The Prague historical collection of tuning forks:
A surviving replica of the Koenig tonometre

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Abstract: Despite the copious advances in acoustic techniques and devices for measuring and displaying acoustic parameters, a steady component of a phonetician’s scientific method remains to be – to this very day – our hearing. This paper therefore focuses on a historical device shared between acoustics and auditory phonetic analysis: Rudolph Koenig’s Grand Tonometre, consisting of more than a hundred tuning forks, which occupies an exceptional position among the vast array of instruments manufactured by Koenig. One copy of the original apparatus survived the Second World War untouched, and is now stationed at the Institute of Phonetics in Prague. The paper describes in detail the Prague collection of tuning forks, with photographs illustrating the device, and provides a commentary on the use of tuning forks in phonetic research of that time. In addition, the intricate history of the Prague tonometre is discussed, pertaining to the efforts of Josef Chlumský, the founder of the Czech phonetics institute, to obtain the device from the French colleagues.

1. Introduction

Phoneticians have benefited from acoustic developments at least from the year 1863 onwards, when Hermann von Helmholtz published the first edition of his treaty on acoustics and the perception of sound, Die Lehre von den Tonempfindungen [1]. Although various devices for acoustic analysis and graphic displays of acoustic parameters have since been constructed (e.g. the oscilloscope, the sound spectrograph, or digital signal processing tools), a phonetician’s scientific method still relies to a large part on the human ear. Auditory analysis is as important as acoustic analysis, and the two approaches should ideally complement each other (this is also a premise of many forensic phoneticians; see [2]).

The current paper focuses on the work of the nineteenth-century acoustician, Rudolph Koenig (1832–1903, settled in Paris), who designed and manufactured a great number of acoustic devices that were renowned for their precision and craftsmanship, in addition to performing experiments with these instruments himself. The celebrated Grand Tonometre, of which Koenig made several versions during his life, occupies an exceptional position among the vast array of instruments offered in Koenig’s catalogue [3]. The aims of this paper are

- to highlight key events in Koenig’s life and work as a precision instrument maker, especially related to the tonometre (mostly based on Pantalony’s excellent biography [4]);
- to describe the Prague collection of tuning forks in its present state, including photos of the apparatus, and document the way it was assembled and maintained;
- to provide a commentary on the use of tuning forks in phonetic research.

The study is based on available primary and secondary literature, as well as on archival material of the Institute of Phonetics in Prague. Photographic documentation of the apparatus was carried out by the author.
2. Rudolph Koenig and the Grand Tonometre

2.1. Koenig the instrument maker

The course of Rudolf Koenig’s life was to a large extent determined by his upbringing. He was born in 1832 in Königsberg (Prussia), a city renowned for its scientific atmosphere, and his father, a teacher of mathematics and physics, steered young Rudolph towards an interest in science and music. Importantly, among his father’s circle of friends there was a certain Hermann von Helmholtz, then a professor in physiology. Nevertheless, failing to complete formal schooling, Koenig decided to move to France and make a living in Paris. He became an apprentice to a celebrated violinmaker, Vuillaume, under whom Koenig stayed for several years and developed the skills that would later become so important – great precision, attention to timbre and the selection of the right material for a harmonically rich sound [4: 6]. What Koenig carried off was above all the passion about his profession, making “work of arts” rather than mere “products for sale” [4: 8].

It was only natural for Koenig to seize the opportunity and aim his attention to the quickly developing field of acoustics. Paris was at the time a centre in the scientific instrument trade (acoustics, optics, electricity), dominating the market. Koenig quickly developed a reputation of a very skilled artisan worker and a reliable business partner, resulting in his unrivalled position as the precision acoustical instrument maker from the 1860s until his death forty years later [4]. In this specific trade Koenig simply had no serious competitors; he sold his instruments – always on a personal basis – to a variety of individuals and institutions, including customers in Germany (e.g. Helmholtz), Britain, the USA and Canada. Many important discoveries were thus made possible. As a mark of his internationally prominent status, the French-German manufacturer received a number of awards for his work: a medal of distinction at the 1862 London exhibition, a gold medal at the 1867 Paris exhibition and, above all, a medal of distinction at the famed 1876 Philadelphia Centennial Exhibition [3].

