Mechanical Processing in Internally Coupled Ears

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TMP Thesis Defence
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Elite Master Course
Theoretical and Mathematical Physics

Outline for Section 1

Auditory Systems

Independent Ears

Eustachian tubes generally very narrow.

Effectively independent eardrum vibrations.

Coupled Ears

Wide eustachian tubes open into the mouth cavity.

Eardrums vibrations influence eachother.

Binaural Hearing Cues

Interaural Time Difference

Phase difference between the (pressure) **inputs** to the ears.

- ITD

Interaural Level Difference

Amplitude difference between the **inputs**.

- ILD

Internal Time Difference

Phase difference between the eardrum **vibrations**.

- iTD

Internal Level Difference

Amplitude difference between the **vibrations**.

- iLD

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Advantages of Coupled Ears

- Low frequencies result in reduced degradation of hearing cues in dense enviroments.

Outline for Section 2

ICE Model

- An extension of the model first presented by Vossen et al (2010).
- Circular eardrums connected by a cylindrical cavity.

- The Aim is to accurately reproduce the direction and frequency dependence of the system.

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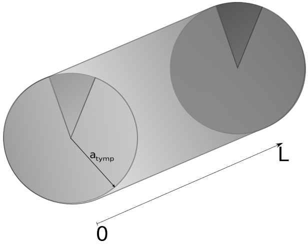
Mouth Cavity

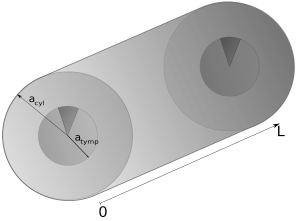
Previous Model



a_{tymp} fixed.

$V_{\mathrm{cyl}} = \pi a_{\mathrm{tymp}}^2 L$

Our Model



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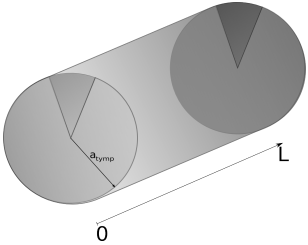

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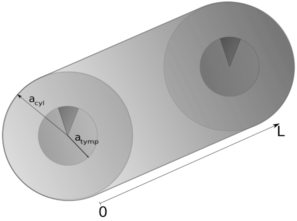

$a_{\text{tymp}}, \; V_{\text{cyl}}$ fixed.

$a_{\text{cyl}} = \sqrt{V_{\text{cyl}}/\pi L}$

Cavity Pressure

3D Wave Equation

$$\frac{1}{c^2}\partial_t^2 p(x,r,\phi,t) = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p(x,r,\phi,t)}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 p(x,r,\phi,t)}{\partial \phi^2} + \frac{\partial p(x,r,\phi,t)}{\partial x^2} \tag{1}$$

To be solved using the separation ansatz

$$p(x,r,\phi,t) = f(x)g(r)h(\phi)e^{j\omega t}.$$

Separated Equations

x- and ϕ- directions

$$\frac{d^2 f(x)}{dx^2} + \zeta^2 f(x) = 0 \longrightarrow f(x) = e^{\pm j\zeta x} \tag{2}$$

$$\frac{d^2 h(\phi)}{d\phi^2} + q^2 h(\phi) = 0 \longrightarrow h(\phi) = e^{\pm jq\phi} \tag{3}$$

r-direction, Bessel functions

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial g(r)}{\partial r}\right) + \left[\nu^2 - \frac{q^2}{r^2}\right] g(r) = 0 \longrightarrow g(r) = J_q(\nu r) \tag{4}$$

where, $\nu^2 = k^2 - \zeta^2$

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Boundary Conditions - ϕ

Smoothness and Continuity in ϕ.

