# MEASURING THE ACCURACY OF HISTORIC PHONETIC INSTRUMENTS

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## ABSTRACT

The fundamental experimental findings on speech and musical sounds date back to the pre-electronic era. It is interesting to estimate the accuracy of the mechanical measurement tools which have been used in that time. For this purpose, the authors performed measurements at historic acoustic resonators and at some prototypes of MAREY's capsules. The results are summarized in this paper.

**Keywords:** Helmholtz resonator, resonator tubes from Schaefer, Marey's capsules

## 1. INTRODUCTION

If we look for famous textbooks which laid the fundament of the modern speech and audio signal processing, we will find them in the time of emerging experimental phonetics at the end of the 19th and the beginning of the 20th century (e. g. [1, 8, 10, 11]). Clearly, the huge amount of experimental investigations of speech and music signals, which was carried out for these and similar works, was performed in the pre-electronic era. A large number of special mechanical devices was developed for recording sound and measuring its parameters. It is interesting to study how they worked. Especially, we want to know the measurement accuracy which was obtained by these historic instruments.

For this purpose, a number of experiments was performed with selected instruments from the historic acoustic-phonetic collection (HAPS) of the TU Dresden. This collection was originally focused on the local history of experimental phonetics and speech technology at Berlin, Dresden, and some smaller places [3]. It was essentially expanded when the Phonetic Institute of the Hamburg University was closed in 2005, and the famous Hamburg collection of early phonetic instruments, which was founded by the renowned phonetician G. PANCONCELLI-CALZIA [5], was united with the HAPS [2].

The following investigations are concentrated to two types of resonators and a selection of MAREY's capsules, all of them being part of the HAPS collections.

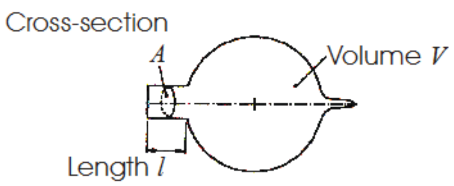
## 2. ACOUSTIC RESONATORS FOR FREQUENCY MEASUREMENT

The spectral components of sound can be measured with acoustic resonators. Two typical constructions have been applied in experimental phonetics.

### 2.1. Helmholtz resonators

Acoustic resonators with a cavity and an attached open piece of a tube are known since the antiquity. H. V. Helmholtz (1821-1894) investigated this arrangement in detail. He used it for the experimental analysis of sounds, the timbre of musical instruments, and the spectral content of the human voice [1].

**Figure 1:** Geometric parameters of a Helmholtz resonator.




The air in the volume *V* acts as acoustic spring. The moving air in the attached tube (Fig. 1, left side) acts as acoustic mass. With the parameters from Figure 1 and the sound velocity $c$ = 343 m/s, the resonance frequency $f_0$ is calculated as

$$f_0 = \frac{c}{2\pi}\sqrt{\frac{A}{lV}}. \qquad (1)$$

Helmholtz resonators have only a single resonance frequency. Therefore a larger number of different resonators is required for systematic investigations. This allows exact measurements for selected discrete frequencies; e. g. 11 values between 102 Hz and 794 Hz in the series of Figure 2. The transfer functions and the resonance frequencies $f_0$ of these resonators were measured using an electronic analyzer.

The measurement accuracy was estimated by listening experiments with six test persons in an anechoic chamber. The observer puts the earpiece (Fig. 1, right side) in one ear and directs the aperture of the device to the loudspeaker while the other ear is closed. The frequency of the sound is controlled by the observer to find the frequency $f_{max}$ with the loudness maximum. The relative deviations $\Delta f_1/f_1 = (f_{max} - f_1)/f_1$ were calculated. The mean of the amounts of all measured relative deviations is $\overline{|\Delta f_1/f_1|} = 1.4$ %.

**Figure 2:** Set of Helmholtz resonators, Leppin & Masche, Berlin 1913 (HAPS Dresden).

## 2.2. Resonator tubes of SCHAEFER

The resonators from K. L. Schaefer (1866-1931) are tubes, the length of which can be varied continuously by the experimenter. One end of the tube is open and is directed to the sound source. The other, closed end of the tube is equipped with a thin pipe (earpiece) serving as connection for a short piece of rubber hose which is put into the auditory canal of the experimenter. He or she perceives a maximum of loudness if the length $l$ of the tube is equal to a quarter of the wavelength $\lambda$ of the investigated sound. The frequency $f_1$ of the sound is therefore calculated as

$$f_1 = \frac{c}{4 \cdot l}\,. \tag{2}$$

A mouth correction $\Delta l = \pi R/4 = 23.3$ mm has to be added to the geometrical tube length $l$ if the resonance frequency is calculated. This is due to the fact that a certain amount of air outside of the open end of the tube is additionally vibrating in the direction of the tube axis.

