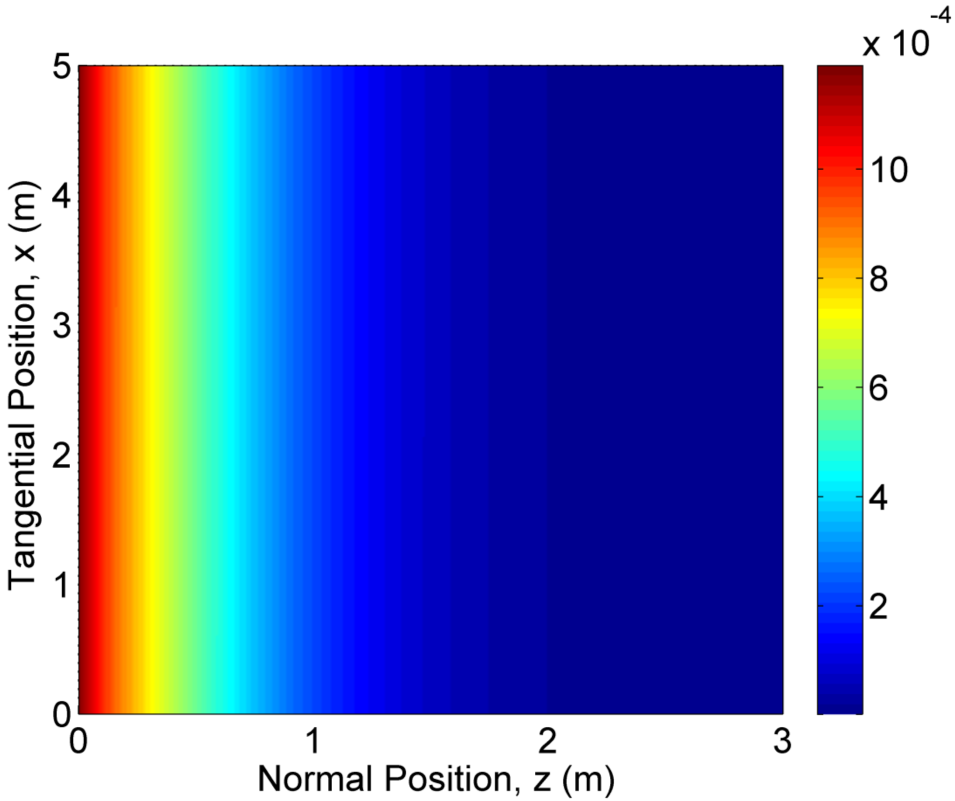
Approximate parameters for $|\widetilde{R}| = 0$

