

Reflection and Refraction in Fluid Boundaries

ELEC-E5610 Acoustics and the Physics of Sound, Lecture 5

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Fluid Boundary



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Let us consider the boundary between two fluids.

Continuity at the Boundary





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Let us consider the boundary between two fluids.

Continuity at the Boundary

Fluid 1: ρ_1, c_1, K_1, z_{c1}





Let us consider the boundary between two fluids.

Continuity at the Boundary

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Continuity at the Boundary





Continuity at the Boundary

Also, the normal component of particle velocity (or displacement) must be continuous at the boundary.



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Continuity at the Boundary Also, the **normal component of particle velocity** (or displacement) **must be continuous at the boundary**.

if it were not, there would either become a vacuum at the boundary, or the fluids would overlap each other



Continuity at the Boundary Also, the **normal component of particle velocity** (or displacement) **must be continuous at the boundary**.

- if it were not, there would either become a vacuum at the boundary, or the fluids would overlap each other
- ⇒ the normal component of the particle velocity must be zero at the boundary between an infinitely rigid wall and a fluid



Perpendicular Reflection



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If the incident angle is 90° w.r.t boundary, a *perpendicular reflection* occurs

Particle velocity	Fluid 1	. v	Fluid 2
Relation between Coefficients	ρ_1, c_1, K_1, z_{c1}	^)	ρ_2, c_2, K_2, z_{c2}
Intensity			
Example			
Material Table			x
Sound Field in Front of a Boundary			\longrightarrow "
Impedance in front of a Boundary			
Reflection from Multilayer Medium			



Pressure

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If the incident angle is 90° w.r.t boundary, a *perpendicular reflection* occurs Pressure consider an incoming plane Particle Velocity Fluid 2: ρ_2, c_2, K_2, z_{c2} Fluid 1: $\uparrow Y$ ρ_1, c_1, K_1, z_{c1} wave p_i (temporal term Relation between Coefficients omitted) Intensity sound pressure pr reflects Example $p_{\mathrm{i}} = p_0 e^{-ik_1 x}$ $p_{\rm t} = T p_0 e^{-ik_2 \lambda}$ R is the reflection coefficient Material Table for pressure Sound Field in Front sign of the exponential of a Boundary $p_{\rm r} = R p_0 e^{ik_1 x}$ changes (why?) Impedance in front of a Boundary pressure pt propagates into Reflection from fluid 2 Multilaver Medium

T is the transmission coefficient for pressure





Note: $k_1 = \frac{\omega}{c_1} \neq \frac{\omega}{c_2} = k_2$ (different fluids!)



2 Perpendicular Reflection: Particle Velocity

Pressure

Particle Velocity

- Relation between Coefficients
- Intensity
- Example
- Material Table
- Sound Field in Front of a Boundary
- Impedance in front of a Boundary
- Reflection from Multilaver Medium

Particle velocities behave in a similar manner

- We recall the relation between sound pressure and particle velocity: $\frac{\partial u}{\partial t} = -\frac{1}{2} \frac{\partial p}{\partial x}$
- fluid 1.
 - incident particle velocity $u_i = \frac{p_0}{z_{-1}} e^{-ik_1 x}$
 - reflecting particle velocity $u_{\rm r} = -\frac{Rp_0}{2} e^{ik_1x}$
 - note: the signs of the exponential and the term itself change (why?)

(animations: https://www.acs.psu.edu/drussell/Demos/

phase-p-u/phase-p-u.html)

- fluid 2
 - transmitted particle velocity $u_{\rm t} = \frac{T p_0}{Z_{\rm s}} e^{-ik_2 x}$



Pressure

Pressure continuity:

Particle Velocity

Relation between Coefficients

Intensity

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Material Table

Sound Field in Front of a Boundary

Impedance in front of a Boundary

Reflection from Multilaver Medium $p_0 + Rp_0 = Tp_0 \Rightarrow T = 1 + R$



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Pressure Particle Velocity Pressure continuity:

$$p_0 + Rp_0 = Tp_0 \Rightarrow T = 1 + R$$

Relation between Coefficients

Intensity

Example

Material Table

Sound Field in Front of a Boundary

Impedance in front of a Boundary

Reflection from Multilaver Medium Continuity for the normal component of particle velocity:

p_0	Rp_0	_ Tp ₀ _	<u>1 – R</u>	_ T
$\overline{Z_{c1}}$	$\overline{z_{c1}}$	$\overline{z_{c2}}$	$\overline{z_{c1}}$	$\overline{z_{c2}}$



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Pressure Particle Velocity

Relation between

Pressure continuity:

$$p_0 + Rp_0 = Tp_0 \Rightarrow T = 1 + R$$

Coefficients Intensity

Continuity for the normal component of particle velocity:

