DOI: 10.61782/fa.2023.0327

TONAL TIMBRE VARIATIONS OF HISTORICAL RECORDERS AND TRANSVERSE FLUTES COMPARED TO PIPE ORGAN RANKS

Frank Hergert[1*] **Michael Haverkamp**[2]
[1] Koblenz University of Applied Sciences, Germany
[2] Independent Researcher, Köln, Germany

ABSTRACT

It is characteristic for historic FLUTES and their replica that a variety of sound spectra occurs at each individual instrument. Moreover, the spectra can differ from tone to tone across the tonal compass. This causes an audible variability of timbre across the tone range, which is a determining feature of such instruments.

This work analyses sound spectra characteristics of RECORDERS and one TRANSVERSE FLUTE built according to historical designs of the Renaissance and Baroque era. ALTO RECORDERS generate five types of spectra: 1) with a *dominating fundamental*, 2) with relatively weak even harmonics (comparable to the sound of a *chalumeau*), 3) patterns with a weak second or 4) a weak fourth harmonic partial, 5) those being comparably rich in harmonic content. The TRANSVERSE FLUTE produces the aforementioned spectra plus a sixth type with a strong second harmonic.

This classification of each tone is compared to calculated timbre parameters, which are meaningful for pipe organ ranks. Thus, the FLUTE spectra are complemented by two flute ranks, because pipe organ ranks are tonally refined until their timbre changes smoothly upon pitch, while the acoustical properties of FLUTES vary due to different fingering. Finally, common observations of both methods are discussed.

Keywords: *Organology, Recorder, Transverse Flute, Sound Spectra, Tonal Timbre, Tone-to-tone variation*

1. INTRODUCTION

Previous studies showed that timbre of FLUTES significantly changes from tone to tone [1], which becomes easily audible by normalizing all tones to same pitch (e. g. A_4). This timbre variability has been observed at RECORDERS and TRANSVERSE FLUTES. Historic FLUTE designs with inverse conical bore, few or no mechanical keys, and fingering patterns of the “old system” are characterized by this effect. Thus, it appears to be a typical feature of such instruments rather than a technical fault caused by limited skills in instrument making. Although modern BOEHM FLUTES are designed for more unified timbre throughout their gamut, such variations still occur.

As an example for a popular opinion of 19th century FLUTE players, A.B. Fürstenau notes that timbre changes from dull to bright are essential to express emotions and to put listeners into excitement [2]. To play the full chromatic tone range, historic FLUTES require fork fingering (cross fingering), i.e. closed tone holes surround one or more open holes. This causes different acoustic properties of the instrument for nearly each tone. On the contrary, the pipes in a pipe organ are individually scaled to match each tone and thus the tonal timbre within a rank of pipes is expected to be controllable much tighter.

Previous studies indicated that timbre differences in FLUTES are mainly determined by the magnitude ratios of their lowest five harmonics [3]. These magnitudes refer to the acoustic power and are proportional to the sound pressure level (SPL); knowledge of its absolute values is not necessary for relative comparisons. If inharmonic partial tones had occurred in the evaluation of the sound spectra, they were ignored, because their SPL were comparably weak at the investigated instruments. To visualise the different kinds of tonal timbre and their changes, a colour scale has been proposed [3]. The sound spectra were classified into six categories depicted in Fig. 1.

---

[*] ***Corresponding author***: *hergert@hs-koblenz.de.*

RECORDERS designed according to instruments of the Renaissance and Baroque era produce five types of sound spectra, of which the *chalumeau-like* spectrum appears most frequently. This spectrum type possesses weak even partials, known as *duodecimal* according to T. Lerch [4]. The spectral types found at recorders may also occur at TRANSVERSE FLUTES, but with much lower frequency of occurrence. However, the most characteristic tones show another type with a strong first and second harmonic. Lerch designates this type as *octavial* [4]. It shall be added that modern BOEHM FLUTES occasionally generate spectra, whose fundamental f_1 is unusually weak (marked in grey in Fig. 1) and that the flautist can intensify this behaviour in the low register.

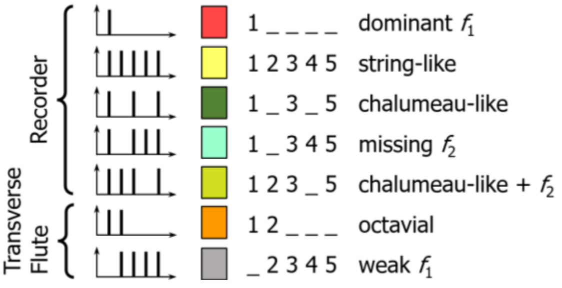

Figure 1. Characteristic patterns of FLUTE spectra classified by the first five harmonic partials $f_1 \ldots f_5$.

The characteristic patterns (Fig. 1) serve as prototypes to aid classification. However, the measured spectra are often modified by additional harmonic partial tones towards more string quality. The colour scale indicates the contribution of such high harmonics by fading of the respective colour (i.e. from green to light green in Fig. 3).