$$\phi \rightarrow h(0) = h(2\pi) \quad \text{and} \quad h'(0) = h'(2\pi)$$

$$\Rightarrow h(\phi) = \cos q\phi, \;\; q = 0, 1, 2, \ldots \tag{5}$$

Boundary Conditions - r

Impenetrable boundary at $r = a_{\mathrm{cyl}}$, i.e. normal derivative vanishes

$$-j\rho\omega\mathbf{v} = \mathbf{n}.\,\nabla p(x, r, \phi; t)\big|_{r=a_{\mathrm{cyl}}} \equiv \left.\frac{\partial g}{\partial r}\right|_{r=a_{\mathrm{cyl}}} = 0 \qquad (6)$$

$$\Rightarrow g(r) = J_q(\nu_{\mathrm{qs}} r / a_{\mathrm{cyl}}) \qquad (7)$$

Bessel Prime Zeros

- ν_{qs} - zeros of J'_q, $s = 0, 1, 2, \ldots$
- ν_{00}=0

General Solution

Pressure Modes

$$p(x, r, \phi, t) = \sum_{q=0,s=0}^{\infty} \left[A_{\mathrm{qs}} e^{j\zeta_{\mathrm{qs}} x} + B_{\mathrm{qs}} e^{-j\zeta_{\mathrm{qs}} x} \right] p_{\mathrm{qs}}(r, \phi) e^{j\omega t} \quad (8)$$

$$p_{\mathrm{qs}}(r, \phi) = \cos q\phi J_q(\nu_{\mathrm{qs}} r / a_{\mathrm{cyl}}) \quad (9)$$

where, $\zeta_{\mathrm{qs}} = \sqrt{k^2 - \nu_{\mathrm{qs}}^2 / a_{\mathrm{cyl}}^2}$

Plane Wave Mode

$$p_{\mathrm{pw}}(x, r, \phi; t) = \left[A_{00} e^{jkx} + B_{00} e^{-jkx} \right] e^{j\omega t} \quad (10)$$

General Solution

Pressure Modes

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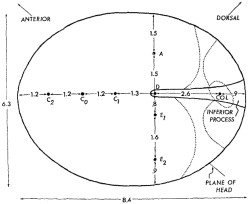
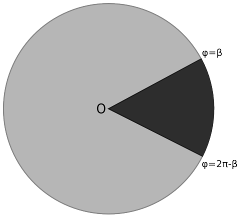
Eardrum

Sketch of a Tokay eardrum as seen from the outside (G.A. Manley, 1972).



COL - approximate position opposite the extracolumella insertion.

The ICE Eardrum.



Extracolumella (dark) - rigid, stationary.

Tympanum - assumed linear elastic.

Rigidly clamped at the boundaries ($r = a_{\text{tymp}}$ and $\phi = \beta,\ 2\pi - \beta$)

Membrane Vibrations

Membrane EOM

$$-\partial_t^2 u(r,\phi;t) - 2\alpha\partial_t u(r,\phi;t) + c_M^2 \Delta_{(2)} u(r,\phi;t) = \frac{1}{\rho_m d}\Psi(r,\phi;t) \tag{11}$$

Membrane parameters

α - damping coefficient, c_M^2 - propagation velocity

ρ_m - density, d - thickness.

Free-Undamped Membrane, $\alpha \to 0$, $\Psi \to 0$

Separation Ansatz

$$u(r, \phi; t) = f(r)g(\phi)h(t) \tag{12}$$

Separated Equations

$$\frac{d^2 g(\phi)}{d\phi^2} + \kappa^2 g(\phi) = 0 \tag{13}$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial f(r)}{\partial r}\right) + \left[\mu^2 - \frac{\kappa^2}{r^2}\right] f(r) = 0 \tag{14}$$

$$\frac{d^2 h(t)}{dt^2} + c_M^2 \mu^2 h(t) = 0 \tag{15}$$

Boundary Conditions

ϕ-direction: $u(r, \beta; t) = u(r, 2\pi - \beta, t) = 0$

$$\Rightarrow g(\phi) = \sin \kappa(\phi - \beta) \tag{16}$$

$$\text{where, } \kappa = \frac{m\pi}{2(\pi - \beta)}, \quad m = 1, 2, 3, \ldots$$

r-direction: $u(a_{\mathrm{tymp}}, \phi; t) = 0$

$$\Rightarrow f(r) = J_\kappa(\mu_{\mathrm{mn}} r / a_{\mathrm{tymp}}) \tag{17}$$

where, μ_{mn} is the n^{th} zero of J_κ

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Free eigenmodes

$$u_{\mathrm{mn}}(r,\phi) = \sin\kappa(\phi-\beta)J_\kappa(\mu_{\mathrm{mn}}r) \tag{18}$$