$\theta_1^* \approx 9.3657°, \beta^* \approx 1.07 \times 10^{-4}$ rad/m

Numerical Results: Air-Solid

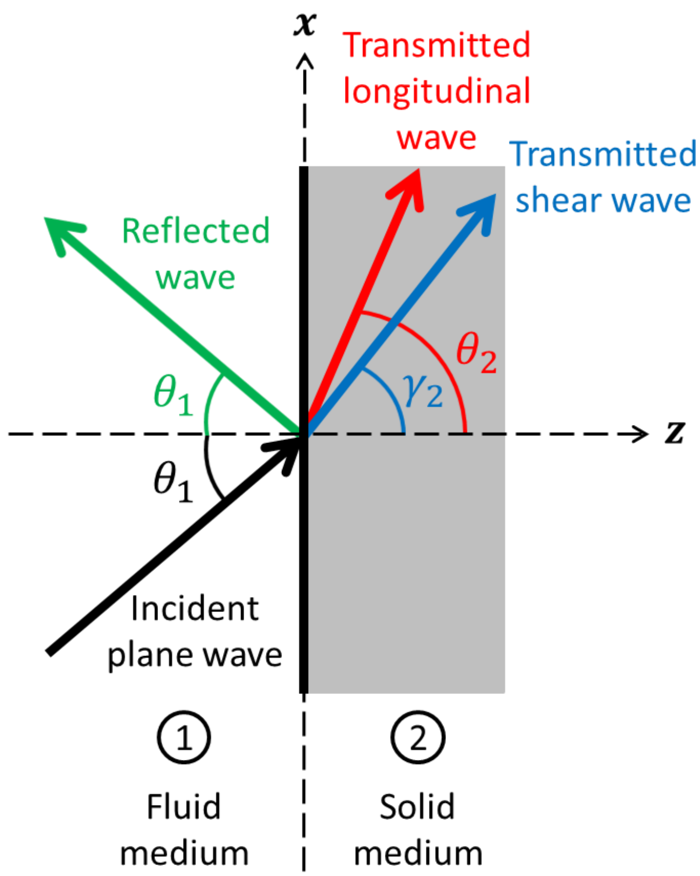


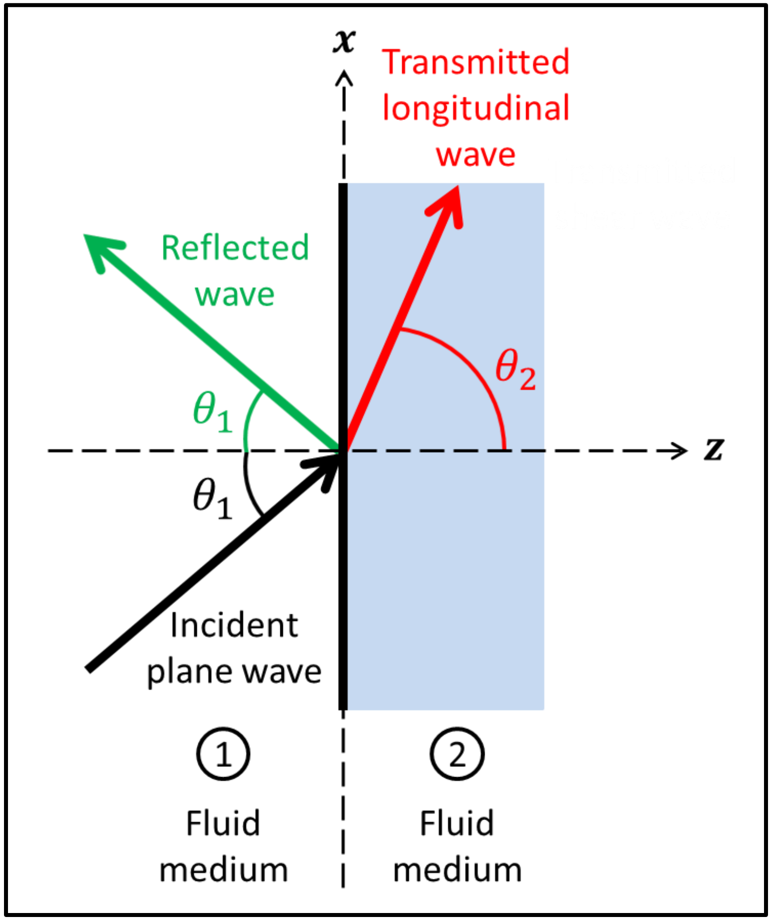
Transmitted Normal Intensity (W/m²)



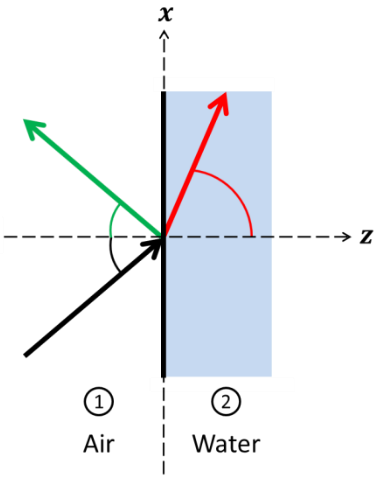
Compare with $\sim 5 \times 10^{-7}$ W/m² for homogeneous waves below the critical angle

