An Experimental Method for Measuring Transfer Functions of Acoustic Tubes

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Abstract

This work proposes an experimental method for direct measurement of transfer functions of acoustic tubes. The method obtains a pressure-to-velocity transfer function from measurement of input volume velocity and output pressures of a target tube. Steady sinusoidal waves from 100 Hz to 5 kHz with a 10-Hz increment were used as a source signal. Experimental results compared with transmission line simulations indicate the following: (1) transfer functions obtained from the measurements agree well with those from transmission line simulations; (2) differences between the resonant frequencies obtained from the measurements and simulations with a uniform tube are less than 2.6%. These results show conclusive evidence that the proposed method permits accurate measurements of transfer functions of acoustic tubes.

Aim

To develop a method for measuring transfer functions of acoustic tubes and evaluate its accuracy.

What for ?

- Transfer functions of replicas of the vocal tract help to clarify the effects of the fine structures of the vocal tract on speaker characteristics in detail.
- Transfer functions obtained by experimental method would also be useful as benchmarks for numerical simulations.

3D MR image

3D CAD data

replica

A replica of the vocal tract of a male subject producing the Japanese vowel /a/ from volumetric MRI data [Fujita et al. 2003].

Watch a demo movie of *"vocal tract quartet"* at http://www.atr.jp/his/bpi/index_e.html

Theoretical Considerations

A pressure-to-velocity transfer function of an acoustic tube $H(\omega)$:

$$H(\omega) = \frac{P_{out}(\omega)}{U_{in}(\omega)} \qquad (1)$$

$P_{out}(\omega)$ the sound pressure at the output end of the tube.
$U_{in}(\omega)$ the volume velocity at the input end of the tube.

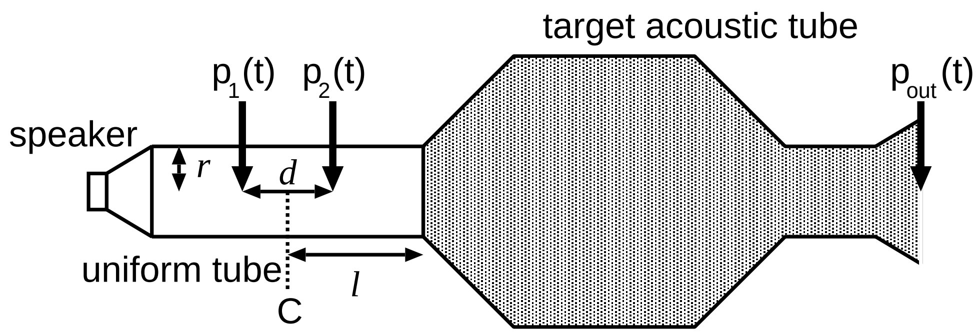
It is difficult to directly measure $U_{in}(\omega)$.

↓

In order to derive $U_{in}(\omega)$, a uniform tube is inserted between a speaker and the target tube and the sound pressures at two adjacent points placed in the uniform tube are measured.

↓

How to derive $U_{in}(\omega)$



Assuming plain wave propagation in the uniform tube,

- The particle velocity at the point *C* $v_c(t)$:

$$v_c(t) = -\frac{1}{\rho d}\int_{-\infty}^{t}\left[p_2(\tau) - p_1(\tau)\right]d\tau \qquad (2)$$

ρ the air density.

d a distance between two microphones measuring the sound pressure.

- The sound pressure at the point *C* $p_c(t)$:

$$p_c(t) = \frac{p_1(\omega) + p_2(\omega)}{2} \qquad (3)$$

The microphone distance *d* determines the upper valid frequency *f* of measurement. For this reason, *d* must be

$$d < \frac{c}{2f} \qquad (4)$$

c the speed of sound.

The accuracy of measurement for the lower frequency region deteriorates if *d* become too small. In this study, therefore, *d* is obtained experimentally.