A specific capability of the aforementioned method to classify the spectra is that it enables mapping of the perceived associative (iconic) content of sound. The ability of fast involuntary assignment of perceived timbre to other sound sources, in this case to different instrument types, is an essential element of perception. It enriches perception of music, even in case that some timbres sound familiar, but cannot exactly be attributed to a specific instrument. For the associative content of sound, however, methods of quantifications are not yet available.

An approach suitable to obtain quantitative parameters for tonal timbre based on psychoacoustic determinants is to calculate the loudness and the spectral centroid from the spectra. A previous study on the sound spectra of pipe organ ranks has shown that these two parameters plus a third one, derived from the slope of the spectrum, widely describe the tonal timbre of the steady part of the tone [5].

In this work, we apply both methods to the sound spectra of different FLUTES as well as to two flute ranks of a pipe organ. This allows detecting similarities of these air-blown resonators and quantifying timbre variations.

2. MATERIALS AND METHODS

Four ALTO RECORDERS and one TRANSVERSE FLUTE are part of this study. The historical model of one RECORDER (after Ganassi) was originally manufactured in the Early Baroque era, whereas all other instruments follow designs of Late Baroque. Such rebuilds appear in historically informed performances (HIP) and are assumed to produce an appropriate authentic sound. Nevertheless, instrument builders often apply small improvements to meet recent musical and performance requirements.

The RECORDERS and the TRANSVERSE FLUTE are handmade replica built according to historic designs of

a) Sylvestro Ganassi ($G_4 \ldots C_7$, 440 Hz, boxwood),
b) Peter I. Bressan[1] ($F_4 \ldots C_7$, 415 Hz, ebony),
c) Jacob Denner ($F_4 \ldots C_7$, 415 Hz, blackwood),
d) Jan Steenbergen ($F_4 \ldots C_7$, 442 Hz, boxwood), and
e) Carlo Palanca ($D_4 \ldots A_6$, 440 Hz, blackwood).

The instruments a) and b) were manufactured by Luca de Paolis, c) and d) by Stephan Blezinger, and e) by Martin Wenner, and are depicted in Fig. 2. Professional flautists were asked to play all semitones on these FLUTES and to record them in stereo at 1 m distance in front of the instrument. Then the steady-state phase of the sound has been extracted for each tone, but its original articulation and the delay phase have been removed. All signals were transferred to mono and equalized in magnitude. No distortions caused by room modes were visible in the spectra. A frequency normalization has been done to remove the pitch dependent component of timbre. All signals were then presented and analysed with same fundamental frequency set according to the standard tuning of the individual instrument (415 Hz or 440 Hz). The pitch normalisation was done in time domain to avoid distortions caused by the FFT and a standard fade function was added to the beginning and the end of each tone (for details see [1, 3]).

“Flutes” are well-known as pipe organ ranks forming a distinct family of organ tone. Thus, for comparison, two pipe organ ranks were analysed in the tonal range $C_4 \ldots C_7$. Both ranks belong to the flute family of organ tone and are part of the digital sample set “St. Anne´s” natively included in the software “Hauptwerk” (see [5] for details). The pipe organ of “St. Anne´s” is located in Moseley, UK; it contains 30 stops distributed over three manuals and pedal [6].

---

[1] birth name Pierre Jaillard

Figure 2. Photographs of the replica of the historic FLUTES a)-e) and sketches of the pipe organ ranks A) and B) as described in the text.

A significant fraction of the pipework of this organ dates back to its installation in 1883, while the other pipes have been included in the major rebuilt and enlargement in 1907, with later additions [6]. The ranks chosen for this study are:

A) LIEBLICH GEDACT 8´ with stopped wooden pipes below B_5 and open metal pipes in the treble ($B_5 \ldots C_7$), built by Lewis & Co., London in 1883 [6]. Note that the wooden pipes possess pierced stoppers and can thus be classified as wooden CHIMNEY FLUTES. Their sound spectra are nonetheless typical of stopped flute (GEDACKT) pipes. Fig. 2 depicts a sketch for a C_4 pipe of this construction.

B) CLEAR FLUTE 4´ consists of open metal pipes, added by Brindley & Foster, Sheffield, in 1907 [6]. The drawing in Fig. 2 refers to a pipe with pitch C_5.

As no pictures of these organ pipes were readily available, the sketches in Fig. 2 are based on descriptions of these and related ranks from the early 1900s [7, 8].

The steady part (10 s duration) of each recorded semitone was selected for calculating its sound spectrum. These spectra of the pipe organ ranks were classified according to the strength of the first five partials as shown in Fig. 1. For that task, details of processing were identical to the FLUTES, as described above.