Material Interfaces



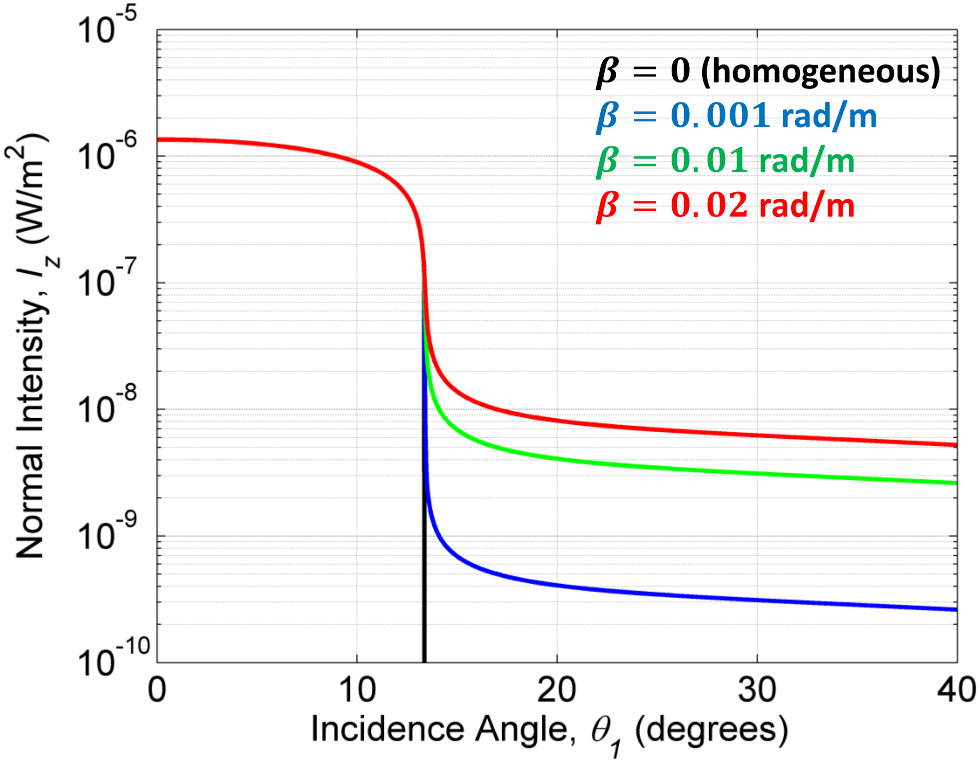


Numerical Results: Air-Water



Transmitted Normal Intensity (W/m²)

