03.04 (火)

교재

① Acoustics – An introduction H. Kuttruff

② Fundamental of Acoustics (4^{th} Ed) L.E. Kinsler et al. Wiley 2000

음향공학(音響工學) ; 소리의 공학 (전에 존재하지 않던 걸 만듦.)

음향학 (音響學) ; 소리의 과학 (이미 있는 걸 찾는거)

자연

음향학 history

물리학의 한 분야로, 英 Lord Rayleigh (1842–1919)에 의해 19C말~20C초 체계화 됨.

본명 John William Strutt, 3^{rd} Baron Rayleigh

소리(sound, 音)란 ?

① 공기입자의 진동

② 인간의 청각 기관에 감각을 유발하는 그 원인

③ 인간의 청각기관이 감지한 내용 (심리학, 음향 심리학, 심리 음향학)

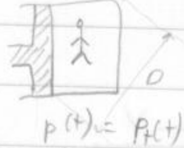
주체

④ 물질 내의 역학적인 교란 (disturbance)

물질: 기체 / 액체 / 고체 — 진공(X)

역학적: 전자기적(X) / 화학적(X)

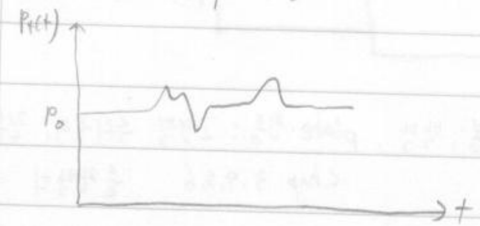
$D \ll \lambda$ (particle)

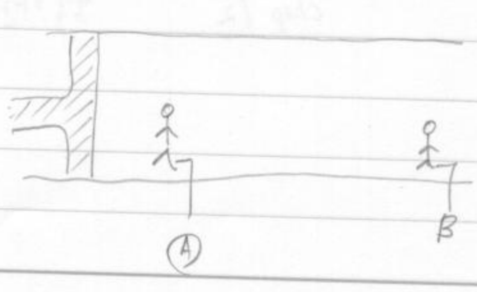


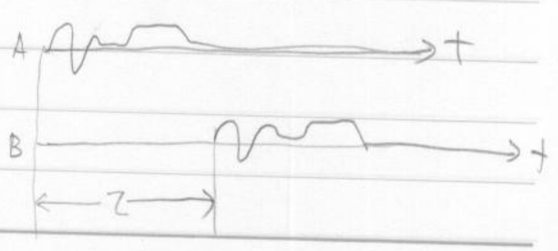
대기압

$p(t) = P_t(t) - P_0$

acoustic pressure







$\tau = l/c$　　c: 음속 (sound speed)

$p(t)$ [Pa]　　$1\,P_a = 1\,N/m^2$

$p(x,t) \longrightarrow$ 3차원 $p(x,y,z,t)$

음향학적 물리량　　　　압력↑ ⟶ 밀도↑

음압　$p = P_t - P_0$　　밀도 (ρ)　　(disturbance pattern의 이동속도)

입자속도 (particle velocity)　$\vec{v} = (V_x, V_y, V_z)$. 입자속도 $\neq$ 음속
[m/s]

(입자) 변위

(입자) 가속도

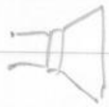
음속, velocity potential, (sound) intensity etc

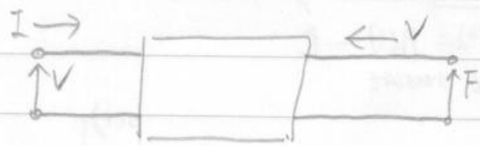
03.06 木　(자습 내용)

Kinsler　　　　　　　　Kuttruff

Chap 1.　　　　　　　　chap 2.　진동의 기초 → 변환기 (transducer)

"electro mechanical analogy" 전기-역학적 대응관계

(contents) 

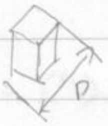


Chap 2~4 ⟶ 현, 봉, 박막, plate 진동 : 고전적 수리물리, 진동학의 기초

chap 5~7　　　　　　Chap 3,4,5,6　음향학의 기초

Chap 11　　　　　　chap 12　청각 기관

〈이번 학기에 다룰 내용〉	Kinsler	Kuttruff
Sound in closed space		Chap 9.
Room Acoustics 〈실내 음향학〉	Chap 12	Chap 13.
Building Ac 〈건축 〃〉 - 소리제거	chap 13	chap 14.
Electroacoustic transducer (전기 음향 변환기)	14	17
Microphones	14	18
Loudspeakers	14	19
Underwater Acoustics (수중 음향학)	15	



$D \ll \lambda$ 입자속도 $\vec{v} = \frac{\partial \vec{s}}{\partial t}$ s: 변위 (3.1)

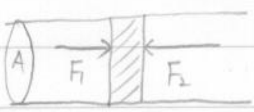
$\vec{v} = -\nabla \Phi$ → velocity potential (3.2)

$P_t = P_0 + P_\sim$ → acoustic pressure (교류 음압) [N/m²] = [Pa]

$\rho_t = \rho_0 + \rho_\sim$

sound wave

(1-D)



① $F_1 - F_2 = m\vec{a}$ (Newton)

$F_1 = P_1 A$; $F_2 = P_2 A$

② continuity

들어온 양 - 나간 양 = 증가한 양 (질량이 증가)

1-D wave eq.

1-D wave eq.

$$\frac{\partial^2 P}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 P}{\partial t^2} \quad (3.21)$$

D'Alembert sol ⇒ sol : $\begin{cases} f(x-ct) \\ g(x+ct) \end{cases}$

→ $P(x,t) = \hat{P} e^{j(\omega t - kx)}$

$f(x, t=0)$ 초기 disturbance pattern

3-D

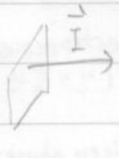
$\nabla^2 P = \frac{1}{c^2}\frac{\partial^2 P}{\partial t^2}$ (3.25) lossless일 때 이상적인 eq

ΔP 절에서 표기

$I = cW$

Intensity → (음향 강도, 소리(의) 세기, 음향 세기, 소리 강도, 인텐시티)

$[J/m^2 \cdot s] = [\frac{W}{m^2}]$



$\vec{I}$ 단위 시간당 몇 J이 통과하나?

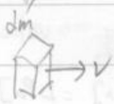
energy density $[J/m^3]$

$\vec{I}_i = p\vec{V} = \frac{F}{A}\frac{\Delta x}{\Delta t} = \frac{J}{m^2 \cdot s}$ J

instant intensity

$\vec{I} = \langle p\vec{V}\rangle_t$ → time average

energy density $W = W_{kin} + W_{pot} = \frac{1}{2}\rho_0\langle V^2\rangle_t + \frac{1}{2}\frac{\langle p^2\rangle_t}{\rho_0 c^2}$



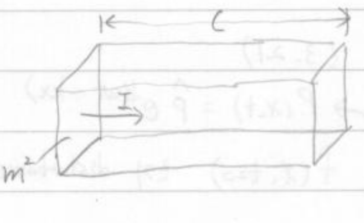
(kinetic energy)

potential energy (탄성)

압력에 의해 눌림

$I = cW$

① 단위 체크 $\frac{W}{m^2} \rightarrow \frac{m}{s}\frac{J}{m^3} = \frac{m}{s}\frac{W \cdot s}{m^3} = \frac{W}{m^2}$



$\frac{I \cdot 1m^2 \cdot 1s}{1m^2 \cdot c \cdot 1s} = W = \frac{I}{c}$ J

부피

~~※ W 일정할 때 $I \propto \frac{1}{c}$~~

03. 11 火

(3.33) $\vec{I} = \frac{1}{2} Re\{p\vec{v}^*\}$

$f = ma$

$\vec{I}$ 방향 $\Rightarrow \vec{v}$ → 직접 측정 못함. 그래서 간접적으로 $\boxed{-\nabla p = \rho_0 \frac{\partial \vec{v}}{\partial t}}$

p, v가 위상차 $\underline{pv\cos\theta}$

음압 레벨 (Sound Pressure Level) — SPL

$L_p = 20 \log\left(\frac{\tilde{P}}{P_0}\right)$ [dB]

$\tilde{P}$: 음압의 실효치

P_0 ref. sound pressure

$20\,\mu Pa = 2 \times 10^{-5}\ Pa$

Loudness Level [phon]

(객관적) 물리적 소리의 크기
모든 f에 대해 일정한 반응

주파수에 따른 감도 차이

(주관적 소리의 크기 - 인간 중심. '나' 중심.)
특정 f에 민감

Loudness [sone]

사람 수용 능력

120 dB → 1초 이상 노출되면 안됨.

→ dynamic range 120dB

90dB 실제로 아래의 15dB 제외하고 안전하게 들을 수 있음.

0 dB

상대적 음압 레벨

$\Delta L_p = 20 \log\left(\frac{\tilde{P}_2}{\tilde{P}_1}\right)$ [dB] $\Delta L_I = 10 \log\left(\frac{I_2}{I_1}\right)$ [dB]

Sound Intensity Level SIL or IL

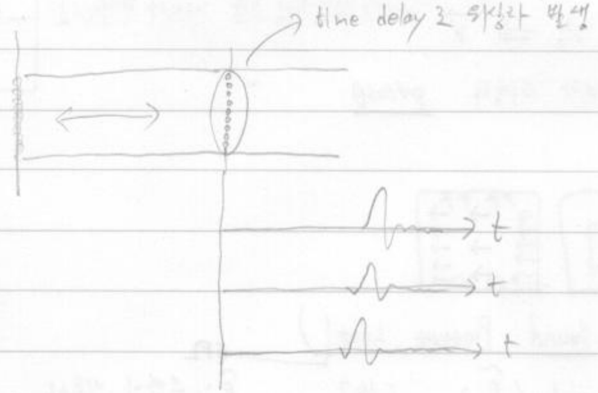
$L_I = 10 \log\left(\frac{I}{I_0}\right)$ [dB] ; $I_0 = 10^{-12}\ \frac{W}{m^2}$

$L_p \approx L_I$

NO. DATE.

Plane Wave

↳ wave front



$p(x,t)$ $\quad \dfrac{\partial^2 p}{\partial x^2} = \dfrac{1}{c^2}\dfrac{\partial^2 p}{\partial t}$

sol: $p(x,t) = \underset{\longrightarrow}{f(x-ct)} + \underset{\longleftarrow}{g(x+ct)}$

단일 주파수

$p(x, t=0) = \hat{p}\cos(kx) \Rightarrow \mathrm{Re}\{\hat{p}\, e^{-jkx}\}$

$\rightarrow f(x-ct)$ $\quad w = kc$

$\hat{p}\, e^{-jk(x-ct)} \rightarrow \underline{\hat{p}\, e^{j(wt-kx)}}$

$\Rightarrow p, \vec{v}, \vec{I}, w$

$\boxed{-\nabla p = \rho_0 \dfrac{\partial \vec{v}}{\partial t}} \Rightarrow -\dfrac{\partial p}{\partial x} = \rho_0 jw\, v \Rightarrow \boxed{v = -\dfrac{1}{jw\rho_0}\dfrac{\partial p}{\partial x}}$

$v=(v_x,0,0)$ 1차 운동

$\left.\begin{array}{l} p(x,t) = f(x-ct) \\ p(x,t) = \hat{p}\, e^{j(wt-kx)} \end{array}\right) \longrightarrow v = \dfrac{1}{\rho_0 c}\, p \quad (4.3)$

$\underline{\dfrac{p}{v} = \rho_0 c = Z_0}$ (acoustic) characteristic impedance (of medium)

특성 임피던스

0.067×10^{-6}

NO. DATE.

ex) $f = 1\,\text{kHz}$, $\overset{\text{평균}}{\hat{p}} = 20\,\mu\text{Pa}$ $\quad p(t) = \hat{p} e^{j\omega t}$ $\quad \omega = 2\pi f$, $f = 1\,\text{kHz}$

$\text{peak} - \hat{p} = \sqrt{2} \cdot 20\,\mu\text{Pa}$

$v(t) = \hat{v} e^{j\omega t}$ $\qquad \dfrac{\hat{p}}{\hat{v}} = \rho_0 c \rightarrow \hat{v} = \dfrac{\hat{p}}{\rho_0 c}$ $\qquad \rho_0 = 1.21\ \text{kg/m}^3$, $c = 343\ \text{m/s}$

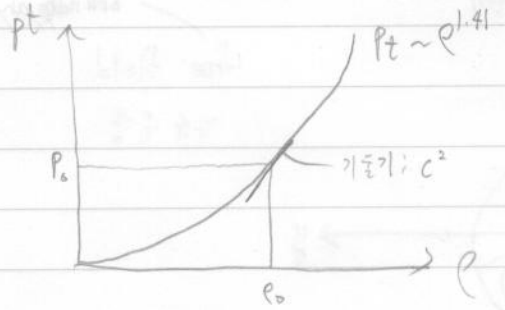
$Z_0 = 1.21 \times 343 \left(\dfrac{\text{kg}}{\text{m}^2 \cdot \text{s}}\right)$ $\qquad \hat{v} = \dfrac{20\sqrt{2} \times 10^{-6}}{415\ \text{rayl}} = 0.067 \times 10^{-6}\ [\text{m/s}]$

$\dfrac{P}{V} = \left[\dfrac{\text{Pa} \cdot \text{s}}{\text{m}}\right] \rightarrow \text{rayl} = 415\ \text{rayl}$

※ $\hat{v} = \dfrac{\text{Pa} \cdot \text{m}^2 \cdot \text{s}}{\text{kg}} = \dfrac{\text{kg}\,\text{m}}{\text{s}^2} \dfrac{1}{\text{m}^2} \dfrac{\text{m}^2 \cdot \text{s}}{\text{kg}} = \left[\dfrac{\text{m}}{\text{s}}\right]$

$\omega = kc$ $\qquad k = \dfrac{\omega}{c} = \dfrac{2\pi f}{\lambda f} = \dfrac{2\pi}{\lambda}$ (wave number, 〃 vector) $\Rightarrow k$

$c = \lambda f$



ad : adiabatic

$c = \sqrt{\left(\dfrac{dP_t}{d\rho_t}\right)^{ad}} \overset{1.41}{=} \sqrt{\dfrac{\kappa R T}{M_r}}$ — gas constant, 절대온도, M_r – 분자량

$= \sqrt{\dfrac{K^{(ad)}}{\rho_0}}$ $\qquad K^{(ad)}$: adiabatic compression modulus $= \left(\dfrac{P}{\frac{\Delta V}{V}}\right)$

$c \propto \sqrt{T}$

$c = \sqrt{\dfrac{\text{탄성계수} \rightarrow \text{탄성}}{\text{밀도} \rightarrow \text{관성}}}$ $\qquad c_{rod} = \sqrt{\dfrac{Y}{\rho_0}}$

※ 전자 저울로 공기 질량 못 재는 이유

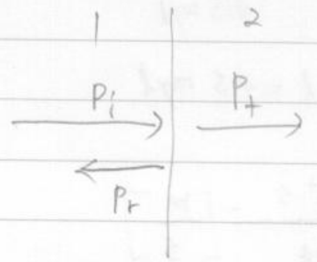
공기 부력 때문에 안됨. 잴려면 공간을 진공으로 만들고 1m^3 의 부피를 가지는 질량이 없는 박스로 공기를 모아서 ↓ 내려서 잰다.

저울

NO. DATE.

물 (해수) $\rho_0 = 10^3\ kg/m^3$, $c = 1500\ m/s$) $\rho c = 1.5\times10^6$ rayl

acoustic hard (밀하다. 밀집되어 있음.)
soft (소하다. ↕ X)



$Z_{o1} \neq Z_{o2}$ 일때 반사 생김.

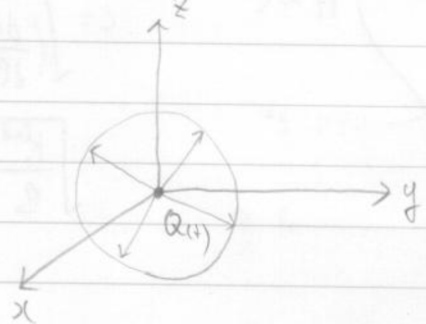
$\boxed{\text{attenuation}} \rightarrow \hat{P} e^{-\alpha x} e^{j(\omega t - kx)}$ $\qquad \alpha = \frac{m}{2}$ ($\because I \sim p^2$)

$I(x,t) = I_0 \cdot e^{-mx}$

03.18 (수) 5. Spherical wave
↳ wavefront 형태

free field — boundary free;
자유 음장

반사양 '0'이 되는 조건
거리 : ∞
되돌아오는 시간 : ∞
attenuation : ∞
boundary가 무한히 멀리 있으므로 반사되어 오는양이 없음.



$$\nabla^2 p = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} \quad (5.1)$$

sol
$\Rightarrow$ (5.3) $\quad p(r,t) = \frac{1}{r}\left[f(r-ct) + g(r+ct)\right]$

$g(r+ct)$ → 반사되어 되돌아오는 게 없는데 여기선 없음.

$f(r-ct)$ → disturbance pattern은 유지

$\frac{1}{r}$: attenuation (geometry)

$I \propto \frac{1}{r^2}$

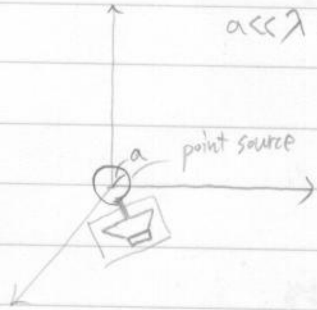
$p \propto \frac{1}{r}$

$$\boxed{-\nabla p = \rho_0 \frac{\partial \vec{V}}{\partial t}}$$

$Q(t)$: volume velocity $[m^3/s]$

$a \ll \lambda$ 이면 point source 표면속도

$$Q(t) = 4\pi a^2 V_s(t)$$



(5.1) sol ⇒ $p(t) = \frac{\rho_0}{4\pi r}\dot{Q}\left(t-\frac{r}{c}\right)$ (5.5)

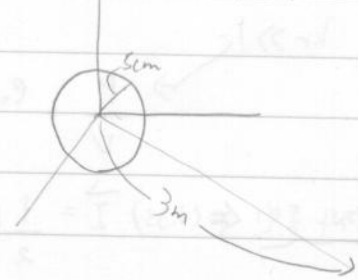
$Q(t) = \hat{Q}e^{j\omega t}$ 경우

$p(t) = \frac{j\omega\rho_0}{4\pi r}\hat{Q}e^{j(\omega t-kr)}$ (5.6)

ex) $f = 100\,Hz$, $\lambda = 3.43m$ (∵ $c = 343\ m/s$ 20°C 공기중 음파속도) $f\lambda = c$

$a = 5cm$ 표면변위 $x(t) = \hat{x}e^{j\omega t}$ ($\hat{x} = 1mm$)

$\hat{p} = ?$, $\tilde{Q} = ?$, $L_p = ?$



from 식 5.6) $\hat{p} = \frac{\omega\rho_0}{4\pi r}\hat{Q}$, $\hat{Q} = 4\pi a^2\hat{x} = 4\pi(5\times10^{-2})^2\cdot10^{-3}\ [m^3/s]$

$= 100\pi\times10^{-7}\ [m^3/s] = 3.14\times10^{-5}\ [m^3/s]$

$\hat{p} = \frac{2\pi\times100\times1.21}{4\pi\times3}\times3.14\times10^{-5}$ $\frac{kg}{m\cdot s\cdot m^3}\frac{m^3}{s} = \frac{2\pi\times1.21\times10^{-3}}{12} \approx 6.28\times10^{-4}\ [Pa]$

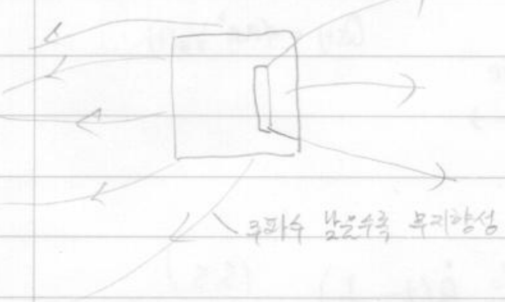
∵ $\frac{kg}{m\cdot s^2} = \overset{N}{\frac{kg\,m}{s}}\frac{1}{m^2} = \frac{N}{m^2} = Pa$

$\tilde{p} = \frac{\hat{p}}{\sqrt{2}} = P_{eff} = \frac{6.28\times10^{-4}}{\sqrt{2}} Pa \simeq 4.5\times10^{-4} Pa$

$2\times10^{-4} Pa \longrightarrow L_p = 20dB$

$\therefore L_p =$ 약 $26dB$

f가 낮을수록 무지향성



주파수 낮을수록 무지향성

$-\nabla p = \rho_0 \frac{\partial \vec{v}}{\partial t}$

$\vec{V} = (V_r, V_\phi, V_\theta)$

point source 일때

$V=V_r$ 성분만 가짐

$$V = \frac{P}{\rho_0 c}\left(1+\frac{1}{jkr}\right) \quad (5.7)$$

P·V 위상각 문제

$\boxed{\text{※ 평면파시 } V = \frac{P}{\rho_0 c} \text{ 평면파 P·V in phase}}$

$$\frac{P}{V} = \frac{\rho_0 c}{1+\frac{1}{jkr}} \qquad kr = \frac{2\pi}{\lambda} r = \frac{2\pi f}{c} r \Leftarrow \cancel{kr}$$

$kr \ll 0 \rightarrow kr \rightarrow 0 \rightarrow \frac{P}{V} = \rho_0 c\, jkr$

$kr \gg 1 \rightarrow \frac{P}{V} = \rho_0 c$

$I = \frac{\hat{p}^2}{\rho_0 c}$ (5.8) 평면파와 동일 $\Leftarrow$ (3.33) $\vec{I} = \frac{1}{2} Re\{p\vec{v}^*\}$

(5.9) $I = \frac{\rho_0 w^2 \hat{Q}^2}{32\pi^2 c r^2}$ $\quad \frac{1}{r^2}, \hat{Q}^2, w^2$

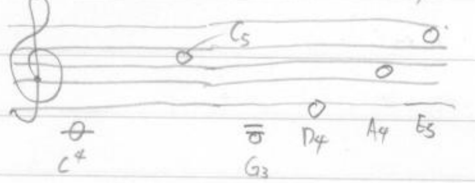
NO. DATE.

완5(7개반음)

완5도씩 내려감 $f(\frac{2}{3}\downarrow)$

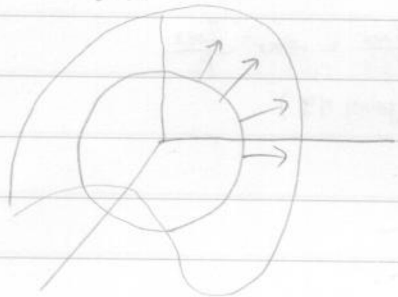
violin G_3, D_4, A_4, E_5 1oct↓ → Cello

viola C_3, G_3, D_4, A_4 $f(\frac{1}{2}\downarrow)$



바이올린에 비해 첼로는 f가 $(\frac{2}{3} \times \frac{1}{2})$로 내려간다. volume velocity가 같으면 I가 $\frac{1}{9}$배 낮아진다. ∴ 키워준다.

$$P_r = \frac{\rho_0 \omega^2 \hat{Q}^2}{8\pi c} \quad (5.10) \qquad \omega^2, \hat{Q}^2$$



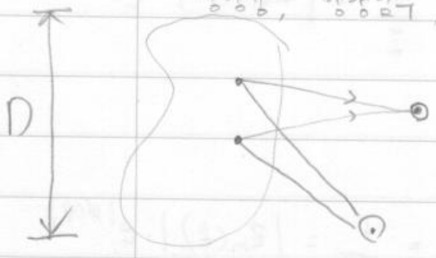
$$P = \oint\!\!\oint \vec{I}\cdot d\vec{s}$$
$$Q_t = \oint\!\!\oint \vec{D}\cdot d\vec{s}$$

$$f' = f\,\frac{c \pm V_r}{c \mp V_s}$$

서로 가까워질때

서로 멀어질때

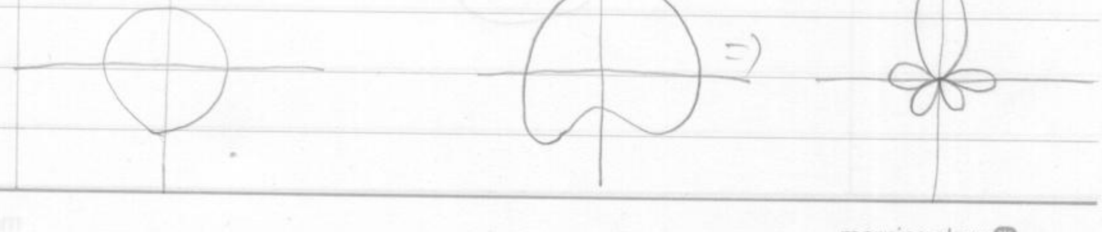
방향성, 방향함수, beam pattern | 단일 주파수



source가 point source의 집합일때 방향성 생김

$D \ll \lambda$ 이면 방향성 X

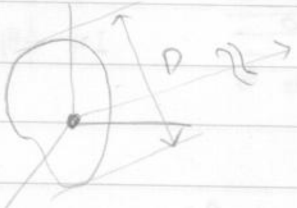
완전 cancel



NO. DATE.

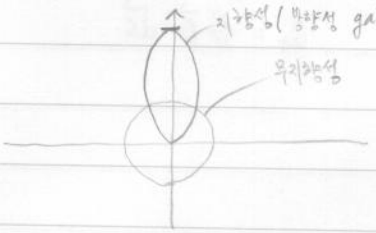
far field에서는 (5.14)로 된다.

far field $r >> \lambda, D$



$R(\theta, \emptyset)$

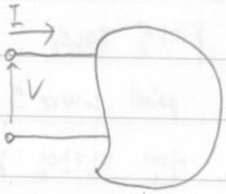
(5.16) gain $\gamma = \frac{I_{max}}{\langle I \rangle} = 4\pi r^2 \frac{I_{max}}{P_r}$



03.20(木) (5.18) Def $Z_r = \frac{F_r}{V_o}$ $F_r \rightarrow$ rad. force, $V_o \rightarrow$ rad. surf. vel

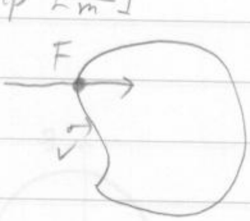
radiation impedance

el. imp



$Z_{el} = \frac{V}{I} = |Z_{el}(f)| \cdot e^{j\phi(f)}$

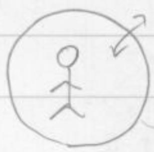
mech imp $[\frac{N \cdot s}{m}]$



$Z_m = \frac{F}{v} = |Z_m(f)| \cdot e^{j\phi(f)}$

NO. DATE.

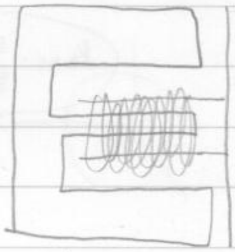
rad imp $[\frac{N\cdot s}{m}]$



$\frac{F_r}{v_0}$

탄성없는 고무풍선

speaker

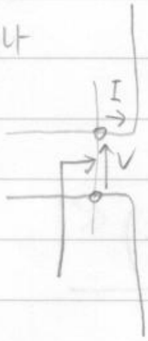


$$Z_r = R_r + jX_r$$

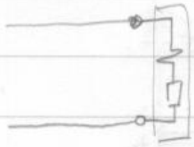
$$P_r = \frac{1}{2}\hat{v}_0^2 \cdot \mathrm{Re}\{Z_r\}$$

$$= \frac{1}{2}\hat{v}_0^2 \cdot R_r$$

안테나

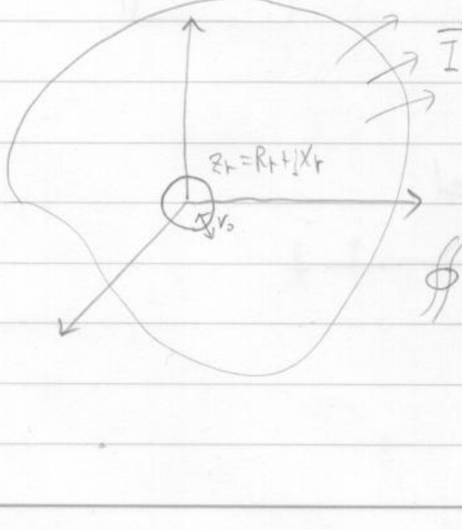


$$P_r = \frac{1}{2}\hat{I}\cdot \mathrm{Re}\{Z_r\}$$



$Z_{r_e} = R_{r_e} + jX_{r_e}$ electrical

rad imp

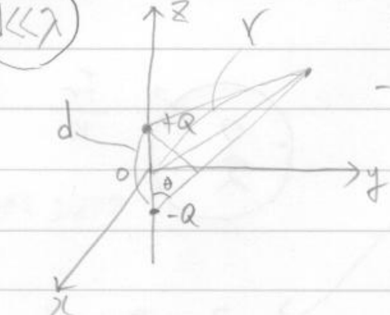


$\oint \vec{I}\cdot d\vec{s}$

$(2\pi)^2 \frac{f^2}{c^2}$ $\frac{(2\pi)^2 d^2}{\lambda^2}$

NO. DATE.

