6.551J/HST.714J ACOUSTICS OF SPEECH AND HEARING
FALL 2004

6.551J Lecture 17 **11/04/04**

SOUND IN TUBES (CONTINUED)

Tube with a narrow constriction

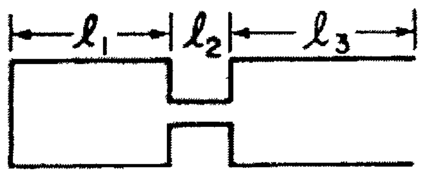
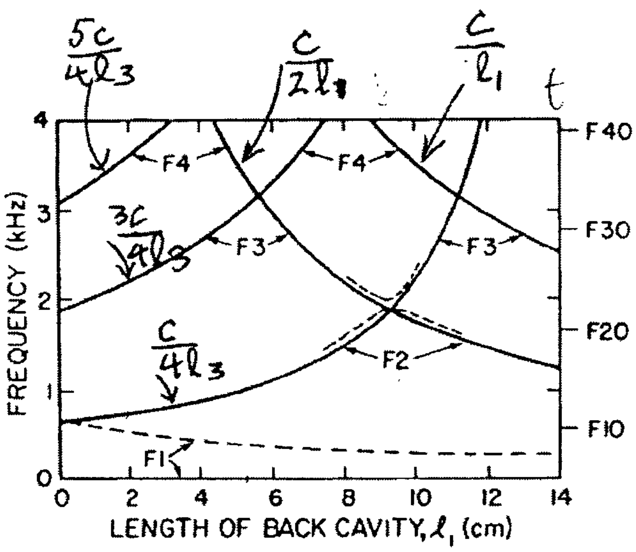


Figure 3.15 Uniform tube with a narrow constriction, used to approximate area functions for consonants.



$\ell_3 = \ell - \ell_1 - \ell_2$

Figure 3.16 Relations between natural frequencies and the position of the constriction for the configuration shown in figure 3.15. The overall length of the tube is 16 cm and the length of the constriction is 2 cm. The lines sloping up to the right represent the resonances of the front cavity (anterior to the constriction); the lines sloping down to the right represent the resonances of the back cavity. The solid lines are the resonances if there is no coupling between front and back cavities. The dashed lines near the point of coincidence of two resonances at $\ell_1 = 9.3$ cm illustrate the shift in the resonant frequencies for the case where there is a small amount of coupling between front and back cavities. When the area of the constriction is very small, $F1 = 0$ as shown. When the constriction is larger, $F1$ increases as shown by the dashed line. The resonances of a 16-cm tube with no constriction are shown by the labeled marks at the right. The curves are labeled with the appropriate formant numbers.

Two-tube configuration

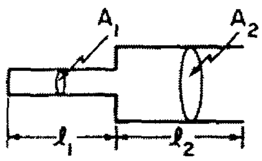


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Figure 3.13 Two-tube configuration used to illustrate coupling of resonators.

If $A_1 \ll A_2$, natural frequencies are:

$\frac{c}{4l_1}, \frac{3c}{4l_1}, \ldots$ and $\frac{c}{4l_2}, \frac{3c}{4l_2}, \ldots$

