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ACOUSTIC EXPERIMENTS WITH WETHLO'S LARYNX MODEL

1. INTRODUCTION

Franz Wethlo (1877 – 1960) was working in Berlin as an educationalist and special pedagogue. Among other fields, he was very engaged in experimental phonetics, especially in mechanical modelling of the larynx.

In 1898, Ewald had proposed an improvement of the existing larynx models (which used simple membranes as models of the vocal cords) by replacing the membranes with air-pressurized cushions. Wethlo investigated this more natural construction very detailed since 1913 (Wethlo 1913; for a complete bibliography, see the Obituary 1960). The model which forms a milestone in the development of voicing theories is known as "Polsterpfeife" (cushion pipe) of Wethlo. During the decades, Wethlo's pipe was further investigated and compared to other larynx models (Lindner 1962; Lindner/Neppert 1994; Neppert 1995). Of course, the experiments were dependent on the available measuring equipment. Meanwhile, digital signal processing allows a more comfortable acoustical evaluation of the device. The purposes of this paper are

– to demonstrate the conditions for voicing and to analyze the signals produced by historical pipes of different sizes which are available at our laboratory,
– to show how the cushion pipe can be utilized to excite a mechanical model of the vocal tract which is used to demonstrate the voice production in education.

The study is part of a project which deals with the development of a collection of historical phonetic devices and their application in the education in speech technology.

2. THE CUSHION PIPE OF WETHLO

2.1. The construction

In Wethlo's larynx model, the three-dimensional imitations of the vocal cords (so-called cushions) are formed by pieces of an elastic foil (*g* in *Figure 1*) clamped over two metallic segments (*p*) cut from a tube (*a* / *w*). The inner space formed by these cushions can be pressurized to provide the vocal cords with a tension (cushion pressure). For voicing, an air flow into the tube (*w*) must be produced (subglottal pressure). Suited combinations of cushion pressure and subglottal pressure result in vibrations of the cushions (voicing).

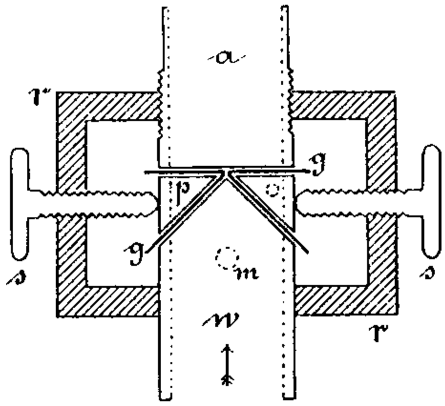

Figure 1: Cross section of the cushion pipe (from the original publication of Wethlo 1913).

2.2. Former investigations

In his initial paper (Wethlo 1913), Wethlo investigated mainly which combinations of the pressures in the supraglottal tube (*w*) and in the cushion (*p*), resp., resulted in voicing, and which tones were produced in these cases. *Figure 2* shows the main results of his experiments. The fundamental frequencies of the tones varied approximately between 500 Hz and 800 Hz.

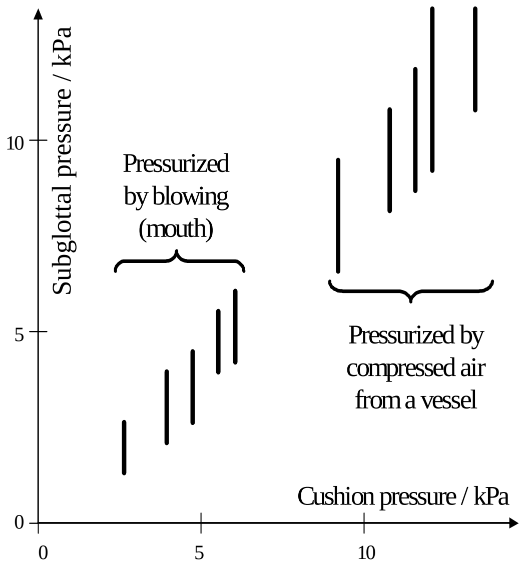

Figure 2: Main results of the experiments of Wethlo. The lines indicate the ranges of subglottal pressure in which voicing occurred for a given cushion pressure (after Wethlo 1913).

The vibrations could not be investigated in detail at that time. In the 1960s, Lindner aimed to visualize the vibrations of the cushions more exactly than it is possible by stroboscopic means. High-speed films with 3.000 images per second showed especially that both cushions do not vibrate synchronously if the membranes are not biased equally (Lindner 1962).