$$u_{\mathrm{free}}(r,\phi;t) = \sum_{m=0,n=1}^{\infty} C_{\mathrm{mn}}u_{\mathrm{mn}}(r,\phi)e^{j\omega_{\mathrm{mn}}t} \tag{19}$$

where, $\omega_{\mathrm{mn}} = c_M\mu_{\mathrm{mn}}$

Damped membrane

$$\widetilde{u}_{\mathrm{free}}(r,\phi;t) = \sum_{m=0,n=1}^{\infty} \widetilde{C}_{\mathrm{mn}}u_{\mathrm{mn}}(r,\phi)e^{j\omega_{\mathrm{mn}}t-\alpha t} \tag{20}$$

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Forced Vibrations: $\Psi = pe^{j\omega t}$

Steady State Solution

$$u_{\mathrm{ss}}(r,\phi;t) =: \sum_{m=0,n=1}^{\infty} C_{\mathrm{mn}} u_{\mathrm{mn}}(r,\phi) e^{j\omega t} \tag{21}$$

Substitute u_{ss} in Membrane EOM.

$$C_{\mathrm{mn}} = \frac{p \int dS u_{\mathrm{mn}}}{\Omega_{\mathrm{mn}} \int dS u_{\mathrm{mn}}^2} \tag{22}$$
$$\Omega_{\mathrm{mn}} = \rho_M d \left[(\omega^2 - \omega_{\mathrm{mn}}^2) - 2j\alpha\omega \right]$$

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Forced Vibrations contd.

Transient Solution

Same as the solution for a free damped membrane

$$u_{\mathrm{t}}(r,\phi;t) = \sum_{m=0,n=1}^{\infty} \widetilde{C}_{\mathrm{mn}} u_{\mathrm{mn}}(r,\phi) e^{j\omega_{\mathrm{mn}}t-\alpha t} \tag{23}$$

$\widetilde{C}_{\mathrm{mn}}$ determined from the membrane displacement at $t = 0$.
$u_{\mathrm{t}} \to 0$ exponentially as $t \to \infty$.

Steady State Approximation

$$u \approx u_{\mathrm{ss}}.$$

Forced Vibrations contd.

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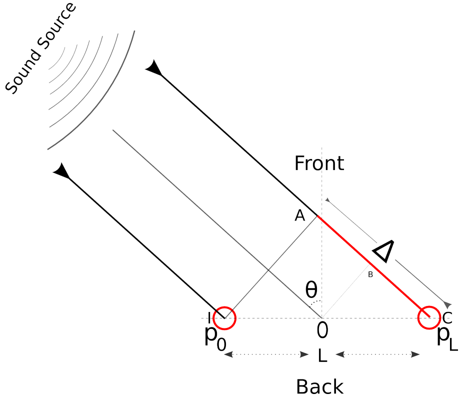
Acoustic Head Model

- **I** - Ipsilateral ear, **C** - Contralateral ear.
  $p_0, \ p_L$ - sound pressure on eardrums, θ - sound source direction.
- Sound source “far away”.
- No appreciable amplitude difference, $|p_0| = |p_L|$.
- Phase difference between sound at both ears - $\Delta = kL\sin\theta$.
- $p_0 = pe^{j\omega t - .5kL\sin\theta}$
  $p_L = pe^{j\omega t + .5kL\sin\theta}$



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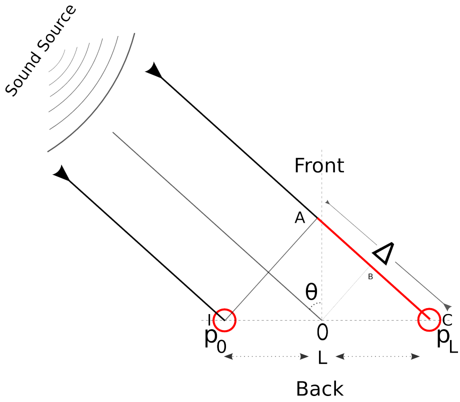