In addition, two timbre parameters were calculated from the harmonic sound spectra (containing typically twelve detectable harmonic partials, more at lower pitch, fewer at higher pitch). The first parameter is the position of the spectral centroid c (in Hz), alternatively given as non-dimensional spectral centroid c/f_1 (i.e. normalised to the fundamental frequency f_1). The second one is a parameter comprising information on the slope of the envelope function of the harmonic spectrum. It is calculated from the slopes between two adjacent harmonic partials (e.g. at f_1 and $f_2 = 2 \cdot f_1$) expressed in dB/8ve. These values are summed for all adjacent partials up using different weight factors for each partial calculated according to n^{-q}, where n is the number of the lower of the two adjacent partials; using the value $q = 1.73$ has shown to produce a meaningful weighted average slope parameter s (see [5, 9] for details). The parameters c and s were selected because a previous study [5] has shown that they reasonably classify the steady part of the sound spectra of organ pipes. The loudness could be added as third important parameter, if desired. When plotting the pitch-dependent values $s(c)$ one recognises regular and characteristic courses for different organ pipe ranks. The tone families of the pipe organ occupy typical regions in such timbre charts [5, 9].

3. CLASSIFICATION OF THE SOUND SPECTRA

This chapter depicts tonal timbre differences in two ways. Both methods utilise the steady part of the sound spectra for evaluation of the relative magnitude of the harmonic partials.

3.1 Visual categorization

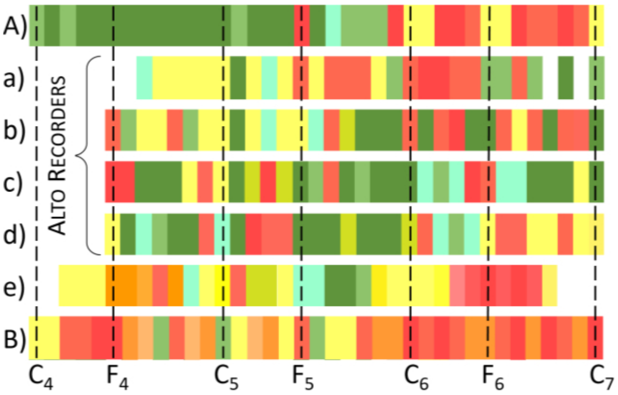

Figure 3. Patterns of spectral types for the FLUTES build according to RECORDER designs a)-d) and the TRANSVERSE FLUTE e) as described in the text compared to the two selected pipe organ ranks A) LIEBLICH GEDACT 8´ and B) CLEAR FLUTE 4´.

Fig. 3 shows the classification of the spectral patterns for the available tonal range. Further details on the FLUTES are given elsewhere [1, 3]; the pipe organ ranks were classified accordingly. The result for the LIEBLICH GEDACT 8´ rank clearly shows the change from stopped to open pipes. As expected, the stopped pipes generate *chalumeau-like* timbre (with one exception at F$_5$), while tones with *dominant fundamental* and *string-like* behaviour appear at B$_5$ and above.

3.2 Calculated timbre parameters

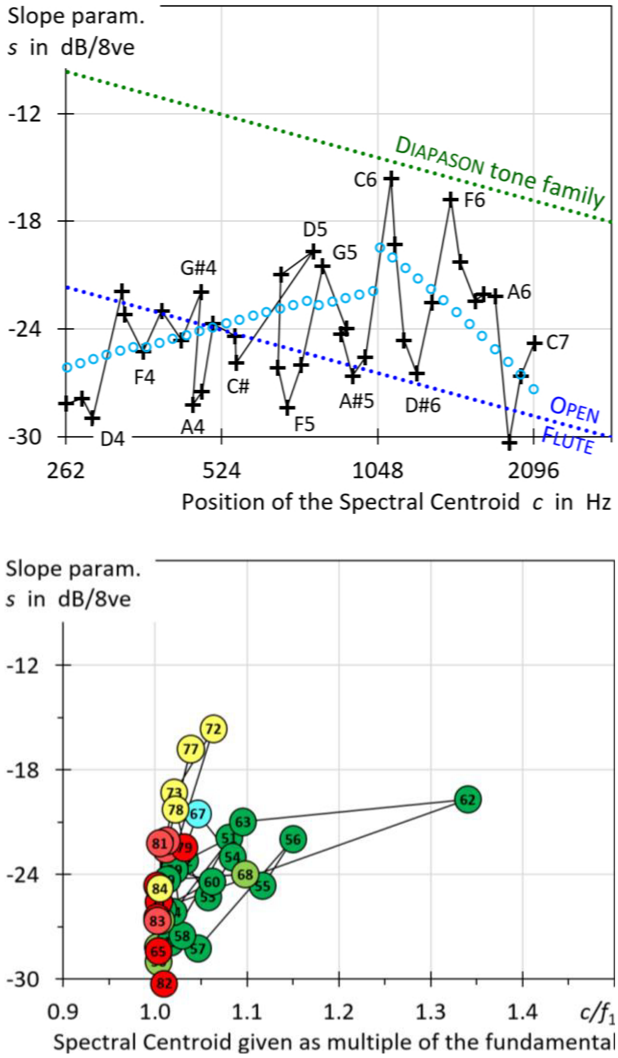

Figure 4. Timbre charts for the LIEBLICH GEDACT (A). The circles in the top chart show average values.