On the occasion of reactivating some cushion pipes found in the collection of the Institute of Phonetics of the Hamburg University, Lindner and Neppert published for the first time results of acoustic measurements (Lindner/Neppert 1994). Finally, Neppert discussed aspects of the physics of the vibrations compared to other larynx models (Neppert 1995).

3. Experiments with single pipes

3.1. Experimental setup

For this investigation, three pipes of different sizes were available (inner diameter of the tube = larynx length of 28, 20, and 15 mm, resp.). The origin of these historic devices is not completely clear, but at least one of them comes from Wethlo's own equipment.

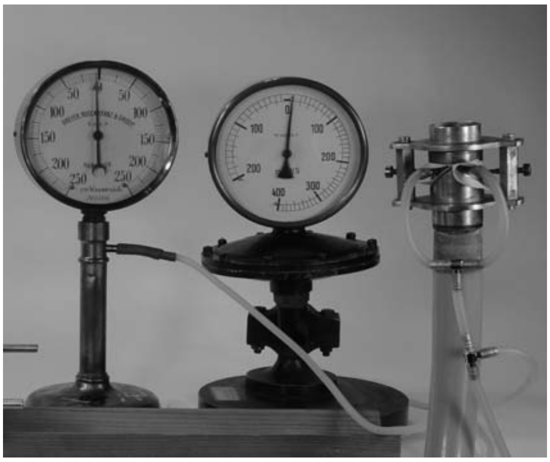

Figure 3 (left): Experimental setup for the measurements with the cushion pipes.
Figure 4 (right): Top view of the large cushion pipe with inserted cushions.

Figure 3 shows the experimental setup. The pipe is mounted on the top of the tube which supplies it with air from one of three different sources:

- a vacuum cleaner,
- a container for compressed air,
- the pipeline for compressed air available in the laboratory.

To achieve the lowest acoustic noise, we finally applied the air from the pipeline. The air for pressurizing the cushions was fed to them from the same source but via separate hoses and valves. The pressures were measured by two manometers (also from the historic collection).

3.2. Cushion materials

Originally, rubber foils of .5 mm thickness were used to form the cushions. Because the historic materials are no more available, we tried to use different plastic foils. The results of the tests are summarized in *Table 1*. For the following experiments, we selected the materials #1 and #2 because they required the lowest pressures for stable voicing. Especially, the material #1 allowed the application of comparatively low pressures in the large pipe which was in turn leading to a fundamental frequency which was relatively low. Their moduli of elasticity were measured to be $E = 1.0 \cdot 10^6$ Nm^{-2} for #1 and $E = 1.2 \cdot 10^6$ Nm^{-2} for #2, resp.

Table 2 summarizes the conditions which resulted in best (stable and loud) voicing. The regularity of the vibrations of the cushions was observed by means of a stroboscope.

Material		Thickness/ mm	Subglottal pressure / MPa							
#	Type		.42	.51	.59	.77	1.0	1.1	1.3	1.5
1	Balloon	0.15 ··· 0.30	+	+ •	+ •	+ •	+ •	+ •	+ •	+ •
2	Stretch band red	0.15 ··· 0.20		+	+	+ •	+ •	•	•	•
3	Stretch band blue	0.20				+ •	+ •	+ •	•	
4	Stretch band green	0.25					+ •	+ •	+ •	+
5	Rubber cloth	0.30								
6	Rubber glove	0.40					+	+	+ •	+ •
7	Rubber glove	0.45							+ •	+ •

Table 1: Suitability of different cushion materials, pressurized with air from a vacuum cleaner. + successful voicing in the large pipe, • successful voicing in the medium pipe. (The vacuum cleaner was not able to excite the small pipe.)

Larynx model	∅ / mm	Cushion material (Tab.1)	Best results in voicing		
			Subglottal pressure / kPa	Cushion pressure / kPa	Fundamental freq. / Hz
Large	28	1	0.49	1.2	290
Medium	20	2	2.45	4.9	700
Small	15	1	4.41	7.4	958

Table 2: Overview of the best results in voicing for the three cushion pipes, pressurized from an air pipeline.

3.3. Acoustic measurements

The most surprising effect connected with the first successful excitation experiments was the fundamental frequency of the vibration of the cushions which is essentially greater than that of the human voice (cf. the last column of *Table 2*). However, Wethlo described this effect already and tried to explain it with the low mass of the cushions (Wethlo 1913).