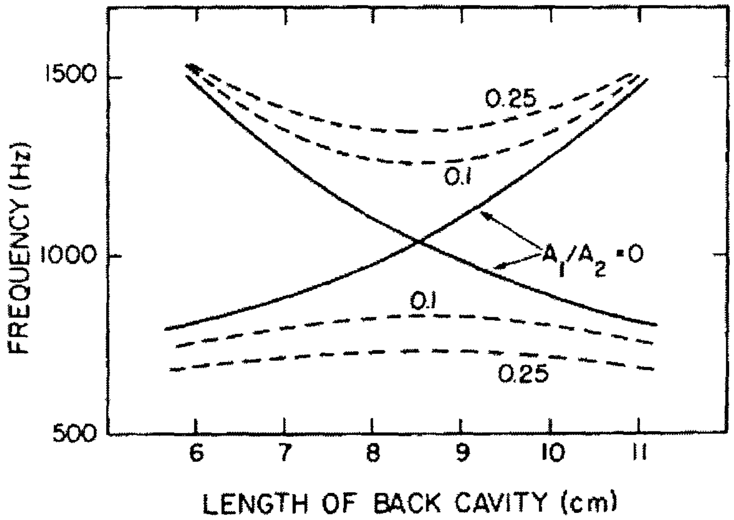

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Figure 3.14 First two natural frequencies of the two-tube resonator in figure 3.13 as a function of the back-cavity length ℓ_1, for various area ratios A_1/A_2. Area ratio $A_1/A_2 = 0$ corresponds to no acoustic coupling between the tubes. The total length $\ell_1 + \ell_2$ is fixed at 17 cm.

Natural frequencies are spread apart as A_1/A_2 becomes larger

Losses in tubes

viscosity at walls
heat conduction at walls
yielding walls
radiation
effect of flow through tube, especially at a constriction

Acoustic losses in Tubes: formant bandwidths

Table 3.1 Calculation of contributions of radiation (B_r), vocal tract walls (B_w), viscosity (B_v), and heat conduction (B_h) to the formant bandwidths for two different vocal tract configurations

a. Uniform tube, length 15 cm, cross-sectional area 3 cm²

	Formant frequency (Hz)	B_r (Hz)	B_w (Hz)	B_v (Hz)	B_h (Hz)	*Total B* (Hz)
First formant	592	3	8	6	3	20
Second formant	1682	24	1	10	4	39
Third formant	2804	67	0	12	5	84
Fourth formant	3927	131	0	15	6	152

b. Resonator with dimensions in figure 3.28a, with area of opening equal to 0.32 cm²

	Formant frequency (Hz)	B_r (Hz)	B_w (Hz)	B_v (Hz)	B_h (Hz)	*Total B* (Hz)
First formant	300	0	28	12	2	42
Second formant	1475	0	1	8	3	12
Third formant	2950	0	0	11	5	16

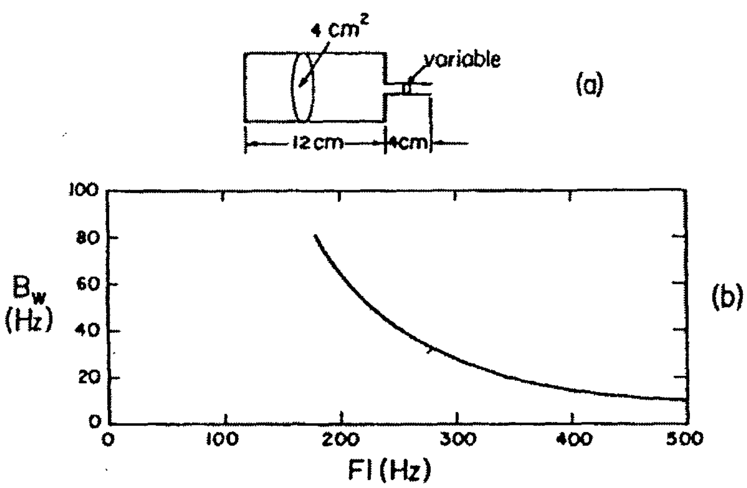
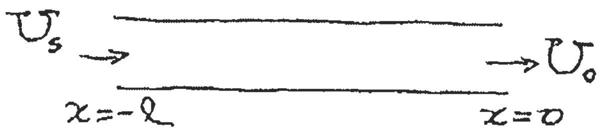


Figure 3.28 Contribution (B_w) to bandwidth of the first formant due to losses at the walls of the vocal tract. The vocal tract is modeled as a Helmholtz resonator with the dimensions shown in (a), in which the resonant frequency *F1* is changed by manipulating the cross-sectional area of the opening. The bandwidth contribution B_w as a function of *F1* is shown in (b).

