The sound-damping characteristics of the vocal tract cavities

Vojtěch Mišun

Brno University of Technology, Faculty of Mechanical Engineering, Technická 2, 61669 Brno, Czech Republic

Abstract

The spectral and modal properties of the vocal tract are important acoustic characteristics since they take part in generating the formants of individual vowels. The positions of vowel formants on the spectrum frequency axis are mainly determined by the parameters and properties of the vocal tract: its size and geometry, boundary conditions (opening mouth and glottis, closing) and absorption characteristics of its walls. This paper presents results of experimental analysis of acoustic damping properties of the pig's vocal tract soft parts (tongue) which are, with regard to the acoustic properties in focus, related to the human vocal tract properties. The overview of the experimental methods for evaluation of the damping factors of acoustic cavities is also presented in the paper.

Keywords: Vocal tract, Acoustic cavity, Acoustic damping factors, Absorption coefficient

1. Introduction

The human voice is produced in the larynx and passes through the vocal tract of specific acoustic properties. These properties may affect both propagation of the sound waves through the vocal tract and its spectral properties.

The positions of vowel formants on the spectrum frequency axis are mainly determined by the parameters and properties of the vocal tract: its size and geometry, boundary conditions (opening mouth and glottis, closing) and absorption characteristics of its walls.

The following basic problems were to be considered:

- what are the values and ranges of the mentioned acoustic characteristics?
- do they affect the generation of the voice frequency components, that means the vowel formants generation?
- do they influence the spectral and modal properties of the vocal tract cavities?

The damping characteristics of the vocal tract walls can significantly influence the vowel formant position in the corresponding spectrum.

For evaluation of signal damping characteristics are used generally sets of different parameters. For acoustic cavities the reduction of the acoustic signal level (above all acoustic pressure) is given by absorption properties of the inner walls of the cavity.

The acoustic damping parameters are mainly:

- acoustical absorption coefficient
- acoustical reflection coefficient
- complex acoustical impedance or admittance

The reduction of the acoustic level in cavity is possible to evaluate from dynamic response in the cavity at frequency $f_{\text{Hz}}$. For many systems the overall response level is inversely proportional to the damping level. This is presented in the power balance equation for an isolated system by

$$ P_{\text{in}} = P_{\text{dis}} = 2\pi f_\eta E_{\text{tot}} $$

(1)

where $P_{\text{in}}$ is the input power, $P_{\text{dis}}$ is the dissipated power, $E_{\text{tot}}$ is the total energy of the dynamical response and parameter $\eta$ is so called modal damping loss factor.

The damping loss factor $\eta$ can be related to a number of other dissipation parameters that occur in other types of dynamical analyses. We define some of them only:

- critical damping ratio
  $$ \zeta = 1/\eta $$
  (2)
- reverberation time
  $$ T_r = 2.2/(f\eta) $$
  (3)
- decay rate
  $$ DR = 27.3f\eta $$
  (4)
• acoustical absorption coefficient

\[ \alpha = \frac{8 \pi f V}{cA^2} \]  

where \( A \) is the area of inner cavity walls, \( V \) is cavity volume, \( c \) is the speed of sound.

2. The damping characteristics of the vocal tract

The vocal tract walls have specific absorption properties that stimulate the change to the natural frequencies of this cavity. Therefore these acoustic characteristics should be studied and taken into account.

There are several possibilities and methods for evaluating these characteristics. The paper presents the results of coefficients of inner losses, and those of absorption or acoustic impedance developed by the inside walls of the vocal tract.

The methods will be applied using the following principles:

• impedance tube (interferometer), i.e. the principle of interference of incident and reflected acoustic waves on the followed sample
• decay rate method
• modal bandwidth method.

2.1. Impedance tube (interferometer)

The measurement set used for measuring of acoustic damping properties of the followed samples (pig’s tongue) consists of the following devices:

• impedance tube (interferometer)
• frequency analyser.

Fig.1 shows the impedance tube diagram. The loudspeaker generates the acoustic wave of a chosen frequency \( f \) and the acoustic pressure amplitude \( A \). The wave extends through the tube and is reflected back by the tested sample. Both these wave motions mutually add up—they interfere.

\[ \alpha = 1 - \beta^2 = \frac{4n}{(n+1)^2} \]

The reflection coefficient of the sample is then defined by the relation

\[ \beta = \frac{B}{A} = \frac{n-1}{n+1} \]

and the absorption coefficient by the relation

We introduce the standing wave coefficient

\[ n = \frac{A+B}{A-B} \]

\[ \alpha = 1 - \beta^2 = \frac{4n}{(n+1)^2} \]

(8)

Specific acoustic impedance consists of the following two components:

• real part

\[ x/z_0 = \frac{1 - |\beta|^2}{1 + |\beta|^2 - 2|\beta| \cos \gamma} \]

• imaginary part

\[ y/z_0 = \frac{|\beta| \sin \gamma}{1 + |\beta|^2 - 2|\beta| \cos \gamma} \]

with a phase parameter

\[ \gamma = \pi \left( \frac{2k_1}{k_2 - k_1} - 1 \right) \]

(11)

and the air wave resistance \( z_0 = 410 \text{ Pa.s/m} \).

Fig. 3 demonstrates evaluation and courses of the sound absorption coefficients and components of the
2.2. Decay rate method

This method for measurement damping is based on the transient response of a resonant mode with linear damping. After an initial excitation is terminated, the energy of the mode at its resonance frequency \( f \) will decay in time at a rate proportional to \( e^{-\pi \eta f t} \).