Summarizing our experiments and some results from the literature, the following observations are valid:

1. The frequency range of a cushion pipe depends strongly on its geometry.
2. By variation of the pressure relations, a certain control of the frequency is possible (approx. by a musical fifth) with lower pressure meaning lower frequency.
3. There is (surprisingly) nearly *no* dependency between the cushion material (especially its thickness) and the frequency, apart from the fact already mentioned that softer materials allow the application of lower pressures and that's why it may result in lower frequency voicing.

In our experiments, we recorded and analyzed the signals for different conditions. As an example, the waveform and the spectrum are shown in *Figure 5* for the large pipe with the conditions indicated in *Table 2*. Despite the large aeroacoustic noise, the harmonic structure of the spectrum is clearly visible.

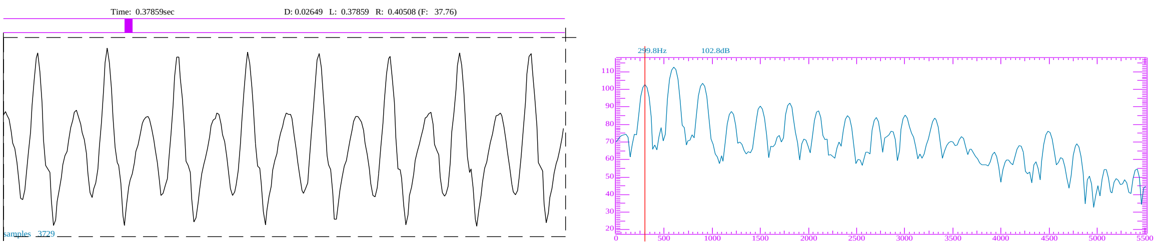

Figure 5: Waveform and spectrum of the signal produced by the large cushion pipe according to the conditions described in Table 2. Frequency range of the spectrum: (0 … 5.5) kHz.

4. Experiments with a historic vocal tract model

4.1. The model

The value of mechanical models of the vocal tract in teaching is accepted in general. It was emphasized by presenting a replica of a historical Japanese model three years ago (Arai 2001; Arai et al. 2001). For our experiments, we used a historic model which was formerly built at the Chair of Phonetics of the Cologne University at the suggestion of Professor Georg Heike (Heike 2003).

This wooden model shown in *Figure 6* consists of a frame and a collection of 78 quadratic plates of 10 x 10 cm^2 which have in each case a centric hole of a certain diameter. Each plate has a thickness of 5 mm. To form a vowel, a sequence of selected plates is arranged and forced in the frame to form an interiour cavity which may be excited by a suited generator.

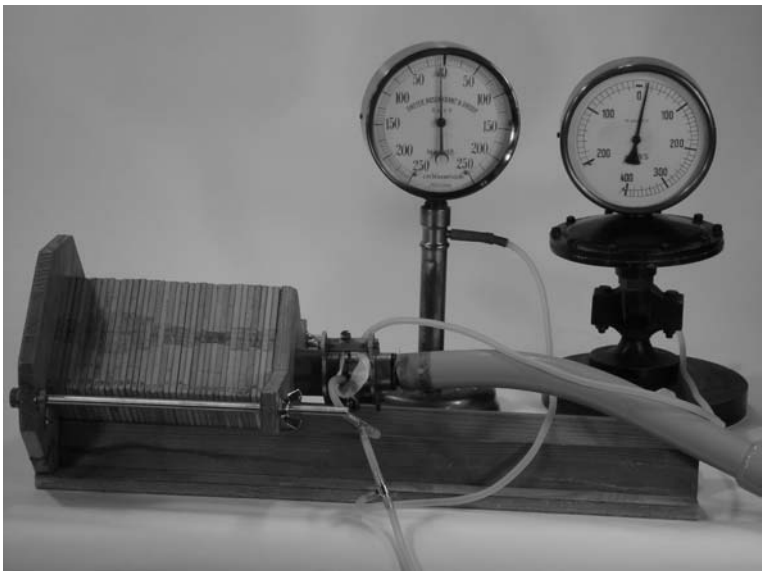

Figure 6: The experimental setup consisting of the wooden vocal tract model and the large cushion pipe.