Timbre charts were calculated from the magnitudes of the harmonic partials of the sound spectra. The upper charts in Fig. 4-10 show the slope parameter over the frequency of the spectral centroid, whereas the abscissa in the lower charts represents the spectral centroid given as partial number. The filled circles show the timbre of each tone with the colour according to Fig. 3 and its pitch category (C$_4$ = 48, C$_5$ = 60 etc.). The dotted straight lines in the upper charts of Fig. 4-10 shall indicate a typical DIAPASON and OPEN FLUTE rank representing distinct families of the pipe organ tone.

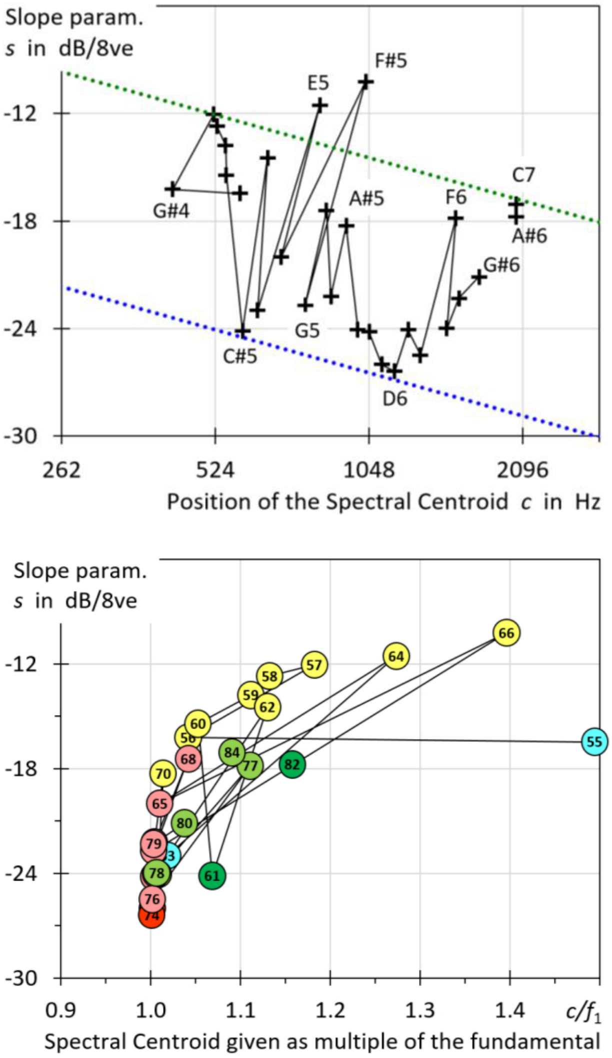

Figure 5. Timbre charts for RECORDER (a) plotted over frequency (top) and normalised to f_1 (bottom).

The upper charts of the pipe organ ranks (Fig. 4 and 10) contain average values of their timbre parameters (least-squares´ fit with all 37 semitones). This fit uses seven

parameters to approximate the envelope function of a pipe organ rank and allows them to depend linearly on the pitch category [5]. As the LIEBLICH GEDACT rank consists of stopped and open pipes, the numerical refinement had to be performed separately in each of the two ranges. The modelled average values of the timbre parameters indicate the intended course of the tonal timbre for these organ ranks. A previous study of several ranks has shown that an increasing course of $s(c)$ is typical for STOPPED FLUTES while it decreases for OPEN FLUTES, DIAPASONS [9] and other ranks with open pipes.
The open pipes for the top octave of the LIEBLICH GEDACT produce tones with a dominating fundamental or string quality (Fig. 4). Since these organ pipes do not possess tone holes (with different fingering applied as with FLUTES) their timbre is expected to remain constant or to change smoothly after careful voicing following the calculated average values (circle symbols in Fig. 4).
In addition, the dotted lines in Fig. 4 indicate the courses of typical DIAPASON and OPEN FLUTE ranks.

3.3 Results of both methods

This section contains the results of the timbre parameter calculation and combines them with the outcome of the spectral classification. Correlations between the two data evaluation methods mentioned in Ch. 2 are discussed.
We observe considerable variation of timbre from tone to tone in the investigated RECORDERS and the TRANSVERSE FLUTE. Plotting the slope parameter s over the spectral centroid c, one recognises that this variation can be as large as the difference between a typical OPEN FLUTE and a DIAPASON rank of the pipe organ, i.e. the timbre distance between two distinct families of organ tone.
Surprisingly, the tonal timbre in the two investigated organ ranks is not uniform either. It is likely that the differences from pipe to pipe have gradually increased over the decades past their installation and typically years after their last cleaning and voicing. For example, dust might have deposited near the flue slits and the pipe mouths of metal pipes may have deformed slightly since then. One can speculate that the course of the timbre of freshly voiced organ ranks behaves more even than shown here.
The change in the timbre of the RECORDERS and the TRANSVERSE FLUTE is influenced by opening tone holes in their resonators, an effect also known from organ pipes in which a tuning slot [10] serves as a single tone hole.
When studying Figs. 3-8, one notes that only five different types of timbre occur in the RECORDERS and in the LIEBLICH GEDACT rank (consisting of stopped and open pipes); *octavial* tones are not present at all.