However, Koenig was not only a great instrument maker and inventor, but also a keen experimenter. Part of his work was to conduct experiments in which he measured the precision of his instruments, thereby perfecting his products and surpassing any potential rivals [4: 49]. He knew very well that his business reputation rested on reliability of the instruments and on credit with the scientific community. Although Koenig was a prolific supplier of instruments for Helmholtz, he did not stop there: much of Koenig’s time was occupied by disputes with the famous German scientist over the objectivity of combination tones, which Koenig was unable to confirm in his experiments (see [4: Chapter 7] for details). The Germans backed up Helmholtz, but especially the English and the Americans sided with Koenig. This stimulating activity frequently led to innovation or even invention of new instruments on part of Koenig.

Pantalony claims that through his instruments and experiments Koenig transformed the field of acoustics itself [4: 167]. Tuning forks, resonators, wave sirens or manometric flames [3] became a standard apparatus at many universities and physics laboratories [5]. Koenig offered hundreds of instruments, as evidenced by his five catalogues he issued over the years (1859, 1865, 1873, 1882, 1889). He also published extensively throughout his life [6], writing on beats, timbre, vowels, and even ultrasonics, and gave many lectures. Scientists and teachers gathered at his atelier in Paris, sometimes staying at Koenig’s apartment for the summer and performing experiments with the expensive instruments [4: 140]. Koenig was the man you went to see first when you swept through Europe procuring equipment for your laboratory. He had many connections, gave advice gladly, and did not strive to enrich himself [7: 13-14].
2.2. The Grand Tonometre

A *tonometre* is simply a set of tuning forks spanning several frequencies. The term was coined at the beginning of the 19th century by Johann Scheibler, a German silk manufacturer with an interest in acoustics, who assembled the first such device [8: 14]. Scheibler’s tonometre included 56 tuning forks, covering the range of a single octave from A220 to A440 with a difference of 4 Hz between individual forks. However, it was Koenig who revolutionized the device. As noted above, Koenig produced precision acoustical instruments of excellent quality, which applies to tuning forks as well. He manufactured thousands of them during his lifetime, and he gained invaluable experience by daily work with the various instruments and by running experiments. It can be said without exaggeration that the tuning work, as created in Koenig’s acoustical workshop, became “the fundamental instrument of nineteenth-century acoustics” [4: 83], symbolizing the “analytic, elemental theory of sound” [4: 55-56].

Constructing a tuning fork was a very minute and time-consuming process. First, the right (i.e., soft) steel had to be selected so that the sound would be as pure as possible, containing few harmonics. Koenig had to examine its structure, find any cracks in it, and perform experiments regarding its shape and temperature [4: 92-95]. After a rough blank, prepared by Koenig or his assistants, the forks were fine-tuned by hand, which Koenig almost always did by himself as the most critical phase in the process [4: 92]. Even small pieces of steel (less than one millimetre) filed off at various parts of the prongs could make a huge difference. The length and width of the prongs, together with their shape and mass, determined the resulting frequency and quality of the sound [9: 153]. Finally, a tuning fork usually received a wooden resonator box made of pine (see Fig. 1) – Koenig thus amply utilized his violin-making beginnings.

![Figure 1: A tuning fork with a resonance box (from the publication of Koenig [3: 21]).](image)

Koenig’s exhibition stand was always a great attraction at the international fairs, and much of this popularity was due to the tonometre and some other important instruments for visualizing the qualities of sound (e.g. the phonautograph or the manometric flame capsule; see [6] for the description of the devices). At the London exhibition, Koenig impressed the audience with his first complete tonometre, comprising 65 tuning forks and covering a single octave in 4-Hz steps [4: 55]. The tonometre was a major success and Koenig incorporated it into his catalogue of instruments. At the Paris exhibition, Koenig displayed a more advanced version with 330 tuning forks ranging from 16 Hz to 2,048 Hz [4: 91]. Although he sold many of the smaller instruments, including some tuning forks, the complete tonometre was too expensive even for the Americans [4: 75-77]. The most famous version of the apparatus, the Grand Tonometre, appeared at the 1876 Philadelphia exposition. It consisted of 692 precisely built tuning forks (an amazing number), which corresponded to more than 800 tones as some of the lower frequency forks had adjustable sliders [4: 91]. The total range of frequencies amounted to 16 Hz – 4,096 Hz. Being even more expensive than the previous version, Koenig
experienced tremendous difficulties selling the apparatus (and other instruments as well); the tonometre eventually ended up at the US Military Academy at West Point [4: 124-126]. It is presently placed at the Smithsonian Institution in Washington, D.C. (see a photo in [10]).