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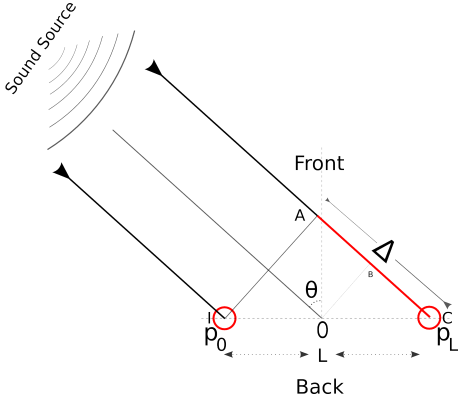
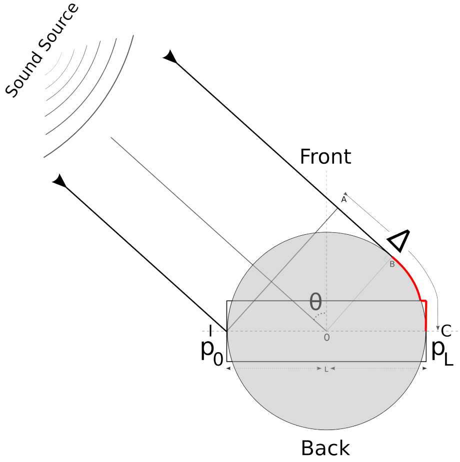


Acoustic Head Model contd.

- $|p_0| = |p_L|$.
- Increased phase difference due to diffraction - $\Delta = 1.5kL\sin\theta$.
- $p_0 = pe^{j\omega t - .75kL\sin\theta}$
  $p_L = pe^{j\omega t + .75kL\sin\theta}$



Coupled Membranes

$$u_{0/L} = \sum_{m=0,n=1}^{\infty} C_{\mathrm{mn}}^{0/L} u_{\mathrm{mn}}(r,\phi) e^{j\omega t} \tag{24}$$

Membrane Equations

$$\sum_{m=0,n=1}^{\infty} \Omega_{\mathrm{mn}} C_{\mathrm{mn}}^{0} u_{\mathrm{mn}}(r,\phi) e^{j\omega t} = p_0 e^{j\omega t} - p(0,r,\phi;t) \tag{25}$$

$$\sum_{m=0,n=1}^{\infty} \Omega_{\mathrm{mn}} C_{\mathrm{mn}}^{L} u_{\mathrm{mn}}(r,\phi) e^{j\omega t} = p_L e^{j\omega t} - p(L,r,\phi;t) \tag{26}$$

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"Surface" Velocity

$$U_{0/L} = \begin{cases} u_{0/L},\ 0 < r < a_{\mathrm{tymp}} \text{ and } \beta < \phi < 2\pi - \beta \\ 0, \text{ otherwise} \end{cases} . \tag{27}$$

Velocity in $x-$direction

$$v_x = -\sum_{q=0,s=0}^{\infty} \frac{\zeta_{\mathrm{qs}}}{\rho\omega} \left(A_{\mathrm{qs}} e^{j\zeta_{\mathrm{qs}} x} - B_{\mathrm{qs}} e^{-j\zeta_{\mathrm{qs}} x} \right) p_{\mathrm{qs}}(r, \phi) e^{j\omega t} \tag{28}$$

Boundary Conditions

Exact

$$U_0 = -\frac{1}{j\omega} v_x(0, r, \phi; t) \tag{29}$$

$$U_L = \frac{1}{j\omega} v_x(L, r, \phi; t) \tag{30}$$

Approximate

$$U_{0/L} \approx S^{0/L}(t) =: \int dS U_{0/L} \tag{31}$$

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Boundary Conditions

Higher pressure modes disappear, i.e.

$$p = \left[A_{00}e^{jkx} + B_{00}e^{-jkx}\right] e^{j\omega t}$$

$$A_{00} = -\frac{\rho\omega^2}{2k \sin kL}\left(S^0 e^{-jkL} + S^L\right) \tag{32}$$

$$B_{00} = -\frac{\rho\omega^2}{2k \sin kL}\left(S^0 e^{jkL} + S^L\right) \tag{33}$$

Coupled Equations

$$\sum_{m=0,n=1}^{\infty} \Omega_{\mathrm{mn}} C_{\mathrm{mn}}^{0} u_{\mathrm{mn}}(r,\phi) = p_0 + \frac{\rho\omega^2}{k}\left(\frac{S^0}{\tan kL} + \frac{S^L}{\sin kL}\right) \quad (34)$$

$$\sum_{m=0,n=1}^{\infty} \Omega_{\mathrm{mn}} C_{\mathrm{mn}}^{L} u_{\mathrm{mn}}(r,\phi) = p_L + \frac{\rho\omega^2}{k}\left(\frac{S^0}{\sin kL} + \frac{S^L}{\tan kL}\right) \quad (35)$$

Decoupling

Decouple by taking the sum and difference of the above equations.