Since the energy is proportional to the square of the peak response amplitude \( C \) (displacement, acoustic pressure, etc.), the response amplitude will decay at a rate, \( C \sim e^{-\pi \eta f t} \). At two successive times, \( t_1 \) and \( t_2 \), the amplitude decay in decibels will be

\[
20 \log \frac{C_1}{C_2} = 27.3 f \eta (t_2 - t_1) \quad (12)
\]

From this relation is then damping loss factor

\[
\eta = \frac{DR}{27.3f} \quad (13)
\]

where for acoustic pressure is the decay rate

\[
DR = \frac{20 \log \frac{C_1}{C_2}}{t_2 - t_1} \quad [\text{dB/s}] \quad (14)
\]
The value of DR is most easily determined when the response signal is plotted as the log amplitude vs. linear time. A constant value of $\eta$ gives a straight line decay of the response peaks in this plot.

An alternate approach uses a linear amplitude plot and a measure of the half-amplitude decay time, $T_{1/2}$, which is defined as the time required for the response amplitude do decay by 1/2 (or 6 dB).

Since $DR=6.0/T_{1/2}$, the damping factor is given by

$$\varphi = \frac{0.22}{fT_{1/2}}$$  \hfill (15)

For the measurement of the damping of a single frequency, one must be sure that the responses of the other frequencies are rather long distance each other.

This method is convenient for measurement and evaluation of the damping factor of the signal generating inside the human vocal tract. Using a continuous excitation by the vocal folds, the vocal tract is driven with a periodic input with the harmonic components to the fundamental frequency of the voice ($F_0$). The vocal folds are then turned off rapidly enough to observe the decay.

So that we obtain the decay of individual harmonic component amplitudes in the chosen fixed position inside the vocal tract – Fig. 4. The diagram shows the decay amplitudes of individual harmonic components to the fundamental frequency, $F_0 = 112$ Hz, when the vowel “a” is generated aloud.

For the seventh harmonic frequency component, $7F_0 = 780$ Hz – Fig. 6, is the factor $\eta = 0.00130$.

In the next calculation of the damping loss factor we will use the response signal to be plotted as the log amplitude vs. linear time. In Fig. 7 we calculate the decay ratio again for fundamental voice frequency $F_0 = 112$ Hz. From the Fig. 7 we evaluate

$$DR = 50 \text{dB} /500 \text{ms} = 100 \text{ dB} /\text{s}$$  \hfill (17)

and than damping loss factor

$$\varphi = \frac{DR}{27.3 F_0} = 0.0327$$  \hfill (18)

For formant frequency of the vowel to be generated in a whisper it is possible to evaluate the damping loss factor more accurate, because the formant is from continuous spectrum to define directly.

2.3. Half-power bandwidth methods

The value of the damping can also be determined from the bandwidth of a resonance in a frequency response function of a vocal cavity. The most common form of this
method is the half-power bandwidth method – Fig. 8. The value $\Delta f$ is taken off from amplitude response spectrum.

Fig. 5. Decay of amplitudes of the fundamental frequency component

Fig. 6. Decay of amplitudes of the 7th harmonic frequency component

Fig. 7. Decay of amplitudes of fundamental frequency component
when the 3 dB down peak value is used. This peak of amplitude response is at the natural frequency \( f_0 \).

The damping loss factor is then

\[
\eta = \frac{\Delta f}{f_0}
\]  

(19)

The value of \( \eta \) should be averaged over several excitation points to reduce the experimental error.

In Fig. 8 is presented spectrum of the vowel “a” to be generated in a whisper. So that this method is convenient for evaluation of the factor \( \eta \) from spectra of vowels to be generated in a whisper.

After estimation of the value \( f_0 = 870 = F1 \) Hz (the first formant of vowel “a”) and \( \Delta f = 40 \) Hz we calculate the damping loss factor by equation (19), \( \eta = 0.0470 \).

3. Analysis of results

The results of the experimental analysis of acoustic properties of the tested samples indicate that internal surfaces of vocal tracts reach very low values of sound absorption coefficients almost over the whole monitored frequency range (250 - 5000)Hz.

The measurements prove that acoustic characteristics of the soft parts only change slightly within the human speech or singing frequency range, that is within the frequency range (80 - 2048)Hz. It can be stated that coefficients of acoustic absorption of all the soft tissues of the vocal tract are found within the value range of \( 0.03 \leq \alpha \leq 0,15 \) in the given frequency range.

4. Conclusion

The measurements of acoustic properties of the soft parts of the vocal tract have confirmed the expected values based on the presumption that their internal surfaces have very low acoustic absorption coefficients.

The low values of absorption coefficients reflect the necessary property of the vocal tract since the acoustic wave must pass through it with the smallest possible acoustic losses. It is necessary that the acoustic power generated by the vocal folds and speech organ is taken out of the vocal tract into the surrounding outer space without any difficulties.

More suitable methods for evaluation of the damping characteristics and parameters of the acoustic signals have been introduced in the paper.

It should be emphasised that damping mechanisms are often complicated and non-linear and, therefore, most damping models and measurements are approximate with an accuracy no better than about 20%. Fortunately, this accuracy is usually sufficient to keep associated errors in system response estimates to within 1 dB.

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