If the length and the area of the section from point *C* to the input end of the target tube are given, the particle velocity at the input end $V_{in}(\omega)$ can be derived by using a transmission matrix of the section.

$$\begin{bmatrix} P_{in}(\omega) \\ V_{in}(\omega) \end{bmatrix} = \begin{bmatrix} \cosh \gamma l & Z \sinh \gamma l \\ Y \sinh \gamma l & \cosh \gamma l \end{bmatrix} \begin{bmatrix} P_c(\omega) \\ V_c(\omega) \end{bmatrix} \qquad (5)$$

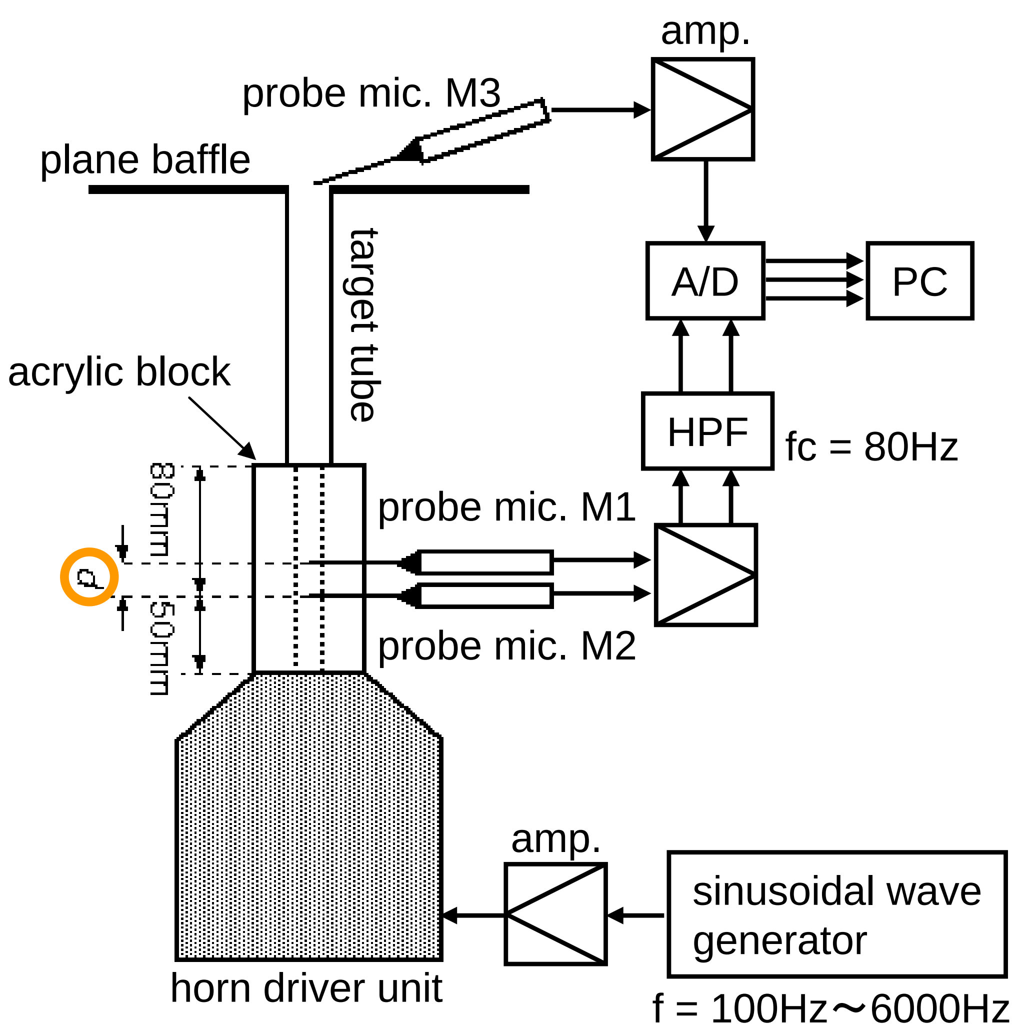
l	the length of the section.	Z	the characteristic impedance.
γ	the propagation constant.	Y	the characteristic admittance.

The volume velocity at the input end $U_{in}(\omega)$:

$$U_{in}(\omega) = \pi r^2 V_{in}(\omega) \qquad (6)$$

Now, the pressure-to-velocity transfer function of an acoustic tube is obtained by Eq. (1).

Experimental Approach



A diagram of measurement setup.

The acrylic block has:

- Main conduit with a diameter of 5 mm.
- Narrow holes to insert a probe tube into the main conduit.