$d \ll \lambda$



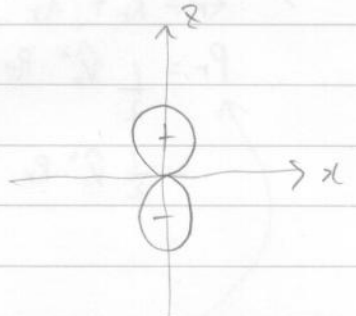
$+Q = \hat{Q} e^{jwt}$

$-Q = -\hat{Q} e^{jwt} = \hat{Q} e^{j(wt+\pi)}$

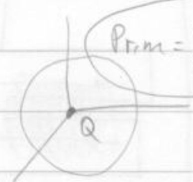
$$p(r,t) = -\frac{w^2 \rho_0 \hat{Q} d}{4\pi r c} \cos\theta \, e^{j(wt-kr)}$$

① 방향함수

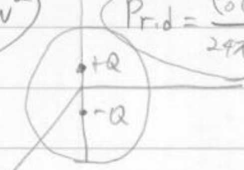
② rad · 비효율적



$P_{r,m} = \frac{\rho_0 \hat{Q}^2}{8\pi c} w^2$



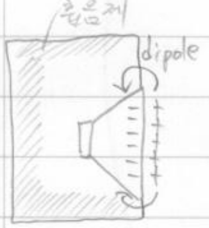
$P_{r,d} = \frac{\rho_0 \hat{Q}^2 d^2}{24\pi c^3} w^4$

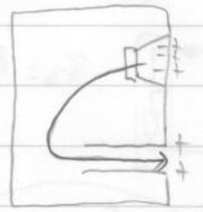


$$\frac{P_{r,d}}{P_{m,d}} = \frac{d^2 w^2}{3c^2} = \frac{1}{3}(kd)^2$$

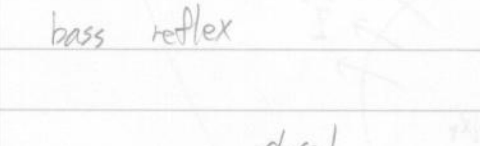
$k = \frac{2\pi}{\lambda}$, $kd = 2\pi\left(\frac{d}{\lambda}\right) \ll 1$

acoustic short





bass reflex

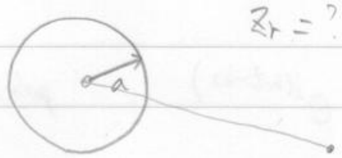


NO. DATE.

array
- ① 등간격, 동일 weighting
- ② 〃, 다른 weighting
- ③ 다른 간격, 동일 〃
- ④ 다른 간격, 다른 〃

5.7 pulsating sphere

$a \ll \lambda$



$a \ll \lambda$로 보고 point source 처리

$Z_r = ?$ ① $p(r,t) = \frac{j\omega \rho_0 \hat{Q}}{4\pi r} e^{j(\omega t - kr)}$

② $p(r=a)$, $F_r = p(r=a) \cdot 4\pi a^2$

$Q(t) = \hat{Q} \cdot e^{j\omega t}$

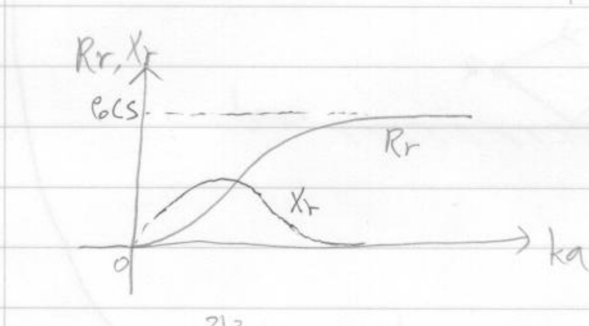
$\hat{Q} = \hat{V}_0 \cdot 4\pi a^2$

$$Z_r = \frac{\rho_0 c S}{1 + \frac{1}{jka}} = R_r + jX_r \quad (5.27)$$

$S = 4\pi a^2$

$$R_r = \rho_0 c S \frac{(ka)^2}{1+(ka)^2} \quad (5.28)$$

$$X_r = \frac{\rho_0 c S (ka)}{1+(ka)^2}$$

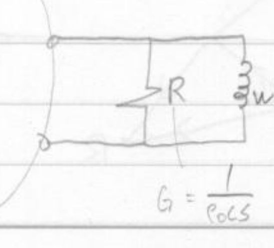


$$P_r = \frac{1}{2} \hat{V}_0^2 \cdot R_r$$

반경이 커서 평면과 취급 $\frac{P}{V} = \rho_0 c$

$$Z_r = \frac{F_r}{V_0} = S\left(\frac{P}{V}\right)_{surf} = S \cdot \rho_0 c$$

$$Y_r = \frac{1}{Z_r}$$



$G = \frac{1}{\rho_0 c S}$

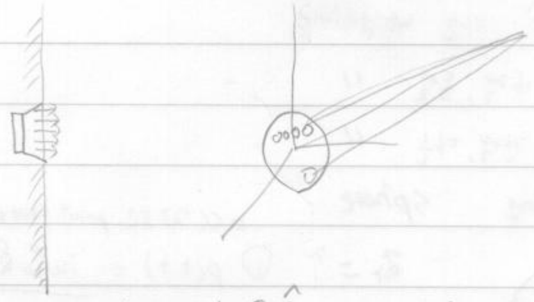
$Z_r = R_r + jX_r$

$Y_r = G_r + jB_r$

$X_r = \omega m_r$

$4\pi a^3 \rho_0$

5.8 piston



$$p(r,t) = \frac{j\omega\rho_0\hat{Q}}{4\pi r} e^{j(\omega t - kr)}$$ point source

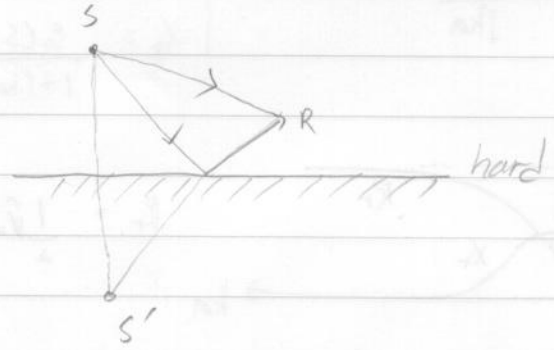
→ 벽의 영향으로 2자로 대체

infinite baffle (크기 $Z_m \to \infty$)

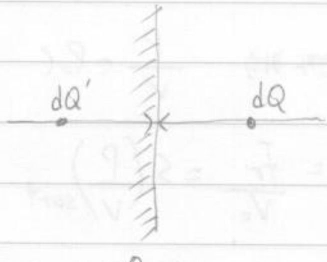
image source

soft → hard (부호 그대로)

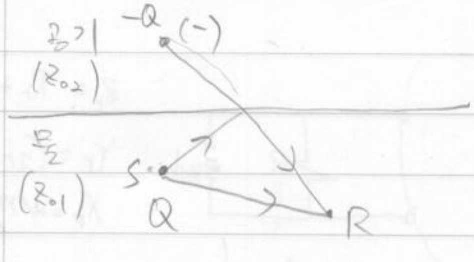
hard → soft (부호 바뀜.)



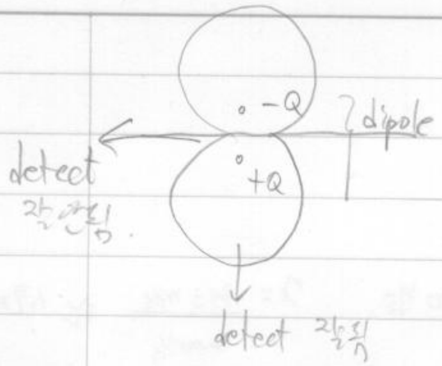
$dQ \to 2dQ$ so



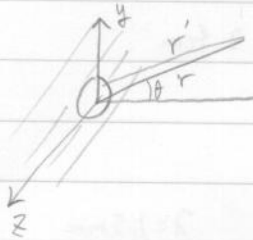
$Z_{01} >> Z_{02}$



NO. DATE.



03. 25 (水)

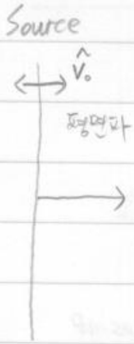


$p(r, \theta, t) = (5.31)$

phasor

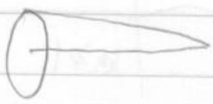
(5.34)

축상에서는 $p(r,t) = \underbrace{\rho_0 c \hat{v}_0}_{\text{평면파}} \left(e^{j(\omega t - kr)} - \underbrace{e^{-j(\omega t - k\sqrt{r^2+a^2})}}_{\text{edgewave}}\right)$



$p(x,t) = \rho_0 c \hat{v}_0 e^{j(\omega t - kx)}$

$\frac{P}{V} = \rho_0 c$, $\hat{P}(x=0,t) = \rho_0 c \hat{v} e^{j\omega t}$



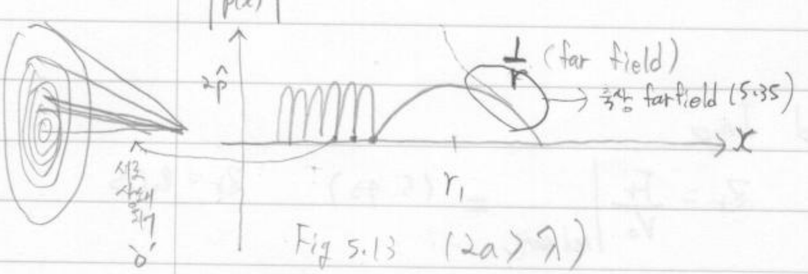


Fig 5.13 $(2a > \lambda)$

$(D > \lambda \rightarrow r_1$ 존재$)$

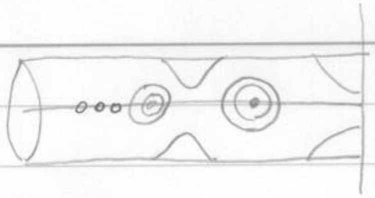
$$r_1 = \frac{D^2 - \lambda^2}{4\lambda}$$

D : diameter $D = 2a$

물리학 · farfield 조건 ; $r > \sqrt{S}$ $(S = \pi a^2)$

$r > \sqrt{\pi}\, a$

NO. DATE.



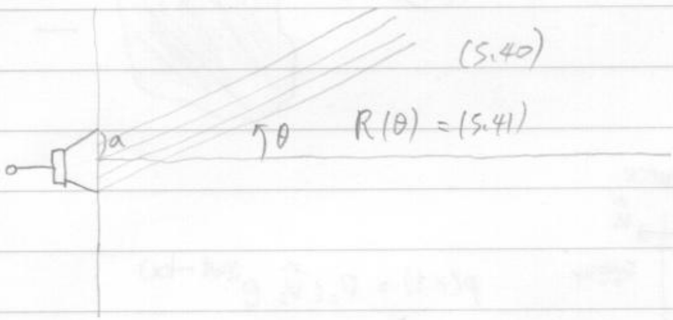
$r_1 = ?$

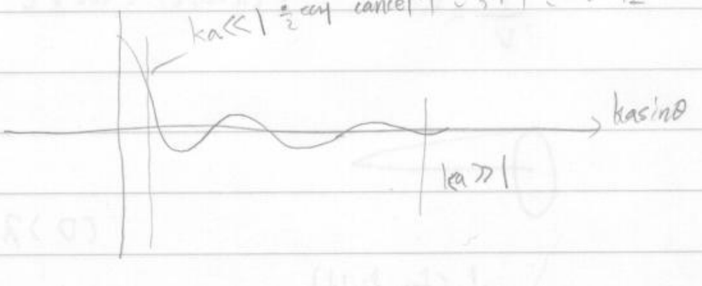
① 공기중 $D = 30cm$ $f = 200\,Hz$ $\lambda = \frac{343\ m/s}{200\ 1/s} \approx 1.7m$

$f = 10kHz$로 변화시 $\lambda = 3.4cm$

$$r_1 = \frac{(30cm)^2 - (3.4cm)^2}{4 \times 3.4cm} =$$

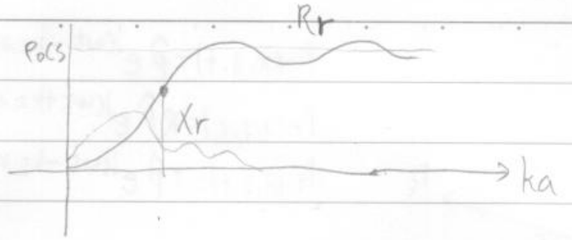
② 물 $D = 25.4mm$, $f = 1MHz$ $\lambda = 1.5mm$

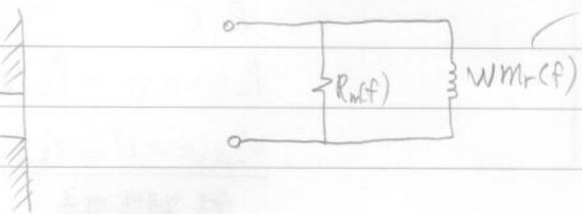




5.8.3 Rad Imp

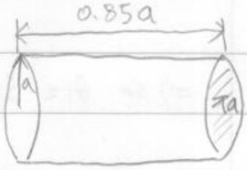
$$Z_r = \frac{F_r}{V_0}\Big|_{rad\ surf} = (5.43) \qquad Z_r = \rho_0 c S$$

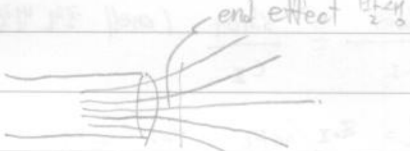




$$m_r = \rho_0 \left(\frac{8}{3\pi}\right) \cdot \pi a^2 \quad (5.46)$$

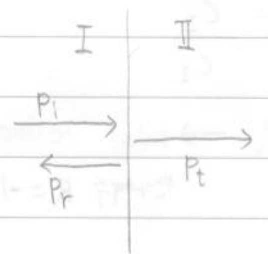
$\frac{8}{3\pi}$: 0.85a





$$Z_r = \frac{F_r}{V_0} = R_r + jX_r \longrightarrow P = \frac{1}{2}\hat{V}_0^2 \cdot R_r$$

Kutt Chap 6. | Kinsler Chap. 6 (반사와 굴절)



$$P_i = \hat{P} e^{j(\omega t - k_I x)}$$
$$P_r = R\hat{P} e^{j(\omega t + k_I x)}$$
$$P_t = T\hat{P} e^{j(\omega t - k_{II} x)}$$

$$P_I(x,t) = P_i + P_r = \hat{P} e^{j\omega t}\left(e^{-jk_I x} + Re^{jk_I x}\right)$$

$$V_I(x,t) = \frac{\hat{P} e^{j\omega t}}{(\rho_0 c)_I}\left(e^{-jk_I x} - Re^{jk_I x}\right)$$

$$-\frac{\partial P}{\partial x} = \rho_0 \frac{\partial \vec{V}}{\partial t}$$

$$P_{II}(x,t) = P_t = T\hat{P} e^{j(\omega t - k_{II} x)}$$

$$V_{II}(x,t) = \frac{T\hat{P}}{(\rho_0 c)_{II}} e^{j(\omega t - k_{II} x)}$$

※ B.C. (Boundry Condition)

massless일 때 같고
질량있으면 달라야 함.

i) $x=0$ $P_I(x=0,t) = P_{II}(x=0,t)$ $1+R=T$

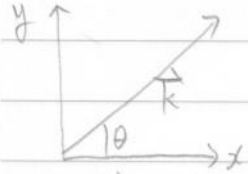
ii) $x=0$ · $V_I(x=0,t) = V_{II}(x=0,t)$ | $S_1(t) = S_2(t)$

$$\frac{1-R}{(\rho_0 c)_I} = \frac{T}{(\rho_0 c)_{II}}$$

$$\Rightarrow R = \frac{(\rho_0 c)_{II} - (\rho_0 c)_I}{(\rho_0 c)_{II} + (\rho_0 c)_I}$$

$$T = 1+R = \frac{2(\rho_0 c)_{II}}{(\rho_0 c)_{II} + (\rho_0 c)_I}$$

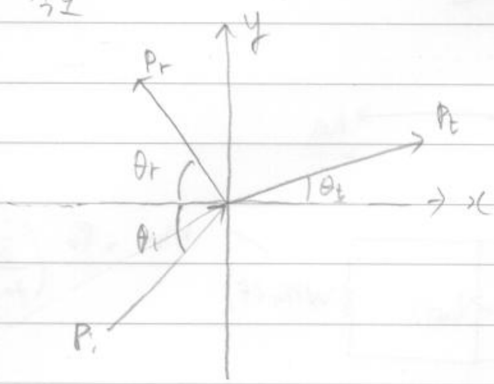
물고기 사람소리 잘 듣고
사람 물고기소리 잘 못듣는 이유



$k_x = |\vec{k}| \cos\theta$

$k_y = |\vec{k}| \sin\theta$

각도



$P_i(x,y,t) = \hat{P} e^{j(\omega t - k_I x\cos\theta_i - k_I y \sin\theta_i)}$

$P_r(x,y,t) = R\hat{P} e^{j(\omega t + k_I x\cos\theta_r - k_I y \sin\theta_r)}$

$P_t(x,y,t) = T\hat{P} e^{j(\omega t - k_{II} x\cos\theta_t - k_{II} y \sin\theta_t)}$

B. C

$P_I(x=0,t) = P_{II}(x=0,t)$

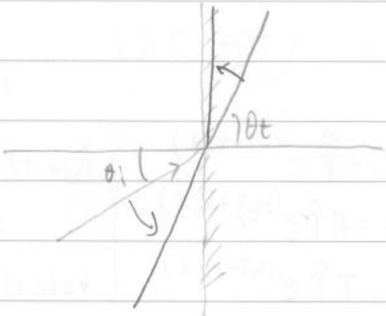
$\underbrace{V_{I,x}(x=0,t) = V_{II,x}(x=0,t)}$

수직 성분만 연속

$\Rightarrow \sin\theta_i = \sin\theta_r$ 즉 $\theta_i = \theta_r$

$\dfrac{\sin\theta_i}{c_I} = \dfrac{\sin\theta_t}{c_{II}}$ (snell 굴절 법칙)

$R = \dfrac{Z_{0II}/\cos\theta_t - Z_{0I}/\cos\theta_i}{Z_{0II}/\cos\theta_t + Z_{0I}/\cos\theta_i}$ Rayleigh 반사계수



임계각

$\sin\theta_c = \dfrac{c_I}{c_{II}}$

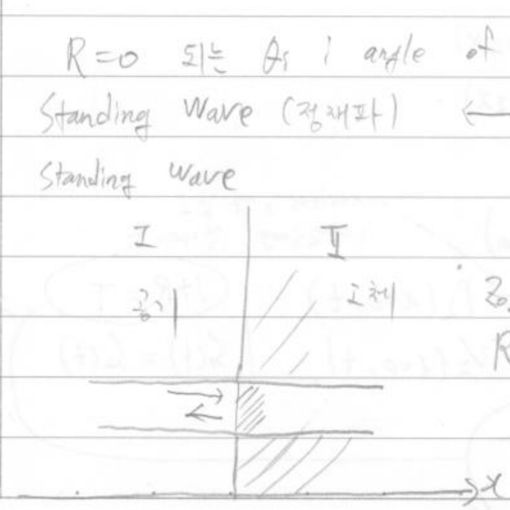
$\theta_i > \theta_c \longrightarrow$ total reflection

반사계수 $R = -1$ ($\because 1+R = T$ 에서 $T=0$ 이므로)

$R=0$ 되는 θ_i : angle of intromission

Standing Wave (정재파) $\longleftrightarrow$ Progressive Wave (진행파)

Standing wave

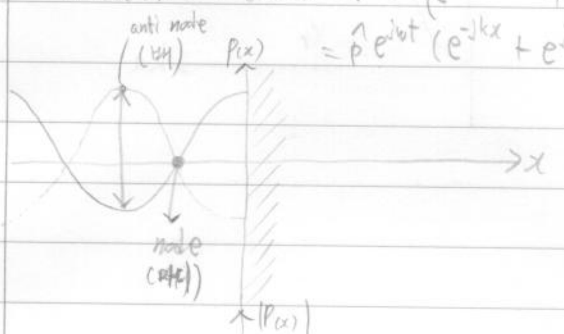


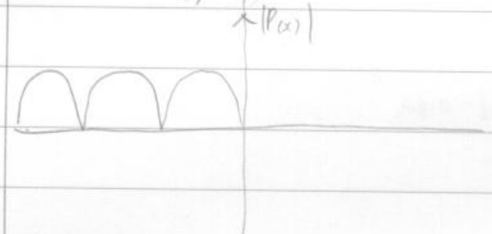
$Z_{0I} \ll Z_{0II}$

$R \approx 1$

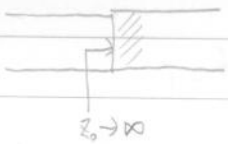
$$P_I(x,t) = P(x,t) = \hat{p}\, e^{j\omega t}\left(e^{(-jkx)} + R e^{jkx}\right)$$

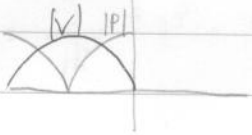
$$= \hat{p}\, e^{j\omega t}\left(e^{-jkx} + e^{jkx}\right) = 2\hat{p}\, e^{j\omega t} \cos(kx)$$





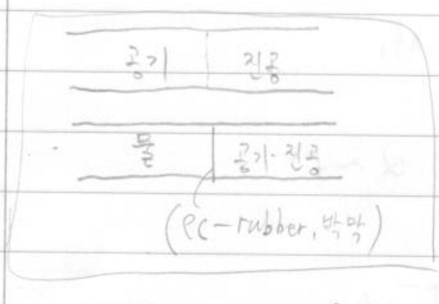
3月27日(木)

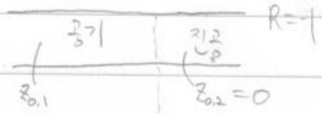




open pipe

ρc - rubber
(ρc)물



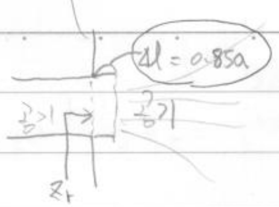


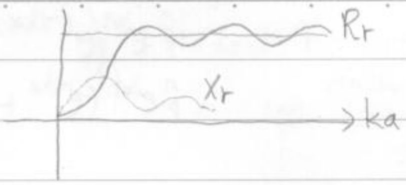
$$P_I(x,t) = \hat{p}\, e^{j\omega t}\left[e^{-jkx} + \overset{-1}{R}\, e^{jkx}\right)$$

$$= -2j\,\hat{p}\sin(kx)\cdot e^{j\omega t}$$

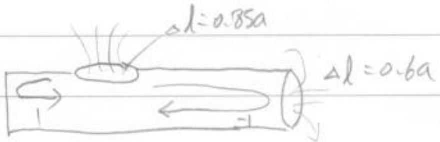
$$V_I(x,t) = \frac{2\hat{p}}{\rho_0 c}\cos(kx)\, e^{j\omega t}$$

flanged





flute



〈개관〉

$l^* = l + 2\Delta l \qquad \lambda \cdot f = c$

mode no.

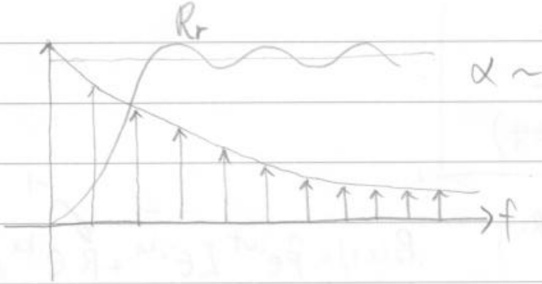
$n=1$  $l^* = \lambda_1/2, \; f_1 = \dfrac{c}{\lambda_1} = \dfrac{c}{2l^*}$

$n=2$  $f_2 = 2f_1$

$n=3$  $f_3 = 3f_1$

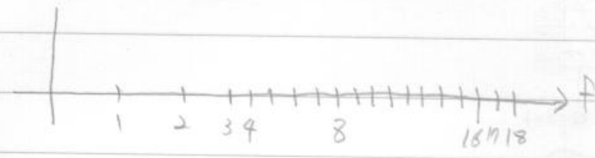
$\vdots$

$f_n = nf_1$



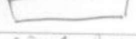
$\alpha \sim f^2$

음공 03.27

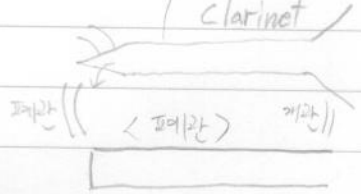


구멍은 작게 만들어야 leak + 반사가 일어남. 크게 뚫으면 ⊏ 관이 짧아지는 효과 나타남.

음악음향에서 고려(X)



(∵ 소리안나므로)



flute (개관모델)

모든차수 f 존재

Clarinet (폐관모델)

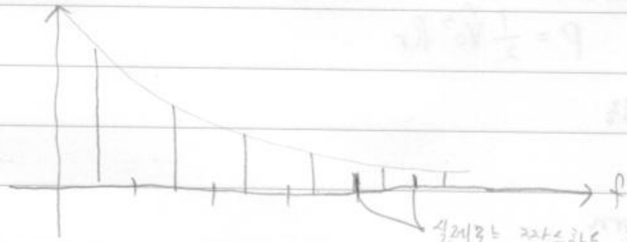
홀수차수 f 존재

$n=1$ $\quad l = \lambda_1/4 \quad f_1 = c/4l$

$n=2$ (X) 짝수차 존재 X

$n=3$ $\quad f_3 = 3f_1$

$n=5$ $\quad f_5 = 5f_1$



실제로는 짝수차도 고주파에서 작은 값을 가진다.