Coupled Equations

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Decouple by taking the sum and difference of the above equations.

Decoupled Equations

$$\sum_{m=0,n=1}^{\infty} \Omega_{\mathrm{mn}} C_{\mathrm{mn}}^{+} u_{\mathrm{mn}}(r,\phi) = p_{+} + \frac{\rho\omega^2}{k} S^{+} \cot\frac{kL}{2} \tag{36}$$

$$\sum_{m=0,n=1}^{\infty} \Omega_{\mathrm{mn}} C_{\mathrm{mn}}^{-} u_{\mathrm{mn}}(r,\phi) = p_{-} - \frac{\rho\omega^2}{k} S^{-} \tan\frac{kL}{2} \tag{37}$$

$$C_{\mathrm{mn}}^{+} = \left[p_{+} + \frac{\rho\omega^2}{k} S^{+} \cot\frac{kL}{2}\right] \frac{\int dS u_{\mathrm{mn}}}{\Omega_{\mathrm{mn}} \int dS u_{\mathrm{mn}}^2} \tag{38}$$

$$C_{\mathrm{mn}}^{-} = \left[p_{-} - \frac{\rho\omega^2}{k} S^{-} \tan\frac{kL}{2}\right] \frac{\int dS u_{\mathrm{mn}}}{\Omega_{\mathrm{mn}} \int dS u_{\mathrm{mn}}^2} \tag{39}$$

Decoupled Equations contd.

$$S^{+} = \frac{p_L + p_0}{\Lambda + \Gamma_{+}} \qquad S^{-} = \frac{p_L - p_0}{\Lambda + \Gamma_{-}} \tag{40}$$

$$\Gamma_{+} = -\frac{\rho\omega^2}{k}\cot\frac{kL}{2}, \qquad \Gamma_{-} = \frac{\rho\omega^2}{k}\tan\frac{kL}{2} \tag{41}$$

$$\frac{1}{\Lambda} = \frac{1}{\pi a_{\mathrm{cyl}}^2}\sum_{m=0,n=1}^{\infty}\frac{\left(\int dS u_{\mathrm{mn}}\right)^2}{\Omega_{\mathrm{mn}}\int dS u_{\mathrm{mn}}^2} \tag{42}$$

Final Expressions

Membrane Displacement

$$S_0(t) = G^s_{ipsi} p_0 + G^s_{contra} p_L \tag{43}$$

$$S_L(t) = G^s_{contra} p_0 + G^s_{ipsi} p_L \tag{44}$$

$$G^s_{ipsi} = \left(\frac{1}{\Lambda + \Gamma_+} + \frac{1}{\Lambda + \Gamma_-} \right) /2 \tag{45}$$

$$G^s_{contra} = \left(\frac{1}{\Lambda + \Gamma_+} - \frac{1}{\Lambda + \Gamma_-} \right) /2 \tag{46}$$