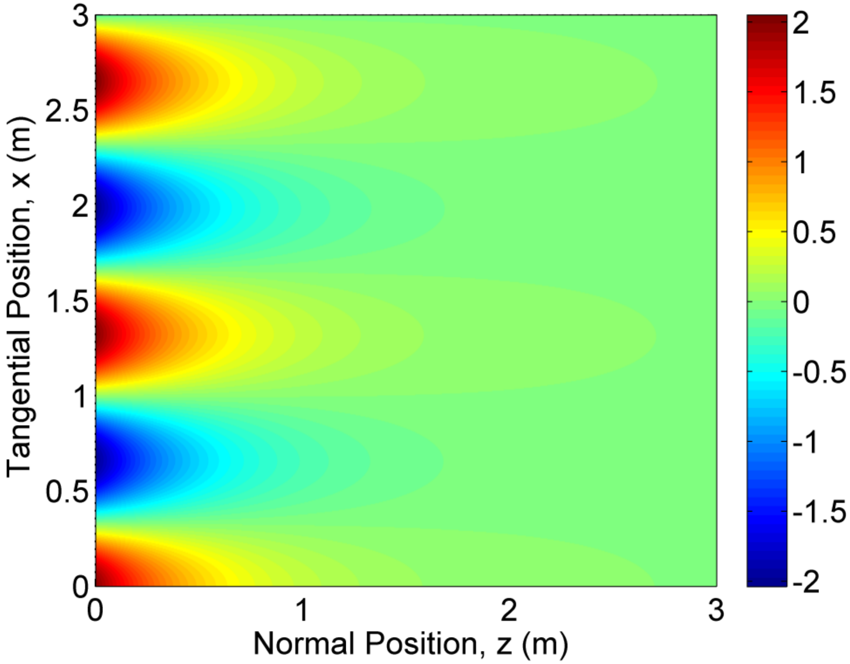
1-Pa, 1000-Hz incident wave



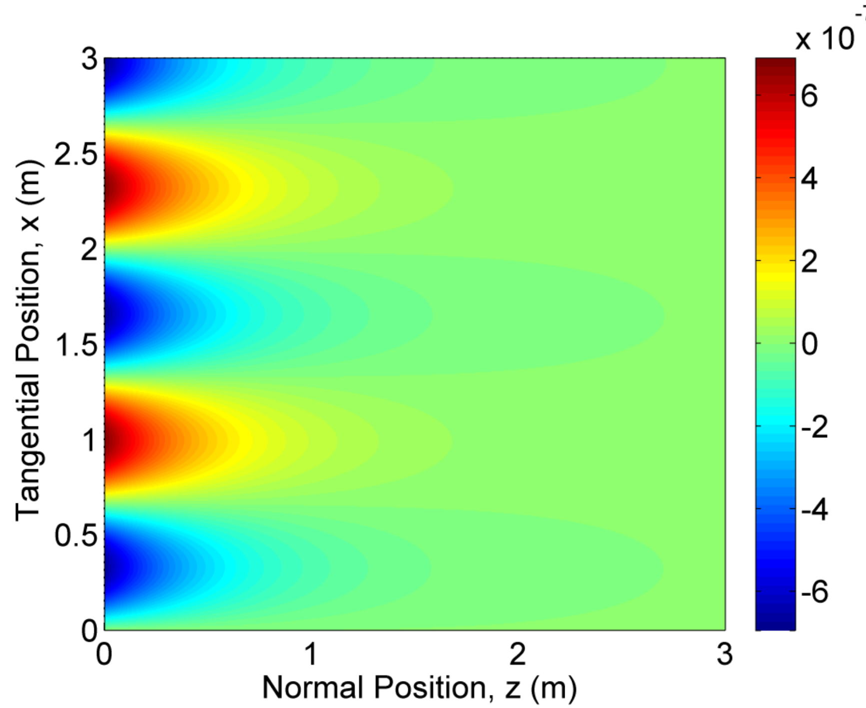
$$I_z = \frac{1}{T}\int_0^T p v_z \, dt$$

Numerical Results: Air-Water

Transmitted Pressure (Pa)



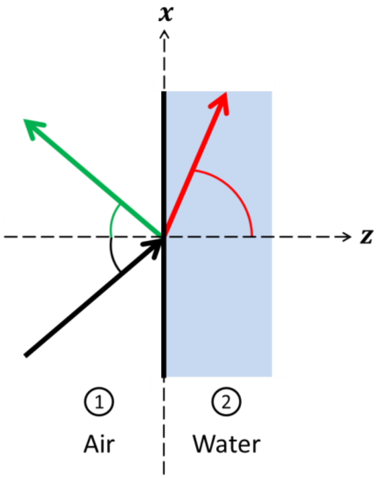
Transmitted Normal Velocity (m/s)