Example		$n_{0} = Bn_{0} = Tn_{0} = 1 = B = T$	
Material Table		$\frac{p_0}{p_0} - \frac{np_0}{p_0} = \frac{np_0}{p_0} \Rightarrow \frac{1-n}{p_0} = \frac{n}{p_0}$	
Sound Field in Front of a Boundary	Thus	Z_{c1} Z_{c1} Z_{c2} Z_{c1} Z_{c2}	
Impedance in front of a Boundary	mus,	$- Z_{c2} - Z_{c1}$	
Reflection from Multilayer Medium		$R = \frac{z_{c2} + z_{c1}}{z_{c2} + z_{c1}}$	(1)
		$T = \frac{2z_{c2}}{z_{c2} + z_{c1}}$	(2)



Pressure Particle Velocity Pressure continuity:

$$p_0 + Rp_0 = Tp_0 \Rightarrow T = 1 + R$$

Relation between Coefficients

Example

Material Table

Sound Field in Front of a Boundary

Thus,

Impedance in front of a Boundary

Reflection from Multilaver Medium Continuity for the normal component of particle velocity:

$$\frac{p_0}{z_{c1}} - \frac{Rp_0}{z_{c1}} = \frac{Ip_0}{z_{c2}} \Rightarrow \frac{1-R}{z_{c1}} = \frac{I}{z_{c2}}$$

$$R = \frac{z_{c2} - z_{c1}}{z_{c2} + z_{c1}} \qquad (-1 \le R \le 1) \qquad (1)$$

$$T = \frac{2z_{c2}}{z_{c2} + z_{c1}} \qquad (2)$$



Pressure Particle Velocity Pressure continuity:

$$p_0 + Rp_0 = Tp_0 \Rightarrow T = 1 + R$$

Relation between Coefficients

Intensity

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Sound Field in Front of a Boundary

Thus,

Impedance in front of a Boundary

Reflection from Multilaver Medium Continuity for the normal component of particle velocity:

$\frac{p_0}{z_{c1}} - \frac{Rp_0}{z_{c1}} = \frac{Tp_0}{z_{c2}}$	$\frac{1-R}{z_{c1}} \Rightarrow \frac{1-R}{z_{c2}} = \frac{T}{z_{c2}}$	
$R = rac{z_{ m c2} - z_{ m c1}}{z_{ m c2} + z_{ m c1}}$	$(-1 \leq R \leq 1)$	(1)
$T=\frac{2z_{\rm c2}}{z_{\rm c2}+z_{\rm c1}}$	(0 ≤ <i>T</i> ≤ 2)	(2)



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Sound Field in Front of a Boundary

Impedance in front of a Boundary

Reflection from Multilaver Medium Since T can be over unity, sound pressure can increase when the wave passes through the boundary



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Sound Field in Front of a Boundary

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"How can this be? Energy can't increase!"



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Sound Field in Front of a Boundary

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Reflection from Multilayer Medium Since T can be over unity, sound pressure can increase when the wave passes through the boundary

"How can this be? Energy can't increase!"

 Remember: the characteristic impedances are different: if the particle velocity decreases, sound pressure increases

of course, intensity can't increase

In fact, also the characteristic impedance is continuous at the boundary (see this by comparing the pressures and particle velocities on both sides)



Pressure

Particle Velocity

Relation between Coefficients

Intensity

Example

Material Table

Sound Field in Front of a Boundary

Impedance in front of a Boundary

Reflection from Multilaver Medium

Incoming intensity:
$$I_{\rm i} = rac{|
ho_{\rm i}|^2}{z_{\rm c1}}$$



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Sound Field in Front of a Boundary

Impedance in front of a Boundary

Reflection from Multilaver Medium Incoming intensity: I_i = ^{|p_i|²}/_{z_{c1}}
Reflecting intensity: I_r = ^{|P_r|²}/_{z_{c1}} = ^{|Rp_i|²}/_{z_{c1}} = |R|² I_i



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Sound Field in Front of a Boundary

Impedance in front of a Boundary

Reflection from Multilaver Medium Incoming intensity: I_i = |P_i|²/Z_{c1}
Reflecting intensity: I_r = |P_r|²/Z_{c1} = |R|² I_i • Transmitted intensity: $I_{t} = \frac{|p_{t}|^{2}}{Z_{c2}} = \frac{|Tp_{i}|^{2}}{Z_{c2}} = \frac{Z_{c1}}{Z_{c2}} |T|^{2} I_{i}$