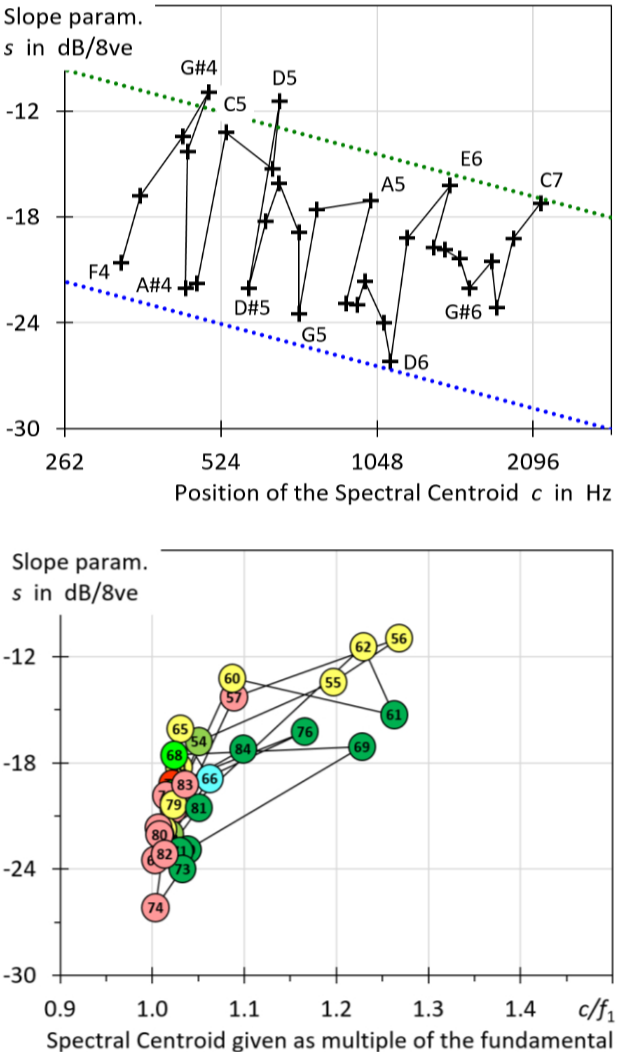

Figure 6. Timbre charts for RECORDER (b) plotted over frequency (top) and normalised to f_1 (bottom).

The RECORDER after Ganassi (Fig. 5) bears a special design supporting the occurrence of tones with pronounced fundamental in the mid tonal range. However, in the Late Baroque RECORDERS (Fig. 6-8) the *chalumeau-like* type spectra appear much more frequent (Fig. 3). This type also dominates the tones of the stopped pipes in the LIEBLICH GEDACT rank (Fig. 4) as expected due to the reflection of sound waves at the closed end.