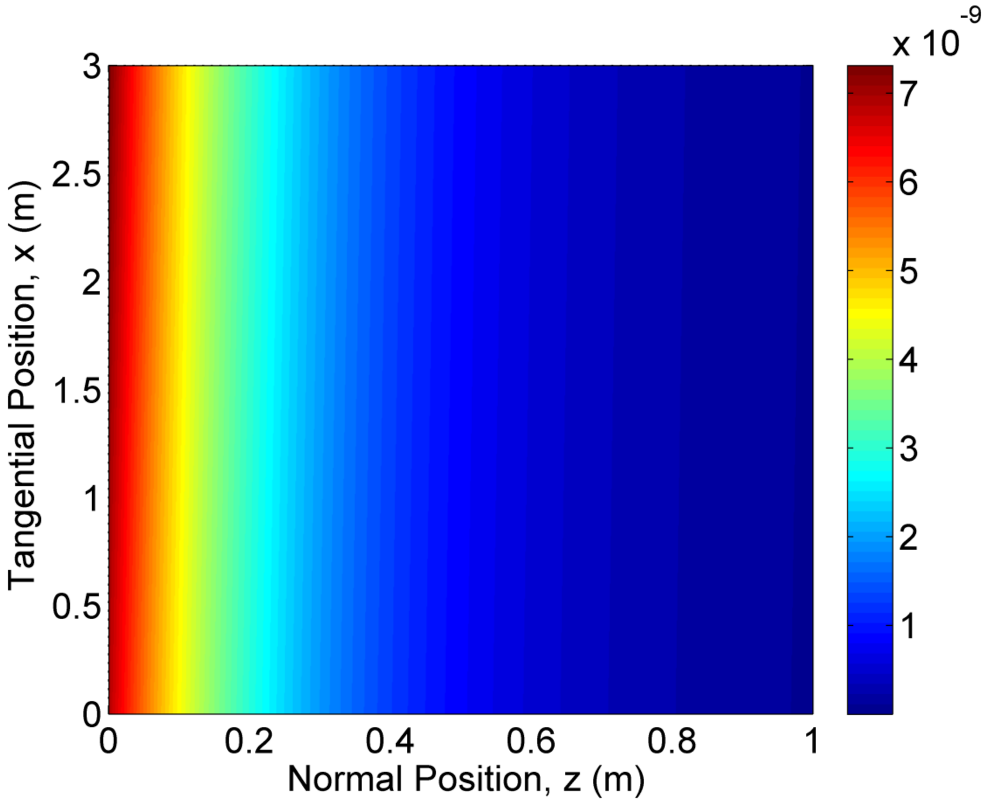
Supercritical angle and decay rate

$\theta_1 = 15°, \beta = 0.01$ rad/m

Numerical Results: Air-Water

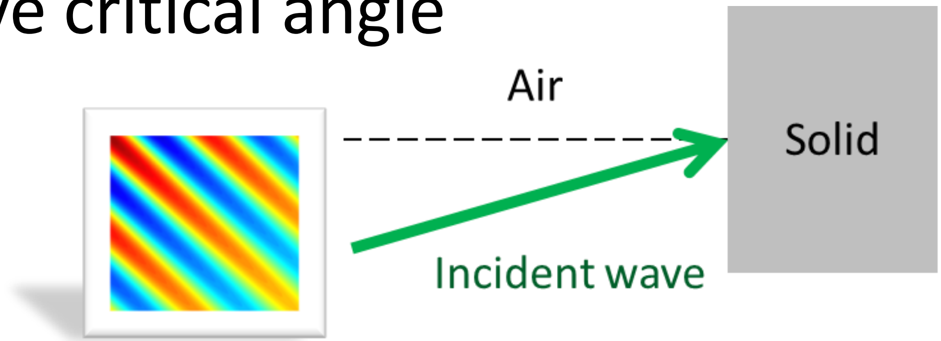


Transmitted Normal Intensity (W/m²)



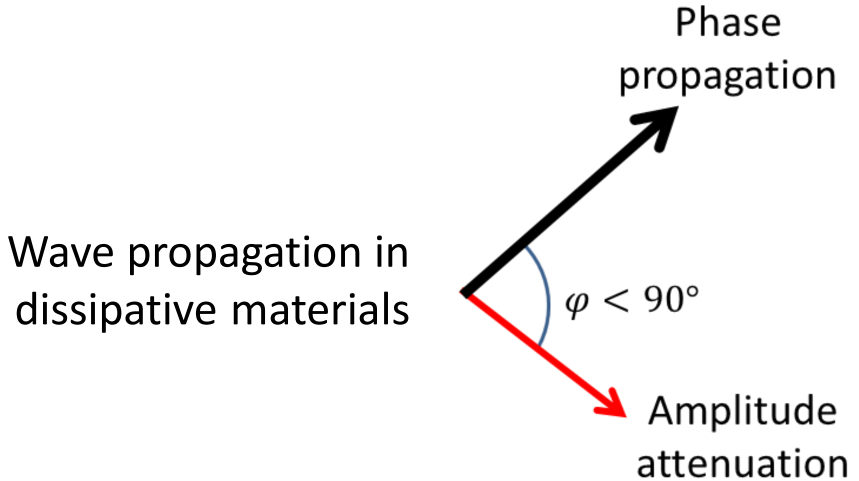
Conclusions

- Use of evanescent acoustic waves for increased stress and energy transmission in solids
  - Exact impedance matching at the Rayleigh angle and optimal decay rate
  - Significant transmission increases
  - Nonzero energy flux for all oblique incidence angles
- Fluid-fluid interfaces: pressure and energy transmission decay above critical angle