$n=1$ $\quad f_1 = c/2l$

$n=2$ $\quad f_2 = 2f_1$

원뿔형

개관과 유사 → $f_1 = c/2l$

$f_2 = 2f_1$

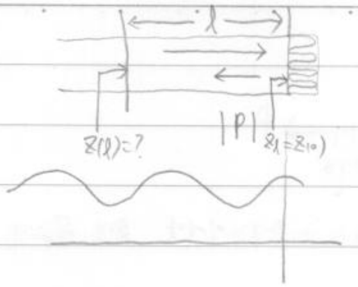
$\vdots$

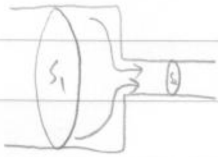
$f_n = nf_1$

single reed → saxophone

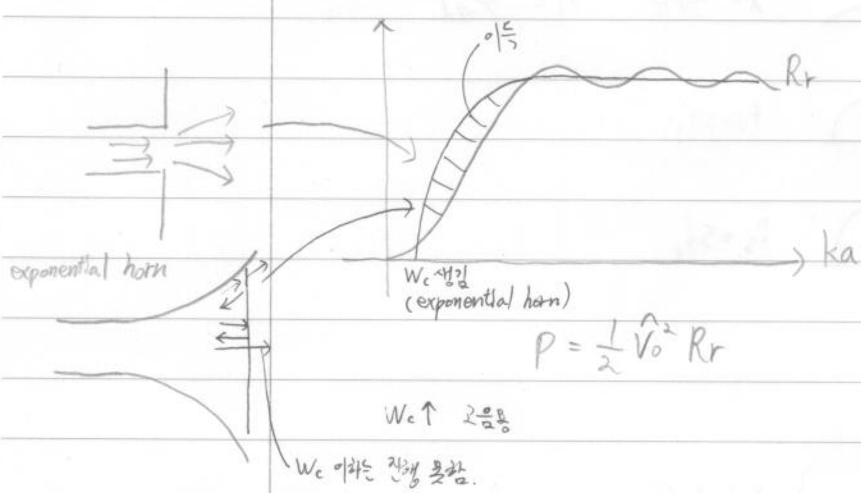
double reed → oboe, bassoon

lip → alphorn, tuba, euphonium





$S_1 V_1 = S_2 V_2$

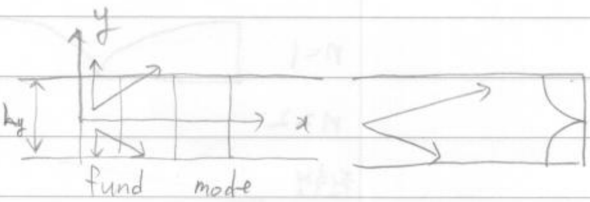


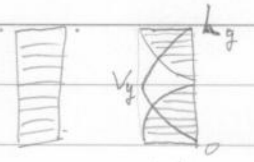
$P = \frac{1}{2} \hat{V}_0^2 R_r$

$W_c \uparrow$ 고음용

exponential horn

1. W_c (cut off frequency 생김)
2. dispersion (음색 변질됨.)





$\vec{k}(\cancel{kx}, \pm ky, 0)$

$kx = k \cdot \cos\phi$

$ky = k \cdot \sin\phi$

$$p = P_1 + P_2 = \hat{p}\left(e^{j(wt - k\cos\phi \cdot x - k\sin\phi \cdot y)} + e^{j(wt - k\cos\phi \cdot x + k\sin\phi \cdot y)}\right)$$

$$= \hat{p}\, e^{j(wt - k\cos\phi \cdot x)}\left(e^{-jky\sin\phi} + e^{jky\sin\phi}\right)$$ y 방향 : standing wave

$$= 2\hat{p}\cos(k y \sin\phi)\, e^{j(wt - k\cos\phi \cdot x)} \quad (8.45)$$ x 방향 : propagation

$$= 2\hat{p}\cos(k_y \cdot y)\, e^{j(wt - k_x \cdot x)}$$

Page 157, 158, 159 참고

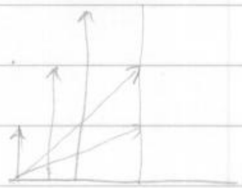
$\vec{k}(k_x, k_y, 0)$

$|\vec{k}|^2 = k^2 = k_x^2 + k_y^2$

$k_x = \sqrt{k - k_y^2} \qquad (k_x > 0,\ k > k_y)$

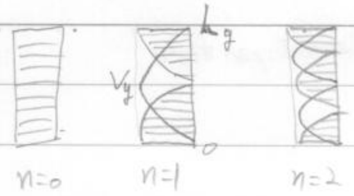
B.C

$y=0,\ V_y = 0 \quad \dfrac{\partial P}{\partial y} = 0$



$y=h,\ V_y = 0 \quad \sin(k_y L_y) = m\pi$

$k_y = \dfrac{m\pi}{L_y}$



$\vec{k}(k_x, \pm k_y, 0)$

$k_x = k \cdot \cos\phi$

$k_y = k \cdot \sin\phi$

$$p = P_1 + P_2 = \hat{p}\left(e^{j(wt - k\cos\phi \cdot x - k\sin\phi \cdot y)} + e^{j(wt - k\cos\phi \cdot x + k\sin\phi \cdot y)}\right)$$

$$= \hat{p}\, e^{j(wt - k\cos\phi \cdot x)} \left(e^{-jky\sin\phi} + e^{jky\sin\phi}\right)$$ y방향 : standing wave

$$= 2\hat{p}\cos(ky\sin\phi)\, e^{j(wt - k\cos\phi \cdot x)} \quad (8.45)$$ x방향 : propagation

$$= 2\hat{p}\cos(k_y \cdot y)\, e^{j(wt - k_x \cdot x)}$$

$\vec{k}(k_x, k_y, 0)$

Page 157, 158, 159 참고

$|\vec{k}|^2 = k^2 = k_x^2 + k_y^2$

$k_x = \sqrt{k - k_y^2} \quad (k_x > 0,\ k > k_y)$

B.C

$y=0,\ V_y = 0 \quad \frac{\partial P}{\partial y} = 0$

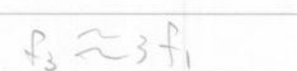
$y=h,\ V_y = 0 \quad \sin(k_y L_y) = m\pi$

$k_y = \frac{m\pi}{L_y}$

4月1日 (水)

flute
recorder

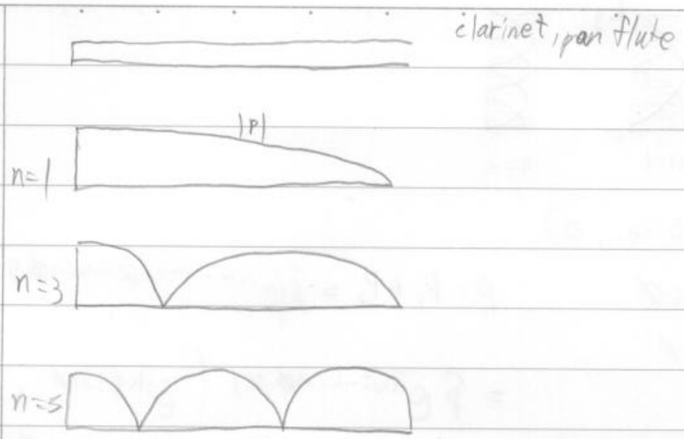
oboe, bassoon, Alphorn (Alpenhorn)
sexophone



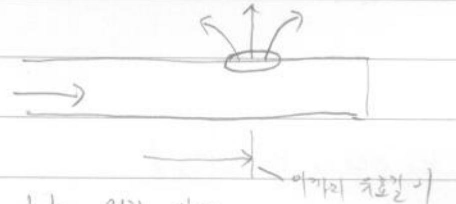
n=1 $f_1 = \frac{c}{2l}$ $f_1 \approx \frac{c}{2l}$

n=2 $f_2 = 2f_1$ $f_2 \approx 2f_1$

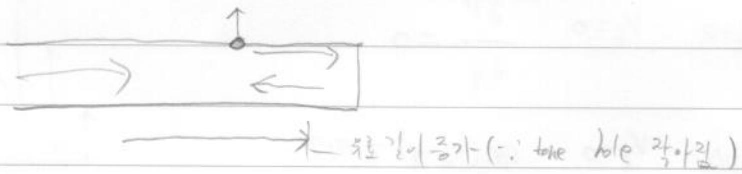
n=3 $f_3 = 3f_1$ $f_3 \approx 3f_1$

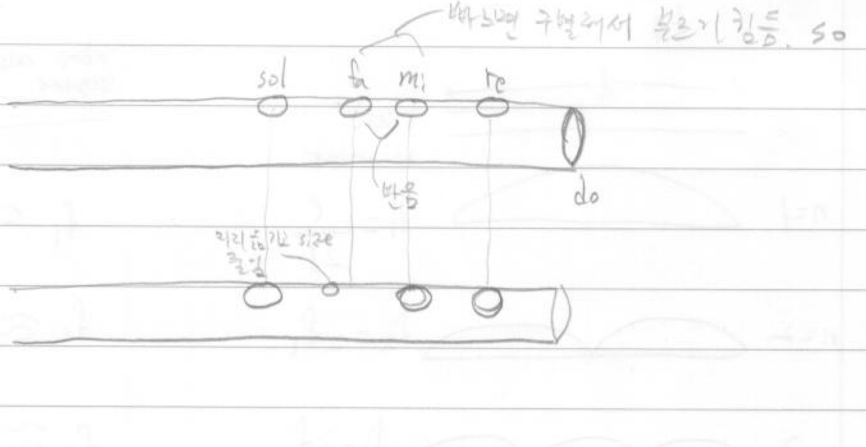


(i)



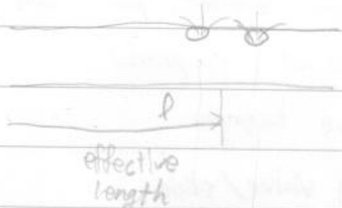
tone hole 위치, size

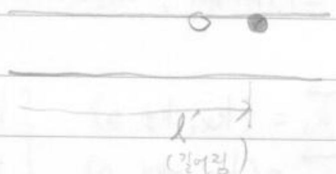


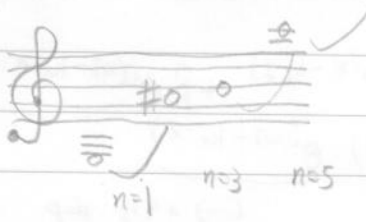


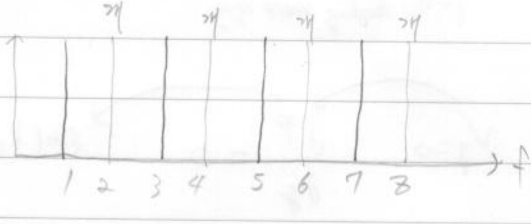
입술 진동
⇒ 금관 악기
리드에 의해서 소리
⇒ 목관 악기

ii) 반음 : cross - fingering
forked - fingering









$C_4 = 261.63\,Hz$

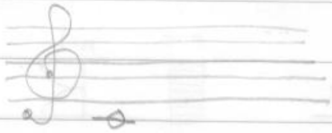
$l \approx 65cm$

약 60cm (2ft)

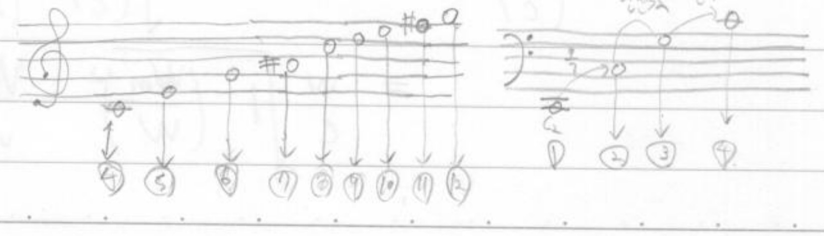
$C_4 \longrightarrow$ 약 60cm

$C_3 \longrightarrow 1.2m$

$C_2 \longrightarrow 2.4m$



2m40



3_m 40 $\longrightarrow$ $F^{\#}$ (이조악기)

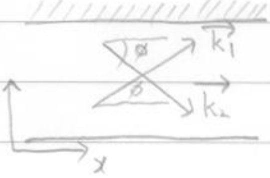
발음 메커니즘으로 구분 (재료로 구분X)

목관 $\begin{cases} \text{air reed (flute. recorder, pan flute)} \\ \text{single reed (clarinet. sexophone)} \\ \text{double reed (oboe. bassoon} \end{cases}$

금관 ; lip reed, 관의 길이 valve/slide

hybrid type (trumpet 마우스피스 + clarinet, serpent, keyed bugle)

P 156.



$$\vec{k_1} = (k_x, k_y, 0) \qquad \begin{cases} k_x = k\cos\phi \\ k_y = k\sin\phi \end{cases}$$
$$\vec{k_2} = (k_x, -k_y, 0)$$

$$P(x, y, t) = \hat{p}e^{j(wt - k_x \cdot x - k_y \cdot y)} + \hat{p}e^{j(wt - k_x \cdot x + k_y \cdot y)}$$
$$= 2\hat{p}\cos(k_y \cdot y) \cdot e^{j(wt - k_x \cdot x)}$$

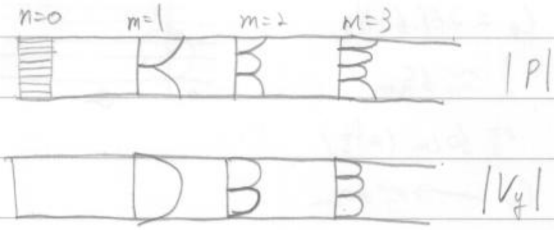
x 방향 : prop

y 방향 : standing wave 형성

B.C

$\left.\begin{matrix} y : 0 \\ y = L_y \end{matrix}\right)$ 에서 $V_y = 0$ $\frac{\partial P}{\partial y} = 0$ $\sin(k_y \cdot y) = 0$ $k_y \cdot L_y = m\pi$

$$k_y = \frac{m\pi}{L_y}$$

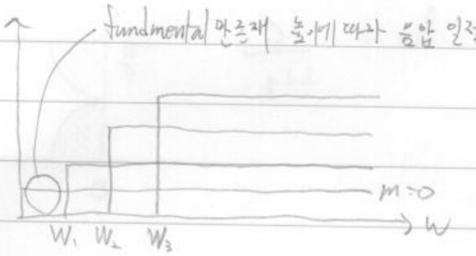


$$k_x^2 + k_y^2 = k^2 = \left(\frac{w}{c}\right)^2 \qquad k_x = \sqrt{k^2 - k_y^2} = \sqrt{\left(\frac{w}{c}\right)^2 - \left(\frac{m\pi}{L_y}\right)^2} = \frac{w}{c}\sqrt{1 - \left(\frac{m\pi c}{wL_y}\right)^2}$$
$$= \frac{w}{c}\sqrt{1 - \left(\frac{W_m}{w}\right)^2}$$

W_m : cut off freq

$w > W_m$ 일때 전파가능

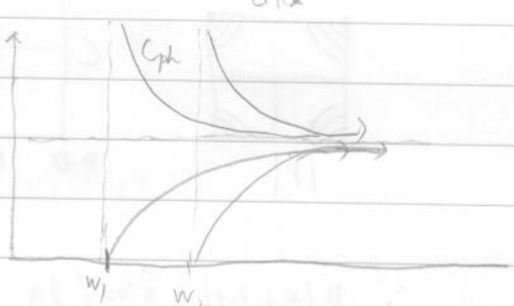
$$W_m = \frac{m\pi c}{L_y}$$



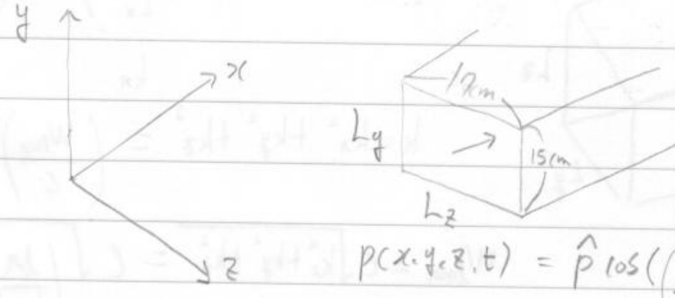
$$f_1 = \frac{1}{2\pi}\frac{\pi c}{L_y} = \frac{c}{2L_y} = \frac{340\ m/s}{2\times 3.4m} = 50Hz$$

phase vel $\quad C_{ph} = \dfrac{\omega}{k_x} = \dfrac{c}{\sqrt{1-(\omega_m/\omega)^2}}$

group vel $\quad C_{gr} = \dfrac{d\omega}{dk_x} = c\sqrt{1-(\omega_m/\omega)^2}$



04.03 (木)



$\frac{\lambda}{2} = 17cm \quad \lambda = 34cm$

$f = \frac{c}{\lambda} = \frac{340m/s}{34cm} = 1kHz$

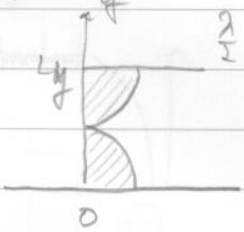
$$p(x,y,z,t) = \hat{p}\cos\Big(\underbrace{\frac{m\pi}{L_y}}_{k_y}y\Big)\cdot\cos\Big(\underbrace{\frac{n\pi}{L_z}}_{k_z}z\Big)\cdot e^{j(\omega t - k_x\cdot x)}$$

$$k_x = \sqrt{k^2-(k_y^2+k_z^2)} \qquad k = k_x^2+k_y^2+k_z^2$$

$$= \frac{\omega}{c}\sqrt{1-\left(\frac{W_{mn}}{\omega}\right)^2} \qquad \left(W_{mn} = \sqrt{\left(\frac{m\pi c}{L_y}\right)^2 + \left(\frac{n\pi c}{L_z}\right)^2} \quad (3.53) \right)$$

$$f_{mn} = \frac{W_{mn}}{2\pi} = \frac{c}{2}\sqrt{\left(\frac{m}{L_y}\right)^2 + \left(\frac{n}{L_z}\right)^2}$$

$n=0,\ m=1$ $\quad f_{1,0} = \dfrac{c}{2L_y}$

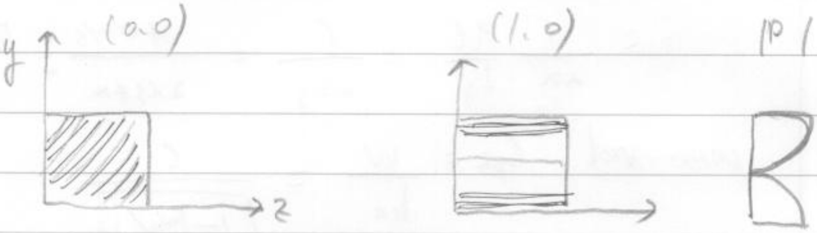


$\frac{\lambda}{2} = L_y \qquad \lambda = 2L_y$

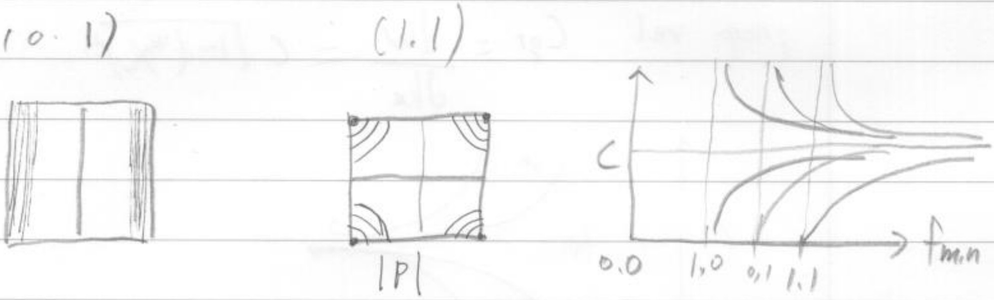
$f = \dfrac{c}{2L_y}$

(m.n) Fig 8.14

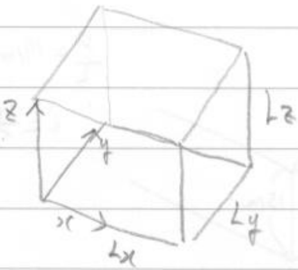
wave guide



fund (평면파) 전파



§ 9.2



$$p(x,y,z,t) = \hat{p}\cos\left(\frac{l\pi}{L_x}x\right)\cos\left(\frac{m\pi}{L_y}y\right)\cos\left(\frac{n\pi}{L_z}z\right)\cdot e^{iW_{lmn}t}$$

$k_x \qquad k_y \qquad k_z$

$$k = k_x^2 + k_y^2 + k_z^2 = \left(\frac{W_{lmn}}{c}\right)^2$$

$$W_{lmn} = c\sqrt{k_x^2 + k_y^2 + k_z^2} = c\sqrt{\left(\frac{l\pi}{L_x}\right)^2 + \left(\frac{m\pi}{L_y}\right)^2 + \left(\frac{n\pi}{L_z}\right)^2}$$

$$f_{lmn} = \frac{W_{lmn}}{2\pi} = \frac{c}{2}\sqrt{\left(\frac{l}{L_x}\right)^2 + \left(\frac{m}{L_y}\right)^2 + \left(\frac{n}{L_z}\right)^2}$$

$$= \sqrt{(f_x)^2 + (f_y)^2 + (f_z)^2}$$

$\frac{340}{2\times x} = 100$ $\frac{340}{200}$ $\frac{1.7}{10}$

x방향 반 파장 개수

$$f_x = \frac{lC}{2L_x} = l\frac{c}{2L_x}$$ (L_x 동안 반파장이 l개)

y방향 반파장 개수

$$f_y = m\frac{C}{2L_y}$$

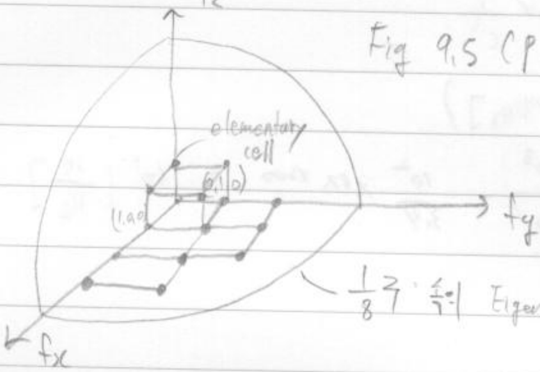


Fig 9.5 (p.172)

$\frac{1}{8}$구 속의 Eigen freq 개수 $\frac{4}{3}\pi V\left(\frac{f}{c}\right)^3$

$10\times 8\times 3.4$ m

L $\frac{340}{2\times 10} = 17$ Hz

microphone 방 모서리에 설치 (hard boundry

Low f 잘 나옴

high f 섞여서 잘 안 나옴

소스 있어도
방에서 안 받아줌

elementary cell (=unit cell) volume → "frequency volume"

$$\rightarrow \frac{C}{2L_x}\cdot\frac{C}{2L_y}\cdot\frac{c}{2L_z} = \frac{C^3}{8L_xL_yL_z} = \frac{C^3}{8V}$$

$\frac{1}{8}$구의 부피 : $\frac{1}{8}\left(\frac{4}{3}\pi f^3\right)$, 0~f 까지의 Eigen frequency 갯수

$$N_f \approx \frac{\frac{1}{8}\left(\frac{4}{3}\pi f^3\right)}{C^3/8V} = \frac{4}{3}\pi V\left(\frac{f}{c}\right)^3 \quad (9.9)a$$

$10m \times 8m \times 2.5m = 200m^3$

$0 \sim 10kHz$ 몇개 eigen freq ?

$$N_f(f=10kHz) = \frac{4\pi}{3} 200 \left(\frac{10^4}{340}\right)^3 \frac{m^3}{s^3}\frac{s^3}{m^3} \approx \frac{4\pi}{3} \cdot 200 \cdot 30^4 \approx 2\times10^7 (개)$$

$$\frac{dN_f}{df} \approx 4\pi V \frac{f^2}{c^3}$$

(eigen freq density [개/Hz])

$$4\pi \times 200 \times \frac{10^8}{340} = \frac{10^2}{3.4} \times 4\pi \times 200 = 10^4 \left[\frac{개}{Hz}\right]$$

i) wave

ii) ray → ray tracing (음선 추적법)

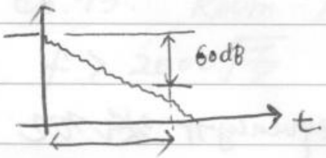
iii) 통계적 방법 → ex) Monte Carlo method

└ diffuse field ┬ 방향 : random

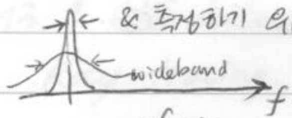
└ energy density : 일정

2008. 4. 8. (화)

〈음향공학〉



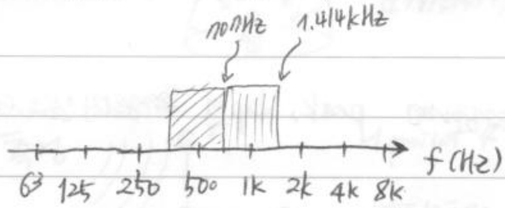
T, T_{60}, RT : reverberation time



$\Delta f \Delta t \geq const.$

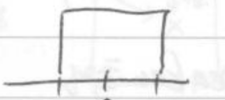
잔향시간을 측정할 때 사용하는 신호 : octave band noise

→ 통계적으로 diffuse field.



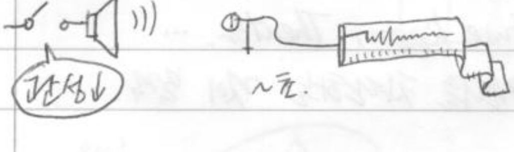
1/1 oct. band filter

1/3



; $f_h / f_l = 2/1$

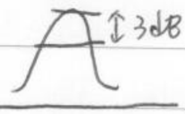
& $f_c / f_l = f_h / f_c = \sqrt{2}$



※ 건축 내장재 분류 : 주파수 band 별 흡음률.

☆ 왜 60dB decay냐?

귀의 dynamic range 120dB 中 (upper 30dB 귀의 손상 / lower 30dB ambient noise)을 제외.



3dB 내에 적어도 3개의 eigenfrequency가 있을 조건

◎ Schröder freq. 아래에서는 eigenfrequency를 따로 구별해서 따져야 하고
이상은 Large Room으로 취급.
= condition of "Large room."

◎ 수정 진동자의 eigenfrequency 측정 (~GHz).

천천히 sweep.

◎

빨리 측정하면 peak, dip이 측정되지 않는다

loudspeaker 측정

(RAUM~)
※ Room Acoustics = 좋은 소리를 위치의 편차 없이 전달하는 것이 목적.
= Concert Hall, Lecture Room, Theater, ...
Building acoustics = 소리를 차단하는 것이 목적.
(BAU-)

1.4
2.3
42
28
3.82

$\frac{3.22}{20}$

0.22 0.18

$1m \times 1.5m \times 2m$

$\sqrt{\frac{0.1}{4}}$ $\frac{\cancel{10}}{2}\sqrt{\frac{1}{10}}$ 0.15

$\frac{1}{20}\sqrt{10}$ $\sqrt{\frac{10}{1000}}$

Ch. 13. Room Acoustics

p258 $f > 2000\sqrt{\frac{T}{V}}$; large room condition.

ex) 자동차 $2000\sqrt{\frac{0.15sec}{4m^3}} \sim 2000\cdot(0.15) = 300Hz$

13.1 Geometric room Acoustics

Ray tracing. (음선추적법).

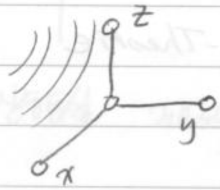
image source가

2π 공간에 골고루 분포되어 있는 것이 좋은 Hall (time delay는 有)

(solid angle)

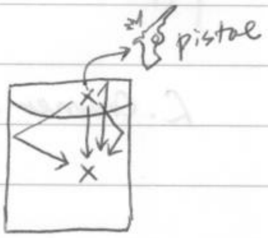
diffusity

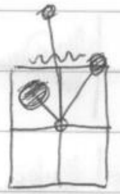
» 측정

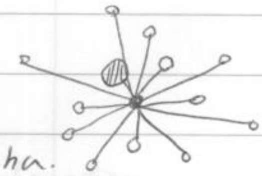


1 point 4

방향측정

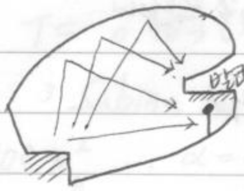






by engineers of Yamaha.

ex)



음영구역이라서

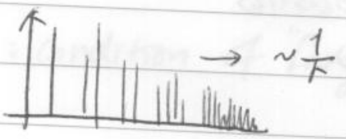
image source들이 가려짐

$\frac{3}{4} \cdot \pi R^2 \left(L_xL_y + L_yL_z + L_xL_z \right)$

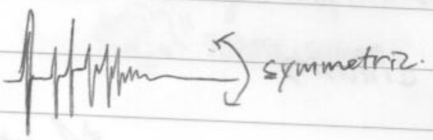
$(L_x + L_y + L_z)$

13.2 Impulse response of a room.

- 음향측정을 위한 무지향성 pistol.
- 큰 딱딱이
- 12면체 무지향성 speaker → pulse



실제 측정



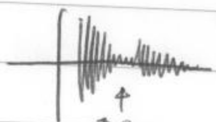
L. Cremer : Tannenbaum-Theorie
(전나무)
Kiefer (소나무)

건강한 전나무.

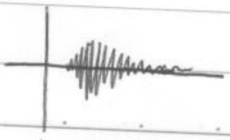
이상한 전나무 ①

[echo : 반향 (분리 됨)
reverb. : 잔향

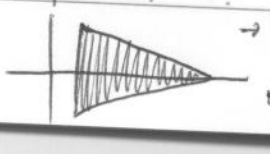
②



③



④



(time domain上)
→ 너무 규칙적. signal density가 너무 uniform.

中国産

p262 · $D = \dfrac{\int_0^{50ms} [g(t)]^2 dt}{\int_0^{\infty} [g(t)]^2 dt} \cdot 100\%.$

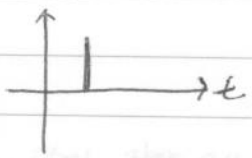
→ Deutlichkeit. 명료도.

· speech의 경우. 50ms 이전의 에너지 비율이 클 수록 명료도↑

p263. · $C = 10\log_{10} \left[\dfrac{\int_0^{80ms} [g(t)]^2 dt}{\int_{80ms}^{\infty} [g(t)]^2 dt} \right] dB.$

→ Clarity

ex) 무향실



잔향실 20 sec ~ 1 min.