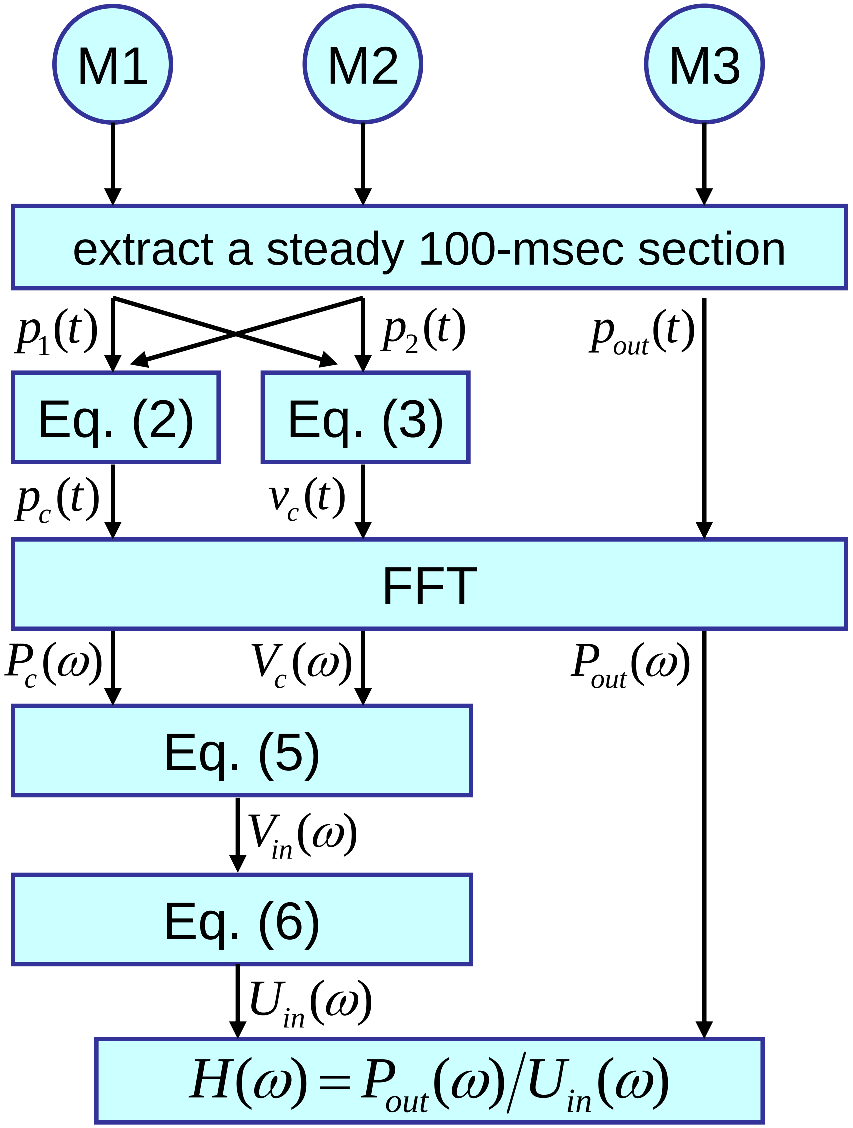
Target tubes were wrapped in putty to avoid wall vibration.

A 300-msec sinusoidal wave from 100 Hz to 5 kHz with 10-Hz increment was used as the source signal.

- The frequency resolution for this measurement is 10 Hz.