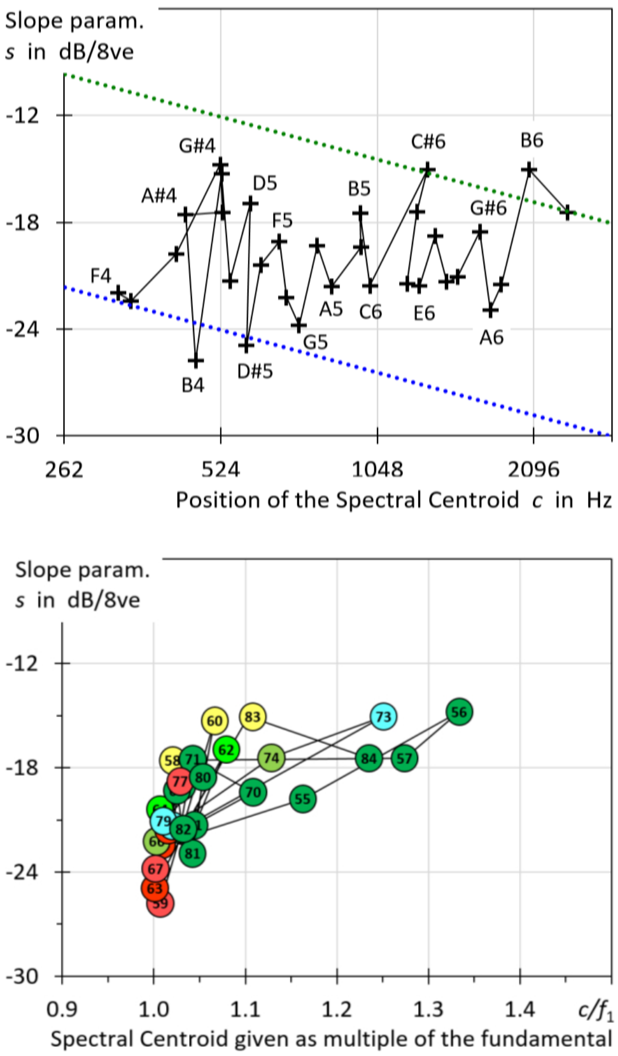

Figure 7. Timbre charts for RECORDER (c) plotted over frequency (top) and normalised to f_1 (bottom).

Thus, we assume that the *chalumeau-like* timbre of many tones correlates with the reflection of the sound wave at the end of the resonator. While in the LIEBLICH GEDACT pipes this occurs at the stopper, it takes place at the central boring in the RECORDERS, because their inner diameter reduces with varied conical incline from the mouthpiece downwards. Future investigations of cylindrical recorders (e.g. TIN WHISTLES) may clarify this assumption.

Note that RECORDER (c) has the highest number of most *chalumeau-like* tones and the course of the $s(c)$ values increases in average (Fig. 7) as expected for a STOPPED FLUTE rank (Fig. 4).

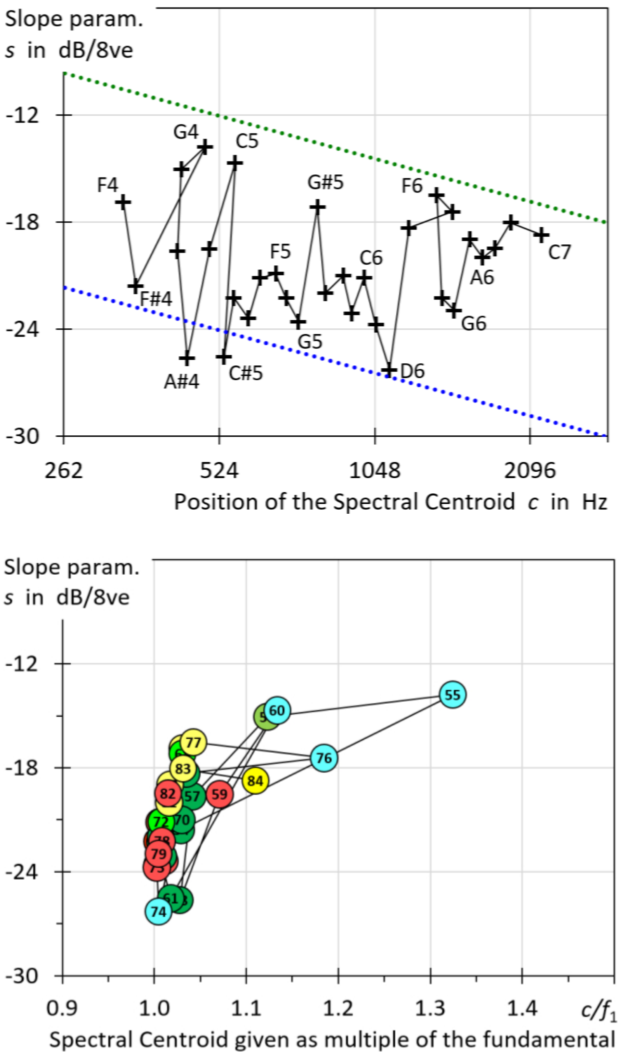

Figure 8. Timbre charts for RECORDER (d) plotted over frequency (top) and normalised to f_1 (bottom).

A few low notes of the TRANSVERSE FLUTE exhibit *octavial* behaviour (Fig. 3 and 9). It is a spectral type typical for transverse flutes, which has not been found in any of the recorders studied. This kind of timbre also occurs frequently in the CLEAR FLUTE (Fig. 10). Its pipes are of wide scale (Fig. 2), and thus the end correction effect of the pipe reduces the magnitude of the second and third harmonic partial. The fitted position over all 37 semitones calculates to $n_G = 2.6$ compared to $n_G = 3$ representing wide-scaled flute ranks [5]. The value $n_G = 2.6$ means that either the second and/or the third partial is affected. Taking account for the measured fluctuations, one either obtains spectra *dominated by the fundamental*, or the *octavial* type (in which the first two partials dominate the spectrum).

The TRANSVERSE FLUTE seems to generate these *octavial* tones, if the amount of the end correction caused by the size of the embouchure hole in relation to the effective length of the resonator just suits to dampen the third partial yielding the first two partials to become dominant. In RECORDERS, the slit in their mouthpiece is too small to generate enough end correction to produce *octavial* tones.