13.3 Diffuse sound field.

13.4 Steady-state Energy density & Reverberation.

p270 (13-22)

$T = 0.163 [s/m] \dfrac{V}{A}$ ... room volume $[m^3]$. 공기가 에너지를 저장하므로.
... 등가흡음 면적. $[m^2]$

→ Sabine 의 잔향공식.

ex) $S = 100 m^2$, $\alpha = 0.02$

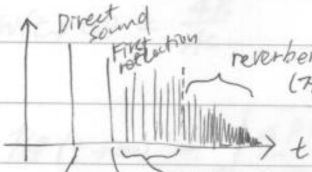
$A = \sum_i^n S_i \alpha_i = 2 m^2$

$A = \alpha_1 S_1 + \alpha_2 S_2 + \cdots + \alpha_n S_n$

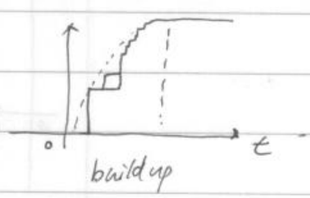
※ S_i를 나눌 때 dimension과 λ의 관계를 고려.
청중의 밀도 & '여름/겨울'에 따른 통계적 결과가 있다
실제적으로 흡음을 하기 때문에 $\alpha > 1$ 인 경우도 있다.

※ 0.163 ... 340m/s (15°C)
0.161 ... 343m/s (20°C)

2008. 4. 10. (木)
〈음향공학〉

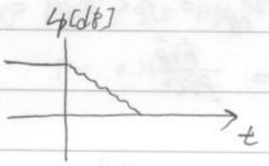


→ 적분하면 switch-on

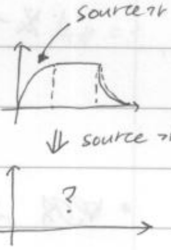


◎ Room Impulse Response

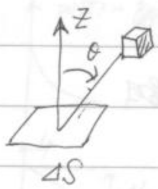
· $\underbrace{\text{직접음} + \text{초기반사음(들)} + \text{잔향음}}$



switch-off



◎ Sabine 교수의 잔향 공식 만들기 (Kinsler)



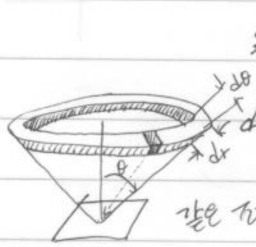
dV ; energy density w를 갖는 volume element. dV

dV 속의 energy : $w\,dV$ [J]

이중 ΔS를 통과하는 에너지는?

dV가 source가 된다

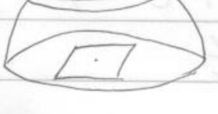
; $\frac{w\,dV}{4\pi r^2}\cdot \Delta S\cos\theta$



$dV_{ring} = 2\pi r\sin\theta\, r\, d\theta\, \Delta r$

같은 조건을 갖는 지점

같은 시간에 도달하는 점들

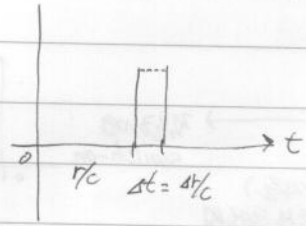


$$\Delta E = \int_0^{\pi/2} \frac{w\,dV}{4\pi r^2}\Delta S\cos\theta\, d\theta$$

$$= \int_0^{\frac{\pi}{2}} \frac{w\cdot 2\pi r^2 \Delta r \Delta S}{4\pi r^2}\sin\theta\cos\theta\, d\theta$$

$$= \frac{w\,\Delta S\cdot\Delta r}{4}$$

PAGE



시간당 Energy의 변화 rate

$$\frac{\Delta E}{\Delta t} = \frac{w \cdot \Delta S \cdot \Delta r}{4(\Delta r/c)} = \frac{w \cdot \Delta S \cdot c}{4}$$

※ 평면파의 Intensity $I = p_{eff} \cdot v_{eff} = \rho_0 c\, v_{eff}^2 = \frac{p_{eff}^2}{\rho_0 c}$

$$w = \frac{I}{c} = \frac{p_{eff}^2}{\rho_0 c^2}$$

- 면적 S, 흡음률 α 인 바닥에서

단위시간당 흡수(소멸)되는 energy는

$$\frac{wc}{4} \cdot S \cdot \alpha = \frac{wcA}{4}$$

A: 등가 흡음면적. (equivalent absorption area) (田) 흡음력

↳ 방의 경우도 동일

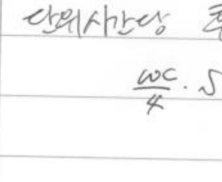
- 방의 balance equation

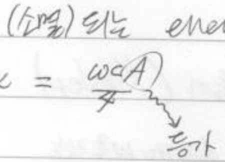
$$P = V\frac{dw}{dt} + \underbrace{\frac{Ac}{4}w}_{\text{stationary part}}$$

공급되는 에너지

$V\frac{dw}{dt}$: [J/s] build-up되는 energy

$\frac{Ac}{4}w$: [J/s]





$$w(t) = \frac{4P_0}{Ac}\left(1 - e^{-t/\tau_E}\right)$$

$$\tau_E = \frac{4V}{Ac}$$

$$W(t\to\infty) = \frac{4P_0}{Ac}$$

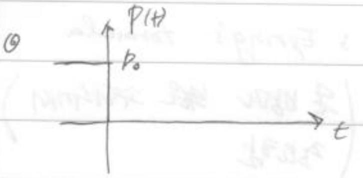
$$p_{eff}(t\to\infty) = \sqrt{\frac{4P\rho_0 c}{A}}$$

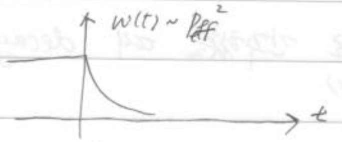
$T = 0.163\frac{V}{A}$ $\left(\bar{\alpha} = 0.02 \to \bar{\alpha} = 0.5 \right.$ 25배 $p_{eff} \to 5$배. $\left. T \to \frac{1}{25}\text{배}. \right)$

ex) 8×10×2.5 방 . 1W source . 잔향 2 sec . $p_{eff} = ?$

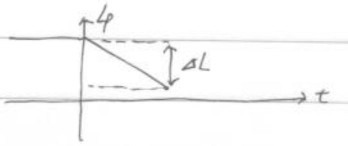
$T = 0.163\frac{V}{A} \to A$, $p_{eff} = \sqrt{\frac{4P\rho_0 c}{A}}$ $p_{eff} =$ ___

⊙





$$W(t) = \frac{4P_0}{Ac} e^{-t/\tau_E} = W(0)\, e^{-t/\tau_E} \sim p_{eff}^2(t)$$



$$\Delta L = 20\log\frac{P_2}{P_1} = 10\log\left(\frac{P_2}{P_1}\right)^2$$

$$\Delta L = L_p(t=0) - L_p(t=T)$$

$$= 10\log\frac{p_{eff}^2(t=0)}{p_{eff}^2(t=T)}$$

$$= 10\log\frac{1}{e^{-T/\tau_E}}$$

$$= 10\log e^{T/\tau_E}$$

$$= 10\frac{T}{\tau_E}\log e \Rightarrow 60dB.$$

$$\therefore T = \frac{60}{10\log e}\tau_E = 13.8\,\tau_E = 55.2\frac{V}{Ac} \quad \left(\tau_E = \frac{4V}{Ac}\right)$$

$$= \begin{cases} 0.163\frac{V}{A} & (c = 343 m/s) \\ 0.161\frac{V}{A}. & (c = 340 m/s) \end{cases}$$

※ $p_{eff}(t\to\infty) = \sqrt{\frac{4P\rho_0 c}{A}}$
너무 흡음률이 높으면
음압이 떨어진다.

"음악명장의 편집 공연"
※ 적당한 잔향시간이 있어야
음악이 아름답게 들린다.
왜? 잔향환경에 익숙하다.(동굴)

※ 울려서 뭔소린지
모르겠다
⇒ T_{60}가 커서
명료도(clarity)가
떨어진다.

PAGE

60
45
24
129　　358

※ 우리가 듣는 소리 = 원래 소리 ⊛ 공간 ⊛ 위치

⊙ Sabine의 잔향공식은 흡음력 큰 공간일수록 error가 커진다

$$T = 0.163\frac{V}{A} \xrightarrow{\text{modify}} 0.163\frac{V}{-S\ln(1-\bar{\alpha})}$$

⟨Sabine⟩ $A = S\bar{\alpha}$　　⟨Eyring⟩

taylor series 전개

$\bar{\alpha}$: 평균 흡음율
S : 벽의 전체면적

$$(A = \alpha_1 S_1 + \cdots + \alpha_n S_n = \bar{\alpha} S)$$

$$\xrightarrow{\text{re-modify}} 0.163\frac{V}{-S\ln(1-\bar{\alpha}) + \underbrace{4mV}_{\text{공기 중의 흡음}}}$$; Eyring's formula

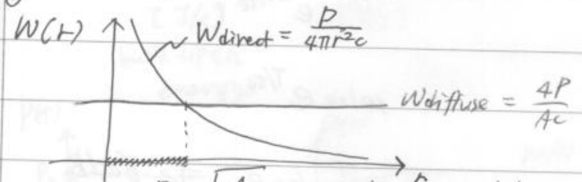
공기 중의 흡음 (큰 방과 높은 주파수에서 중요함)

$I = I_0 e^{-mx}$; 평면파로 간주했을 때 decay rate
$p(x,t) = \hat{p} e^{-\alpha x} e^{j(\omega t - kx)}$
$m = 2\alpha$　$(I \sim p^2)$

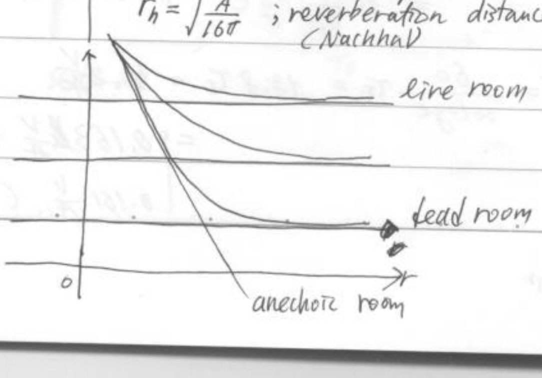
⊙ $f = 500\text{Hz}$ 을 기준으로 했을 때

- Speech 用 공간　$T = 0.6 \sim 1.3$ sec
- Opera (음악 + speech)　$1.3 \sim 1.6$ sec
- Concert　$1.6 \sim 2.1$ sec (2 sec)
- Church (pipe organ)　$2 \sim 3$ (or even ~ 4)
  소리 보다 잔향으로

⊙



$r_h = \sqrt{\frac{A}{16\pi}}$; reverberation distance (Nachhal)



※ 중간고사 5/6(화) 14:30 - 15:45 / 뉴미디 대회의실.
기말고사 6/~~17(화)~~ 5(목) 18:00 - 21:00 / 뉴미디 대회의실

2008. 4. 15. (火)
〈음향공학〉

>> 음악을 들을 때의 잔향시간

○ pipe organ은 긴 잔향시간(2초이상)이 적당.

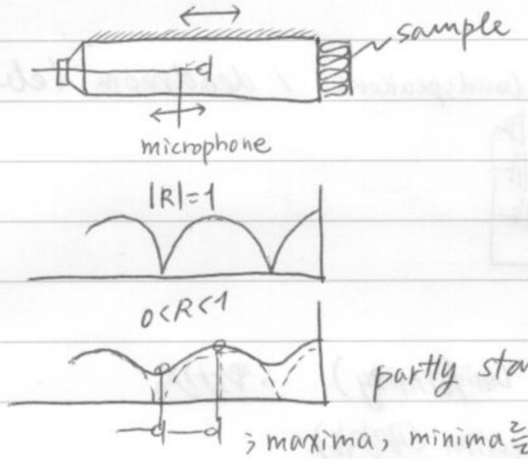
(악기, 예배당, 음악 양식의 영향을 주고 받음)

(헨델은 연주환경에 따라 악기편성·작곡을 하기도…).

※ 소음진동 consulting.
- 산업설비
- 민원
- 주거환경

◎ 흡음율의 측정법

1) Impedance Tube 法



; maxima, minima를 측정해서 비율을 통해 |R|를 구한다.

$|R|$, $\alpha = 1 - |R|^2$

2) 잔향실 法

(i) 빈 잔향실의 잔향시간 측정

$$T_1 = 0.163\frac{V}{A_1}, \quad A_1 = S\bar{\alpha}$$

(ii) Sample (10m² 이상) 바닥에 깔고 잔향시간 측정

$$T_2 = 0.163\frac{V}{A_2}, \quad A_2 = A_1 - S_{sample}(\alpha_{바닥} + \alpha_{sample})$$

$$\alpha_{sample} = \frac{A_2 - A_1}{S_{sample}} + \alpha_{바닥}$$

〈두 측정간의 차이〉

※ Impedance Tube 法은 수직입사
잔향실 法은 random 입사

※ concert Hall 마감재의 data는 어떤 방법으로 측정한 것이 의미가 있는가? 2) 잔향실 法.

① 좋은 Concert Hall ?

1) 적당한 잔향시간.

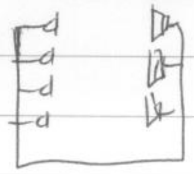
Ramantic : 긴 잔향

Tempo가 빠른 악기 : "

※ variable acoustics

① mechanical

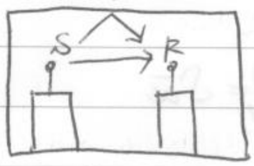
② mics & loudspeakers / deadroom. (electronic control)



2) Diffusity (or Uniformity) : 확산성

~Spatial Impression (공간감)

3) Intimacy (친근감) → 내가 소외당하지 않는 느낌.



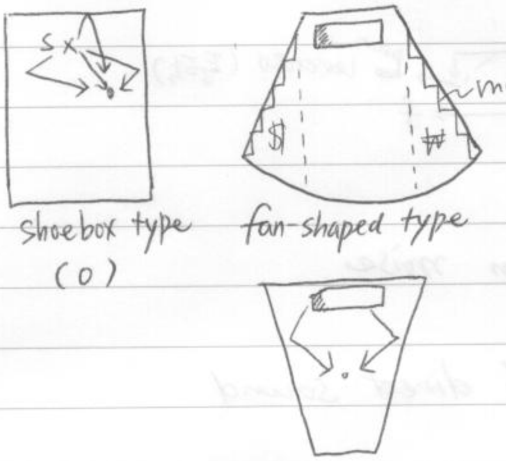
벽으로부터 멀 때 → 소외당한 느낌

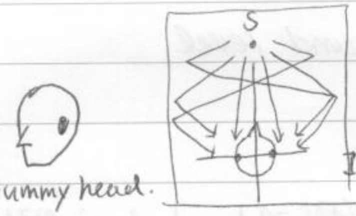
Intimacy가 좋으려면 직접음 도달 後 20 ms 이내에
반사음이 도달해야 한다. (7.8m)

~1970's 에 알게 됨.

4) Spatial Impression (공간감) → 복합적. →
- ∘ early lateral reflections (초기 측면 반사음)
- ∘ IACC (inter-aural cross correlation) 가 적당
  → 左右 귀에 비슷한 신호가 들어오되 그래 다른 부분도 있어야 좋다 (mono → stereo)
  0.3 이하...
- ∘ etc. ...

top3
- Wien
- Amsterdam
- Boston

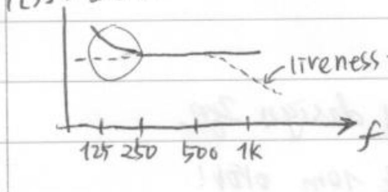




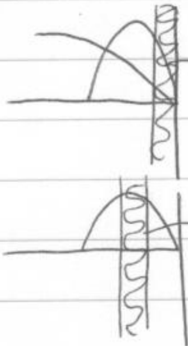
5) 적당한 clarity (definition) ; 장르, 악기에 따라..

6) Warmth (따뜻함) ; 저음부 중심

저음부 잔향시간이 좀 더 길어야...

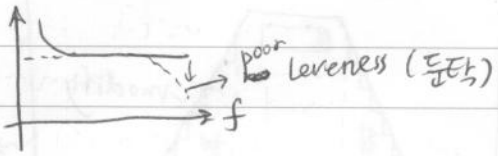


(마감재의 특성에 의해 대부분 만족)



공기입자 마찰이 많게~.

7) Liveness ; 중·고 대역, 충분한 잔향시간.
(음악이 생동감 있게 들림)



8) freedom from noise

9) loudness of direct sound

10) 적당한 reverberant sound level
(직접음-잔향음 간의 조화)

11) 초점, 그늘(shadow) 피할 것! balconi 아래

12) ensemble : hall은 청중만을 위한 것이 아니다.
연주자 상호간 잘 들려야.
(무대 주변 음향)

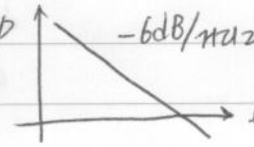
13) balance and blend : 무대 design 중요
ex) 폭 15m 이상이면 무대 천장은 10m 이하!

etc. ...

2008. 4. 17. (木) 〈음향공학〉

Review) 学生들의 comments

① 흡음율 측정 [imp. tube
잔향실法 ; 잔향실 $200m^2$ 이상 (규격)
sample $10m^2$ 이상 (너무 좁으면 error ↑)
→ diffuse field를 만들어야 한다.

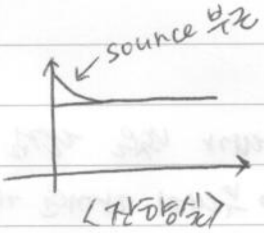


-6dB/거리2배 ⇒ 측정결과가 일치할 수록 좋은 무향실.

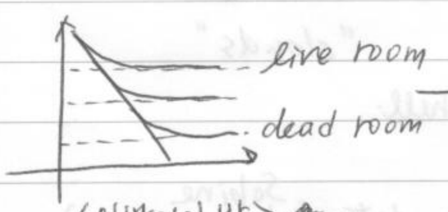
〈무향실〉
; 인공적인 free field

측정시 고려사항 (i) 음원 종류.
(ii) 방향성

ex) $5m \times 8m \times 5m = 200m^2$
$\alpha = 0.02$ (인조대리석)
$A = 2 \times 0.02 \times (5 \cdot 8 + 5 \cdot 8 + 5 \cdot 5)$
$= 0.04(40 + 40 + 25)$
$= 4.2\ m^2$; equivalent absorption Area
$T = 0.163 \times \frac{200}{4.2} \simeq 8\ sec$



〈잔향실〉



〈일반적인 방〉

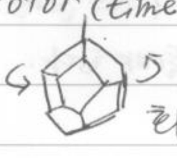
※ 그러나 저음역에서는 standing wave 때문에 diffuse field가 되지않는다.

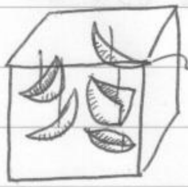
vineyard.

◎해결책.

① 수 많은 diffuser 설치

② rotor (time-varying field)





→ 끼어 딱딱해야 함.

↳ 대신에 불편하고 diffuser가 또 하나의 absorption을 만드는 단점이 있음

② Berlin: "Neue Philharmonie" (1960s) ; B+

~ Vineyard type (포도밭형 콘서트홀)의 효시

5각형 3개 중첩된 모양.

객석=계단식 포도밭

; 무대가 낮은 단점

→ 무대에 가까운 객석이 intimacy 가 나쁘다.

→ 연주자 間 ensemble이 좋지 않다

→ 반사체 설치.

"clouds"

· Ochestra Shell.

※ Kinsler 흡음율 data (Sabine absorptivities)

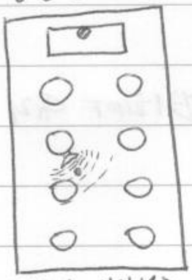
> Glass ; 저음에 대해서는 흡음체
  고음에 대해서는 반사체

> 상암경기장의 Pannel 구조

> München의 Oktober Fest  천막

천 : 흡음이 된다.

③ 명동성당



<기둥속 신부님>

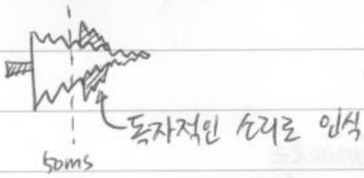
"The Law of 1st Wavefront"

; 처음 도달하는 wave가 direct sound로 인식된다.

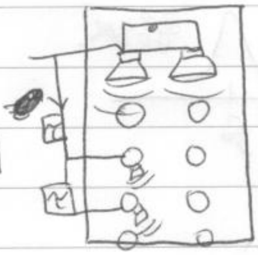
(비슷한 pattern의 소리들에 대해)

» "Haas effect" ; "the Law of 1st Wavefront"를 극복하기 위한 level 차이

상식적 ; 50ms (잔향 / echo의 boundary)



time delay: $\boxed{\tau}$



⑥ 흡음재

① 다공성 (wide-band)

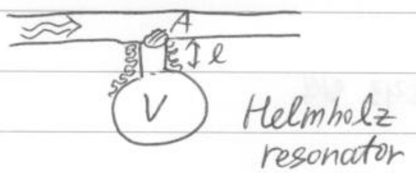
: particle velocity 가 높은 곳에 설치해야 유리 (suspended)

boundary 에 붙일 때는 두껍게

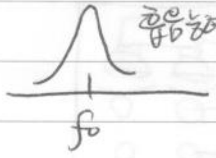
② 작은 m'의 박판 (텐트, 패널)

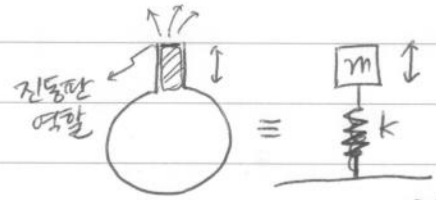
(kg/m²)

③ resonance absorber 공진형 흡음기.

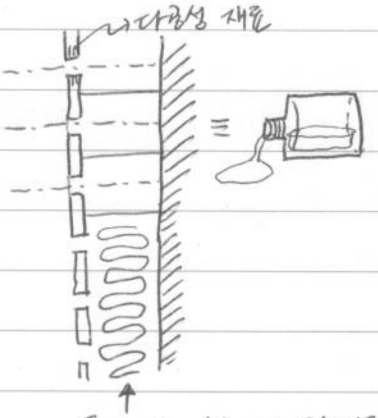


$$f_0 = \frac{c}{2\pi}\sqrt{\frac{A}{Vl}}$$





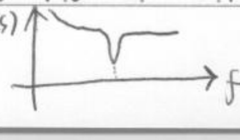
건물에 적용



흡음재를 넣어서 단열효과도 얻을 수 있음.

⇒ Concert Hall 에는 함부로 사용하면 안된다.

필요한 음역대의 손실!!

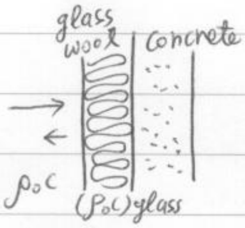


$\frac{1}{100}$ -2.

(Fig 13.12) ◎ 무향실用 흡음 wedge

; 사용 주파수의 99% 이상 흡음.

(−20 dB)

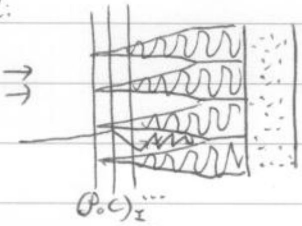


impedance mis-match 때문에 소리가 들어오지 않는다. (밀도↑)

$\rho_{glasswool}$

$$R = \frac{(\rho_0 c)_g - \rho_0 c}{(\rho_0 c)_g + \rho_0 c}$$

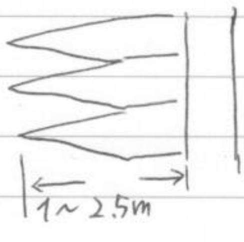
⇒ sol:

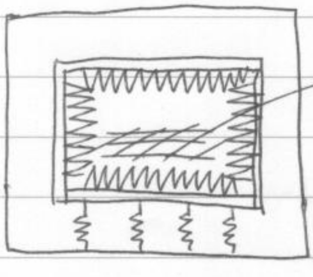


(i) low freq.

layer 별 $\rho_0 c$ 가 점차적으로 증가.

(ii) high freq





※ glass wool ⇒ polyurethane foam
(발암)

뉴미언; 멜라민 $(\rho_0 c)$가 충분히 작다.

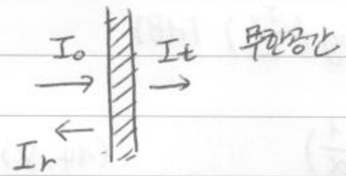
2008. 4. 22. (火) <음향공학>

(Kuttruff p283) ch. 14. Building Acoustics

Sound Transmission Loss (TL)

Sound Reduction Index (RA) (14.1)

소리를 차폐하는 정도



$$TL = RA = 10\log\left(\frac{I_0}{I_t}\right) \ [dB]$$

reduction 이므로 분자분모

(i) 반사

(ii) 흡수

밖에서는 무관

흡수 보다는 반사의 경제적이다 효과가 크다.

energy conversion

$$\vec{I} = \langle \vec{p} \cdot \vec{v} \rangle_t$$

→ 직접 측정하는 게 不可

음압의 gradient (field가 disturb 된다)

$$-\nabla p = \rho_0 \frac{\partial \vec{v}}{\partial t} \Rightarrow j\omega\rho_0 \vec{v}$$

$$v = -\frac{1}{j\omega\rho_0}\nabla p$$

intensity probe (microphone)

같은 특성을 가진 2개의 마이크

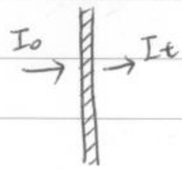
※ B&K (Brüel & Kjær)

소음 측정용 Mic

14.3 단일벽의 차음

Airborne sound insulation of single-leaf partitions.

m' = 단위 면적당 질량



$$R_A = TL = 10\log\left(\frac{I_o}{I_t}\right) \ [dB]$$

$$= 10\log\left(\frac{1}{\alpha}\right) \qquad (14.8)$$

흡음을 묘사하면

$$I_r = |R|^2 I_o$$

$$\alpha = 1 - |R|^2$$

$$= 1 - \frac{I_r}{I_o}$$

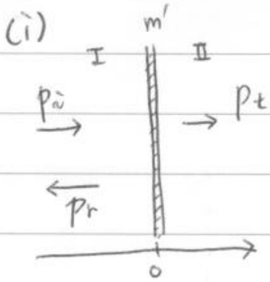
$$= \frac{I_o - I_r}{I_o}$$

$$= \frac{I_t}{I_o}$$

(

>> 측정방법

(i)



$$\begin{cases} p_I = p_i + p_r \\ p_{II} = p_t \end{cases} \qquad \begin{cases} v_I \\ v_{II} \end{cases}$$

boundary condition)

$x=0$, $p_I = p_{II}(x)$

$v_I = v_{II}(0)$

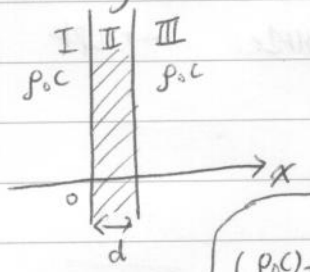
$$\underbrace{(p_I - p_{II})}_{\text{단위면적당 힘}} = \underbrace{m'}_{\text{질량}} \frac{\partial v_{I,II}}{\partial t}$$

※ $m' = 0$

$$R = \frac{(\rho_0 c)_{II} - (\rho_0 c)_I}{(\rho_0 c)_{II} + (\rho_0 c)_I}$$

$$\alpha = 1 - |R|^2$$

(ii) 3-layer



$d \to 0$

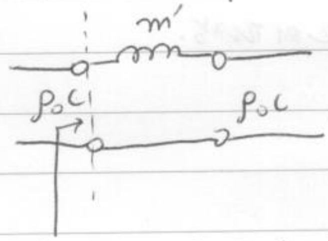
m'

- 전자기파
- 초음파 비파괴검사 日측 탐용

$(\rho_0 c)_{\mathrm{I}} \,|\, (\rho_0 c)_{\mathrm{II}} \,|\, (\rho_0 c)_{\mathrm{III}}$ $\quad d = \lambda_2/4$ $\quad \to$ Z-matching

$(\rho_0 c)_{\mathrm{II}} = \sqrt{(\rho_0 c)_{\mathrm{I}} \cdot (\rho_0 c)_{\mathrm{III}}}$ $\quad \to T = 1$

(iii) ~~[illegible]~~ equivalent circuit



$$Z = \rho_0 c + j\omega m'$$

$$R = \frac{Z - \rho_0 c}{Z + \rho_0 c} = \frac{\rho_0 c + j\omega m' - \rho_0 c}{\rho_0 c + j\omega m' + \rho_0 c} = \frac{j\omega m'}{2\rho_0 c + j\omega m'}$$

$$\frac{I_0}{I_t} = \frac{|p_i|^2}{|p_t|^2} = \frac{1}{1 - |R|^2} = \frac{(2\rho_0 c)^2 + (\omega m')^2}{(2\rho_0 c)^2}$$

415 rayl

$$|R|^2 = \frac{(\omega m')^2}{(2\rho_0 c)^2 + (\omega m')^2}$$

$$\therefore TL = RA = 10\log\frac{1}{1 - |R|^2} = 10\log\left[\frac{(2\rho_0 c)^2 + (\omega m')^2}{(2\rho_0 c)^2}\right]$$

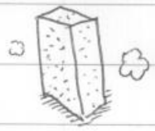
$$= 10\log\left[1 + \left(\frac{\omega m'}{2Z_0}\right)^2\right] \qquad (14.9)$$

판이 아주 얇지 않은 이상 m'이 크므로 $(2\rho_0 c \ll \omega m')$

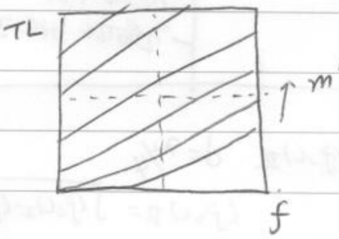
$$\simeq 20\log\left(\frac{\omega m'}{2Z_0}\right) \qquad (14.9a)$$

무거울수록 차음이 좋다

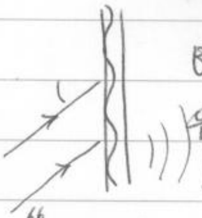
ω가 일정할때, m'가 2배면 6dB 개선 (자연례) “mass law”



m'가 일정할때, ω가 2배면 6dB 개선 ⋯> LPF



(p291)



Bending wave 의 파장.
"
음파의 파장

다시 방사

“Coincidence Effect”

⇒ TL ↓

fig 14.8

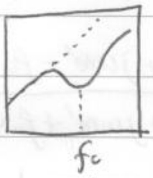
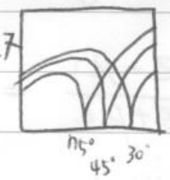
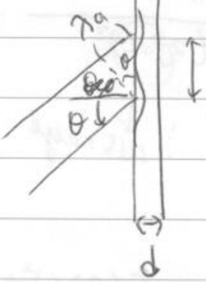


fig 14.7



f_c 조절해서 관심있는 주파수가 영향을 받지 않도록 한다.



$$\lambda_B \sin\theta = \lambda_a$$

$$\lambda_B = \frac{\lambda_a}{\sin\theta}$$

$$C_B = \frac{C_a}{\sin\theta}$$

$$(\therefore C_B > C_a)$$ 공기中

$$C_B = \sqrt{\omega}\,\sqrt[4]{B/\rho_{plate}}$$

일정하지 않다 f-dependent → dispersion 有

$\sin\theta = 1$

$$\sqrt{\omega_c}\ \sqrt[4]{B/\rho_p} = C_\infty$$

$$\omega_c \sqrt{\frac{B}{\rho_p}} = c^2$$

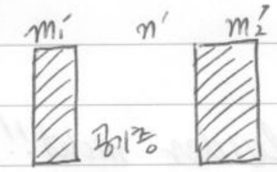
$$f_c = \frac{c^2}{2\pi}\sqrt{\frac{\rho_p}{B}}$$

$f > f_c$ coincidence 発

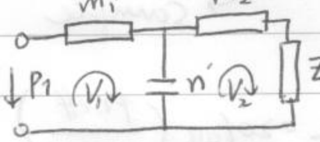
$$B = \frac{d^2}{12} \cdot \frac{Y}{1-\gamma^2}$$ //

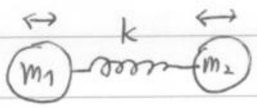
휨(안 굽혀지는 정도).