Excitation of tubes by acoustic sources



a volume-velocity source at $x=-l$

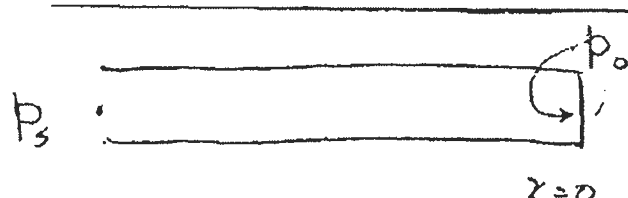
$$p(x) = P_m \sin kx$$

$$U(x) = j\frac{A}{\rho c} P_m \cos kx$$

$$U_s = U(-l) = j\frac{A}{\rho c} P_m \cos kl$$

$$U_o = U(0) = j\frac{A}{\rho c} P_m$$

Transfer function $\dfrac{U_o}{U_s} = \dfrac{1}{\cos kl}$



a sound-pressure source at $x=-l$

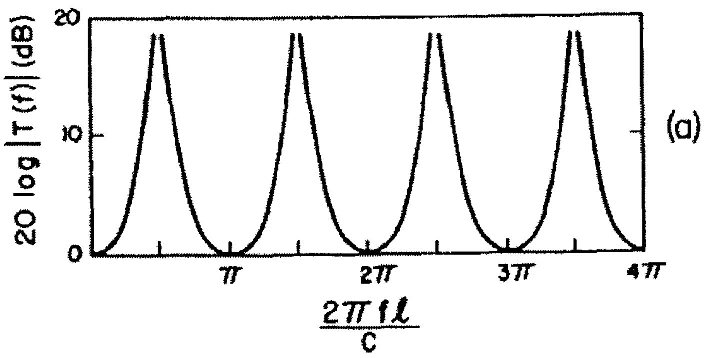
$$U(x) = U_m \sin kx \quad (=0 \text{ for } x=0)$$

$$p(x) = j\frac{\rho c}{A} U_m \cos kx$$

$$p_s = p(-l) = j\frac{\rho c}{A} U_m \cos kl$$

$$p_o = p(0) = j\frac{\rho c}{A} U_m$$

Transfer function $\dfrac{p_o}{p_s} = \dfrac{1}{\cos kl}$



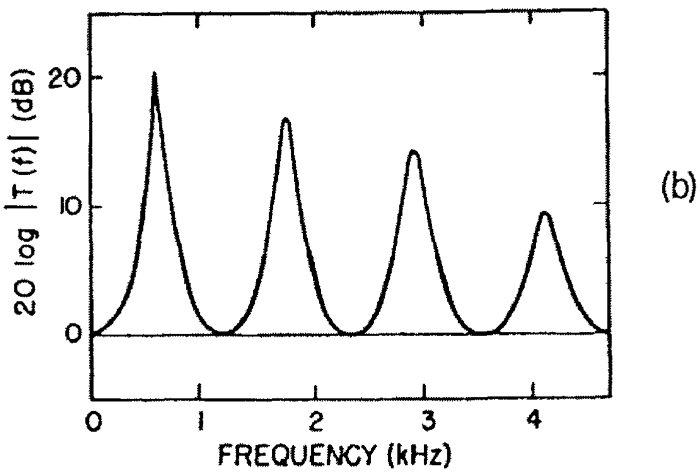
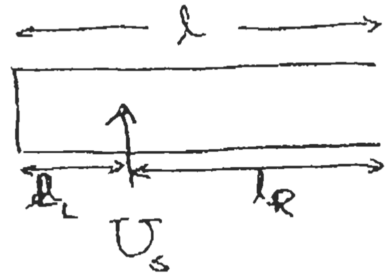
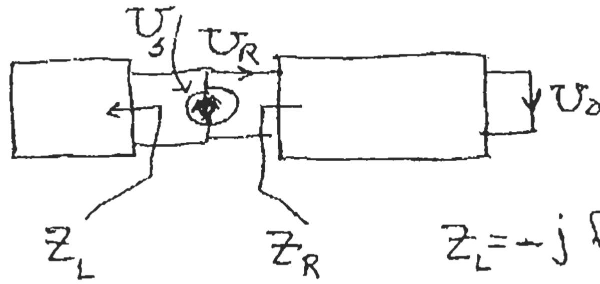