Conclusions

- Future work:
  - Transmission into viscoelastic materials
  - Transmission by bounded wave profiles
  - Measurements of stress and energy transmission in energetic materials



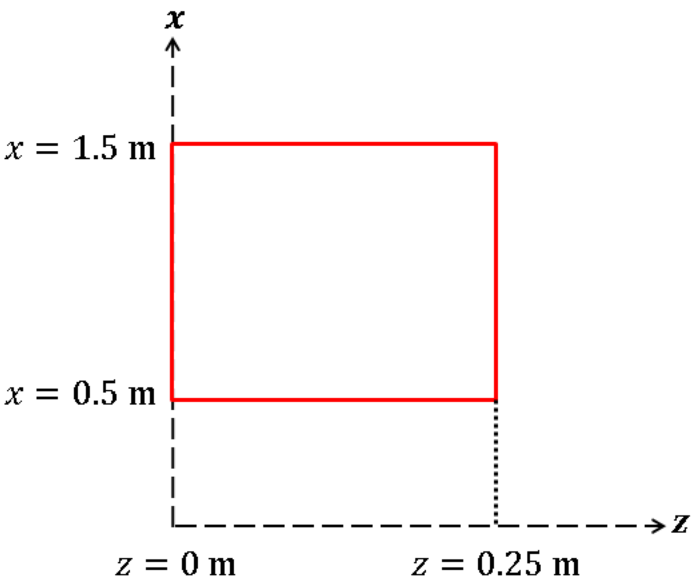
Acknowledgement

The authors would like to thank the U.S. Office of Naval Research for its support of this research under ONR Grant No. N00014-10-1-0958

Energy Conservation

- Verification of energy conservation

Sample Control Volume



Net Energy Fluxes
(W per unit width)

$$Q_{in} = \int_0^{0.25} \vec{I}\,(0.5, z) \cdot \hat{x}\ \mathrm{dz} + \int_{0.5}^{1.5} \vec{I}\,(x, 0) \cdot \hat{z}\ \mathrm{d}x$$

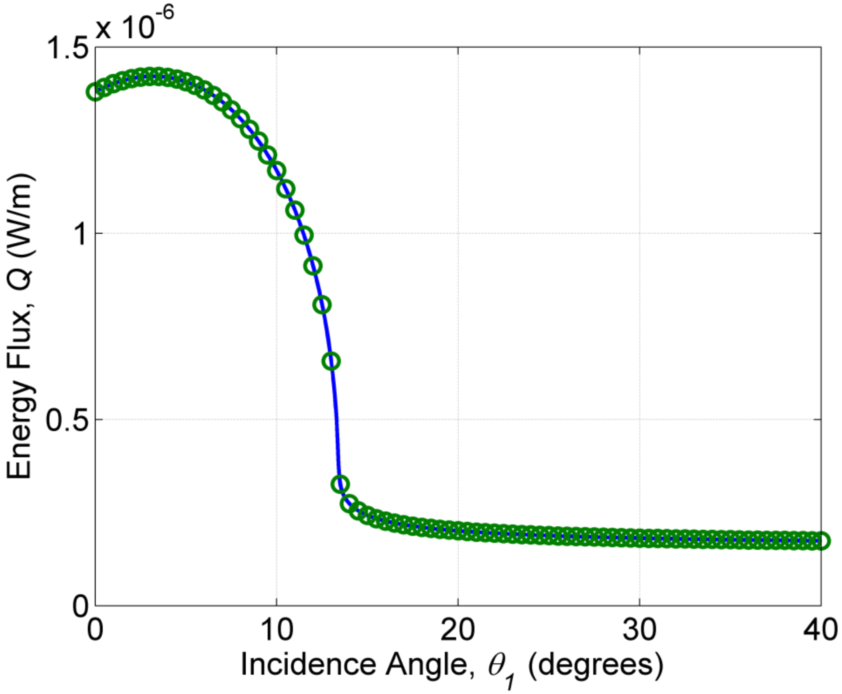
$$= \int_0^{0.25} I_x\,(0.5, z)\ \mathrm{dz} + \int_{0.5}^{1.5} I_z\,(x, 0)\ \mathrm{d}x,$$

$$Q_{out} = \int_0^{0.25} \vec{I}\,(1.5, z) \cdot \hat{x}\ \mathrm{dz} + \int_{0.5}^{1.5} \vec{I}\,(x, 0.25) \cdot \hat{z}\ \mathrm{d}x$$