Outline for Section 3

Tokay Gecko

L$=22\,$mm

$a_{\mathrm{tymp}}=2.6\,$mm

$Q=1.33$

$\rho_m=1\,$mg/mm^3

$d=10\,\mu$m

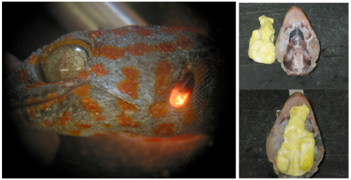
$V_{\mathrm{cav}}=3.5\,$ml

$\beta=\pi/25$

$a_{cyl}\approx 6.6\,$mm

$f_0=1.05\,$kHz

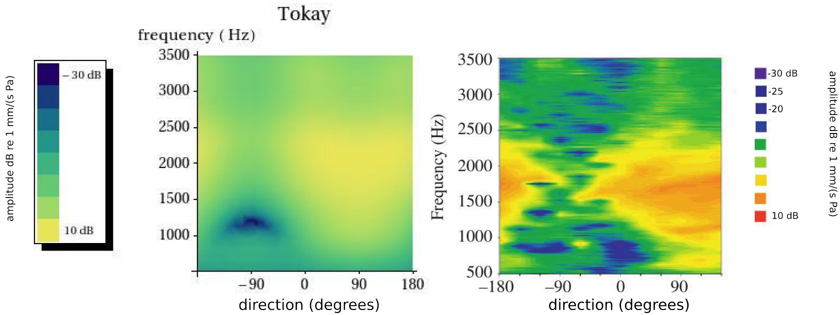
$$f_0=\omega_{01}/2\pi$$



Tokay gecko. Left: Head illuminated from the opposite side[a]. Right: Mouth casts.

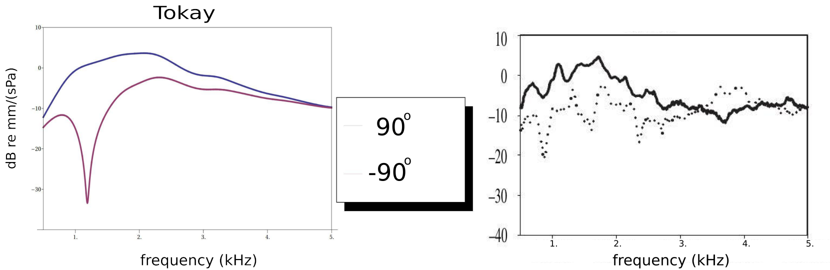
[a] Courtesy J.C. Dalsgaard (Syddansk Universitet)

Density Plot



- Plot of vibration amplitude w.r.t direction & frequency (Left: Calculated, Right: Experimental (Christensen-Dalsgaard et al, 2005).
- $|p_0| = |p_L| = 1$ Pa.

Frequency Dependence

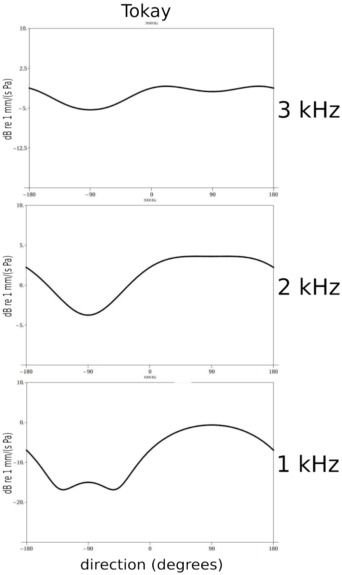


- Frequency dependence of $20\mathrm{Log}_{10}\left|\dot{S}^0/\pi a_{\mathrm{cyl}}^2\right|$ for $\theta = 90^\circ$. (Left:Calculated, Right:Experimental)
- $|p_0| = |p_L| = 1$ Pa.
- Ipsilateral response $>$ Contralateral response.

Direction Dependence.

- Inputs to ears
  - Negligible level (amplitude) difference
  - Small time (phase) difference
- Response is highly directional.

- Independent vibration amplitudes not enough.
- Localization requires using information from both ears.



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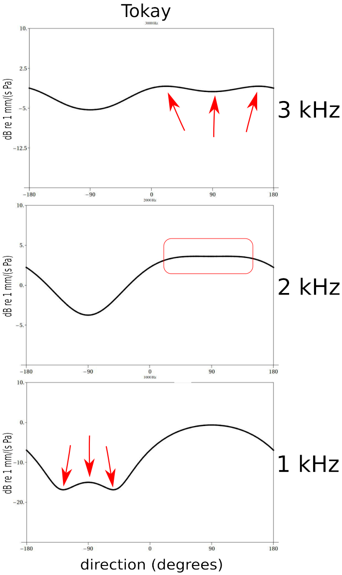

Hearing Cues

Internal Level Difference (iLD) -

$$\text{iLD} := 20\text{Log}_{10}\left|\frac{\dot{S}^0}{\dot{S}^L}\right| \quad (47)$$

Internal Time Difference (iTD) -

$$\text{iTD} := \text{Arg}\left(\frac{\dot{S}^0}{\dot{S}^L}\right)/\omega \quad (48)$$

Requirements

1. Both increase with the adjacency of the sound source. Max at $\theta = 90°$ and min at $\theta = -90°$.
2. Both vanish at $\theta = 0°, \pm 180°$.
3. iTD $\approx$ constant for a given frequency range. Advantageous for neuronal processing.