Koenig immediately began constructing a new tonometre with substantially higher ambitions. It took him decades to complete, until 1894. Although the apparatus included only 158 tuning forks, these were mostly adjustable with sliding weights so that the number of tones represented was more than ten times as many, ranging from 16 Hz to 21,845 Hz [4: 139]. Towards the end of his life, Koenig thus managed to build “the definitive instrument for precision tuning that offered a full range of sounds in the smallest possible gradations of pitch” [4: 140]. Moreover, as he extended the upper range even higher – up to the unbelievable 90,000 Hz [7: 196], [11] – and conducted experiments with the apparatus, Koenig seems to be the first person to measure and record the ultrasound [4: 160]. The grand tonomètre universal is shown in Figure 2.

Figure 2: Koenig’s grand tonomètre universal in the laboratory of Rousselot (from Hála [12: 62]).

3. The Prague collection of tuning forks

3.1. Description of the device

The Prague collection of tuning forks was intended to be a faithful copy of Koenig’s universal tonometre. However, the range of frequencies never reached the 90 kHz of the original. Available information ([12: 62] and an inventory of tuning forks in our archives) confirms that in the 1940s there were in total 99 tuning forks covering the frequencies from 140 Hz to 3296 Hz; except for some of the lower forks missing, this is also the current state of the tonometre (Figure 3). Like the Parisian model, the Prague tonometre was mounted on a wooden construction in which the tuning forks were arranged, in several levels, from the lowest (left) to the highest (right) frequencies. In the 1990s, the tonometre also included a certain number of forks above the 3296-Hz limit, but the precise values are not known. These were located in the currently empty uppermost level (Fig. 3). The largest tuning fork in the collection, with the frequency of 16 Hz (adjustable), is 137 cm high and has a special metal stand (Fig. 4).
Since the frequency of each tuning fork was adjustable – with the help of small sliders – to several values, the researcher was able to produce all frequencies within the range of the tonometre in calibrated increments of 4 Hz. By way of example, Figure 5 depicts a 1600-Hz tuning fork the frequency of which can easily be set to the values of 1568, 1572, 1576, 1580, 1584, 1588, 1592 or 1596 Hz if we add the sliders and position them accordingly.

Figure 3: The Prague copy of Koenig’s tonometre in 2015 (photo by author).

Figure 4: The largest tuning fork (16 Hz, set to 40 Hz) in the collection (photo by author).

Figure 5: 1600-Hz tuning fork with adjustable sliders from 1568 Hz to 1596 Hz (photo by author).
All tuning forks are made of fine steel and were manufactured in Paris by Henry Lepaute. Thanks to the high craftsmanship, the forks are capable of producing almost pure tones with no significant overtones (see the spectral peaks in Figure 6; one second after striking a 1220-Hz fork there was a relatively strong first harmonics, but it nearly disappeared after two more seconds). The vibrations are strong and last for a long time (up to a minute) when the tuning fork is placed in a wooden resonator box and struck with a rubber hammer (Fig. 7). Moreover, the quality of the material ensures that the characteristics of the tuning forks are stable; after decades of use and then storage, the frequency of the forks did not shift much (only by 5 Hz and 14 Hz for the two forks in Fig. 6).

**Figure 6:** Spectrum of (1) a 1220-Hz tuning fork measured one second after initiation; (2) the same fork measured three seconds after initiation; (3) two simultaneous forks, 1220 Hz and 2316 Hz, measured one second after initiation of the second fork.

**Figure 7:** A rubber hammer with three tuning forks: 3296 Hz, 1152 Hz and 774 Hz (from left to right). Photo by author.
3.2. Assembling and maintaining the Prague collection

This section surveys the sources of the Koenig apparatus in Paris and its establishment in the Prague laboratory. Towards the end of his life, Koenig created a universal tonometre which he was planning to sell to the experimental phonetician, Abbé Rousselot, whom he befriended [7: 195]. However, after his death, there were several interested parties involved, including Rousselot, but none of them could afford to pay the full price [4: 142], [7: 195]. Fortunately, Rousselot managed to get a reduced price for the apparatus and procure this still substantial sum from the Collège de France. The long-desired tonometre was transported to his laboratory.

The Czech connection arose through Josef Chlumský (1871–1939), who stayed at Rousselot’s laboratory for several years as part of his training. Chlumský proved to have great aptitude for the phonetic science and became Rousselot’s most prominent pupil, his “right hand” (Rousselot’s personal dedication to Chlumský). He was even reckoned with as Rousselot’s successor, but this came to no avail [13: 5]. Chlumský, very well acquainted with the new experimental methods, resolved to build a similar laboratory in Prague after his return from France in 1914. The laboratory was officially established at Charles University in 1919.