4.2. Experiments and results

Before we arranged a combination of the vocal tract model and the larynx model, we were interested to know the properties of the separate device. For this purpose, we adapted the vocal tract geometries indicated by the famous Fant model (Fant 1960) for the different basic vowels as close as possible by the available wooden plates. The excitation of the cavities was performed by blowing into a purr pipe which is available in the historic collection also. The purr signal has an excellent broadband quality.

In our first trials, there was no audible difference between the signals produced with different geometries. We suspected that the model could not work correctly because of its rough inner surfaces.

To make the inner surface more smooth and hard, the corresponding parts of the plates were polished and lacquered four times with a resin lacquer. By means of these measures, the acoustic properties of the model improved so far that there was a clear audible difference between the three sound classes /a/, /i/, /u/, forming the corners of the vowel triangle. For achieving finer audible differences, the quality of the device is not good enough.

5. Experiments with the combined devices

5.1. Experimental setup

For the final experiments, the wooden vocal tract model was combined with the large type of the cushion pipes according to *Figure 6*. The connection between the two devices was performed by a hand-lathed part. The pressures were adjusted as indicated in *Table 2* resulting in an excitation frequency of approx. 290 Hz. We recorded the sounds for the three geometric configurations (/a/, /i/, /u/) mentioned already in Section 4.2.

5.2. Listening experiments

For evaluation purposes, we performed two types of experiments with the sounds recorded according to 5.1.

At first, listening experiments with sequential presentation of groups of two or three stimuli showed that listeners are able to recognize the vowels reliably in contrastive hearing.

Although this result seemed to be sufficient to justify the application of the experimental setup for demonstrations in the lecture room, we performed a second experiment to evaluate the quality of the stimuli more precisely.

For this purpose, a group of 20 listeners (17 male, 3 female) was asked to listen to a series of 30 stimuli (10 /a/, 10 /i/, 10 /u/ in mixed order). The results are summarized in *Table 3*. They show that in most cases the vowels are recognized correctly in non-contrastive presentation also.

Vowel	/a/	/i/	/u/
Recognition rate	66 %	59 %	84 %

Table 3: Results of the non-contrastive listening experiments with 600 stimuli, equally distributed between the basic vowels.

5.3. Acoustic measurements

Of course, we also performed a spectral analysis of the signals recorded for different configurations. As an example, *Figure 7* shows the waveform and the spectrum produced with the /i/-configuration. Despite the large distance between the harmonics, a comparison of the *Figures 5* and *7* shows that the model of the vocal cavity produces spectral maxima in the range below 500 Hz and between 2.5 and 3 kHz, resp. Obviously, this formant-like structure is sufficient to produce an /i/-impression in hearing.

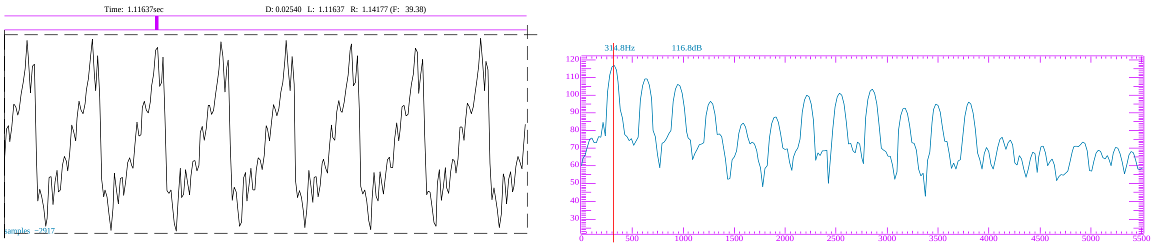

Figure 7: Waveform and spectrum of the signal produced by the large cushion pipe according to the conditions described in Table 2, exciting the vocal tract model for /i/. The frequency range of the spectrum is (0 … 5.5) kHz.

6. Conclusion

In this study, we reactivated two historical models and showed their properties. Especially, we demonstrated for the first time that Wethlo's cushion pipe can act as excitation of a vocal tract model. This is of special interest because the authors of former publications (Lindner/ Neppert 1994; Neppert 1995) had profound doubts about that. It is possible to produce (at least) three types of vowel-like sounds which can be clearly distinguished when listened to comparatively. This result is completely sufficient for demonstration purposes in teaching.

Of course, the wooden vocal tract model which we used does not show optimum performance compared to models made from state-of-the-art materials. It was our aim, however, to demonstrate this historical model as an authentic part of the historic collection of the Dresden University.

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