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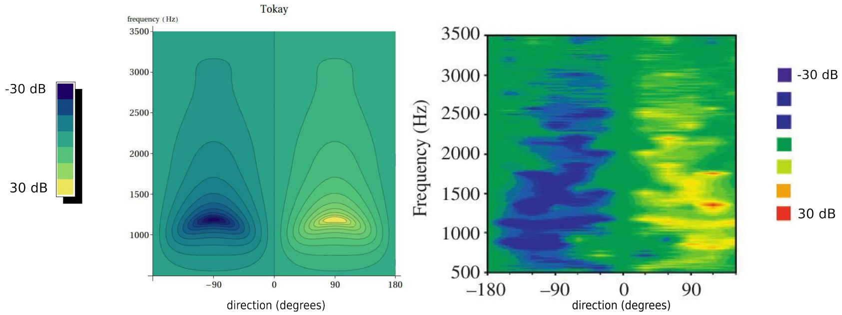
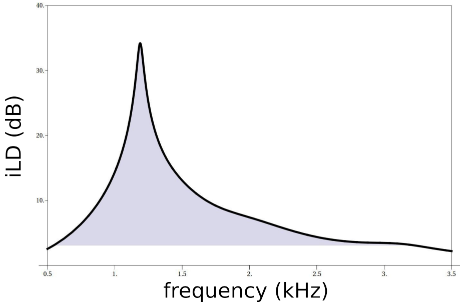
iLD Density Plot

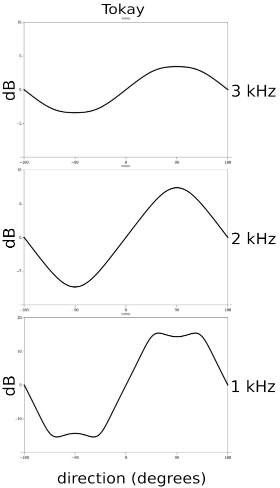


- Plot of iLD, against frequency and direction.
- Left: Calculated, Right: Experimental

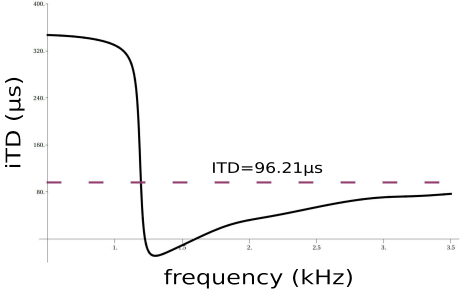
iLD Frequency/Direction Dependence

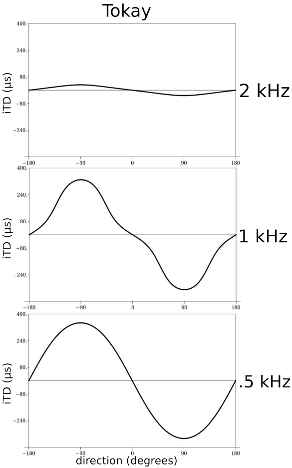


- iLD is a better cue at higher frequencies.
- Peak response at $\sim f_0$.



iTD Frequency/Direction Dependence

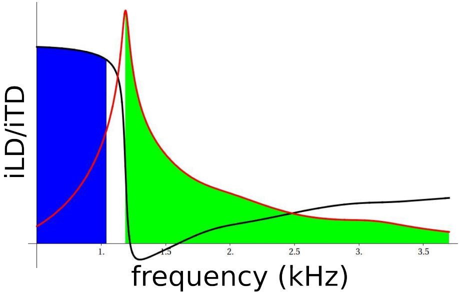




- iTD is a better cue at lower frequencies.
- constant upto $\sim f_0$.
- iTD $\approx 3\times$ITD

iTD/iLD Frequency Regimes

- The frequency for transition from iTD to iLD based localization is determined by f_0.
- Possibility of a frequency regime where both cues can simultaneously be used.



Outline for Section 4

Conclusion

- Single model describes both low and high frequency behaviour.

Thank You