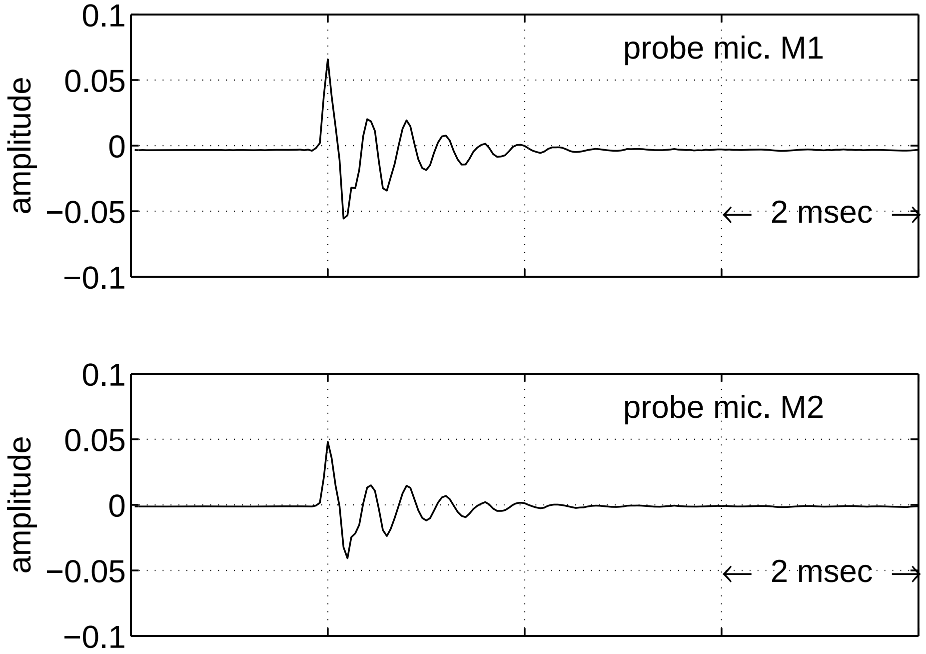
In this study, the mic. distance *d* is obtained experimentally.

Procedure to obtain the transfer function

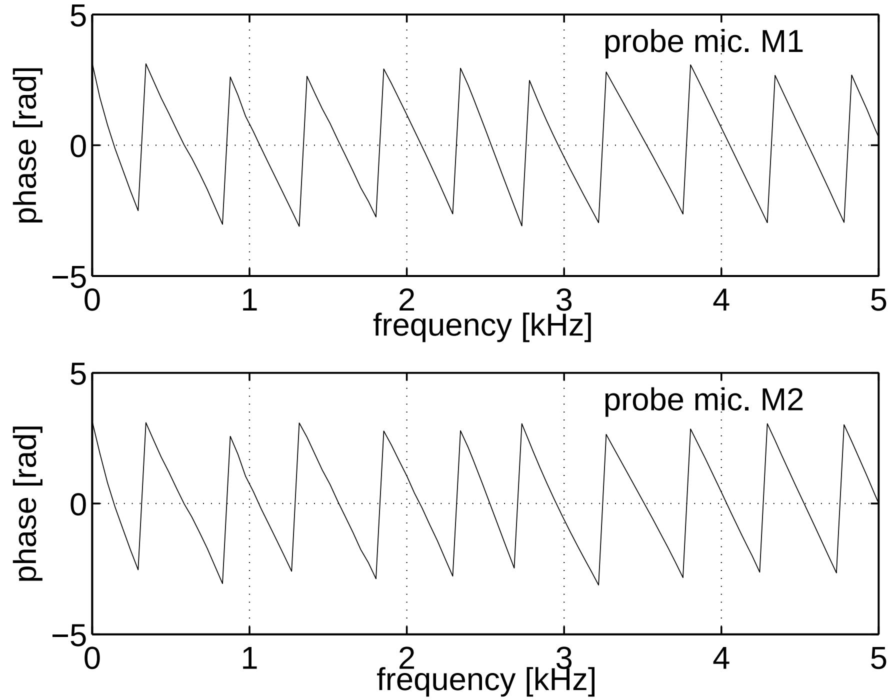


Phase characteristics of the probe microphones

Impulse responses of probe microphone M1 and M2 were measured by using an optimized Aoshima's time-stretched pulse (OATSP) signal [Suzuki et al. JASA 1995].



Impulse responses of probe microphone M1 and M2 for averages of 10 trials.



Phase characteristics of probe microphone M1 and M2 for averages of 10 trials.

M1 and M2 have almost equal phase characteristics.