(p296) 14.4. Double-leaf partitions

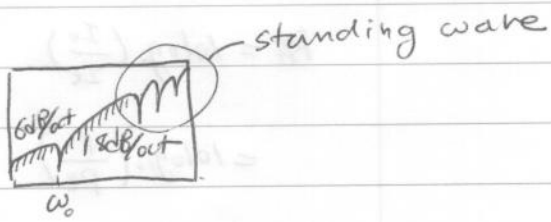


≡





$\omega_0 \dashrightarrow TL \Downarrow$



14.5 Structure-borne Sound insulation

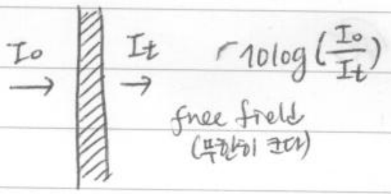
고체구조물을 통해 전달된 소리 — 피아노 있는데요

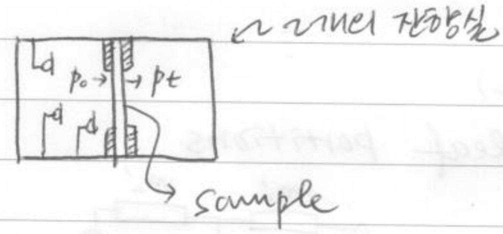
고체 내에 흡음이 되는 게 좋다.

공간에 Z miss match를 시킨다. 

바닥. 천정 floating

≫ TL의 측정.





$$TL = 20\log\left(\frac{p_{1,eff}}{p_{2,eff}}\right)$$ (?) leider nicht!!

$$R_A = 10\log\left(\frac{I_o}{I_t}\right)$$

$$= 10\log_{10}\left(\frac{P_o}{P_t}\right)$$

$P_o = \frac{c \cdot W_1}{4} \cdot S$; 잔향시간 유도할 때 나온식.

$P_t = \frac{c \cdot W_2}{4} \cdot \underbrace{A}$; power balance

Room 2의 equivalent absorption area.

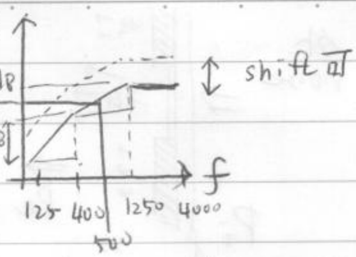
공급되는 power = 사라지는 power

(14.5) $$TL = R_A = L_1 - L_2 + 10\log\left(\frac{S}{A}\right)$$

2008. 4. 24. (木) <음향공학>

(Kuttruff)

(p287) reference curves

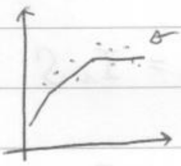


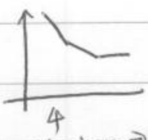
STC

(Sound Transmission class)

⇒ 수치가 클 수록 차음성능이 좋음.

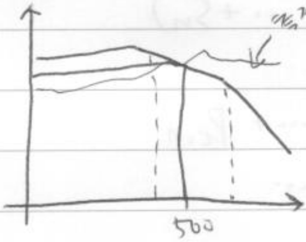
"Insulation of partition."

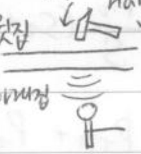




(이렇게 하면 좋긴 하지만 현실적으로 不可)

(p304) Impact Sound Insulation





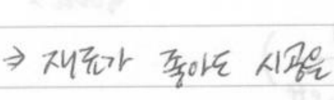
수치가 클수록 차음이 안된다.

$L_{n,w} \le 53$ dB (floor)

※ 日本은 타이어 쿵쿵 을 reference로 삼는다

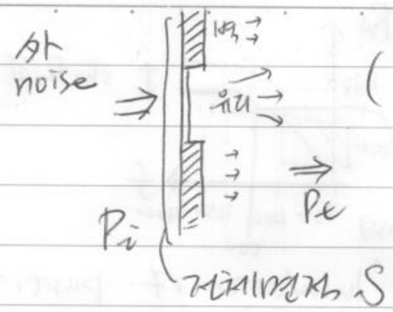
⇒ 해결책 : 탄성층 (floating floor)

sound bridge를 만들면 안된다.



⇒ 재료가 좋아도 시공을 잘 못하면 효과 無.

(Kuttruff p287)



(Compound partition
Composite structure)

$$P_i = I_i S$$

$$= P_{i1} + P_{i2} + \cdots + P_{i,n}$$
$$= I_i (S_1 + S_2 + \cdots + S_n)$$
$$= \frac{P_i}{S}(S_1 + S_2 + \cdots + S_n)$$

※
$$R_A = 10\log\frac{P_i}{P_t}$$
$$\frac{R_A}{10} = \log\frac{P_i}{P_t}$$
$$P_t = P_i 10^{-0.1R_A}$$

$$P_t = P_{t.1} + P_{t.2} + \cdots + P_{t,n}$$
$$\quad R_{A.1} \quad R_{A.2} \quad \cdots$$

$$= P_{i.1} \cdot 10^{-R_{A.1}/10} + P_{i.2} \cdot 10^{-R_{A2}/10} + \cdots$$
$$= \frac{P_i}{S}(S_1 \cdot 10^{-R_{A1}/10} + S_2 \cdot 10^{-R_{A2}/10} + \cdots)$$

(power 에 대한 투과도)

$$= \frac{P_i}{S}(S_1 \cdot T_{P.1} + S_2 T_{P.2} + \cdots)$$

$$R_A = 10\log\frac{P_i}{P_t} = 10\log\frac{1}{\frac{1}{S}(\underbrace{S_1 T_{P.1}}_{\text{1번벽을 통과한것}} + S_2 T_{P.2} + \cdots)}$$

$$= 10\log\left(\frac{1}{T_{p.eff}}\right)$$

example) 3mm 판유리 ($\rho_0 = 3.6 \times 10^3\ kg/m^3$)

$$m' = \underset{kg/m^3}{3.6 \times 10^3} \times 3 \times 10^{-3}_{m} \cancel{\times \ldots m}$$

$$= 10.8\ \cancel{kg}\ kg/m^2$$

$$R_{A,1} = 20\log\left(\frac{\omega m'}{2\rho_0 c}\right)$$

$\uparrow$

($f=500Hz$)

$$= 20\log\left(\frac{2\pi \times 500 \times 10.8}{2 \times 415}\right)$$

$$= 32.2\ dB$$

9-inch brick $m' \simeq 500 kg/m^2$

$$R_{A.2}(f=500Hz) = 20\log\left(\frac{1000\pi \times 500}{830}\right) = 65.5dB$$

$$S_1 : S_2 = 0.5 : 0.5$$

$$T_{p,eff} = 0.5 \times 10^{-32.2/10} + 0.5 \times 10^{-65.5/10}$$

$$= 3.01 \times 10^{-4}$$

$R_{A,eff} = 10\log\frac{1}{3.01\times10^{-4}} = 35.2dB$ „ 하향평준화.

"$32.2dB + 3dB = 35.2dB$".

면적이 절반이고 ~~65.5dB~~.

벽돌벽으로 들어오는 소리 무시.可

※ 값싸고 차음 좋은 문

철문

볶은모래 (부식방지)

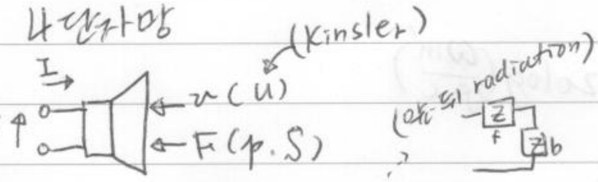
제염

(Kuttruff p359) Ch. 17 Electroacoustic transducers

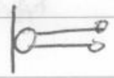
∘ transducer → 에너지 변환 (本)

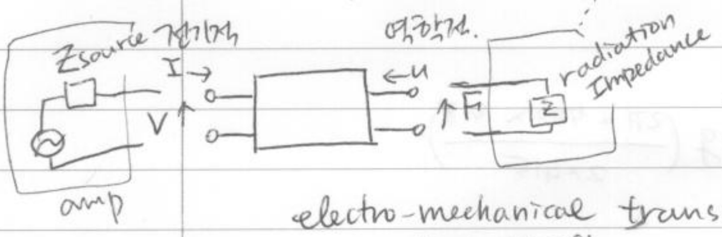
여기서는 signal, 정보가 포함된 변환

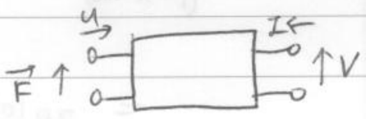
4단자망



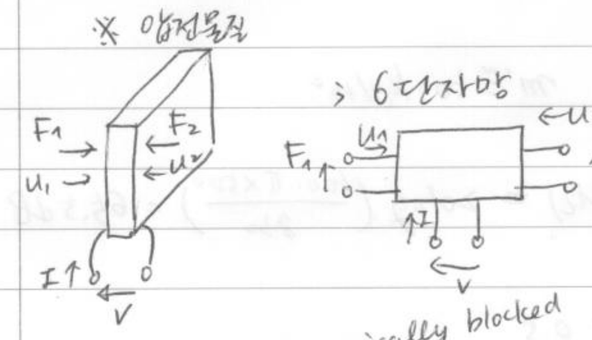
<microphone>







electro-mechanical transducer
(acoustical)



Elec. Mech. analogy

mechanically blocked

$$\begin{cases} V = Z_{EB} I + T_{em} u \\ F = T_{me} I + Z_{MO} u \end{cases}$$

→ notation 주의 open

$u=0$ 으로 만들고 Z_E 측정
(진동판 block)

$$Z_{EB} = \left.\frac{V}{I}\right|_{u=0}$$

$$Z_{MO} = \left.\frac{F_1}{u}\right|_{I=0}$$

→ 여기 꼭 숙지.

$$\begin{cases} Z_{EB} \neq Z_{EF} \\ Z_{MO} \neq Z_{MS} \end{cases}$$

→ free (진공內)

→ short

2008. 4. 29. (火)

<음향공학>

» Transducer에 대한 연구

- 1930~1950 스피커에 대한 음향공학적 이론이 체계화.
  지금은 이미 산업 성숙기, 예술분야가 됨.
- 수산진흥청 
- 새로운 음원을 / 센서를 만들기 위해서 Transduction에 대한 연구 要.

- - - - - - -

$$\begin{pmatrix} V \\ F \end{pmatrix} = \begin{pmatrix} Z_{EB} & T_{em} \\ T_{me} & T_{MO} \end{pmatrix} \begin{pmatrix} I \\ u \end{pmatrix}$$

; Matrix form.
Impedance form
$\begin{pmatrix} F \\ u \end{pmatrix}$ Admittance form
$\begin{pmatrix} V \\ u \end{pmatrix}$ Hybrid form

$$\left(\begin{matrix} Z_{EB} \neq Z_{EF} \\ Z_{MO} \neq Z_{MS} \end{matrix} \right\}$$ electro-mechanical coupling 존재!

전기 $\overset{???}{\Longleftrightarrow}$ 역학

※ $Z_{EB} = Z_{EF}$ 인 경우. 그냥 저항, Capacitor 등…  passive element.

$$V = Z_{EB} I + T_{em} u$$
$$F = T_{me} I + Z_{mo} u$$

» $Z_{ms} = ?$, $V = 0$ (short) $I = -\dfrac{T_{em} \cdot u}{Z_{EB}}$

$$F = T_{me}\left(-\frac{T_{em} u}{Z_{EB}}\right) + Z_{mo} u$$

$$= \underbrace{\left[-\frac{T_{me} \cdot T_{em}}{Z_{EB}} + Z_{mo} \right]}_{Z_{ms}} u$$

$$F = Z_{mo}\left(1 - \frac{T_{em} \cdot T_{me}}{Z_{EB} Z_{mo}}\right)$$

$$Z_{ms} = Z_{mo}\left(1 - \frac{T_{em} T_{me}}{Z_{EB} \cdot Z_{mo}}\right)$$

$$= Z_{mo}(1 - k_c^2)$$

coupling coefficient

$$0 < |k_c| < 1$$

coupling이 크다.

작다; transducer로 적당하지 않다

likewise,

$$Z_{EF} = Z_{EB}(1 - k_c^2)$$

Kinsler (p392).

◎ reciprocal (상반) $\left(T_{me} = T_{em}\right)$

reversible (가역) 음향 → 전기, 전기 → 음향 可

- 도청用 speaker
- 수중 hydrophone을 source로도 사용 可

- irreversible ◦ Carbon microphone (옛날 전화기)  ↕ 저항 변화. 탄소알갱이

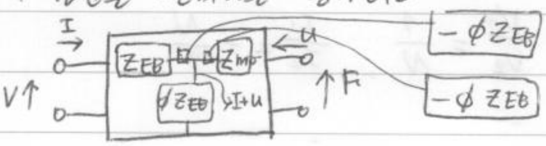
$T_{me} = T_{em} = T$; reciprocal Transducer.

$$V = Z_{EB} I + T u = Z_{EB}\left(I + \frac{T}{Z_{EB}} u\right) = Z_{EB}(I + \phi u) = Z_{EB} I + \phi Z_{EB} u$$

$$F = T \cdot I + Z_{mo} u = \phi Z_{EB} I + Z_{mo} \cdot u$$

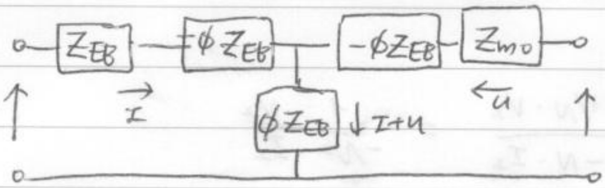
(가역 변환 transducer / receiver) 間 엄밀한 관계식이 존재

⇒ 조건을 만족하는 등가회로



T-形 등가회로

Kinsler (Fig. 14.2.2) (a)



$V = Z_{EB} I + \phi Z_{EB} u \quad \therefore \quad I = \dfrac{V - \phi Z_{EB} u}{Z_{EB}}$

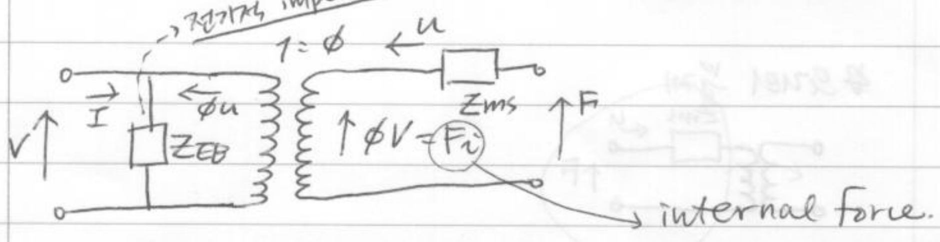
$F = \phi Z_{EB} \cdot I + Z_{mo} \cdot u$

$= \phi \cdot V + \underbrace{(Z_{mo} - \phi^2 Z_{EB})}_{Z_{ms}} u$

$(\because V = 0,\ F = \square u)$ (check 可 $Z_{ms} = Z_{mo}(1 - k_c^2)$)

$F = \phi V + Z_{ms} u$

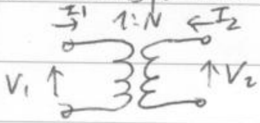
(b)



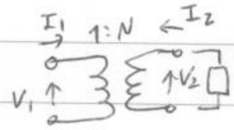
전압에 비례하는 힘 $1:\phi$

우측을 먹여 살리는 힘 (자기몸 움직이기 + sound radiation)

※ Transformer



$$\frac{V_1}{V_2} = \frac{1}{N}, \quad \frac{I_1}{I_2} = -\frac{N}{1}$$



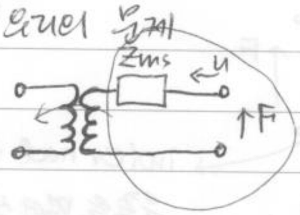
$$Z_{in} = \frac{V_1}{I_1} = \frac{1/N \cdot V_2}{-N \cdot I_2} = \frac{1}{-N^2} \cdot \frac{V_2}{I_2}$$

$$\left(Z_\ell = -\frac{V_2}{I_2}\right)$$

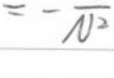
$$= -\frac{1}{N^2}(-Z_\ell) = \frac{1}{N^2} Z_\ell$$

1 :	N
$V_2 \longrightarrow$	$\frac{1}{N} V_2$
$I_2 \longrightarrow$	$N \cdot I_2$
$Z_\ell \rightarrow$	$\frac{Z_\ell}{N^2}$

※ 우리의 문제



(○ vector impedance meter.



↑ V. I. 주파수 바꾸어가며 Z 측정.)

↳ mechanical Z 가 투영되어 측정된다. (Z_{ms})

◎ Antireciprocal Transducer

$T_{em} = -T_{me}$

$V = Z_{E0} I + \phi_M \cdot u$ (M: Moving coil type)

$F_i = \phi_M V + Z_{ms} \cdot u$

(14. 2. 10) ⋯→ 출속변수 u로..

analogy II를 쓰면 reciprocal → antireciprocal ←

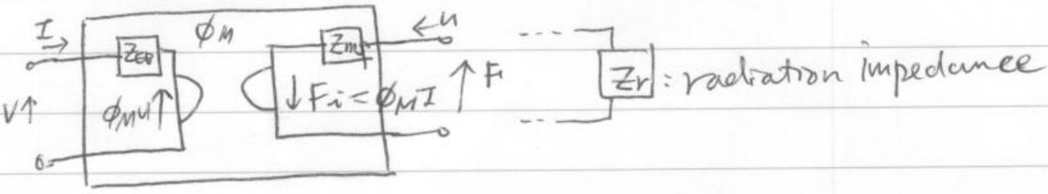
(Fig 14.2-3)

◎ analogy I 으로 표현하려면

gyrator 사용.

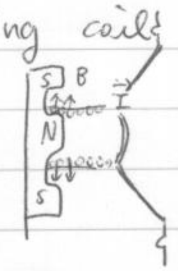
(1차 전류 → 2차 전압
2차 전류 → 1차 전압)

$I \to \phi_M I = F_i$



$F_i = B l I$ ($Bl = \phi_M$) moving coil 의 internal Lorentz force

◎ moving coil



2008.5.1.(木)
〈음향공학〉

Kinsler
(p394) 14.3 Canonical Equations for two simple transducers

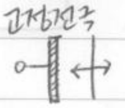
(정세 카톨릭) 교리법에 의한.

~ 규범적인, 올바른 (바른틀 방정식)

(a) Electrostatic Transducer (정전형 변환기)

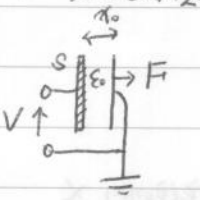
aka. Condenser ┌ Microphone
└ loudspeaker (electro-static loudspeaker)

→ 중.고음에서 깨끗한 음색.
(woofer는 dynamic)



DC전원 필요!

왜? → linearize 하기 위해.



Q:

$V = Ed$.

$\frac{1}{2}QV$

$Q = CV$

$C = \frac{S}{x_0 \varepsilon} V$

((에너지로부터 구하기))

$$W = \frac{1}{2}CV^2 = \frac{1}{2}\frac{\varepsilon_0 S}{x}V^2$$

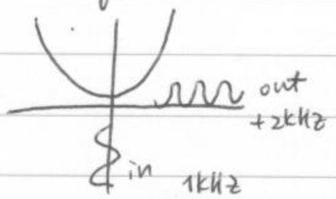
$$C = \frac{\varepsilon_0 S}{x}$$

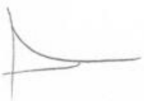
$$\Delta W = F \cdot \Delta x$$

$$F = -\frac{dW}{dx} = \frac{1}{2}\frac{\varepsilon_0 S}{x^2}V^2$$

$$F \sim V^2 \Longrightarrow F \sim V$$

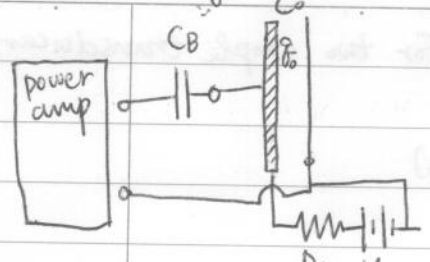
freq. distortion 生





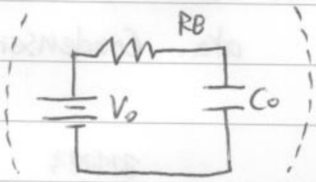
Blocking capacitor

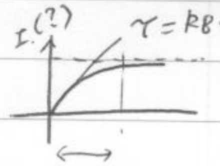
↳ 교류신호만 통과



$\frac{1}{j\omega C_B} \to$ 작게 = 무시할 수 있게.

$R_B \to$ 크게



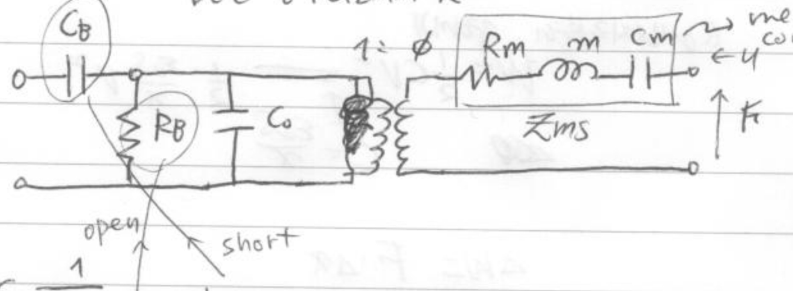


금방 소리가 안나온다.

Charge Q_0를 유지시킴.

(V_0가 없어도 유지)

DC는 등가회로에서 X

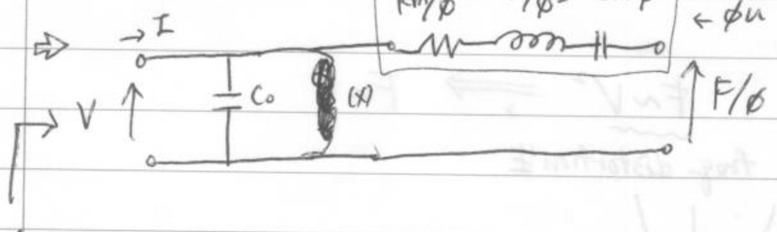


mechanical complience $C_m = \frac{1}{s}$ ← spring constant (k)

$\frac{1}{j\omega C_B} \to$ 작게

$R_B \to$ 크게

Z_{Em}

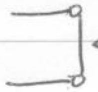


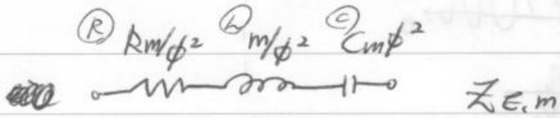
Y_E ?

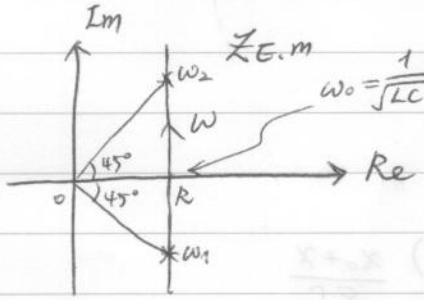
» Impedance plot(?)

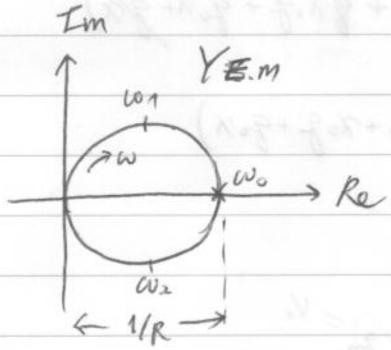
mechanical side에 load Z 가 없어야 계산 可

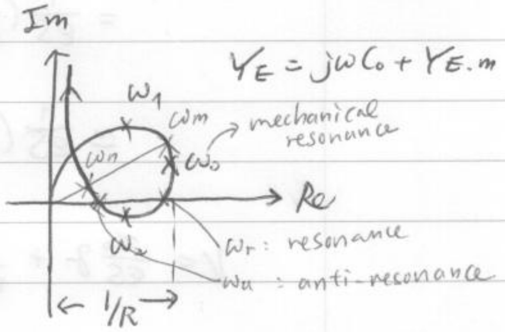
(i) condenser speaker 집중속.





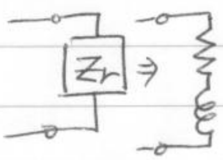






각개의 characteristic Impedance

(ii) Radiation.