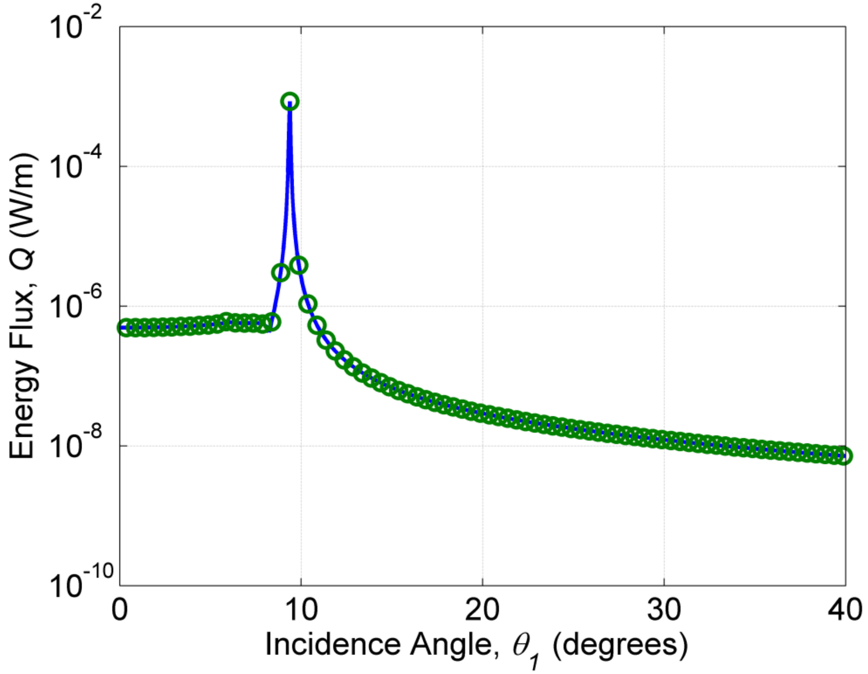
$$= \int_0^{0.25} I_x\,(1.5, z)\ \mathrm{dz} + \int_{0.5}^{1.5} I_z\,(x, 0.25)\ \mathrm{d}x$$

Energy Conservation

Air-Water Interface



Air-Solid Interface

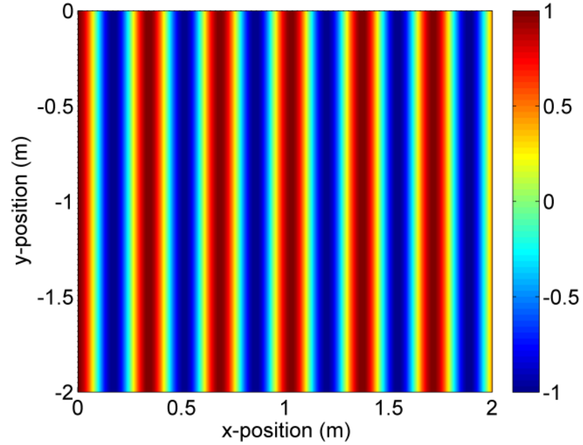


$\beta = 0.01$ rad/m

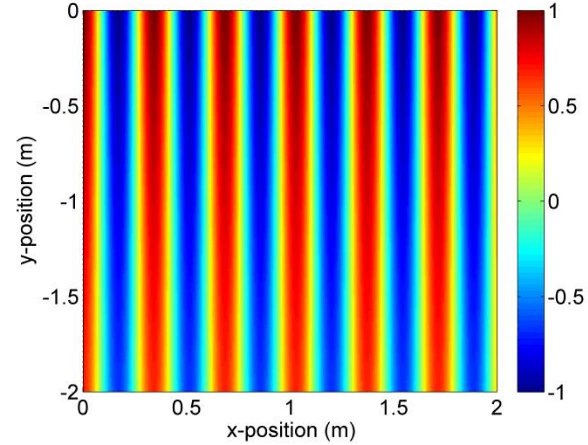
Inhomogeneous Plane Waves in Low-Loss Media