According to several reports [13], [14], Chlumský immediately began securing equipment for the laboratory. Due to its high price, the tonometre could be assembled only gradually; it was financed by special subsidies from the Ministry of Education. Entries in the book of transactions preserved in our archive reveal how the tuning forks were acquired between the years 1921 and 1931. The accounting demonstrates the money that was spent on:

- **tuning forks**: e.g., a set of 13 large tuning forks was bought in 1922 for a total of 4,225 francs, which equalled 24,230 Kč (Czechoslovakian crowns) at the time; in today’s currency, it roughly corresponds to the sum of 700,000 Kč (Czech crowns), or 25,500 euros;
- **commissioned work and various accessories**: with regard to the same set of tuning forks, the calibration, filing, frequency information engraving and adding sliding weights cost nearly as much as the forks themselves (19,728 Czechoslovakian crowns ≈ 570,500 Czech crowns ≈ 20,700 euros);
- **delivery costs**: the boxes were heavy; e.g., the 13 forks were transported in five crates (with other equipment) for the sum of 1,970 Kč (≈ 57,000 Kč today ≈ 2,100 euros);
- **travel expenses**: Chlumský personally went to France to commission orders and also to fine-tune several tuning forks to reduce the price [13], [14].

The entire collection of tuning forks is valued at about 122,000 Czechoslovakian crowns (≈ 3,500,000 Czech crowns ≈ 128,280 euros). However, it must be noted that the conversion is a very rough and inexpert estimate based on a comparison of the monthly income of an office worker in 1930 and in 2015.

In 1931 the laboratory moved to a new faculty building, where it remained ever since, so it was finally possible to find adequate accommodation for the tonometre. There were 95 tuning forks in 1932 [14: 2] and 99 in 1941 [12: 62]. The tonometre is thought to have comprised one additional row of small tuning forks but no written records presumably exist to establish the number or frequencies of these items. However, the wooden construction for the tonometre does indeed contain the additional level, with appropriate holes in it (see Fig. 3). Assuming that there are on average three tuning forks in each one hundred Hertz, the tonometre could theoretically have reached up to approximately 4,000 Hz.

Since the reopening of universities after the Second World War, the apparatus – which magically survived untouched – was kept in the director’s office (i.e., that of Bohuslav Hála), protected by a shield of glass against dust. Hála had used the tuning forks for his study of vowel acoustics [12], but since the 1950s the collection had a status of a historical device. As one of the contemporaries recollects (Z. Palková, 2015, personal communication), interested
students could examine the collection if they wanted to see it, for instance after a lecture which mentioned tuning forks, but no one was allowed to touch it without leather gloves. The collection was relocated to a different room after the director’s retirement in the 1960s, and was later placed in the corridor for a public display where it stayed until 2011. Sadly, about 20 tuning forks (the heaviest pieces representing the lowest frequencies) were stolen in 2004 or 2005 by an unknown perpetrator. Although the remaining tuning forks are kept in a storeroom at the moment, the Institute of Phonetics has immediate plans to arrange a permanent exhibition in the corridor again. We also hope to create some replacement for the missing forks to fill the embarrassingly empty places in the two lowest rows.

3.3. Tuning forks in phonetic research

The tuning fork was not only an indispensable instrument in acoustics, but also in early phonetics. Tuning forks were used in a number of ways in phonetic research.

Perhaps the simplest case was at the same time most important. Tuning forks were used to measure the duration of speech sounds. Chlumský [15] reports that this was common practice at the laboratories in Paris and, by extension, in Prague. A 200-Hz tuning fork was connected to the kymograph and its vibrations were recorded along with the speech sample. Two periods produced by the tuning fork therefore correspond to 10 milliseconds (Fig. 8). This procedure was employed in a wide variety of studies of that time, and kymograph tracings are accompanied in many reports by vibrations of a tuning fork ([6], [16], [17], [18], [19], [20], [21]).

Tuning forks can be used as a tool that helps the experimenter estimate the pitch of a tone. This is a straightforward process. One could take the piano for the same purpose, but tuning forks are much better suited since they offer a finer scale of frequencies (differences of only a few Hertz) and produce few harmonics. The experimenter simply compares the pitch of the given sound to be analyzed with various tuning forks and selects the best fit.

However, other uses of the instrument in phonetic research require substantial training. Rousselot remarks on this in his seminal book [5: 165], and Hála likewise stresses that “working with them is difficult” [12: 269]. In the hands of an experienced researcher, tuning forks can be used as a tool for the investigation of vowel resonances (formants). In vowels, the vocal folds produce a complex tone characterized by the fundamental frequency (F0) and its upper harmonics. This source signal is then shaped by the cavities and articulatory organs above the larynx. Since different vowels have different settings of these articulatory parameters (e.g. tongue position), the resonance characteristics of the supralaryngeal system change accordingly. The fundamental fact is that F0 and formant frequencies are independent of each other. Therefore, it is also possible to investigate vowel resonances in whispered speech despite the lower amplitude of the signal.