Z.Y complex(j)

Z가 real 이면서 큰 쪽 resonance

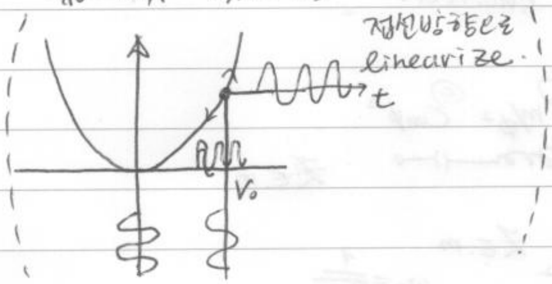
작은 쪽 anti-resonance

◎ 어떻게 linearize 하는가?

$V_0 + V \quad (V \ll V_0)$

$q_0 + q \quad (q \ll q_0)$

$x_0 + x \quad (x \ll x_0)$



$$V_t = \frac{q_t}{C_t}$$

$$V_0 + V = (q_0 + q)\,\frac{x_0 + x}{\varepsilon S}$$

가장 작

$$= \frac{1}{\varepsilon S}\left(q_0 x_0 + x_0 q + q_0 x + \cancel{qx}\right)$$

$$\simeq \frac{1}{\varepsilon S}\left(q_0 x_0 + x_0 q + q_0 x\right)$$

$$V = \frac{x_0}{\varepsilon S} q + \frac{q_0}{\varepsilon S} x$$

$$= \frac{1}{C_0} q + \frac{1}{x_0}\underbrace{\frac{q_0}{C_0}}_{= V_0} x$$

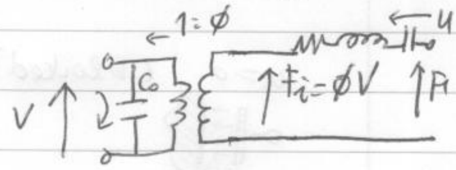
$$= \frac{1}{C_0} q + \frac{V_0}{x_0} x$$

$$= \frac{1}{C_0}\frac{I}{j\omega} + \frac{V_0}{x_0}\frac{u}{j\omega}$$

$$= \frac{1}{j\omega C_0} I + \frac{V_0}{j\omega x_0} u$$

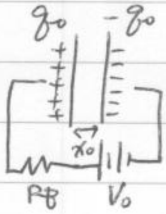
reciprocal transducer   Tem

$V = Z_{EB} I + \phi Z_{EB} \cdot u$ $Z_{EB} = \frac{1}{j\omega C_0}$, $\phi = \frac{V_0}{j\omega x_0} j\omega C_0$



$= \frac{V_0 C_0}{x_0}$
$= \frac{q_0}{x_0}$

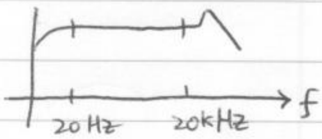
ϕ 크게 하려면
↳ x_0 작게
↳ q_0 크게



F_i들
ϕ를 크게 하는데에 방해가 되는 것
↳ 공기의 spark! (절연파괴)

B&K mic

(i) Freq Response 평탄하여서 넓다.

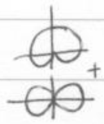


↳ Noise 가 多.
acoustic
electronic

(ii) 무지향성.

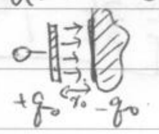
내가 공간의 모든 Noise 수음.

※



$$F = T_{me} \cdot I + Z_{m0} \cdot u$$

$u = 0$ (blocked) $\qquad F = ?$

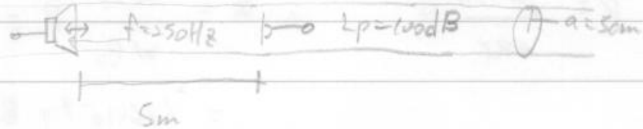


$$F = Eq = \frac{V_0}{x_0} \cdot q = \frac{V_0}{x_0} \frac{I}{j\omega}$$

$$F = \frac{V_0}{j\omega x_0} I + \underbrace{Z_{m0}\, u}_{\text{그냥 쓰면 됨}}$$

5月 8日, (木)　중간 2차 풀이

1.



$f = 250Hz$, $a = 5cm$

$\lambda = \frac{c}{f} = \frac{343}{250} = 1.372m$

$\lambda > 3.41a$ (Kutt 8.57) 이므로

fundamental mode만 전파가능 → 그래서 평면파!

① $L_p = 20\log\left(\frac{\tilde{P}}{P_{ref}}\right)$ [dB]　$P_{ref} = 2\times10^{-5}$ [pa]

$\hat{p} = 2$ [Pa]

② $\hat{v}$? $\frac{\tilde{P}}{\tilde{v}} = \rho_0 c$, $\hat{v} = \frac{\hat{p}}{\rho_0 c} = \frac{2}{415} = 4.82\times10^{-3}$ [m/s]

$Pa = \frac{N}{m^2}$, $N = kg\cdot\frac{m}{s^2}$, $rayl = \frac{kg}{m^3}\cdot\frac{m}{s}$

③ $I = \langle pv\rangle_t = P_{eff}\cdot V_{eff} = \frac{1}{2}\hat{p}\hat{v} = 2\times4.82\times10^{-3}\ \frac{Pa\cdot m}{s} = \frac{W}{m^2}$

$= 9.64\times10^{-3}$ [W/m²]

④ 에너지 밀도

— . T

$w = \frac{I}{c} = \frac{9.64\times10^{-3}\ W/m^2}{343\ m/s} = 2.81\times10^{-5}\left[\frac{J}{m^3}\right]$

⑤ $\hat{\delta}$, $v = \frac{\partial\theta}{\partial t} = j\omega\delta$　$\hat{\delta} = \left|\frac{\hat{v}}{j\omega}\right| = \frac{\sqrt{2}\cdot V_{eff}}{\omega} = \frac{\sqrt{2}\times4.82\times10^{-3}}{2\pi\times250}$

$= 4.34\times10^{-6}\ m = 4.34\ \mu m$

2. $L_p = 65dB$　$\tilde{P} = 2\times10^{-5}\times10^{(65/20)}$ Pa $= 3.56\times10^{-2}$ Pa

$I = \frac{(P_{eff})^2}{Z_0}$ (평면파 & 구면파) $= \frac{(3.56\times10^{-2})^2\ [Pa]^2}{415\ \ rayl} = 3.05\times10^{-6}\left[\frac{W}{m^2}\right]$

$\frac{Pa^2}{rayl} = \frac{N^2}{m^4}\cdot\frac{m^2\cdot s}{kg}$

$= \left(\frac{kg\cdot m}{s^2}\right)^2\frac{m^2\cdot s}{m^4\ kg}$

$= \frac{kg}{s^3}$

(구면파) $V = \rho_0 c\left(\frac{1}{1+\frac{1}{jkr}}\right)$, $I = \langle pv\rangle_t = P_{eff}\cdot V_{eff}\cdot\cos\theta \rightarrow \frac{P_{eff}^2}{\rho c}$

① $P = \oint\vec{I}\cdot\vec{ds} = I\cdot4\pi r^2 = 3.05\times10^{-6}\cdot4\pi\cdot1 = \frac{W}{m^2}\cdot m^2 = 3.83\times10^{-5}\ W$

② point source

1st sol $p = \frac{j\omega\rho_0\hat{Q}}{4\pi r} e^{j(\omega t - kr)}$, $\hat{Q} = \frac{4\pi r}{\omega \rho_0}\hat{p} = \frac{4\pi \sqrt{2}\times 3.56\times 10^{-2}}{2\pi\times 500\times 1.21} = 1.66\times 10^{-4}$

$= 1.66\times 10^{-4} \left[\frac{Pa\cdot m^4\cdot s}{kg} = \frac{m^3}{s}\right]$

2nd sol (Kuttruff 5.9)

$I = \frac{\rho_0 \omega^2 \hat{Q}^2}{32\pi^2 c r^2} \Rightarrow \hat{Q} = \sqrt{\frac{32\pi^2 c r^2 I}{\rho_0 \omega^2}} = 1.66\times 10^{-4}\ m^3/s$

3rd $L_p \approx L_I$ $I = 3.16\times 10^{-6}$, $P = I\cdot 4\pi r^2 = 3.97\times 10^{-5}\ W$

3. $L_x = 8m$, $L_y = 10m$, $L_z = 3m$

① $f_{lmn} = \frac{c}{2}\sqrt{\left(\frac{l}{L_x}\right)^2 + \left(\frac{m}{L_y}\right)^2 + \left(\frac{n}{L_z}\right)^2}$

l	m	n	f_{lmn} (낮은순)	
0	1	0	17.15Hz	①
1	0	0	21.44Hz	②
0	0	1	57.17Hz	
1	1	0	27.45Hz	③
0	2	0	34.3Hz	④
2	0	0	42.88Hz	
1	2	0	40.45Hz	⑤

②. $\frac{dN_f}{df} \approx 4\pi V \frac{f^2}{c^3}$, $\left.\frac{dN_f}{df}\right|_{f=1kHz} = 4\pi\times 240 \frac{10^6}{(343)^3}\left(\frac{m^3}{s^2}\frac{s^3}{m^3}\right)$

$= 74.937 \frac{1}{Hz}$

평균거리 $\delta f = \frac{1}{\left(\frac{dN_f}{df}\right)} = 0.0134\ Hz$

4. $T = 0.163 \frac{V}{A}$ (Kutt) , $T = 0.161 \frac{V}{A}$ (Kinsler)

$7 \times 10 \times 4.7$ ① 잔향실 벽 면적 , $V = 329 m^3$

$S = 2 \times (7 \times 10 + 10 \times 4.7 + 7 \times 4.7) \, m^2 = 299.8 m^2$

$\to 5 \times 10 \times 7.5$ $A = \alpha \cdot S = 0.02 \times 299.8 = 5.996 \, m^2$

standing wave 많이 생겨서 안좋음. $T = 0.163 \frac{7 \times 10 \times 4.7}{5.996} = 8.94[s]$

② $T' = 0.163 \frac{V}{A'}$, $T' = 3.65$ $A' = \frac{0.163 \times 329}{3.6} = 14.896 m^2$

$A' = A - \alpha S_s + \alpha_s S_s$

$14.896 = 5.996 - 0.02 \cdot 20 + \alpha_s \cdot 20$

$\alpha_s = 0.465$

5. 실내 $P = V \frac{dW}{dt} + \frac{Ac}{4} W$

steady state $P = \frac{Ac}{4} W$ $V = 1.5 \times 10^4 \, m^3$

$T_{(500Hz)} = 2.1s$

$A = ?$

$T = 0.163 \frac{V}{A}$, $A = \frac{0.163 \times 1.5 \times 10^4}{2.1} = 1.164 \times 10^3 \, m^2$

$L_p = 100dB \longrightarrow P_{eff} = 2 P_a$

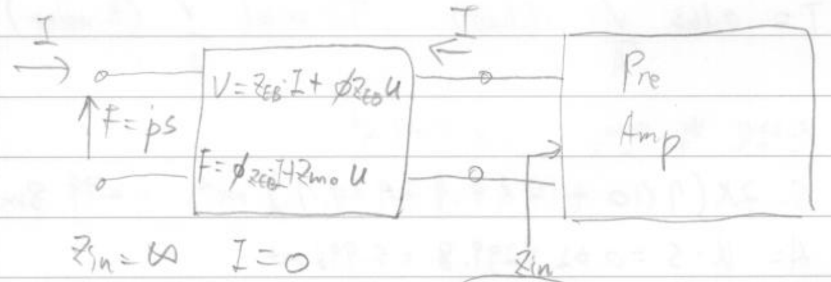
$W = \frac{I}{c} = \frac{1}{c} \cdot \frac{(P_{eff})^2}{\rho_0 c} = \frac{1}{343} \cdot \frac{4}{415} \left(\frac{Pa^2 \cdot s \cdot m^2 s}{m \, kg} \right)$

$= 2.83 \times 10^{-5} \left[\frac{J}{m^3} \right]$

Total power $= \frac{1.164 \times 10^3 \times 343 \times 2.83 \times 10^{-5}}{4} = m^2 \cdot \frac{m}{s} \cdot \frac{J}{m^3} = 2.82 [W]$

단원 1명당 평균 $\frac{2.82}{100} W = 28.2 mW$

6.



$I = 0$

$u = \dfrac{1}{\phi Z_{EB}} V$

$F = \dfrac{Z_{mo}}{\phi Z_{EB}} V$

$Z_{in} = \infty \quad I = 0$

$$\frac{V}{p} = \frac{V}{F/S} = \left(\frac{V}{F}\right) S = \frac{\phi Z_{EB}}{Z_{mo}} \cdot S$$

$\left(\dfrac{V}{p}\right) \uparrow$, $\phi \uparrow$ or $Z_{EB} \uparrow$, $S \uparrow$, $Z_{mo} \downarrow$ → 질량, 손실, 탄성계수 작게

실제로는 bad

→ 진동판 면적↑ 그러나 파장에 비해 작게

$\phi = \dfrac{q_0}{x_0}$

작게

5月13日. (火) P 396.

(14.3.8)

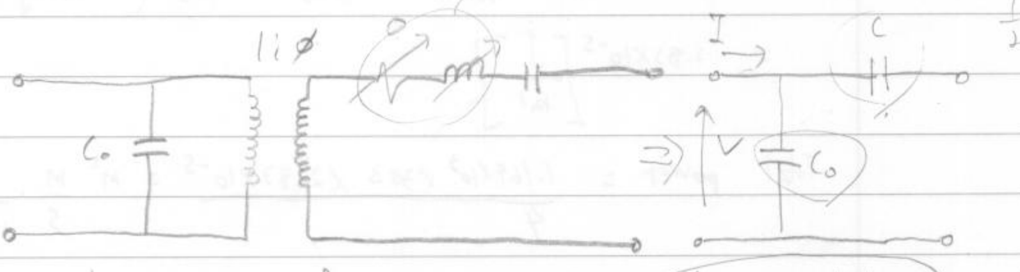
$k_c^2 = \dfrac{C}{C_0 + C}$ (reciprocal)

(14.3.17) $k_m^2 = \dfrac{L_M}{L_0 + L_M}$ (antireciprocal)

(14.2.3) $Z_{ms} = (1 - k_c^2) Z_{mo}$

$Z_{EF} = (1 - k_c^2) Z_{EB}$

(14.2.12) $Z_{mo} = (1 - k_m^2) Z_{ms}$ $\dfrac{1}{j\omega C}$ 에 비해 매우 작음.



mech loss 작고, low freq

$k^2 = \dfrac{\text{mech. stored energy}}{\text{total energy}} = \dfrac{C}{C_0 + C}$

2008.5.13.(火) <음향공학>

(Kinsler 14.3.8) p396 "Coupling Coefficients"

$k_c^2 = \frac{C}{C_0 + C}$ (reciprocal)

(14.3.17)

$k_m^2 = \frac{L_M}{L_M + L_0}$ (antireciprocal)

(14.2.3)

$Z_{ms} = (1 - k_c^2) Z_{mo}$

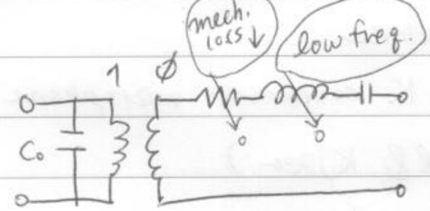
(14.2.5)

$Z_{EF} = (1 - k_c^2) Z_{EB}$

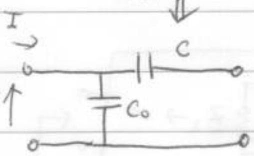
(14.2.12)

$Z_{mo} = (1 - k_m^2) Z_{ms}$

$Z_{EF} =$



mechanical loss 小;
low freq.



$$k^2 = \frac{\text{mechanical stored energy}}{\text{total energy}}$$

$$= \frac{C}{C_0 + C}$$

$E = \frac{1}{2} C V^2$

if $k = 0$, no coupling.

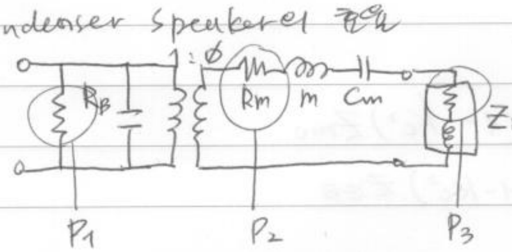
ex) 압전물질 ㅏ $k = 0.707$, $k^2 = 0.5$ ½이 coupling.

그러나 k 가 효율은 아니다

- coupling coefficient (k) $k^2 = \dfrac{\text{mech. stored energy}}{\text{total energy}}$
- 효율 (efficiency) ; $\dfrac{\text{유용하게 사용한 output power}}{\text{input power}}$
- 감도 (sensitivity) ; $\dfrac{\text{output 크기(수신)}}{\text{input 크기(입력)}}$ 예) $\dfrac{V}{p}$

예) Thermo-couple $\mathrm{mV/K}$

예)
condenser speaker의 효율



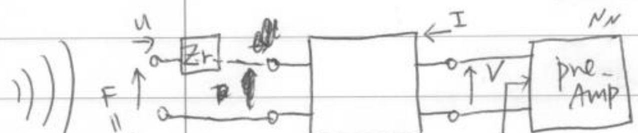
$$\text{efficiency} = \frac{P_3}{P_1 + P_2 + P_3}$$

(14.9)

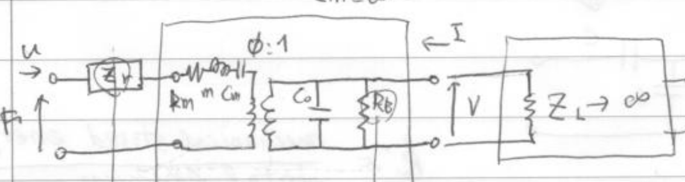
◦ Condenser microphone

※ 표준용 mic : B & K condenser microphone

(Brüel & Kjær)

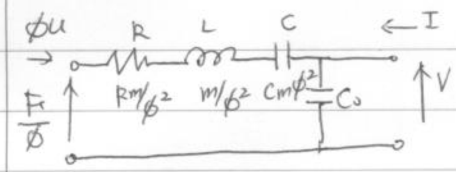


"전류 흐르지 않으면서 전압을 높이기 위해."



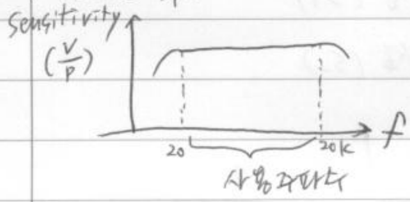
Z_{out}는 작게 해서 전류가 잘 흐르도록~

전기적인 domain으로..

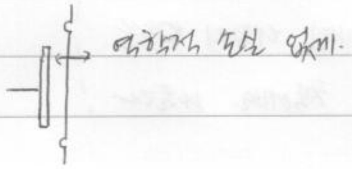


$$\phi = \frac{E_0}{x_0}$$

☆ 원하는 spec.



→ Rm : 아주 작게



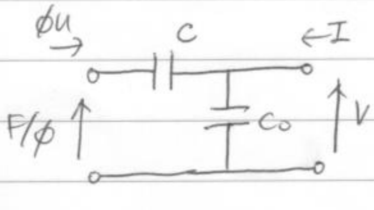
L 을 작게 하고 C지 않고

$\omega_0 = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{m \cdot C_m}}$ 를 높임 ("high-tuned")

$\omega \ll \omega_0$ 인 주파수를 사용.

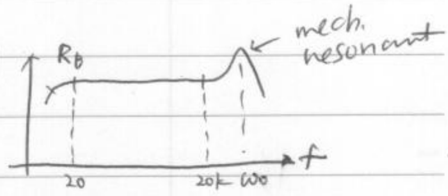
$\frac{1}{\omega C}$ $\quad \omega L$

저주파 고주파 dominent



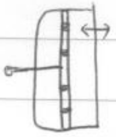
→ Capacitive Voltage divider.

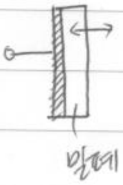
$$\frac{V}{F/\phi} = \frac{C}{C_0 + C} = \frac{\phi^2 C_m}{C_0 + \phi^2 C_m} \left(\approx \frac{\phi^2 C_m}{C_0} \right)$$



$$\frac{\phi V}{Sp} \quad \therefore \frac{V}{p} = \frac{S}{\phi} \cdot \frac{C}{C_0 + C}$$; 주파수와 무관하게 Constant

※ Rm를 높여서 저주파에서 떨어지지 않게 하면 Infra sound를 측정할 수도 있다.





$C_m = ? = \frac{1}{s}$

(i) 박막 자체의 탄성 (S_1)

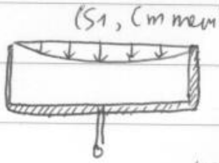
(ii) 막뒤공기의 탄성 (S_2)

$S = S_1 + S_2$

$$\frac{1}{C_m} = \frac{1}{C_{m,membrane}} + \frac{1}{C_{m,air}}$$

~~S_2 ($C_{m,air}$)~~

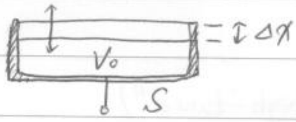
(S_1, C_m membrane)



→ 이런것까진 다루지 않음

ref) Rossi 책에는 나온다

(S_2, $C_{m,air}$ 구하기) 우리는:



$V_0 \rightarrow V_0 - \Delta V$

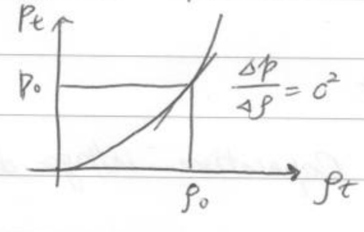
$\rho_0 \rightarrow \rho_0 + \Delta \rho$

$p_0 \rightarrow p_0 + \Delta p$

$F = \Delta p \cdot S$

adiabatic process

note!

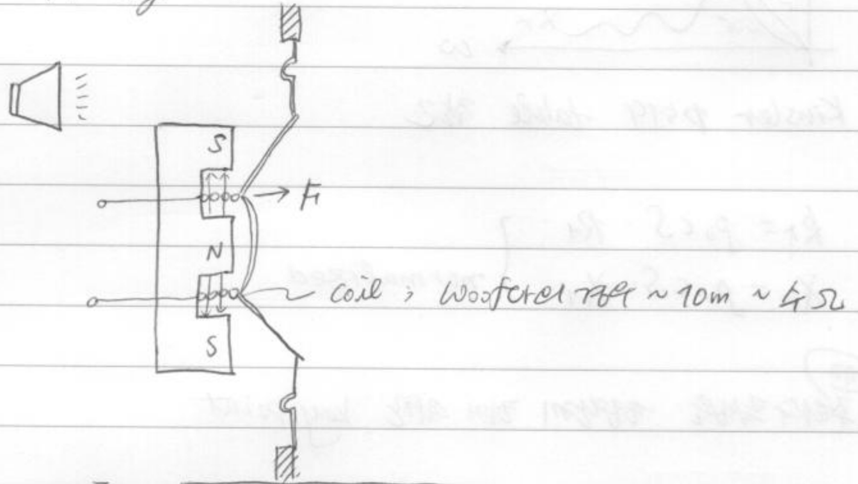


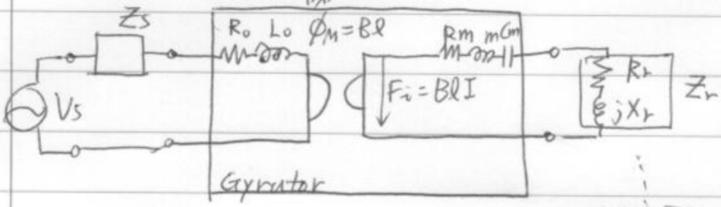
transmitter

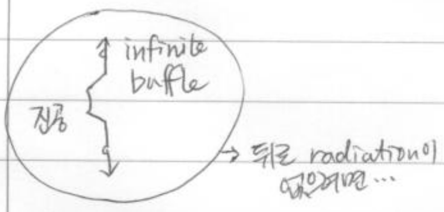
◎ Electrodynamic loudspeaker

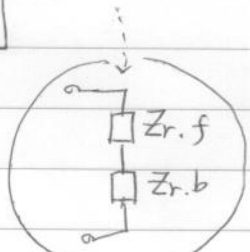
Dynamic ״

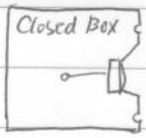
Moving-coil ״



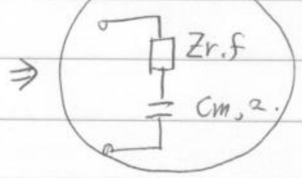


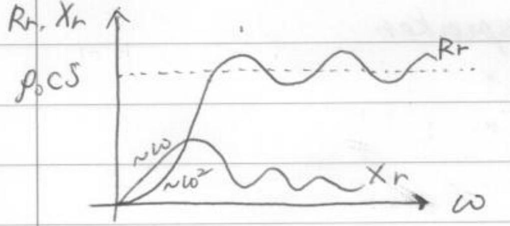






$Z_{r,b}$ 가 complience 처럼 된다.





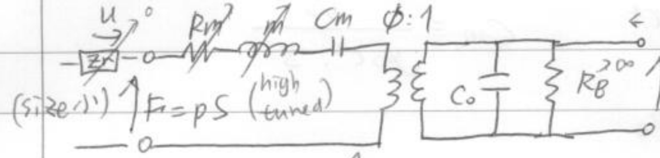
Kinsler p519 table 참고

$$R_r = \rho_0 cS \cdot R_1$$
$$X_r = \rho_0 cS \cdot X_1$$
normalized

예고
⇒ 주파수 특성을 평탄케 하기 위한 key point

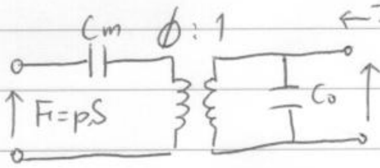
2008. 5. 15. (木) (Review) "condenser mic 주파수 특성 평탄하게 만들기"

<음향공학>



$\omega \ll \omega_0$, $\omega_0 = \frac{1}{\sqrt{mC_m}}$

R_B: 빌레의 R_B + 다음단입력 imp.



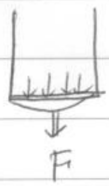
sensitivity; $\frac{V}{p} = \frac{\phi^2 C_m}{C_0 + \phi^2 C_m} \simeq \frac{\phi^2 C_m}{C_0}$

(Kinsler에서 약간 다르게 표현 but 같은 얘기)

($C_0 = 27.8\, a^2/x_0$ pF)

C_m { membrane의 tension ⇒ Kinsler p.419 (14.9.1)
밀폐 공기의 탄성
↳ membrane이 주도권을 쥐어 dominant

(※

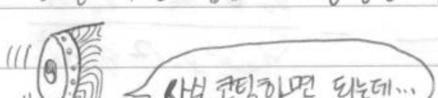


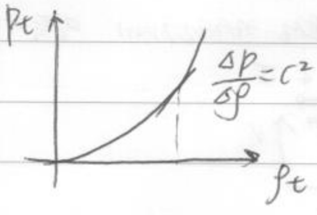
tension [N/m]

얼마나 팽팽하게 diaphragm을 mount 했는가?)

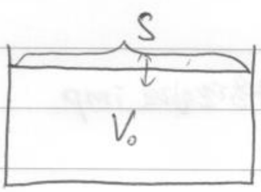
mic는 금속이라 괜찮지만

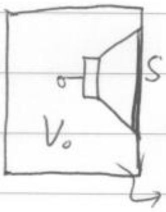
저렴 북은 습도에 영향을 많이 받는다.





$$C_m = \frac{V_0}{\rho_0 c^2 \cdot S^2}$$





↳ resonance freq. 生.