Pressure field (Pa)
1-Pa, 1000-Hz wave in air

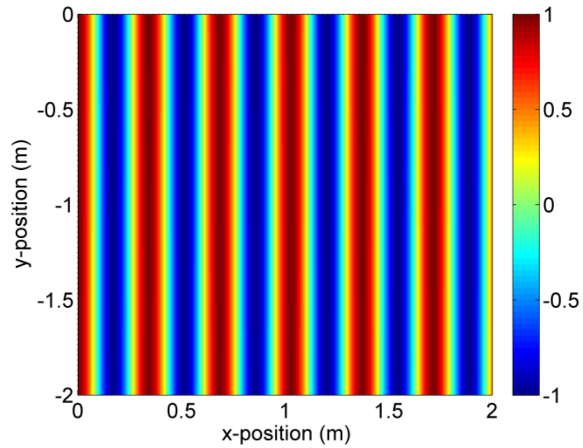
0° inhomogeneity



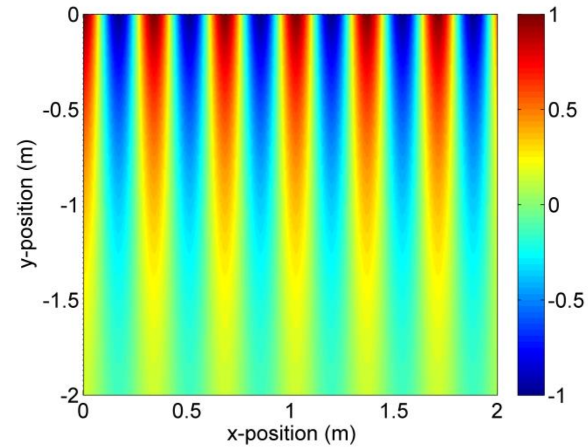
89.95° inhomogeneity



89° inhomogeneity



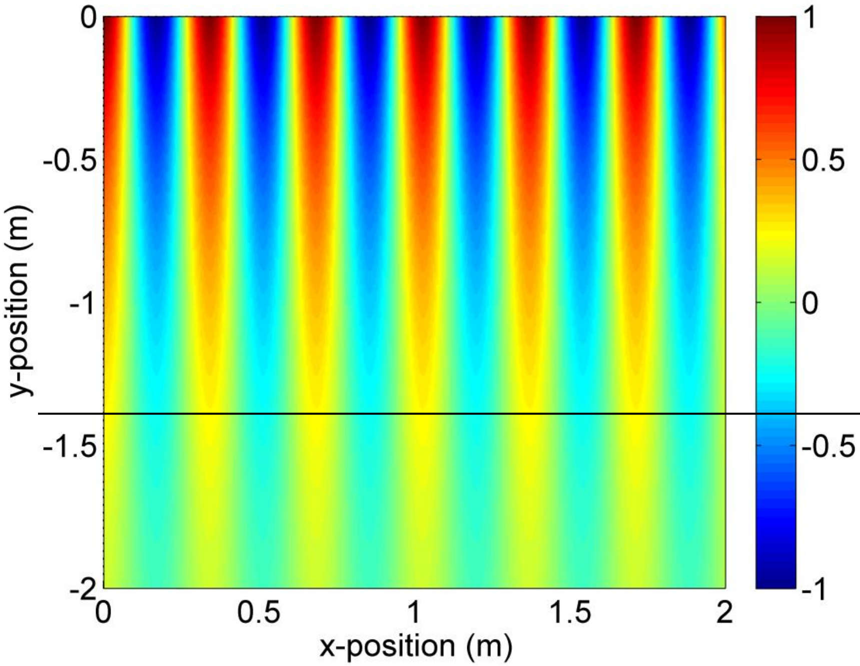
89.99° inhomogeneity



Inhomogeneous Plane Waves in Low-Loss Media

Pressure field (Pa)
1-Pa, 1000-Hz wave in air

89.99° inhomogeneity



Lossless approximation ($\beta \approx 1.01$ rad/m)