Pressure

Particle Velocity

Relation between Coefficients

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Material Table

Sound Field in Front of a Boundary

Impedance in front of a Boundary

Reflection from Multilaver Medium • Incoming intensity: $I_i = \frac{|p_i|^2}{z_{c1}}$ • Reflecting intensity: $I_{\rm r} = \frac{|p_{\rm r}|^2}{z_{\rm r1}} = \frac{|Rp_{\rm i}|^2}{z_{\rm r1}} = |R|^2 I_{\rm i}$ • Transmitted intensity: $I_t = \frac{|p_t|^2}{z_{c2}} = \frac{|Tp_i|^2}{z_{c2}} = \frac{z_{c1}}{z_{c2}} |T|^2 I_i$ $I_i - I_r = I_t$ (check the math to verify)



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Material Table

Sound Field in Front of a Boundary

Impedance in front of a Boundary

Reflection from Multilayer Medium Incoming intensity: I_i = |P_i|²/_{Z_{c1}}
Reflecting intensity: I_r = |P_r|²/_{Z_{c1}} = |R|² I_i
Transmitted intensity: I_t = |P_t|²/_{Z_{c2}} = |T_{Pi}|²/_{Z_{c2}} = Z_{c1}/_{Z_{c2}} |T|² I_i
I_i - I_r = I_t (check the math to verify)
Transmitted intensity can also be given as

$$I_{\rm t} = I_{\rm i} - I_{\rm r} = (1 - |R|^2)I_{\rm i}$$
 (3)

in other words, obtained using the incoming intensity and characteristic impedances!



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Sound Field in Front of a Boundary

Impedance in front of a Boundary

Reflection from Multilayer Medium The result in Eq. (3) holds for the active intensity also when z_{c2} is complex

denote $z_{c2} = r_2 + ix_2$, $z_{c1} = r_1$

Remember Eq. (1):
$$R = rac{Z_{c2}-Z_{c1}}{Z_{c2}+Z_{c1}}$$



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Sound Field in Front of a Boundary

Impedance in front of a Boundary

Reflection from Multilayer Medium The result in Eq. (3) holds for the active intensity also when z_{c2} is complex

denote
$$z_{c2} = r_2 + ix_2, z_{c1} = r_1$$
demember Eq. (1): $R = \frac{z_{c2} - z_{c1}}{z_{c2} + z_{c1}} \Rightarrow |R|^2 = \frac{|r_2 + ix_2 - r_1|^2}{|r_2 + ix_2 + r_1|^2}$
the energy transfer coefficient becomes
$$-|R|^2 = \frac{|r_2 + ix_2 + r_1|^2 - |r_2 + ix_2 - r_1|^2}{|r_2 + ix_2 + r_1|^2} = \frac{4r_1r_2}{(r_1 + r_2)^2 + x_2^2}$$

if also
$$z_{c2}$$
 is real, $x_2 = 0$ and we get
 $1 - |R|^2 = \frac{4r_1r_2}{(r_1 + r_2)^2}$



R

2 Example: Sound from Air to Water

Pressure

Particle Velocity

Relation between Coefficients

Intensity

Example

Material Table

Sound Field in Front of a Boundary

Impedance in front of a Boundary

Reflection from Multilaver Medium



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Let's consider a case where a plane wave arrives perpendicularly from air to water.

2 Example: Sound from Air to Water

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Material Table

Sound Field in Front of a Boundary

Impedance in front of a Boundary

Reflection from Multilaver Medium Let's consider a case where a plane wave arrives perpendicularly from air to water. What is the ratio between the transmitted and incoming

- (a) sound pressures?
- (b) intensities?



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Reflection from Multilaver Medium Let's consider a case where a plane wave arrives perpendicularly from air to water. What is the ratio between the transmitted and incoming

- (a) sound pressures?
- (b) intensities?

$$\begin{split} \rho_{\rm air} &= 1.2 \ {\rm kg/m^3}, \ \rho_{\rm water} = 1000 \ {\rm kg/m^3}, \\ c_{\rm air} &= 343 \ {\rm m/s}, \ c_{\rm water} = 1500 \ {\rm m/s}. \end{split}$$



Pressure

Particle Velocity

Relation between Coefficients

Intensity

Example

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Sound Field in Front of a Boundary

Impedance in front of a Boundary

Reflection from Multilaver Medium Let's consider a case where a plane wave arrives perpendicularly from air to water. What is the ratio between the transmitted and incoming

- (a) sound pressures?
- (b) intensities?

$$z_{
m c,air}=
ho_{
m air}c_{
m air}=$$
 412 Pas/m,

$$\begin{split} \rho_{\rm air} &= 1.2 \ {\rm kg/m^3}, \ \rho_{\rm water} = 1000 \ {\rm kg/m^3}, \\ c_{\rm air} &= 343 \ {\rm m/s}, \ c_{\rm water} = 1500 \ {\rm m/s}. \end{split}$$



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Material Table

Sound Field in Front of a Boundary

Impedance in front of a Boundary

Reflection from Multilayer Medium Let's consider a case where a plane wave arrives perpendicularly from air to water. What is the ratio between the transmitted and incoming

- (a) sound pressures?
- (b) intensities?