다시 sensitivity로 돌아와서

$$\frac{V}{p} \simeq \frac{\phi^2 C_m}{C_0} = \frac{q_0^2}{x_0^2} \cdot \frac{V_0}{C_0 \rho_0 c^2 S^2} = \frac{q_0^2 \cancel{V_0}}{V_0^{2} C_0 \rho_0 c^2}$$

$(x_0 S = V_0)$

$$= \frac{q_0^2}{V_0} \frac{x_0}{\varepsilon_0 S \rho_0 c^2}$$

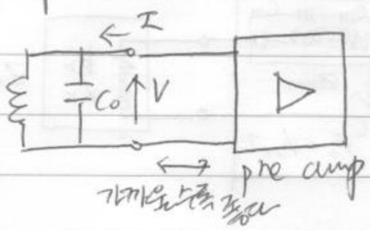
$\left(C_0 = \varepsilon_0 \frac{S}{x_0}\right)$

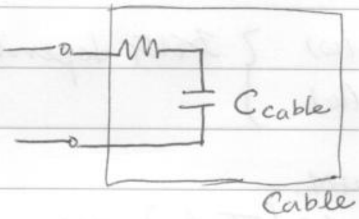
$$= \frac{q_0^2 x_0}{\varepsilon_0 x_0 S^2 \rho_0 c^2} = \frac{V_0^2 \cancel{C_0} x_0 \varepsilon_0^2 S^2}{x_0 S^2 \rho_0 c^2 \varepsilon_0 x_0^2}$$

$q_0 = C_0 V_0$

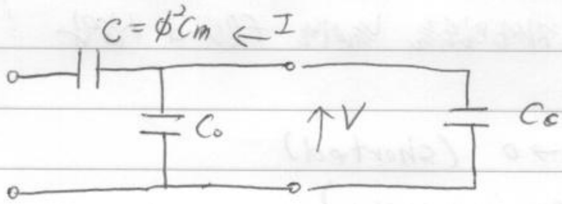
$$\frac{(C_0 V_0)^2}{x_0^2} \frac{V_0}{C_0 \rho_0 c^2 S^2}$$

o 왜 pre amp가 필요한가?





$$M_0 = \frac{\phi^2 C_m}{C_0 + \phi^2 C_m}$$

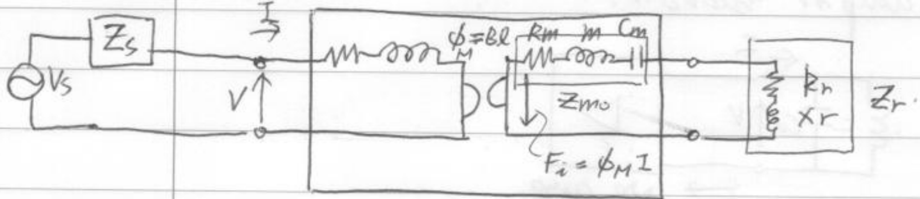


$$M_0 = \frac{\phi^2 C_m}{C_0 + \underset{\sim}{C_c} + \phi^2 C_m}$$; sensitivity가 점점 떨어진다

C_0 가 크면 C_c 의 영향이 작다.

∴ mic 면적이 넓으면 유리.

(Speaker)

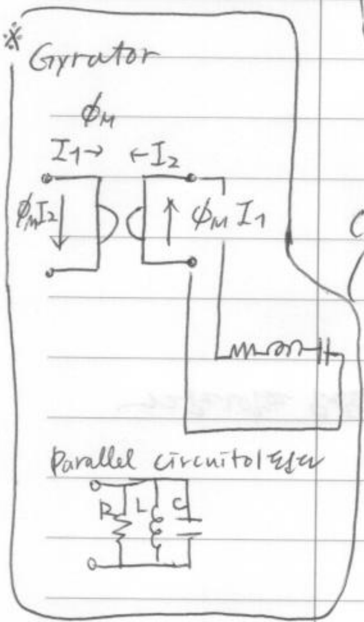


$$\left.\begin{array}{l} R_r \rightarrow R_r(\omega) \\ X_r \rightarrow X_r(\omega) \end{array}\right\}$$ 주파수 dependent

▷ 스피커의 자속
B; 0.8 ~ 1.2 [Tesla] 정도

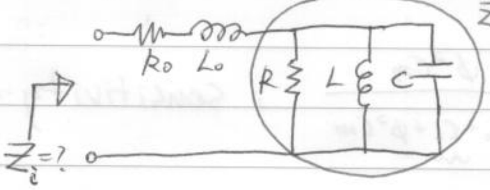
▷ 고급 스피커는 B ↑

▷ or 자속밀도를 높이는 fluid 삽입



(i) $Z_r \rightarrow 0$ (shorted)

(Kinsler p403 fig 14.4.5(b))



$$R = \frac{\phi_M^2}{R_m}, \quad L = \phi_M^2 \cdot C_m, \quad C = \frac{m}{\phi_M^2}$$

Gyrator 에서 $L \leftrightarrow C$ 바뀐다.

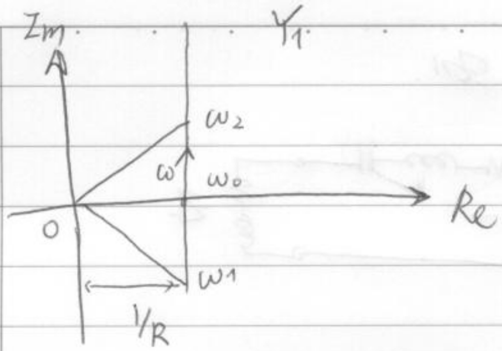
(analogy-II p398 fig 14.2.3(c))

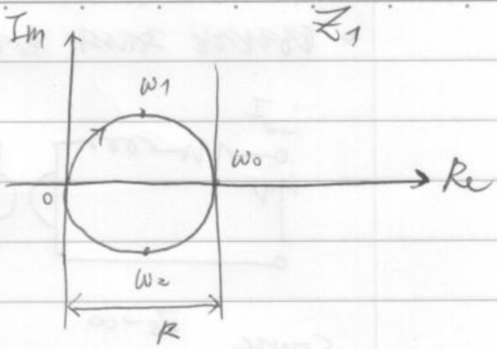
실제 radiation이 있다면 $R_m \rightarrow R_m + R_r$

$m \rightarrow m + m_r$ (radiation mass)

$\left(\begin{array}{l} jX_r = j\omega m_r \\ m_r = \frac{X_r}{\omega} \end{array} \right)$

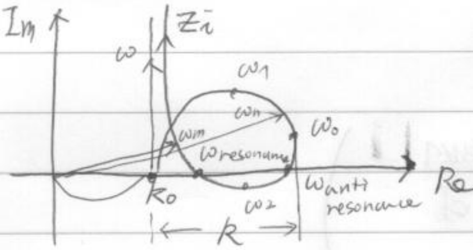
낮은 주파수에서는 constant이지만
일반적으로는 변한다.





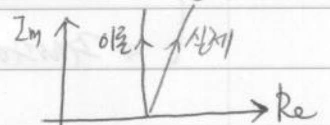
$Z_i = ?$

$= R_0 + j\omega L_0 + Z_1$

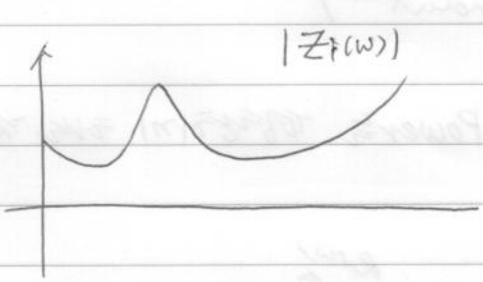


※ Coil의 Impedance

$Z_0 = R_0 + j\omega L_0$



skin effect?

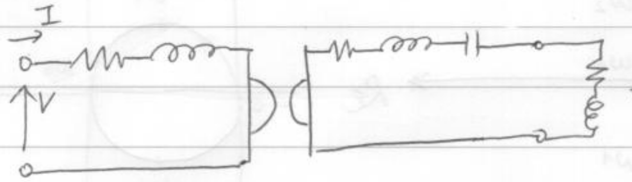


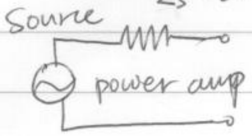
Kinsler
p405 fig 14.4.6 (c) 와 같이
실제로 loss 가 증가한다
(eddy current loss)

 Driver Unit 만 가지고 하면
Z 구할 수 있다 (Cabinet, infinite baffle 없이)
dipole-like

 중진 달면 m_r 측정 可

◦ 평탄한 주파수 특성 얻기.





ideal
; Current Source 가 된다

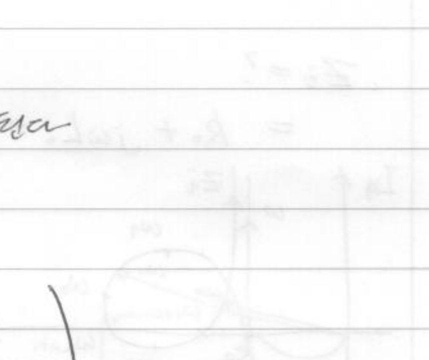
$$I = \frac{V_s}{Z_s + Z_1} \cong \frac{V_s}{Z_s}$$

(혹은 전자회로를 이용해서
Current로 drive 함
⇒ 주파수에 independent)

R_r 에서 소모되는 Power를 평탄하게 하는 것이 목표

$$P_r = \frac{1}{2}\hat{u}^2 R_r$$

($a \ll \lambda$; 즉 point source)



$R_r \sim \omega^2$

$\Rightarrow \hat{u} \sim \frac{1}{\omega}$ 이면 되겠구나!!

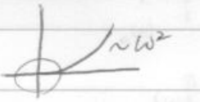
$$u = \underbrace{\frac{F_i}{R_r + R_m + j\omega(m+m_r) + \frac{1}{j\omega C_m}}}$$

역학적 impedance

$F_i = BlI$

$$= \frac{BlI}{R_r + R_m + j\omega(m+m_r) + \frac{1}{j\omega C_m}}$$

$R_r + R_m$ → 작게. (어차피 작다)



$\omega_0 = \frac{1}{(m+m_r)C_m}$ low-tuned (cf) condenser mic high-tuned)

$\omega \gg \omega_0$ 인 주파수에서 사용.

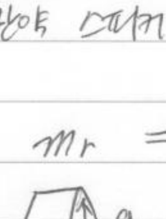
($m + m_r$ 이 dominant 하도록)

$$\simeq \frac{F_i}{j\omega m_{total}}$$

⇒ radiated power 가 일정.

(만약 스피커가 무지향성이면 주파수 특성이 평탄할 것이다.)

$$m_r = \underset{\text{공기}}{\rho_0} \cdot \pi a^2 \cdot \frac{8}{3\pi} a$$



ex) Woofer $a = 0.1m$

$m_r = 1.21\ kg/m^3 \cdot \pi \cdot (0.1)^2_{m^2} \cdot \frac{8}{3\pi}(0.1)_m$

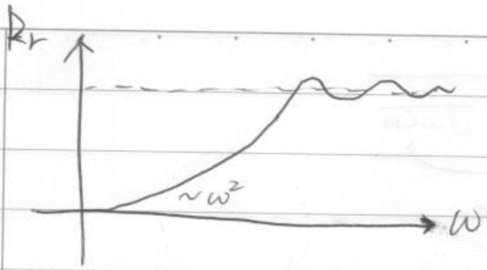
$\simeq 4g$

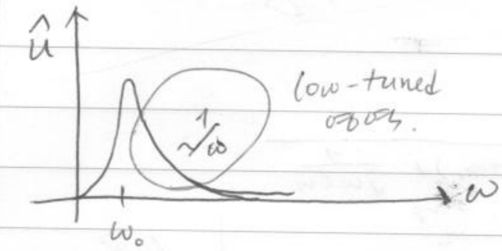
한쪽으로 radiation을 일어나게 할 경우 → 진동판(m) 질량에 따라 영향을 받을 수도 있다. 무시할 수도 있다.

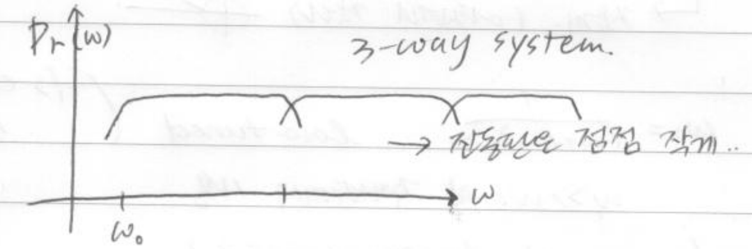
Cabinet에 mount 하지 않으면 효율이 작다. (dipole-like)

0.403

3)1.21 0.001. 3.







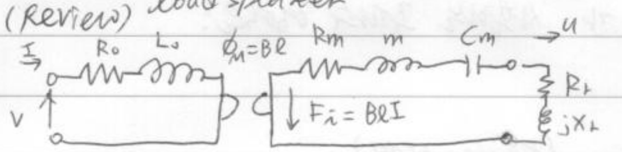
ω_0를 낮추려면 m을 크게 하면 되지만
~~sensitivity~~가 떨어진다
efficiency

up to now) infinite baffle

next)

2008. 5. 20. (K)
〈음향공학〉

(Review) loud speaker



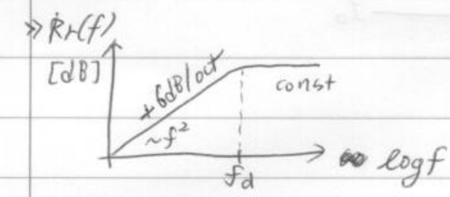
radiated power $P = \frac{1}{2}\hat{u}^2 R_r$

$R_r \sim \omega^2$ (즉 point source 영역에서)

$\hat{u} \sim \frac{1}{\omega}$ ($\omega \gg \omega_0$ 영역, $\omega_0 = \frac{1}{\sqrt{m^* C_m}}$

m^* $\left(= m + \underbrace{m_r}_{\text{radiation mass}} \right)$

» $R_r(f)$



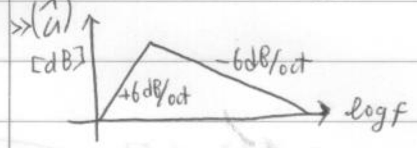
f_d where $\underbrace{ka}_{\text{piston 반경}} = \sqrt{2}$

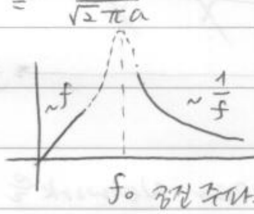
$\left(k = \frac{2\pi}{\lambda} = \frac{\omega}{c} = \frac{2\pi f}{c} \right)$

$\frac{2\pi f_d a}{c} = \sqrt{2}$

$f_d = \frac{\sqrt{2}c}{2\pi a} = \frac{c}{\sqrt{2}\pi a}$

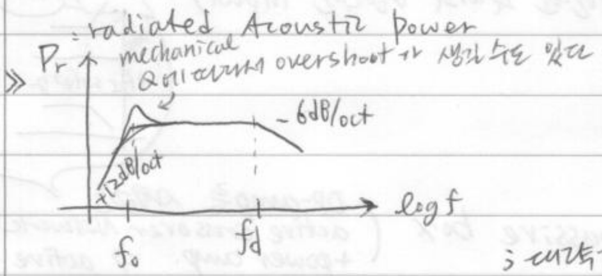
» $(\hat{u})^2$





» P_r : radiated Acoustic Power

mechanical Q에 따라서 overshoot가 생길 수도 있다



; 대략적인 P_r

1.41
3.14
504
141
423

(4.42) 1.4

4.42
0.15
2210
442
0.6630

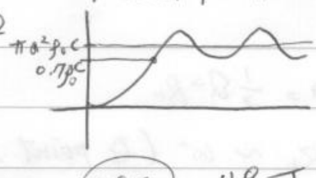
0.66
660/1000 . 343.

√343

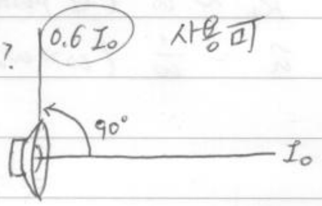
◎ 실제로 Woofer 가 사용하는 주파수 영역은?

$ka = \sqrt{2}$ (Kinsler p519)

$2ka = 2.828$



↳ 방향함수는?
$ka \sin\theta$
$x = 1.4$

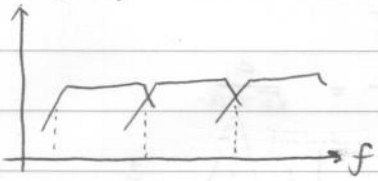


$a = 15$ cm (직경 30 cm)

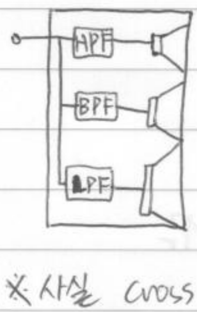
$$f_d = \frac{343}{\sqrt{2}\pi \times 0.15} = 514.7\,Hz \simeq 500\,Hz$$

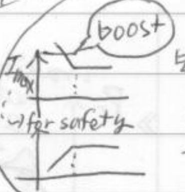
↳ 이 값 기준으로 사용해도 되지만…

◎ 3-way system



"cross over Network"을 이용해서 Band를 나눈다.
(신호 자체를 제한된 주파수 영역만 input)



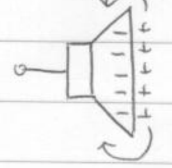


보상可
허나 hardware 자체로 견딜 수 있어야 한다

; passive box (OP-amp를 사용한 active crossover Network + power amp. ⇒ active box)

(※ 사실 cross over network도 회로에 포함시켜야 한다.)
equivalence circuit

⑦

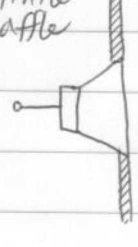


⇒ acoustic short (dipole)

; compression이 잘 일어나지 않는다.

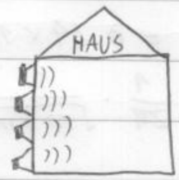
∴ infinite baffle 사용

해법 (i) infinite baffle

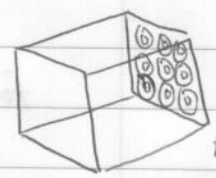


⇝ $Z_r = R_r + jX_r$

well-known (계산 可 / Table 有



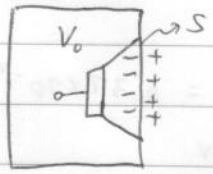
<결혼조건>



<파주의 스피커회사>

좀 더 현실적으로...

(ii) closed Box



→ acoustic short는 방지 可

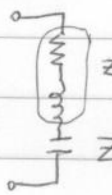
뒤로 방사된 소리는 Box내의 흡음을 통해 열로 변환 → 공진 주파수 ↑

재생할 수 있는 주파수 하한 ↑

(Box가 작을수록 많이 ↑)

· complience $C_{m,box} = \frac{V_0}{\rho_0 c^2 S^2}$; 커야 한다

◉ 등가회로



Zr.b → Cm.box ; (작게) Capacitance ↓

· 보내 진공속 공진점 $\omega_0 = \frac{1}{\sqrt{(m+m_r)C_m}}$

Box 포함 공진점 $\omega_0' = \frac{1}{\sqrt{(m+m_r)C_m^*}}$, $\frac{1}{C_m^*} = \frac{1}{C_m} + \frac{1}{C_{m,box}}$

$C_m^* < C_m$, $\omega_0' > \omega_0$

63.2×10^{-3}
0.69×10^{-3}
5688
3792
43608

$\sqrt{43.6 \times 10^{-6}}$

6.28
$\sim 6.5 \times 10^{-3}$
3140
3768

6.5
6.5
325
390
4225

40820

40.8×10^{-3}

$\frac{1}{40}$ 0.025 40 1200

0.025

(Cm.box를 크게하면
1/Cm.box를 무시 可.
→ $Cm^* \simeq Cm$)

ex) $f_0 = 18Hz$, $a = 128mm = 128 \times 10^{-3} m$

$m = 63.2g = 63.2 \times 10^{-3} kg$

$Cm = 0.69\ mm/N$

$= 0.69 \times 10^{-3}\ m/N$

$f_0 = \frac{1}{2\pi} \cdot \frac{1}{\sqrt{m\ Cm}} = ?\ 24.10\ Hz$

직경 700mm

① Box 0.5m ~~×0.5m ×0.5m~~ ×0.4m ×0.7m

$V_0 = 0.14\ m^3$

$Cm.box = \frac{V_0}{\rho_0 c^2 S^2} = 0.00037121 = 3.7121 \times 10^{-4} = 0.37 \times 10^{-3}\ m/N = 0.37\ mm/N$

$Cm^* = 2.4136 \times 10^{-4} = 0.24136\ mm/N$

$f_0' = 40.75\ Hz$

l = 0.6598m = 66cm (?)

② Box $0.8\,m \times 1.0\,m \times 1.5\,m$

$V_0 = 1.2\ m^3$

$Cm.box = 0.0031818 = 3.1 \times 10^{-3}\ m/N = 3.1mm/N$

$Cm^* = 5.670 \times 10^{-4} = 0.567mm/N$

$f_0' = 26.59\ Hz$

$l = 0.1808m = 18cm$

구하기 : $\frac{c}{2\pi}\sqrt{\frac{A}{Vl}} = \frac{1}{2\pi}\frac{1}{\sqrt{mCm}}$

$$\frac{c^2 A}{Vl} = \frac{1}{mCm}$$

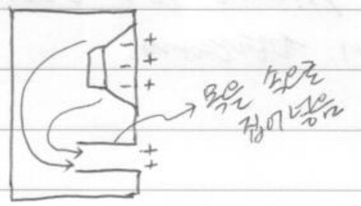
$$l = \frac{c^2 A\ m\ Cm}{V}$$

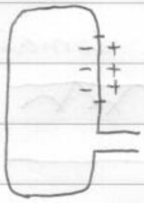
◎ Closed Box의 단점

공진 주파수 ↑

Pr. back 을 無用

↳ 해결 : Bass-reflex (위상 반전형)



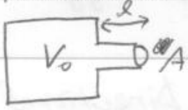


※ $f_0 = \frac{1}{2\pi\sqrt{m\cdot C_m}} = \frac{1}{2\pi}\sqrt{\frac{\rho_0 c^2 A^2}{m V_0}}$

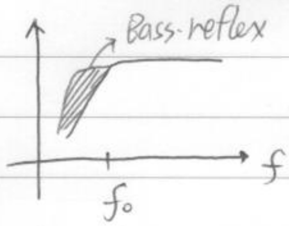
$= \frac{c}{2\pi}\sqrt{\frac{\rho_0 A^2}{l \cdot A \rho_0 V_0}}$

$= \frac{c}{2\pi}\sqrt{\frac{A}{V l}}$

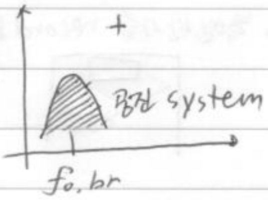
Helmholtz resonator

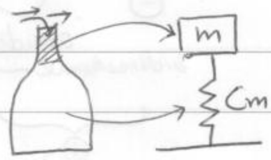


$f_0 = \frac{c}{2\pi}\sqrt{\frac{A}{Vl}}$



> 병목을 입으로 불면...



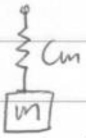


C_m : 공기의 탄성.

$f_0 = \frac{1}{2\pi\sqrt{mC_m}}$

> Bass-reflex의 경우.

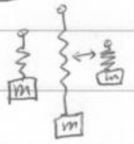
(exciting point가 다르다.
공진 주파수는 같다.)

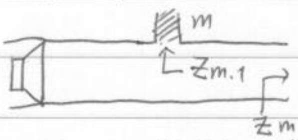


(i) 천천히 내리면 (quasi static) 위상차 無

(ii) 공진 주파수부근에서는 위상 반대.

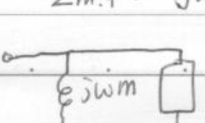
(iii) 높은 주파수에서 어떤 영향을 받는가?





낮은 주파수에서는 공기가 새어나오지만,

$Z_{m,1} = j\omega m$ 높은 주파수에서는 block된 것과 같다



⇒ 목관악기에서 낮은 음을 불 때 구멍을 확실히 닫아야 한다. (no-leak allowed)

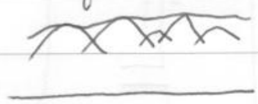
⊙(Kinsler p420)

Electrodynamic
Moving-coil   microphone (전동형)

(fig 14.10.1)

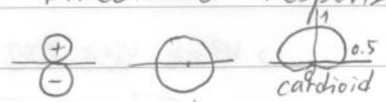
역학적인 resonance system을 많이 만듦

→ freq. domain에서. 평탄하게.

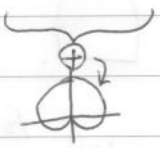


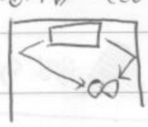
; 저렴, rugged, no DC needed

Kinsler
(p425) Directional Response



bidirectional → 측면 반사음 record (X)





∘ 변종...

super-cardioid
hyper-cardioid

2008. 5. 22. (木)

<음향공학>

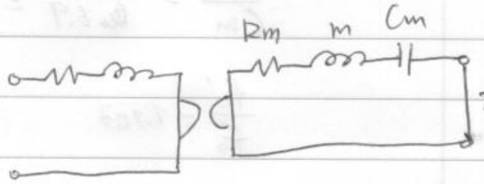
Woofer design

$a = 128mm = 0.128m$

$m = 63.2g$

$C_m = 6.9 \times 10^{-4}\ m/N$

(i) 진공중



$f_0 = 18Hz$?

$f_0 = \frac{1}{2\pi}\frac{1}{\sqrt{mC_m}} = 24.10Hz$

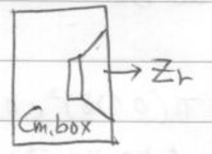
$2R_r$

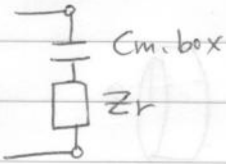
$2m_r$

를 고려해도 $= 22Hz$

안 맞는다.

(ii)





capacity가 직렬로 연결

$C_{m.box} = \frac{V_0}{\rho_0 c^2 S^2}$ ① $(V_0 = 0.5 \times 0.4 \times 0.7 = 0.14m^3)$

$= \frac{0.14}{415 \cdot 343 \cdot \pi^2 (0.128)^4}$

$= 3.71 \times 10^{-4}\ m/N$

$C_m^* = \frac{C_m \cdot C_{m.box}}{C_m + C_{m.box}} = 2.41 \times 10^{-4}\ m/N$

$f_0' = \frac{1}{2\pi\sqrt{mC_m^*}} = 40Hz$

$\frac{C_m^*}{C_m} = \frac{2.41}{6.9} = 0.35$

$\frac{f_0'}{f_0} = \frac{1}{\sqrt{0.35}} = 1.69\uparrow$

Box의 단성 때문에...

② $V_0 = 0.8 \times 1 \times 1.5 = 1.2 m^3$

$C_{m,box} = 31.8 \times 10^{-4}$ m/N

$C_m^* = \frac{6.9 \times 31.8}{6.9 + 31.8} \times 10^{-4}$ m/N

$= 5.67 \times 10^{-4}$ m/N

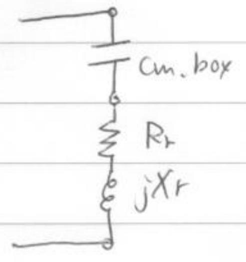
$\frac{C_m^*}{C_m} = \frac{5.67}{6.9} = 0.822$

$\frac{f_0'}{f_0} = 1.103$

$f_0' = 27.2 Hz$

box & 진동의 radiation

※

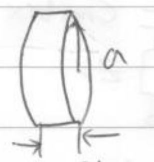


Radiation mass를 고려하여.

$jX_r = j\omega m_r$

m_r로 인해 공진점을 내리게 된다.

m_r:



$\left(\frac{8}{3\pi}a\right)$

$m_r = \pi (0.128)^2 \times 0.85 \times 0.128\, m^3 \times 1.21\ kg/m^3$

$= 6.78 \times 10^{-3}$ kg

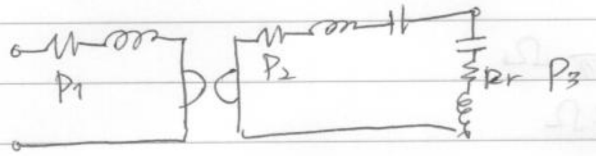
$= 6.78$ g

$m \rightarrow m + m_r = 10g$

$f_0' = \frac{1}{2\pi\sqrt{(m+m_r)C_m^*}}$; 더 정확한 식.

○ Efficiency 효율 : η (%)

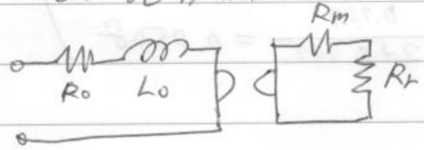
①에서 $f_0' \xrightarrow{\text{마르며}} 38Hz$



$$\eta = \frac{P_3}{P_1 + P_2 + P_3}$$; 주파수의 함수가 된다

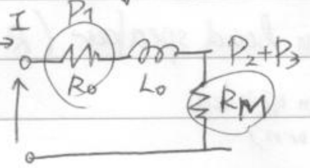
$\eta(f = f_0') = ?$

Box 공진점에서의 효율



등가회로가 간단해진다.

⇓ 전기 domain으로 이동.