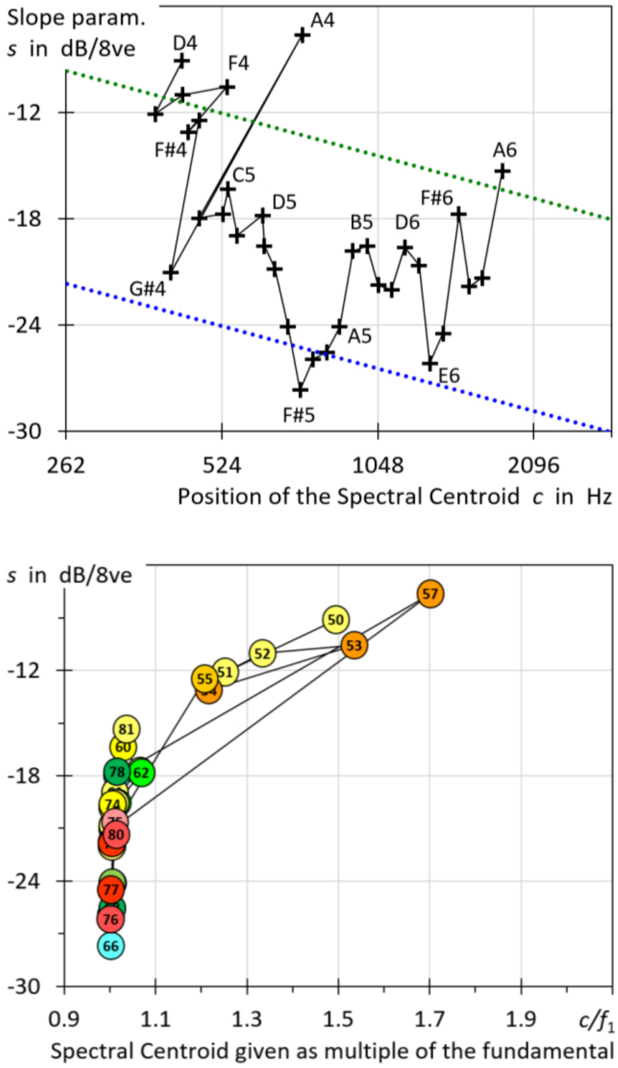

Figure 9. Timbre charts for the TRANSVERSE FLUTE (e). A few tones possess *octavial* timbre (orange).

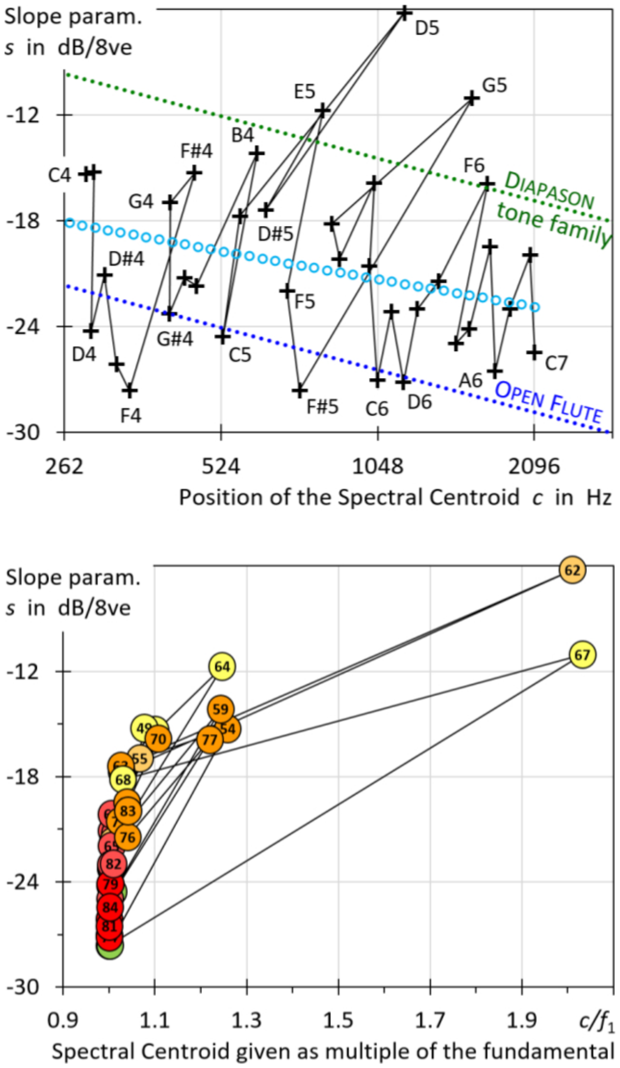

Figure 10. Timbre charts for the CLEAR FLUTE rank (B). The circles in the top chart show average values.

3.4 Comparison of both methods to visualise timbre

Both methods presented here neglect the inharmonic part of the sound spectrum. As we are dealing with tonal musical instruments this simplification seems acceptable. Furthermore, spectral analysis showed that the spectra were dominated by the harmonic partials. However, we have omitted the onset (articulation) and the decay of each tone to concentrate on the steady part of the sound.