Figure 8: Kymograph engraving showing a tuning fork of 200 Hz at the bottom as a measure of time (from the original publication of Chlumský [15: 19]).
Specifically, the investigator places a tuning fork (or a whole set of tuning forks) in front of the speaker’s mouth and examines which of the forks are forced to vibrate as a result of the sound (Figure 9; [11], [12], [22]). If the particular frequency is present in the vowel, the tuning fork will start to vibrate. Importantly, the experimenter pays attention to the force with which the tuning fork responds, comparing it across different frequency bands. If the response is, at a specific region, markedly greater than at other regions, it corresponds to a formant of the given vowel. However, it is possible to investigate only the first three resonances (plus F0), the effect is otherwise quite weak [12: 61]. In addition, tuning forks can be supplemented with resonators to reinforce specific frequency bands.

![Figure 9: Determining formant resonances by means of a tuning fork](from the original publication of Rousselot [22: 23]).

Tuning forks were employed, for instance, by Helmholtz [1] and Koenig [6] to determine vowel resonances for German, or by Rousselot [11], [23] for French. Bohuslav Hála conducted an extensive study of Czech vowels, which was published in 1941 as *Acoustical Basis of Vowels* [12], a book of more than 300 pages. Hála examined Czech vowels by means of auditory analysis, tuning forks and resonators and mathematically by computing harmonic Fourier analyses of the waveform. All these methods were exacting and extremely time-consuming, so it took several years before the research was completed. Hála had to determine the frequencies and amplitudes of formant resonances in different types of material (words, sentences, connected speech) produced by four speakers. It is notable that despite the limited technical possibilities Hála was able to describe the formant values quite accurately (cf. [24]).

The forth use of tuning forks pertains to *vowel synthesis*. By choosing the right set of forks with appropriate amplitudes of the individual frequencies, one can synthesize, from pure tones, the desired vowel qualities [5: 166-168]. Rousselot [5: 167] includes a drawing of Helmholtz’s electrically-operated synthesizer improved and created by Koenig, which uses tuning forks to provide harmonics starting from 128 Hz, and a set of resonators that are manually adjustable for sensitivity to the excitation from the vibrating tuning forks, thus simulating the resonances. See also the description in Helmholtz [1: 120-123] or in [4: 32].

Finally, tuning forks were used to *estimate the auditory range of the listener* [11: 23-24], [23: 11]. Since Koenig managed to manufacture forks exceeding the upper limit of hearing, both patients and healthy subjects can be screened for their ability to detect tones presented to them. Similarly, Hála [12: 120] employed tuning forks for investigating the *perceptual sensitivity to individual frequencies* by measuring the distance to which the sound of a given tuning fork, brought into motion by a constant force across trials, was still perceptible to the listeners. The results confirmed that the ear was not uniform in its sensitivity within the range. He conducted the experiment in a large forest clearing under favourable weather conditions in 1933.
4. Conclusion

The purpose of this article was to describe the Prague collection of tuning forks, a legacy more than a hundred years old. Koenig’s final version of his universal tonometre, covering the frequencies between 16 Hz and 90,000 Hz, was purchased by the Parisian experimentalist Abbé Rousselot in 1901. Josef Chlumský, Rousselot’s student and collaborator for several years, returned to Prague with a vision to establish a laboratory of experimental phonetics similar to the one he had grown to love in Paris. Over the years, starting from 1921, Chlumský commissioned and gradually procured a faithful copy of Koenig’s tonometre (only with a smaller number of tuning forks). The Prague tonometre has survived until today, although a part of it was, sadly, misappropriated. In addition to the written and photographic description of the device, it has also been shown here how tuning forks can – or used to be – employed in phonetic research. Our main argument is that despite the far-reaching development in technology, phonetic experimentalists at the beginning of the twentieth century made significant contributions to the field even with relatively simple and less accurate instruments. Bohuslav Hála’s book on the acoustics of Czech vowels, drawing mainly on auditory analysis and on work with tuning forks and resonators, was ground-breaking in its scope and thoroughness, and, by and large, remained unparalleled ever since (needless to say, new descriptions of formant values, based on a larger population and contemporary material, will be more useful to modern researchers; this, however, does not lessen the significance of Hála’s work). The historical background regarding R. Koenig and the early researchers helped to frame the Czech situation within a larger, European perspective.

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