 $z_{c,air} = \rho_{air}c_{air} = 412 \text{ Pas/m},$ $z_{c,water} = \rho_{water}c_{water} = 1.5 \text{ MPas/m},$

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 $\rho_{\rm air} = 1.2 \text{ kg/m}^3$, $\rho_{\rm water} = 1000 \text{ kg/m}^3$,

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 $c_{\rm air} = 343 \text{ m/s}, c_{\rm water} = 1500 \text{ m/s}.$

 $z_{\rm c,air} = \rho_{\rm air} c_{\rm air} = 412 \text{ Pas/m},$ $z_{c.water} = \rho_{water} c_{water} = 1.5 \text{ MPas/m},$ Eq. (2): $T = \frac{2z_{c,water}}{z_{c,water}+z_{c,air}} \approx 2$



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Reflection from Multilayer Medium Let's consider a case where a plane wave arrives perpendicularly from air to water. What is the ratio between the transmitted and incoming

- (a) sound pressures?
- (b) intensities?

Eq. (3): $\frac{h}{L} = 1 - |R|^2$,

 $z_{c,air} = \rho_{air}c_{air} = 412 \text{ Pas/m},$ $z_{c,water} = \rho_{water}c_{water} = 1.5 \text{ MPas/m},$ Eq. (2): $T = \frac{2z_{c,water}}{z_{c,water} + z_{c,air}} \approx 2$

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 $\rho_{\rm air} = 1.2 \text{ kg/m}^3$, $\rho_{\rm water} = 1000 \text{ kg/m}^3$,

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 $\rho_{\rm air} = 1.2 \text{ kg/m}^3$, $\rho_{\rm water} = 1000 \text{ kg/m}^3$, $c_{\rm air} = 343 \text{ m/s}, c_{\rm water} = 1500 \text{ m/s}.$

$$\begin{split} z_{\text{c,air}} &= \rho_{\text{air}} c_{\text{air}} = 412 \text{ Pas/m}, \\ z_{\text{c,water}} &= \rho_{\text{water}} c_{\text{water}} = 1.5 \text{ MPas/m}, \\ \text{Eq. (2): } T &= \frac{2z_{\text{c,water}}}{z_{\text{c,water}} + z_{\text{c,air}}} \approx 2 \\ \text{Eq. (3): } \frac{h}{l_{\text{i}}} &= 1 - |R|^2, \text{ Eq. (1): } R = \frac{z_{\text{c,water}} - z_{\text{c,air}}}{z_{\text{c,water}} + z_{\text{c,air}}} \Rightarrow \\ \frac{h}{l_{\text{i}}} &= 1 - |R|^2 \approx 0.0011 \end{split}$$



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$$ho_{air} = 1.2 \text{ kg/m}^3,
ho_{water} = 1000 \text{ kg/m}^3, \ c_{air} = 343 \text{ m/s}, c_{water} = 1500 \text{ m/s}.$$

$$\begin{split} z_{\text{c,air}} &= \rho_{\text{air}} c_{\text{air}} = 412 \text{ Pas/m}, \\ z_{\text{c,water}} &= \rho_{\text{water}} c_{\text{water}} = 1.5 \text{ MPas/m}, \\ \text{Eq. (2): } T &= \frac{2z_{\text{c,water}}}{z_{\text{c,water}} + z_{\text{c,air}}} \approx 2 \\ \text{Eq. (3): } \frac{h_{\text{t}}}{l_{\text{i}}} &= 1 - |R|^2, \text{ Eq. (1): } R = \frac{z_{\text{c,water}} - z_{\text{c,air}}}{z_{\text{c,water}} + z_{\text{c,air}}} \Rightarrow \\ \frac{h_{\text{t}}}{l_{\text{i}}} &= 1 - |R|^2 \approx 0.0011 \end{split}$$

 \Rightarrow large impedance mismatch, poor power transfer.