In the charts, in which the slope parameter is plotted over the non-dimensional spectral centroid, some of the timbre prototypes (Fig. 1) can be distinguished by their positions:

- Tones with *fundamental* timbre accumulate at $c/f_1 \approx 1.0$. They easily separate from tones with *string-like* behaviour by using the calculated value of the spectral centroid.
- *String-like* generally tones possess higher values of the slope parameter and tend to concentrate on top of the other data points (see e.g. Fig. 5 and Fig. 6).
- *Chalumeau-like* tones appear in the right part of the charts, where *string-like* tones can occur, too. In both cases, this is due to their higher value of the spectral centroid. This appears to be reasonable since the content of harmonics has been defined as the main determining feature for the spectral classification.

Note that the spectral centroid is insufficient to distinguish *fundamental* and *string-like* spectra from the *chalumeau-like* and *octavial* types, which are seen to be determining for RECORDERS and TRANSVERSE FLUTES. The weighted slope parameter provides additional information to separate those timbres.

The other colours of Fig. 1 do not reliably correlate with the position in the timbre charts, because different spectra can generate the same numerical values of the slope parameter and the spectral centroid. However, these two-dimensional charts cannot distinguish six timbre colours unambiguously; nevertheless, such timbre charts provide a quick overview and are useful to recognise irregularities across pipe organ ranks [5].

4. CONCLUSION

This study has shown how different the tones of Baroque RECORDERS and TRANSVERSE FLUTE are for different tones within their tonal compass. Compared to previous work, the colour scale categorising tonal timbre has been compared to quantitative timbre parameters calculated from the steady part of the harmonic sound spectrum. This method has been developed for classifying pipe organ ranks and is suitable to recognise timbre deviations across the scale. The timbre charts depict the dependence of the slope parameter on the spectral centroid. They can only plot some of the timbre differences and their dependency on pitch. Of course, two parameters cannot express the same information as coded in the colour categorisation, but such charts provide a quick method to visualise the evenness of timbre upon pitch.

It has been found that timbre variations occur in both, FLUTE instruments and flute ranks in the pipe organ. In the FLUTES, the timbre variation is possibly due to the shape of the resonator and the different fingering for each tone. The pipe organ ranks showed to be less regular than expected, probably due to the age of their pipes. The five investigated FLUTES and the two ranks varied as much as the difference between the Flute and the Diapason tone family.

Octavial tones occurred in the TRANSVERSE FLUTE and the pipe organ rank CLEAR FLUTE. This indicates that this kind of timbre requires a high contribution of the end correction suppressing the third partial. In the TRANSVERSE FLUTE this could be achieved by the size of the embouchure hole.

5. REFERENCES

[1] M. Haverkamp: "How can we approach the topic of the tone-to-tone timbre variability of historical instruments?" *Proc. Mtgs. Acoust.*, vol. 49 no. 1, p. 035005 (13 p.), 2022.

[2] A.B. Fürstenau: *Die Kunst des Flötenspiels in theoretisch-practischer Beziehung*, *op. 138*. Leipzig: Breitkopf und Härtel (Paris: J. Meissonnier), 1844.

[3] M. Haverkamp, "Subjective and objective evaluation of the tone-to-tone timbre variability of historical flute designs." *Proc. Euroregio / BNAM 2022 Joint Acoustics Conf.*, (Aalborg, Denmark) pp. 67–76, 2022.

[4] T. Lerch: "Der Klang historischer Blockflöten," in: G. Wagner (ed.): *Jahrbuch des Staatlichen Instituts für Musikforschung Preußischer Kulturbesitz.* Stuttgart: Metzler, 1997 (pp. 146–168).

[5] F. Hergert and N. Höper: "Envelope Functions for Pipe Organ Ranks and the Influence of Pitch on Tonal Timbre," *Proc. Mtgs. Acoust.*, vol. 49, no. 1, p. 035012 (13 p.), 2022.

[6] *The National Pipe Organ Register*. St. Anne, Moseley, UK (entry D02877); www.npor.org.uk

[7] J.I. Wegdwood: *Dictionary of Organ Stops* (3rd ed.). London: The Vincent Music Company, 1907.

[8] G.A. Audsley: *The Art of Organ Building* (vol. II). New York: Dover Publications, 1965 (corrected reprint of the 1st ed. from 1905).

[9] F. Hergert: "Design Principles of Pipe Organ Mixtures – viewed from a psychoacoustic Position," *Proc. Mtgs. Acoust.*, vol. 49, no. 1, p. 035010 (13 p.), 2022.

[10] P. Rucz et al.: "Acoustic behaviour of tuning slots of labial organ pipes," *J. Acoust. Soc. Am.*, vol. 135, no. 5, pp. 3056–3065, 2014.