Transmission line model

- To evaluate the accuracy of the measurements.
- With consideration given the effects of viscous and thermal loss.
  - We assumed that wall vibration of target tubes was suppressed in the measurements.
- The radiation impedance of a target tube was approximated by the equation by Caussé et al. [JASA 1984]

$$\frac{Z_R}{\rho c} = \frac{z^2}{4} + 0.0127z^4 + 0.082z^4 \ln z - 0.023z^6 + j(0.6133z - 0.036z^3 + 0.034z^3 \ln z - 0.0187z^5)$$

$z = k \times r$

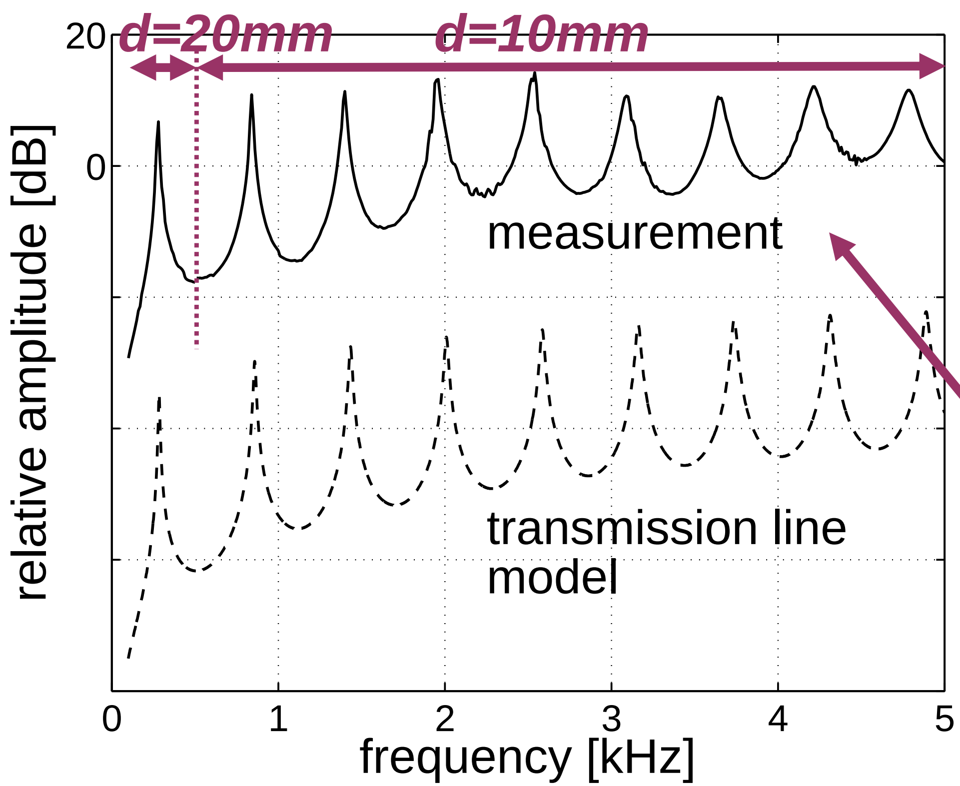
k the wave number.

r the radius of the output end.

This equation is valid for a frequency region of *kr* < 1.5.

Results

Transfer function of a uniform tube



Pressure-to-velocity transfer functions of the 300-mm uniform tube.

A uniform tube
- 300-mm aluminum tube.
- internal diameter is 16.8 mm.
- wall thickness is 1.6 mm.
- wrapped in putty

The microphone distance *d*
- 10 mm, 20 mm, 30 mm

The microphone distance d was set at 20 mm for the frequency region below 500 Hz and 10 mm for that above 500 Hz.

The resonant frequencies obtained by measurements and a transmission line model.

	model [Hz]	measurement [Hz]		
		d = 10 mm	*d = 20 mm*	*d = 30 mm*
F1	284	270 (4.9%)	280 (1.4%)	280 (1.4%)
F2	859	840 (2.2%)	840 (2.2%)	840 (2.2%)
F3	1,434	1,400 (2.4%)	1,400 (2.4%)	1,390 (3.1%)
F4	2,009	1,960 (2.4%)	1,960 (2.4%)	---
F5	2,585	2,540 (1.7%)	2,530 (2.1%)	---
F6	3,161	3,090 (2.2%)	---	---
F7	3,737	3.640 (2.6%)	---	---
F8	4,313	4,220 (2.2%)	---	---
F9	4,889	4,780 (2.2%)	---	---