2 Table: Sound from Air to Different Materials

Transmission loss in dB:

Particle Velocity

Relation between Coefficients

Intensity

Example

Material Table

Sound Field in Front of a Boundary

Impedance in front of a Boundary

Reflection from Multilaver Medium

$$\mathrm{TL} = -10 \log_{10} \frac{l_{\mathrm{t}}}{l_{\mathrm{i}}}$$

Table: Perpendicular reflection from air to different materials

Material	<i>z</i> _c [Pas/m]	$I_{\rm t}/I_{\rm i}$	TL [dB]
steel	3.9 · 10 ⁷	$4 \cdot 10^{-5}$	44
concrete	9 · 10 ⁶	18 · 10 ⁻⁵	38
glass	1.4 · 10 ⁷	$11 \cdot 10^{-5}$	40
oak	2.8 · 10 ⁶	$6 \cdot 10^{-4}$	32
mineral wool	1000	0.83	1



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2 Table: Sound from Air to Different Materials

Transmission loss in dB:

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mineral wool	1000	0.83	1

Note: TL gives here only the effect of a single boundary, not dissipative losses (inside the material), etc.



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		C	3	э	u		c	

Particle Velocity

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Sound Field in Front of a Boundary

Impedance in front of a Boundary

Reflection from Multilayer Medium



The sound field in front of the boundary consists of

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Reflection from Multilaver Medium The sound field in front of the boundary consists of the incoming wave

 $p = p_{i} + p_{r}$



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Reflection from Multilaver Medium The sound field in front of the boundary consists of the incoming wave and the reflecting wave

 $p = p_{i} + p_{r}$



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Reflection from Multilaver Medium The sound field in front of the boundary consists of the incoming wave and the reflecting wave

$$p = p_{\mathrm{i}} + p_{\mathrm{r}} = p_0(e^{-ik_1x} + Re^{ik_1x})$$



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Sound Field in Front of a Boundary

Impedance in front of a Boundary

Reflection from Multilaver Medium The sound field in front of the boundary consists of the incoming wave and the reflecting wave. Another interpretation is a standing wave plus

$$p = p_{i} + p_{r} = p_{0}(e^{-ik_{1}x} + Re^{ik_{1}x})$$

 $= \begin{cases} p_0(2R\cos(k_1x) + (1-R)e^{-ik_1x}), \text{ when } R \ge 0\\ p_0(2iR\sin(k_1x) + (1+R)e^{-ik_1x}), \text{ when } R \le 0 \end{cases}$



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Pressure

Particle Velocity

Relation between Coefficients

Intensity

Example

Material Table

Sound Field in Front of a Boundary

Impedance in front of a Boundary

Reflection from Multilaver Medium The sound field in front of the boundary consists of the incoming wave and the reflecting wave. Another interpretation is a standing wave plus a propagating wave

$$egin{aligned} p &= p_{\mathrm{i}} + p_{\mathrm{r}} = p_0(e^{-ik_1x} + Re^{ik_1x}) \ \left(egin{aligned} p_0(2R\cos(k_1x) + (1-R)e^{-ik_1x}), & ext{when } R \geq 0 \ p_0(2iR\sin(k_1x) + (1+R)e^{-ik_1x}), & ext{when } R \leq 0 \end{aligned}
ight. \end{aligned}$$



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 $\begin{cases} p_{0}(2R\cos(k_{1}x) + (1-R)e^{-ik_{1}x}), \text{ when } R \geq 0 \\ p_{0}(2iR\sin(k_{1}x) + (1+R)e^{-ik_{1}x}), \text{ when } R \leq 0 \end{cases}$



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Material Table

Sound Field in Front of a Boundary

Impedance in front of a Boundary

Reflection from Multilayer Medium The sound field in front of the boundary consists of the incoming wave and the reflecting wave. Another interpretation is a standing wave plus a propagating wave

$$p = p_{\mathrm{i}} + p_{\mathrm{r}} = p_0(e^{-ik_1x} + Re^{ik_1x})$$

= $\begin{cases} p_0(2R\cos(k_1x) + (1-R)e^{-ik_1x}), \text{ when } R \ge 0 \\ p_0(2iR\sin(k_1x) + (1+R)e^{-ik_1x}), \text{ when } R \le 0 \end{cases}$

Remember: a standing wave transmits no energy (active intensity is zero)



Pressure

Particle Velocity

Relation between Coefficients

Intensity

Example

Material Table

Sound Field in Front of a Boundary

Impedance in front of a Boundary

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Remember: a standing wave transmits no energy (active intensity is zero). Similar equations can be derived for the particle velocity.