Four resonator tubes (Figure 3/4) with the same diameter $2R = 60$ mm and adjustable lengths between 60 mm and 770 mm allow the measurement of frequencies from 1036 Hz to 108 Hz. Each one-sided closed tube acts as a resonator not only at the frequency $f_1$ but also at higher harmonics

$$f_2 = \frac{3\,c}{4\,l};\ f_3 = \frac{5\,c}{4\,l};\ \text{etc.} \tag{3}$$

This means, that the applicable frequency range of each tube is larger than indicated by $f_1$ which our investigations are restricted to.

In our measurements, the accuracy is estimated based on listening experiments. At first, the resonance frequencies $f_1$ were measures for selected tube lengths with an electronic analyzer in an anechoic chamber. Then, the test person connected one ear with the earpiece of the resonator. The other ear was closed. While listening to the test sound from a loudspeaker (loudness level $L = 38$ dB), he adjusted the frequency $f_{max}$, where the maximum of the loudness was heard, at the sound generator. Such measurements were performed in the range between 100 Hz and 1 kHz with five normal-hearing observers. Figure 5 shows the relative deviations $\Delta f_1/f_1 = (f_{max} - f_1)/f_1$ for all single observations. The mean of all amounts of these relative deviations is $|\Delta f_1/f_1| = 2.3$ %. Figure 5 shows additionally that users of the SCHAEFER resonators tend to an estimate of the frequency which is about 2 % too high which cannot be explained easily.

**Figure 3:** A complete series of resonators from K.L. Schaefer (HAPS Dresden).


**Figure 4:** Longitudinal section of a resonator tube from K. L. Schaefer.

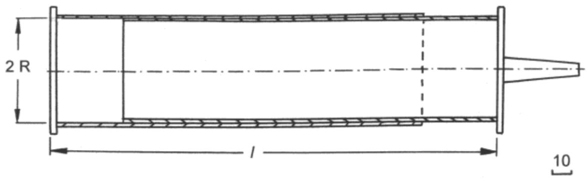
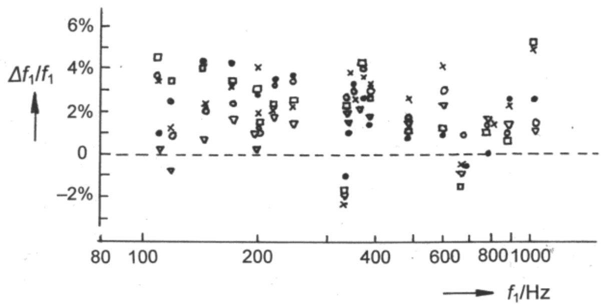



**Figure 5:** Relative deviation $\Delta f_1/f_1 = (f_{max} - f_1)/f_1$ of the frequency $f_{max}$, which is adjusted by the test person to obtain the loudness maximum, from the physically measured resonance frequency $f_1$.

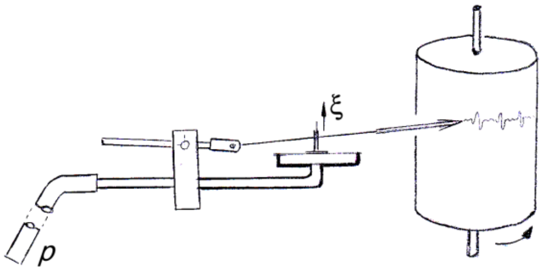


## 3. MAREY'S CAPSULES AS ACOUSTIC-MECHANIC TRANSDUCERS

### 3.1. The standard transducer design

Transducer, which convert speech sound in mechanic movements of writing pins, have been used successfully for the waveform recording in the early experimental phonetics. The sound is transmitted through a hose into a flat, normally circular capsule, which is closed by a thin rubber membrane. The movement of the membrane is transferred to a light lever with an attached pin. The tip of the pin scratches the waveform in the sooted paper at the revolving drum of a kymograph (Figure 6). Such recordings can be interpreted with high precision [7].

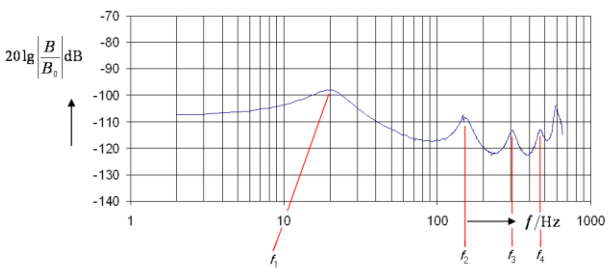
**Figure 6:** Principle of a capsule of MAREY writing at the drum of a kymograph.