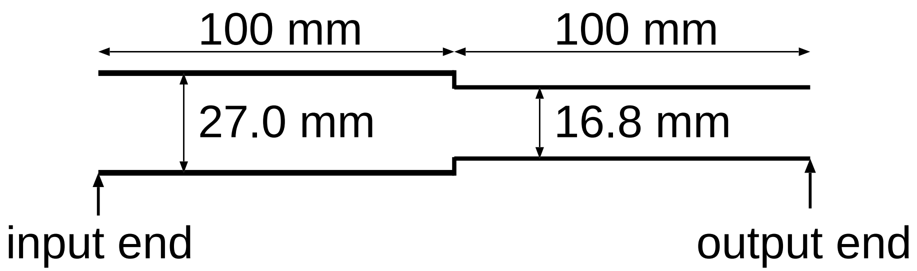
The difference in the resonant frequencies obtained between the measurement and the transmission line model are less than 2.6%.

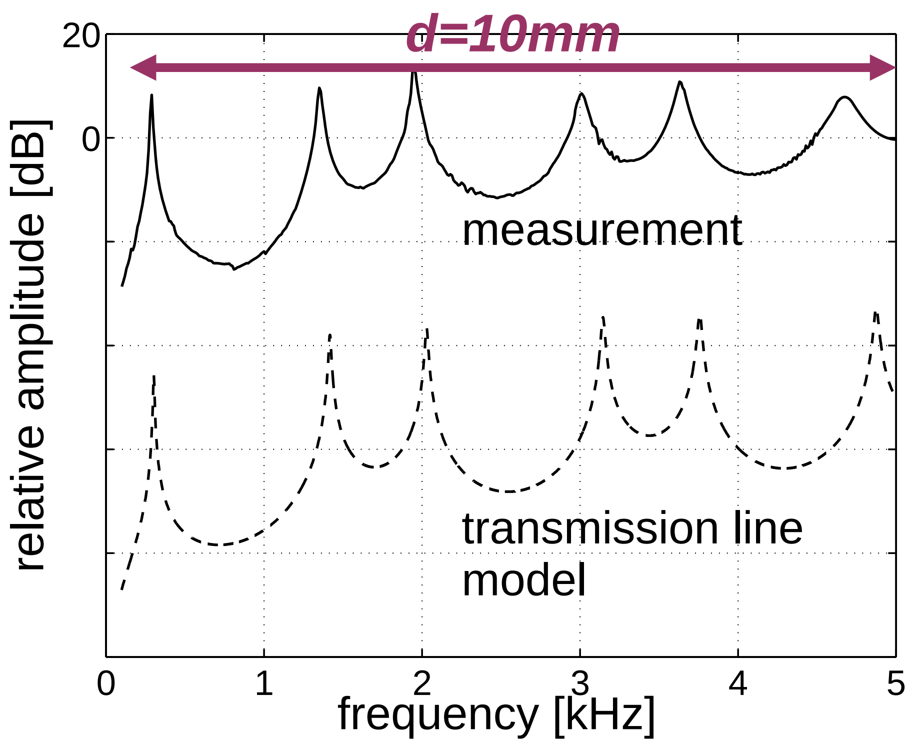
Conclusions

- A method for direct measurement of transfer functions of acoustic tubes are proposed.
- This method obtains a pressure-to-velocity transfer function by measuring input volume velocity and output pressures of a target tube.
- Experimental results supported the feasibility of this method.

- The method is applicable not only for cylindrical tubes, but also for bent and asymmetrical tubes.
- The method can also be adopted for an acoustical tube with unknown radiation impedance, such as the vocal tract.

Transfer function of a tube having two diameters





Pressure-to-velocity transfer functions of the tube having two diameters. The microphone distance d is fixed to 10 mm.

The resonant frequencies obtained by measurements and a transmission line model.

	model [Hz]	measurement [Hz] d = 10mm
F1	303	290 (4.3%)
F2	1,418	1,350 (4.8%)
F3	2,029	1,980 (2.4%)
F4	3,146	3,010 (4.3%)
F5	3,758	3.630 (3.4%)
F6	4,875	4.680 (4.0%)

The difference in the resonant frequencies are less than 4.8%.