2 Impedance in front of a Boundary

Pressure

Particle Velocity

Relation between Coefficients

Intensity

Example

Material Table

Sound Field in Front of a Boundary

Impedance in front of a Boundary

Reflection from Multilaver Medium

Specific acoustic impedance at the distance d = -x from the boundary can be given as

$$z_c = rac{p_x}{u_x} = z_{c1} rac{e^{-ik_1 x} + Re^{ik_1 x}}{e^{-ik_1 x} - Re^{ik_1 x}}$$

(4)

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2 Impedance in front of a Boundary

Pressure

Particle Velocity

Relation between Coefficients

Intensity

Example

Material Table

Sound Field in Front of a Boundary

Impedance in front of a Boundary

Reflection from Multilayer Medium Specific acoustic impedance at the distance d = -x from the boundary can be given as

$$z_{c} = \frac{p_{x}}{u_{x}} = z_{c1} \frac{e^{-ik_{1}x} + Re^{ik_{1}x}}{e^{-ik_{1}x} - Re^{ik_{1}x}}$$
$$= z_{c1} \frac{z_{c2}\cos(k_{1}d) + iz_{c1}\sin(k_{1}d)}{z_{c1}\cos(k_{1}d) + iz_{c2}\sin(k_{1}d)},$$

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2 Impedance in front of a Boundary

Pressure

Particle Velocity

Relation between Coefficients

Intensity

Example

Material Table

Sound Field in Front of a Boundary

Impedance in front of a Boundary

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$$z_{c} = \frac{p_{x}}{u_{x}} = z_{c1} \frac{e^{-ik_{1}x} + Re^{ik_{1}x}}{e^{-ik_{1}x} - Re^{ik_{1}x}}$$

= $z_{c1} \frac{z_{c2} \cos(k_{1}d) + iz_{c1} \sin(k_{1}d)}{z_{c1} \cos(k_{1}d) + iz_{c2} \sin(k_{1}d)},$
= $z_{c1} \frac{z_{c2} + iz_{c1} \tan(k_{1}d)}{z_{c1} + iz_{c2} \tan(k_{1}d)}$ (4)



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Consider a structure consisting of a multilayer medium.

Pressure			
Particle Velocity			
Relation between Coefficients			
Intensity			
Example			
Material Table			
Sound Field in Front of a Boundary	y,	N	
Impedance in front of a Boundary	Medium 1:	Medium 2:	Medium 3:
Reflection from Multilayer Medium			
			X



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	Consider a structure consisting of a multilayer medium. The		
Pressure	impedance to the r	ight at $x = 0$ dependence	
Particle Velocity			
Relation between Coefficients			
Intensity			
Example			
Material Table			
Sound Field in Front of a Boundary	у .	、 	
Impedance in front of a Boundary	Medium 1:	Medium 2:	Medium 3:
Reflection from Multilayer Medium			
		<i>x</i> = 0	X

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Pressure	Consider a structur impedance to the r	re consisting of a night at $x = 0$ depe	nultilayer medium. The nds on
Particle Velocity	properties of	media 2 and 3	
Relation between Coefficients	reflection at x	c = d z	$z_0 = z_{c2} \frac{z_{c3} + iz_{c2} \tan(k_2 d)}{z_0 + iz_0 \tan(k_2 d)}$
Intensity			$z_{c2} + i z_{c3} \tan(n_2 \sigma)$
Example	With multiple layers	s, one starts evalua	ating the boundary
Material Table	impedances from r	ight to left using th	e above equation
Sound Field in Front of a Boundary	y ,		
Impedance in front of a Boundary	Medium 1: ρ_1, c_1, K_1, z_{c1}	Medium 2: ρ_2, c_2, K_2, z_{c2}	Medium 3: $\rho_3, c_3, K_3, z_{c_3}$
Reflection from Multilayer Medium	, . , . , . ,	, _, _, _, _, _	
		x = 0 .	$\overrightarrow{x} = d \qquad \overrightarrow{x}$



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Pressure	Is it possible to sel thickness <i>d</i> so that	lect the material for t there is no reflect	medium 2 and ion back to medium 1?
Particle Velocity	I. e. this would me	an $z_0 = z_{c1}$ for $z_0 =$	$= Z_{c2} \frac{Z_{c3} + iZ_{c2} \tan(k_2 d)}{Z_{c2} + iZ_{c2} \tan(k_2 d)}.$
Relation between Coefficients			$2_{02} + 12_{03} \tan(1_2 \alpha)$
Intensity			
Example			
Material Table			
Sound Field in Front of a Boundary			
Impedance in front of a Boundary	, And		
Reflection from Multilayer Medium	Medium 1: ρ_1, c_1, K_1, z_{c1}		$ \begin{array}{c} \text{Medium 3:} \\ \rho_3, c_3, K_3, z_{c3} \\ \hline x = d \\ \end{array} $