This approach dates back to E. J. Marey (1830-1904) who used it for recordings of the movement of the pulse artery (sphygmograph) and other physiologic motions. Later, it was widely applied in experimental phonetics by P.-J. Rousselot (1846-1924), his scholar G. Panconcelli-Calcia (1878-1966), and other successors.

The relationship between the movement $\xi$ of the membrane and the sound pressure $p$ at the input of the hose (with a mouth funnel) is expressed by the transfer function $B(f) = \frac{\xi}{p}$. We measured the transfer functions of various capsules with different membrane diameters by means of Laser interferometry. Figure 7 shows one representative result.

**Figure 7:** Transfer function $B(f)$ of a capsule of MAREY with a diameter of 16 mm, membrane thickness of 0.3 mm, hose length of 80 cm, and inner hose diameter of 4.5 mm.



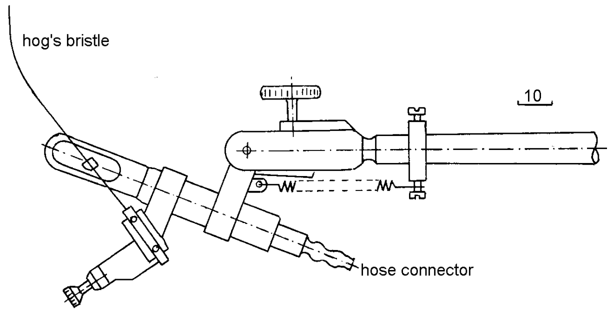

The plot shows several maxima. The first one results from the resonance of the acoustic mass of the air in the hose and the compliances of both the cavity and the membrane of the capsule. The subsequent maxima at $f_2$, $f_3$, etc. are the harmonic resonances of the hose, which acts as acoustic waveguide. Maxima of this type occurred at all investigated capsules, despite of membrane measures, membrane materials, hose lengths, and pin materials [6].

### 3.2. Throat sound recorder of Krüger-Wirth

Later, capsules with essentially lower membrane size have been used for recording the throat sound. A funnel-like metal calotte with a rubber membrane was pressed sideways at the larynx of the test person, serving as input of the sound-transferring hose which was connected to the transducer capsule (Figure 8). One type of such transducers, the throat sound recorder from Krüger-Wirth, applies a nearly oval membrane over a very small capsule volume and a hog's bristle as writing pin (Figure 9). This transducer type is especially useful for recording sounds with higher spectral components than usual.

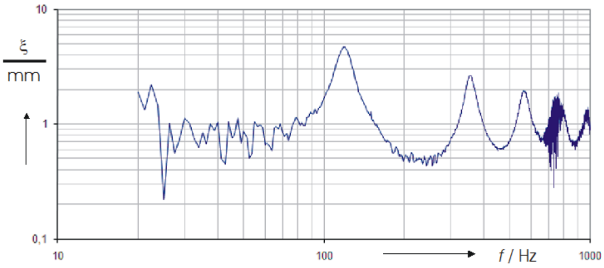
**Figure 8:** G. Panconcelli-calzia demonstrating the recording of the throat sound. (Historic photograph, now in the HAPS collection.)

**Figure 9:** Throat sound recorder of Krüger-Wirth.




Its transfer function shows strong resonance maxima (cf. Figure 10, recorded with laser interferometry). The capsule can be applied at frequencies which are as high as 550 Hz. It was used for investigations of the moment of voicing and of harmonics of the pitch [9].

**Figure 10:** Transfer function of a throat sound recorder of Krüger-Wirth.




## 4. DISCUSSION

The measuring quality of an experimenter, who applies an acoustic resonator for measuring sound frequencies, was expressed by an average deviation. It is rather low for the Helmholtz resonators (1.4 %) and higher for the Schaefer resonators (2.3 %). The difference is due to the fact that the resonance elevation of the latter is clearly less than that of the Helmholtz resonators.

It must be stressed, however, that the better accuracy of the Helmholtz resonators is guaranteed merely at discrete frequencies, while the Schaefer resonators show stable accuracy over the whole interesting frequency range.

The properties of the transducers of the Marey type were evaluated by interferometric measurements of the transfer functions of numerous capsules from the HAPS collection. It became clear that the transfer functions are not at all flat over the interesting frequency range. They show several maxima which are determined by the interplay of the system components, mainly the hose and the capsule. Fortunately, the missing flatness does not influence the period lengths of the recorded signals, which are measured for determining the pitch contour [7].

Kymographic recordings of the speech sound, which show sufficient quality, are obtained if the capsules are excited with a pitch which is approximately in the range of the resonance frequency $f_2$ (Figure 7). The experimenters knew probably the restrictions of the measurements. They owned numerous capsules with different geometries and membrane materials. They selected the capsule type which produced the largest deflection for the given voice.

The so-called throat sound recorders show smaller geometries. Our measurements confirmed that they were useful for applications in higher frequency ranges, compared to the standard constructions.

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