(14.3.14) $R_M = \dfrac{\phi_M^2}{R_m + R_r}$

asume $\phi_M = Bl = 8\ N/A$

$\underset{1\ \text{Tesla}}{B}\ \underset{8m}{l}$

$R_m = 2 kg/s$ $\left(\underset{\text{mechanical } Q}{Q_m} = \dfrac{\omega_0 m}{R_m} \right)$

$R_r = ?$, $R_0 = 8\Omega$

p519 Imp. function

R_1 $R_r = \rho_0 c S \cdot R_1$

$\underset{\text{dimensionless}}{ka} = \dfrac{2\pi f}{c} a = \dfrac{2\pi \cdot 38}{343} \cdot 0.128 = 8.91 \times 10^{-2}$

$2ka = 1.782 \times 10^{-1} = x$ $\quad R_1(x)\Big|_{x=0.2} = 0.005$

$= 0.1782 \approx 0.2$

$R_r = 415 \times \pi (0.128)^2 \times 0.005$

$= 0.107$ kg/s

$$R_M = \frac{64}{2.107} \Omega$$

$$= 30.4\Omega$$

$$\eta = \eta_{em} \cdot \underset{\text{mechano-acoustic}}{\eta_{\underline{ma}}}$$

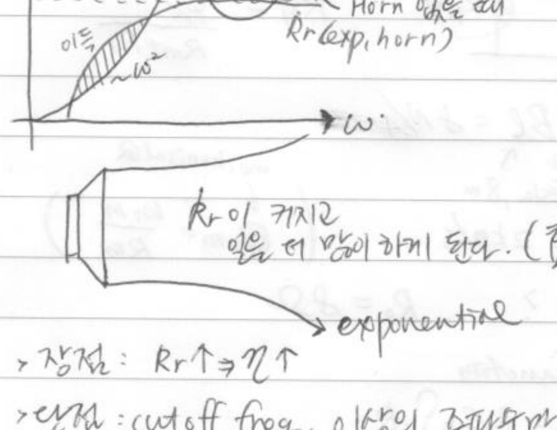
$$\left(\begin{aligned} \eta_{em} &= \frac{R_M}{R_0 + R_M} = \frac{30.4}{8+30.4} = 0.792 \\ \eta_{ma} &= \frac{R_m}{R_m + R_r} = \frac{0.107}{2+0.107} = 0.0508 \end{aligned} \right)$$

$\cong 0.04$

$= 4\%$ 낮구나.

(위에서 다룬 것은 Direct Radiator)

↳ 효율을 개선한 것이 Horn loud speaker (R_r을 크게)



> 장점 : $R_r \uparrow \Rightarrow \eta \uparrow$

> 단점 : cutoff freq. 이상의 주파수만 전파 可

음색 왜곡이 일어난다. ⇐ (ω dependent) phase & group velocity ; dispersion)

ex) dirac-δ

다른 위상 속도로 전파.

° $R_r = \rho_0 c S R_1$

$R_1 = \frac{1}{2}(ka)^2$ (; 낮은 주파수에서)

(ka 작을 때)

° loudspeaker data book 에서

C_m을; $\underbrace{dm^3}_{\text{decimeter}}$ 로 표현.

뭔 소리냐면 ...

$$C_{m,box} = \frac{V_0}{\rho_0 c^2 S^2}$$

$$V_0 = C_m \rho_0 c^2 S^2$$
$$= (dm)^3$$

50cm × 40cm × 80cm

= 5×4×8 = 160 dm^3

equivalent volume 으로 표현

(Kinsler) Ch15 Underwater Acoustics 美

(Hydro-acoustics) 英

15.2

○ 해수 속 음속.

(15.2.1) 경험치를 통해 얻은 음속.

$c(T,\ S,\ P)$

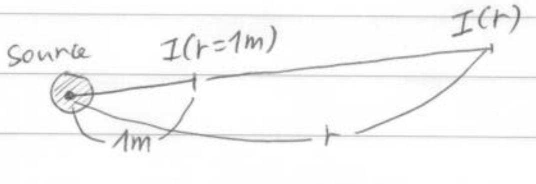
- T → temp.
- S → 염도 (ppt), $S = 35‰$
- P → guage pressure

※ $(S-35)$항

(15.2.2)

$\left(\begin{array}{l} \varphi : \text{위도} \\ z : \text{깊이} \end{array} \right)$ 로 P를 표현

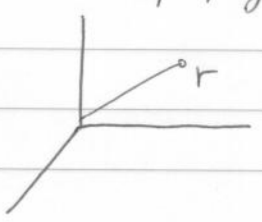
15.3 Transmission Loss



$$TL = 10\log\left[\frac{I(r=1m)}{I(r)}\right] \quad [dB]$$

$(\searrow 0)$

{ point-source
  3-D propagation



$$I = \frac{P}{4\pi r^2}, \quad I = \frac{p_{eff}^2}{\rho_0 c}$$

$$p \sim \frac{1}{r}$$

$p = \frac{j\omega\rho_0}{4\pi r}\hat{Q}\, e^{j(\omega t - kr)}$; medium loss 가 없을 때.

$$p = \underbrace{\frac{A}{r}}_{\text{; geometry에 의한것}} \cdot \underbrace{e^{-\alpha r}}_{\text{; absorption에 의한것}} \cdot e^{j(\omega t - kr)}$$

$$TL = 10\log \frac{I(r=1m)}{I(r)}$$

$$= 20\log \frac{\hat{p}(r=1m)}{\hat{p}(r)}$$

$$= 20\log \frac{\frac{A}{1}e^{-\alpha\cdot 1}}{\frac{A}{r}e^{-\alpha r}} \quad \text{(위상 term 무시)}$$

$$\alpha = \frac{Np}{m}$$

$$= 20\log(r\cdot e^{\alpha(r-1)})$$

$$= 20\log r + \alpha(r-1)\,20\log e$$

$$= 20\log r + \alpha(r-1)\cdot \underbrace{20\log e}_{8.7}$$

$r \gg 1m$

$$\simeq \underbrace{20\log r}_{\text{geometry 의한 TL}} + \underbrace{ar}_{8.7\alpha} \rightarrow \text{absorption 의한 TL}$$

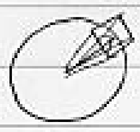
ideal한 유체에서 $\alpha \sim f^2$

2008.5.27.(화)

<음향공학>

○ Spherical Spreading 수중음향 용어.

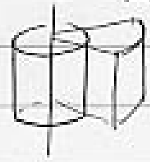
$TL = 20\log r + ar$



$I \sim \frac{1}{r^2}$

○ Cylinderical Spreading

$TL = 10\log r + ar$



$I \sim \frac{1}{r}$

※ geometrical loss는 주파수에 무관

매질에 의한 손실은 주파수에 따라 다름(고주파일 수록 손실이 크다)

※ Concert Hall의 냉난방, 공기조화장치에 의해.

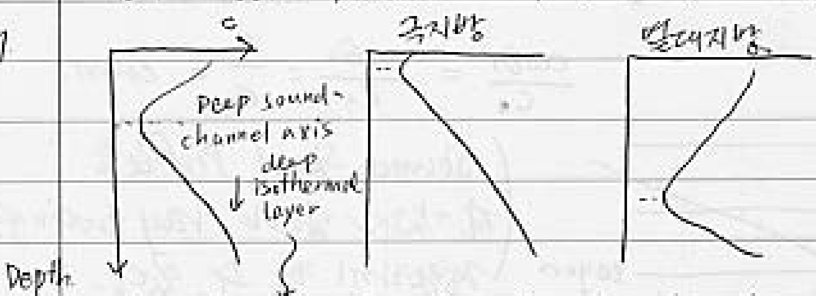
온도분포, 공기유속의 변화로 인해 음파가 직진하지 않는 경우도 있다.

온도 $c \sim \sqrt{T}$ ... in Kelvin

염도

깊이 깊은 바다에서는 bulk modulus ↑, 탄성계수가 커진다.

Fig 15.4.7



아마도 4°C

분포(-1 ~ 5°C)

* positive gradient

$0.016\,(m/s)/m = 0.016\,s^{-1}$

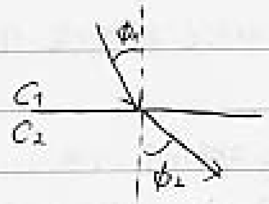
$c = \sqrt{\dfrac{B}{\rho_0}}$: ρ_0 보다 B가 빨리 증가

negative gradient

주지방 main thermo-cline 등.

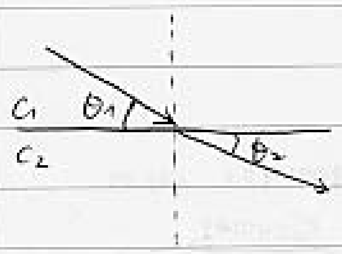
음속의 범위 1475 ~ 1510 ...
해수 1500 ~ (m/s)
담수 1480 ~

② Ray tracing
(基本 : Snell's law) (5.74)



$$\frac{\sin\phi_1}{\sin\phi_2} = \frac{C_1}{C_2}$$

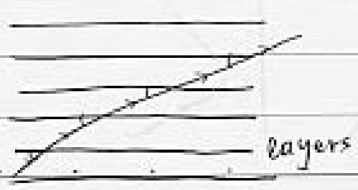
(物理 version)



$$\frac{\cos\theta_1}{\cos\theta_2} = \frac{C_1}{C_2}$$

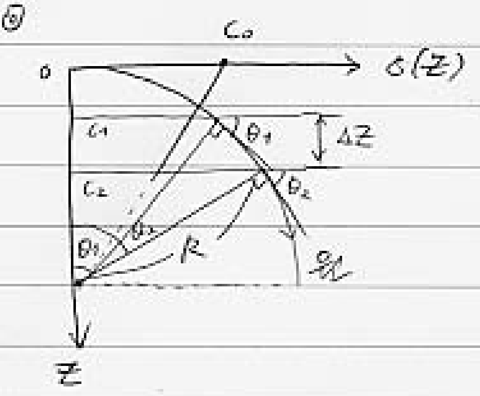
(海軍 version)

$$\frac{\cos\theta_1}{C_1} = \frac{\cos\theta_2}{C_2} = \frac{1}{C_0} = \text{const.}$$



(Sound Speed Profile을 잘 갖추고 있어야 ray tracing을 정확하게 할 수 있다.)

⑥



빛은 휜다.

원으로 계산해야 된다!! → 원이다.

$$\frac{\cos\theta}{c} = \frac{1}{c_0}$$

$$\Delta z = z_2 - z_1 = R\left[\cos\theta_1 - \cos\theta_2\right]$$

$$R = \frac{\Delta z}{\cos\theta_1 - \cos\theta_2} = \frac{c_2 - c_1}{g(\cos\theta_1 - \cos\theta_2)}$$

$$\left(g = \frac{c_2 - c_1}{\Delta z}\right)$$

$$= \frac{(c_2 - c_1)}{g\left(\frac{c_1}{c_0} - \frac{c_2}{c_0}\right)}$$

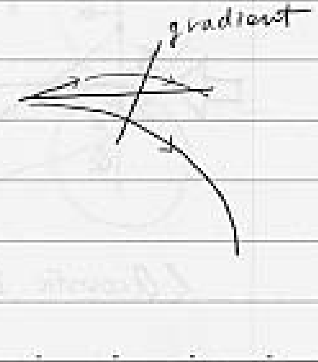
$$\left(\cos\theta_1 = \frac{c_1}{c_0},\quad \cos\theta_2 = \frac{c_2}{c_0}\right)$$

$$= -\frac{c_0}{g}$$

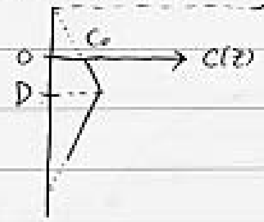
if $g = \text{const}$

$\Rightarrow R : \text{const}$

※



15.5 Mixed Layer



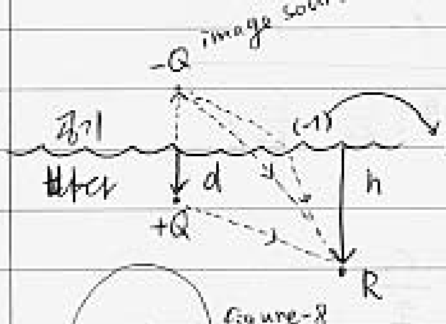
deep sound channel axis를 따라 진행
(멀리까지 전파 됨)

; "SOFAR" channel
(Sound Fixing And Ranging)

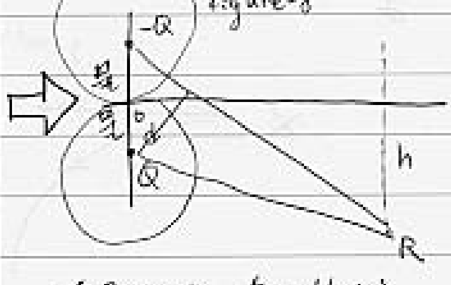
Cylinder spreading-like 형태로 전파

$$TL = 10\log r + ar + 10\log r_t \quad (15.6.6)$$

r_t: channel range



pressure release boundary
(soft boundary)

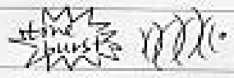
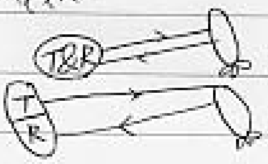


<Acoustic Doublet>

(eq. 15.7.1)
far field에서 ...
경로 차이에 (위상에 의한)
간섭(상쇄) 있다

(※ dipole : acoustic doublet Φ
$d \ll \lambda$ 인 경우.)

13.8 SONAR Equations
↳ Sound Navigation And Ranging

- passive sonar
- active sonar 
  - monostatic case 
  - bi-static case
  - ⋮ multistatic case

◦ Tone Burst

$f_0 \simeq 5kHz$

※ 어뢰 Torpedo (active SONAR system) (short range, high-resolution ~ 50kHz)

◦ resolution ~ λ

물에서 $c = 1500\ m/s$

$f = 1kHz$	$\lambda = 1.5m$
$10kHz$	$15\ cm$
$100kHz$	$1.5\ cm$
⋮	⋮
$5kHz$	$30\ cm$

$\underbrace{30\ cm}_{\text{아주 높은 resolution}}$ [너무 높다 / 낮추면 range 넓힐수있다

⇒ 그러나 transducer 크기의 제한 때문에 주파수를 내리기는 현실적으로 어렵다.

2008. 5. 29. (木)
<음향공학>

※ 기말고사 : 6월 4일(水) 18:00 ~ 21:00
뉴미디어 대학원실

※ Open lab : Neofidelity 이석두 사장 (내일 15:00)

PCM → PWM → 스위칭 증폭 → LPF →

switching mode

V	high	low
I	low	high

$P = VI$ (P를 작게, 효율 90%)

linear analog audio amp 효율 (10~20%)

$$EL \geq DNL + DT \quad (\text{in dB})$$

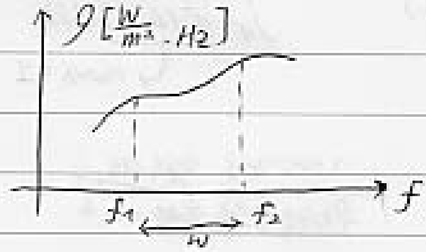
EL: echo level, 수신된 신호

DNL: detected noise level

DT: detection threshold — 50%의 탐지확률 (false alarm)

$$DT = DT_1 - 10\log W$$

DT_1: detection threshold for bandwidth $W = 1\,Hz$



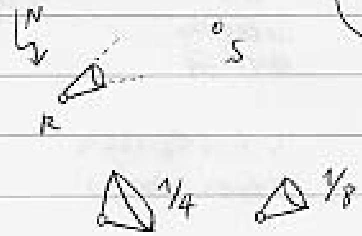
$$I = \int_{f_1}^{f_2} g \cdot df$$

(a) Passive Sonar

$$EL = \underset{\text{source level}}{SL} - \underset{\text{transmission loss}}{TL} \qquad (\text{in dB})$$

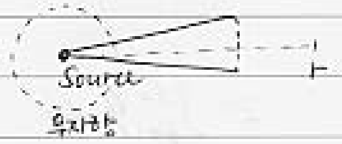
$$DNL = NL - \underset{\text{directivity index}}{DI} \qquad (\text{in dB})$$

방향성이 있으면
Noise를 suppress



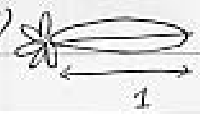
(p189 ~ 190) directivity

$$D = \frac{I_{max}(r)}{I_s(r)} = \frac{4\pi}{\int_{4\pi} \underbrace{H^2(\theta, \phi)}_{max=1} d\Omega}$$



$$\frac{\text{지향성으로 쏘았을 때 } I}{\text{무지향성으로 쏘았을 때 } I}$$

ex)



directivity index

$$DI = 10 \log D \qquad (7.6.18)$$

$$\boxed{SL - TL \geq NL - DI + DT_N}$$: SONAR eq. of passive SONAR

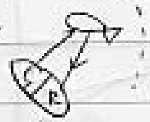
(b) Active Sonar

$$EL = SL - 2TL + TS$$

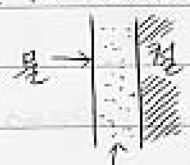
SL ↑ 내가 쏜 것 2TL ↑ 왕복 TS target strength

$$-TL - TL'$$

bistatic



※ TS 줄이는 방법



ρc-rubber로 coating, 얇으면서 decay가 큰 물질 찾아내어 붙여내는 방안도…

⇒ 스텔스化

$$SL - 2TL + TS \geq \underbrace{NL - DI}_{DNL} + DT_N$$; noise limited system

문제점 ① Reverberation (잔향)
by fish, sea surface, bottom, etc..
잔향이 dominant하면…

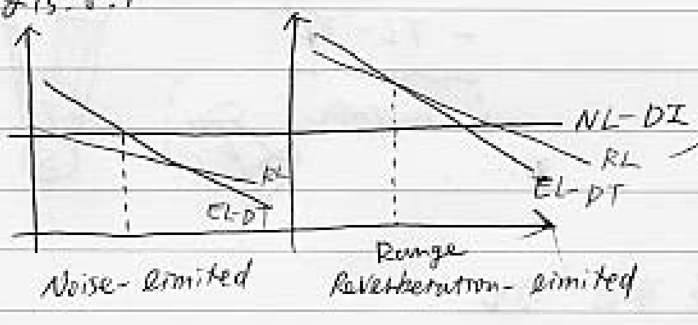
⇒ $DNL = RL$ (reverberation level)

$$SL - 2TL + TS \geq RL + DT_R$$; reverb. limited system

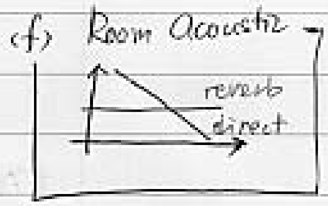
(cascaded system — H_1 — H_2 — H_3 —
transfer function ; Σ)

dB-scale로 더하면 된다.

(p.450) fig 15.8.1



완벽한 Concert Hall의 예시



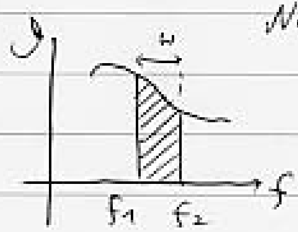
15.9 Noise & Bandwidth Considerations

(a). Ambient Noise

$DNL = NL - DI$

(Fig 15.9.1) $= \underbrace{NSL + 10\log w}_{NL} - DI$

intensity spectral level /Hz



※ intensity spectral level

$I = \int_{f_1}^{f_2} J \cdot df = J \cdot w$

$IL = 10\log\left(\frac{I}{I_{ref}}\right)$

$= 10\log\left(\frac{J \cdot w}{I_{ref}}\right)$

$= 10\log\left(\frac{J \cdot 1Hz}{I_{ref}}\right) + 10\log\left(\frac{w}{1Hz}\right)$

$= \underbrace{ISL}_{\text{intensity spectrum level}} + 10\log w$

intensity spectrum level } 1Hz당

p.451

(fig 15.9.1)

※ sea state : 3
$f = 1\,kHz$) → $NSL = 62\,dB$ relative to $1\mu Pa/\sqrt{Hz}$

여기 봐라

$I = \frac{P_{eff}^2}{\rho_0 c}$, $I \sim P_{eff}^2$

$\mathcal{J} = [W/m^2]/Hz$

$P_{eff} = Pa/\sqrt{Hz}$

$1\,mPa/\sqrt{Hz}$
$60\,dB$

I 에서 ISL은 ⇒ $\frac{10^{-6}}{\underbrace{1.5\times10^{6}}_{\rho_0 c}}\left[\frac{W}{m^2 \cdot Hz}\right]$

(b) self noise

· 저속 : machinary noise dominant

· 고속 : flow noise , Propeller noise

6月3日, (火) Doppler effect

서로 멀어질 때

$$f' = f\,\frac{c \pm U}{c \mp V}$$

U: 관측자 속도 $\quad U \lll c$

V: source 속도 $\quad V \lll c$

$$\approx f\,\frac{c(1+\frac{U}{c})}{c(1-\frac{V}{c})} \approx f(1+\tfrac{U}{c})(1+\tfrac{V}{c}) \approx f(1+\tfrac{U}{c}+\tfrac{V}{c})$$

Doppler shift

$$\Delta f = f' - f \approx \left(\frac{U+V}{c}\right) f$$

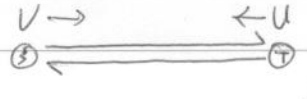
Passive sonar

$$f' = f\,\frac{c + U\cos\phi}{c - V\cos\theta} \approx f\left(1 + \frac{U}{c}\cos\phi + \frac{V}{c}\cos\theta\right)$$

$$\Delta f = f' - f = f\left(\frac{U}{c}\cos\phi + \frac{V}{c}\cos\theta\right) = f\,\frac{\dot R}{c}$$

$$\dot R = \frac{dR}{dt} = V\cos\theta + U\cos\phi \quad \text{"range rate"}$$

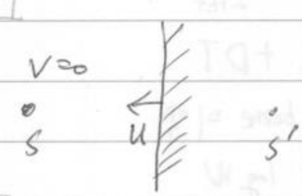
Active Sonar



(i)

$\boxed{V \to 2V}$

f

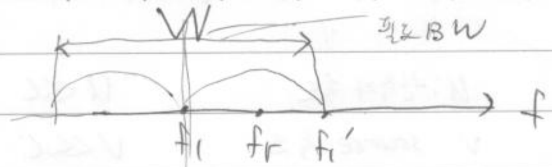


$$\Delta f_1 = 2\,\frac{\dot R}{c}\,f_1$$

$\boxed{U \to 2U}$

$$f_1' = f_1\left(1 + 2\,\frac{\dot R}{c}\right)$$

reverboration $\Delta f_r = f_1\left(1 + 2\,\frac{V\cos\theta}{c}\right)$

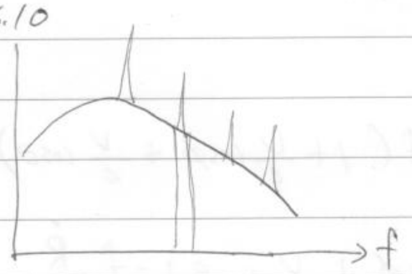


Active $W_a = 2\Delta f = 4\,\frac{\dot{R}}{c} f = \frac{4}{1500}\dot{R}f = 2.67\times10^{-3}\,\dot{R}f$

passive

$W_p = 1.33\times10^{-3}\,\dot{R}f$

15.10



(a) Source

<cont. spectrum source>

$SSL\,(cont) = 10\log\left(\frac{I_s\cdot 1Hz}{I_{ref}}\right)$, $I = I_s * W$

↳ Source Spectrum Level

<tone>

$SL(tone) = 10\log\frac{I}{I_{ref}}$

total $SL = 10\log\frac{I_s\cdot W + I}{I_{ref}} = 10\log\frac{I_s\cdot W}{I_{ref}} + 10\log\left(1+\frac{I}{I_s\cdot W}\right)$

$SL - TL \geq NL - DI + DT$

(i) broadband sys + tone 미약

$SL = SSL + 10\log W$

$NL = NSL + 10\log W$

$SSL(cont) - TL \geq NSL - DI + DT$

(ii) narrow band sys

$I_s \cdot W \ll I$ (tone)

$SL(\text{tone}) - TL \geq NSL + 10\log W - DI + DT$

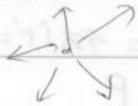
P.456 ex 참고 $V = 4$ knot , $W = 100\,Hz$, $DI = 20\,dB$, $DT = 0\,dB$

sea state : 3 , $f = 1\,kHz$, $SSL = 120$ dB re $1\mu Pa/\sqrt{Hz}$

NSL (sea state 3 , $f = 1\,kHz$) $= 62$ dB re $1\mu Pa/\sqrt{Hz}$

$$\underset{120}{SSL} - TL \geq \underset{62}{NSL} - \underset{20}{DI} + \underset{0}{DT} \rightarrow TL \leq 78\ dB$$

(i) Spherical spreading



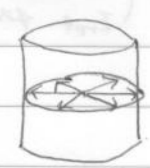
$TL = 20\log r + ar$

식(15.3.6) ⟵ $a(f = 1kHz) = \frac{8\times10^{-5}}{1.7} + \frac{0.04}{6000+1} + 4\times10^{-7} = 5.41\times10^{-5}$

$20\log r + (5.41\times10^{-5})\, r \leq 78$

$r = 7.577$ km

(ii) Cylinderical spreading

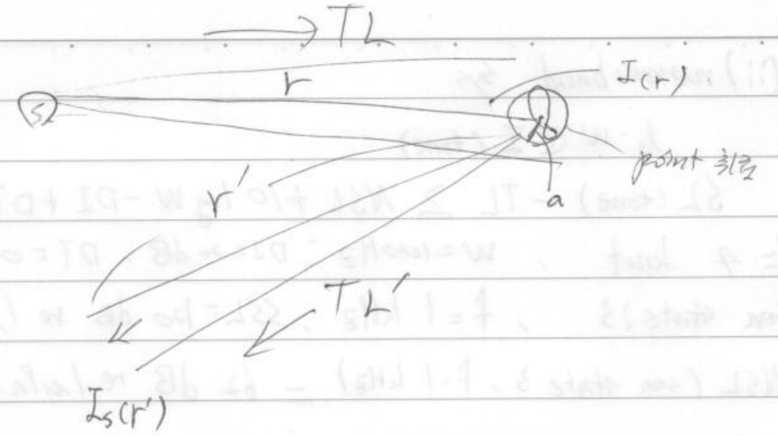


$TL = 10\log r + ar$

$r = 405$ km (?)

(iii) mixed layer

$r = 13.4$ km



apparent power

$$\Pi = P = 4\pi r'^2 \cdot I_s(r')$$
$$= 4\pi (r'=1m)^2\, I_s(r'=1m) = 4\pi \cdot I_s(1)$$

$$I(r) \cdot \sigma = P$$

$$I(r) \cdot \sigma = 4\pi \cdot I_s(r'=1)$$

$$\frac{\sigma}{4\pi} = \frac{I_s(r'=1)}{I(r)} \quad (15.11.1)$$

$$EL = SL - TL$$
$$= 10\log \frac{I_s(r'=1)}{I_{ref}} - TL' = 10\log\left(\frac{I(r)}{I_{ref}}\,\frac{\sigma}{4\pi}\right) - TL'$$

$$TS = 10\log\left(\frac{\sigma}{4\pi}\right)$$

TS 구하기 (i) $ka \ll 1$ ← 작은 구

$$4\pi \cdot I_s(r'=1) = \sigma \cdot I(r)$$

$$I(r) = ?$$

$$\cancel{I_s(r')} \quad \frac{I_s(r'=a)}{I_s(r')} = \left(\frac{r'}{a}\right)^2$$

$$r'=1 \rightarrow \frac{I_s(a)}{I_s(1)} = \left(\frac{1}{a}\right)^2, \quad I_s(1) = a^2 I_s(a)$$ 써

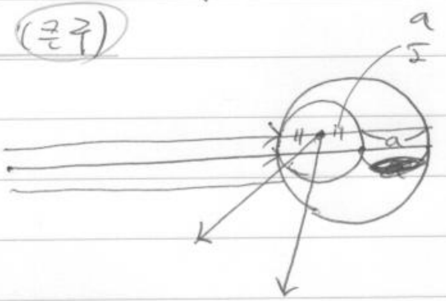
point 취급 $\quad I(r) = I_s(a)$

$$4\pi \cdot I_s(a)\, a^2 = \sigma\, I_s(a)$$

$$\sigma = 4\pi a^2$$

$$TS = 10\log(a^2) = 20\log a$$

ii) $ka \gg 1$ (큰구)



$$TS = 20\log\left(\frac{a}{2}\right)$$

condensor micro phone sensitivity
woofer box안에 넣고 f 차단 구하기) [illegible]