Figure 3.31 (a) Plot of magnitude of transfer function $T(f) = U_o/U_s$, expressed in decibels for an ideal uniform, lossless acoustic tube, shown in figure 3.8. (b) Magnitude of transfer function $T(f)$ for an ideal uniform tube of length 15 cm with losses similar to those occurring in the vocal tract.

Source in tube.





$$Z_L = -j \frac{\rho c}{A} \cot k l_L$$

$$Z_R = j \frac{\rho c}{A} \tan k l_R$$

$$U_R = U_s \cdot \frac{Z_L}{Z_L + Z_R}$$

$$U_o = U_R \frac{1}{\cos k l_F}$$

$$= U_s \frac{-j \frac{\rho c}{A} \cot k l_L}{-j \frac{\rho c}{A} \cot k l_L + j \frac{\rho c}{A} \tan k l_R} \frac{1}{\cos k l_R}$$

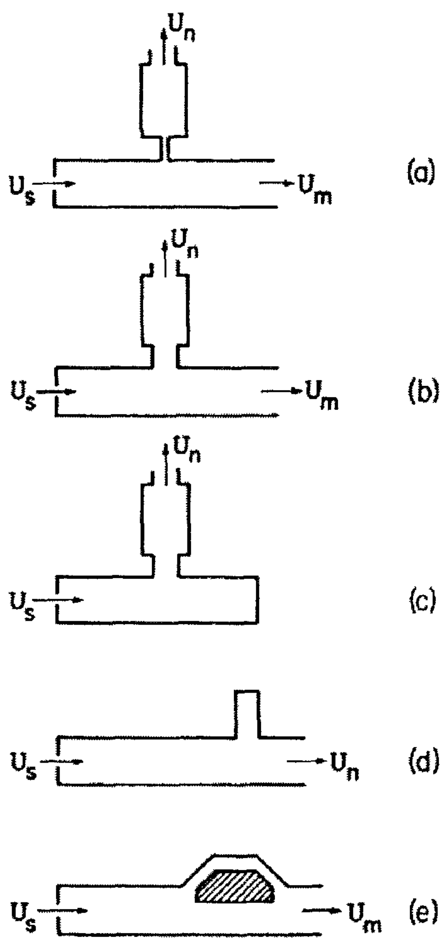
$$\frac{U_o}{U_s} = \frac{\cos k l_L}{\cos k l} \qquad k = \omega/c = \frac{2\pi f}{c}$$

This system function has poles (natural frequencies) at $f = \frac{c}{4l}, \frac{3c}{4l}, \frac{5c}{4l}$, etc.

It also has zeros when $\cos k l_L = 0$, or

$f = \frac{c}{4l_L}, \frac{3c}{4l_L}, \ldots$ i.e. where impedance looking back is zero.

Side branches



nasal

lateral

Figure 3.42 Five models for which there is a side branch in the acoustic path from source volume velocity U_s to output volume velocity (U_m, or U_n, or $U_m + U_n$). (a) and (b) Models for nasal vowels with different degrees of opening of the velopharyngeal port. (c) A model for a nasal consonant. (d) A model for a consonant for which a side branch is formed by the tongue blade. (e) A model for a configuration in which there are two acoustic paths from source to output over some portion of the length of the tube.

Introduce zeros to transfer function U_m/U_s