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Pressure	Is it possible to s thickness <i>d</i> so th	elect the material fo at there is no reflect	r medium 2 and tion back to medium 1?
Particle Velocity	I. e. this would m	lean $z_0 = z_{c1}$ for z_0	$= Z_{c2} \frac{Z_{c3} + iZ_{c2} \tan(k_2 d)}{Z_{c2} + iZ_{c3} \tan(k_2 d)}.$
Relation between Coefficients	Answer: Yes, the	ere are three such c	ases (check the math):
Intensity			
Example			
Material Table			
Sound Field in Front of a Boundary			
Impedance in front of a Boundary		,	
Reflection from Multilayer Medium	Medium 1: $\rho_1, c_1, K_1, z_{c_1}$	$ \begin{array}{c} \text{Medium 2:} \\ \rho_2, c_2, K_2, z_{c2} \\ x = 0 \end{array} $	



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Is it possible to select the material for medium 2 and thickness d so that there is no reflection back to medium 1? Pressure I. e. this would mean $z_0 = z_{c1}$ for $z_0 = z_{c2} \frac{z_{c3} + i z_{c2} \tan(k_2 d)}{z_{c2} + i z_{c3} \tan(k_0 d)}$. Particle Velocity Relation between **Answer:** Yes, there are three such cases (check the math): Coefficients Intensity Trivial case: $z_{c1} = z_{c2} = z_{c3}$ Example Material Table Sound Field in Front of a Boundary Impedance in front of a Boundary **Reflection from** Multilaver Medium Medium 3: Medium 1: Medium 2 ρ_1, c_1, K_1, z_{c1} ρ_2, c_2, K_2, z_{c2} ρ_3, c_3, K_3, z_{c3} x = 0 $\dot{x} - d$ x



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Pressure

Particle Velocity

Relation between Coefficients

Intensity

Example

Material Table

Sound Field in Front of a Boundary

Impedance in front of a Boundary

Reflection from Multilaver Medium Is it possible to select the material for medium 2 and thickness *d* so that there is no reflection back to medium 1? I. e. this would mean $z_0 = z_{c1}$ for $z_0 = z_{c2} \frac{z_{c3}+iz_{c2} \tan(k_2d)}{z_{c2}+iz_{c3} \tan(k_2d)}$. **Answer:** Yes, there are three such cases (check the math): Trivial case: $z_{c1} = z_{c2} = z_{c3}$ Half-wave layer: $z_{c1} = z_{c3}$, $d = \frac{n\lambda_2}{2}$, n = 1, 2, 3...





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Pressure

Particle Velocity

Relation between Coefficients

Intensity

Example

Material Table

Sound Field in Front of a Boundary

Impedance in front of a Boundary

Reflection from Multilayer Medium Is it possible to select the material for medium 2 and thickness d so that there is no reflection back to medium 1? I. e. this would mean $z_0 = z_{c1}$ for $z_0 = z_{c2} \frac{z_{c3} + iz_{c2} \tan(k_2 d)}{z_{c2} + iz_{c3} \tan(k_2 d)}$. **Answer:** Yes, there are three such cases (check the math): Trivial case: $z_{c1} = z_{c2} = z_{c3}$ ■ Half-wave layer: $z_{c1} = z_{c3}$, $d = \frac{n\lambda_2}{2}$, n = 1, 2, 3...Quarter-wave transformer: $z_{c2} = \sqrt{z_{c1} z_{c3}}, d = \frac{(2n+1)\lambda_2}{4}, n = 1, 2, 3...$ Medium 3: Medium 1: Medium 2 ρ_1, c_1, K_1, z_{c1} ρ_2, c_2, K_2, z_{c2} ρ_3, c_3, K_3, z_{c3} x = 0x - dX



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Reflection with Arbitrary Angle



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3 Snell's Law

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Snell's Law	Medium 1:	Medium 2:
Impedance in front of a Boundary		<i>p</i> ₂ , <i>v</i> ₂ , <i>v</i> ₂ , <i>v</i> ₂
Total Reflection		x
Snell's Law in Multilayer Media		
Locally Reacting Surface		



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$$\begin{array}{l} \theta_{i} = \theta_{r} \\ \theta_{i} \neq \theta_{t} \Rightarrow \text{refraction happens!} \\ \text{furthermore, } \frac{c_{1}}{c_{2}} = \frac{\sin \theta_{i}}{\sin \theta_{t}} \end{array}$$



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3 Impedance in front of a Boundary

Snell's Law

Impedance in front of a Boundary

Total Reflection

Snell's Law in Multilayer Media

Locally Reacting Surface

For arbitrary angles, the impedance at distance d from the boundary can be given as (compare to Eq. (4))

$$z = \left(\frac{z_{c1}}{\cos\theta_{i}}\right) \frac{\left(\frac{z_{c2}}{\cos\theta_{t}}\right) + i\left(\frac{z_{c1}}{\cos\theta_{i}}\right) \tan(k_{1}d\cos\theta_{i})}{\left(\frac{z_{c1}}{\cos\theta_{i}}\right) + i\left(\frac{z_{c2}}{\cos\theta_{t}}\right) \tan(k_{1}d\cos\theta_{i})}$$
(5)



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3 Impedance in front of a Boundary

Snell's Law

Impedance in front of a Boundary

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Snell's Law in Multilayer Media

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(5)

Reflection coefficient in this case is

$$R = \frac{\frac{Z_{c2}}{\cos\theta_{t}} - \frac{Z_{c1}}{\cos\theta_{i}}}{\frac{Z_{c2}}{\cos\theta_{t}} + \frac{Z_{c1}}{\cos\theta_{i}}}$$
(6)



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Snell's Law

Impedance in front of a Boundary

Total Reflection

Snell's Law in Multilayer Media

Locally Reacting Surface If $c_1 < c_2$, there is a **critical angle**

$$\theta_{\rm cr} = \sin^{-1} \left(\frac{c_1}{c_2} \right),\tag{7}$$

for which the wave in medium 2 propagates *parallel to the surface*.



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Snell's Law

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Total Reflection

Snell's Law in Multilayer Media

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$$\theta_{\rm cr} = \sin^{-1}\left(\frac{c_1}{c_2}\right),$$
(7)

for which the wave in medium 2 propagates *parallel to the surface*. If $\theta_i > \theta_{cr}$, there is an inhomogeneous plane wave propagating along the surface, and it decays exponentially when moving to medium 2.



Snell's Law

Impedance in front of a Boundary

Total Reflection

Snell's Law in Multilayer Media

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■ sound energy does not propagate into medium 2 ⇒ total reflection of sound energy!



Snell's Law

Impedance in front of a Boundary

Total Reflection

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Snell's Law	У.	1		
mpedance in front of a Boundary				
Total Reflection				
Snell's Law in Multilayer Media				
Locally Reacting Surface				



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Bending of sound due to temperature gradients!



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Bending of sound due to temperature gradients! See also demo at http://www.falstad.com/ripple/



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Snell's Law

Impedance in front of a Boundary

Total Reflection

Snell's Law in Multilayer Media

Locally Reacting Surface Generally, when a wave propagates from one medium to another, it creates a surface wave that propagates along the boundary.



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Snell's Law

Impedance in front of a Boundary

Total Reflection

Snell's Law in Multilayer Media

Locally Reacting Surface Generally, when a wave propagates from one medium to another, it creates a surface wave that propagates along the boundary. It means that the particle velocity on any point on the surface depends both on the

- local sound pressure
- vibration caused by the surface wave



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Snell's Law

Impedance in front of a Boundary

Total Reflection

Snell's Law in Multilayer Media

Locally Reacting Surface

Generally, when a wave propagates from one medium to another, it creates a surface wave that propagates along the boundary. It means that the particle velocity on any point on the surface depends both on the

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Thus, evaluation of the surface impedance becomes complicated.



Snell's Law

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Thus, evaluation of the surface impedance becomes complicated. However, the surface wave may be neglected if

the surface is anisotropic so that it is hard for the surface wave to propagate



Snell's Law

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Thus, evaluation of the surface impedance becomes complicated. However, the surface wave may be neglected if

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 $\bullet c_1 \gg c_2$



Snell's Law

Impedance in front of a Boundary

Total Reflection

Snell's Law in Multilayer Media

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- local sound pressure
- vibration caused by the surface wave

Thus, evaluation of the surface impedance becomes complicated. However, the surface wave may be neglected if

- the surface is anisotropic so that it is hard for the surface wave to propagate
- C₁ ≫ C₂
- medium 2 is highly dissipative, so that the surface wave attenuates quickly



Snell's Law

Impedance in front of a Boundary

Total Reflection

Snell's Law in Multilayer Media

Locally Reacting Surface

If some of these conditions hold, the surface is called **locally** reactive.



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Snell's Law

Impedance in front of a Boundary

Total Reflection

Snell's Law in Multilayer Media

Locally Reacting Surface If some of these conditions hold, the surface is called **locally reactive**. Properties of locally reactive surfaces:

- the particle velocity at any point on the surface depends only on the local sound pressure
- the direction of an incoming plane wave becomes irrelevant



Snell's Law

Impedance in front of a Boundary

Total Reflection

Snell's Law in Multilayer Media

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Examples of locally reacting media (when air is medium 1):

- most acoustic absorption materials, such as mineral wools
- perforated materials
- soft soil



Snell's Law

Impedance in front of a Boundary

Total Reflection

Snell's Law in Multilayer Media

Locally Reacting Surface

Example of a locally reacting surface: perforated material.





ELEC-E5610 Acoustics and the Physics of Sound, Lecture 5 Geora Götz Aalto DICE

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