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Acoustic Analysis of the modern Recorder

Bachelor Thesis of Musikalische Akustik 1, SE

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Abstract

This thesis considers the acoustic analysis of the so-called Helder Tenor, a modern recorder. Since the Helder Tenor is a rather new instrument and poorly studied, the analysis is focused on the frequency response characteristics and the partial harmonics of the flute. In order to make any conclusions, a baroque model, the most common used recorder model, and two more, are analysed, too. This allows to draw a direct comparison from the new model, which is still in development, to a well-tried model. Ultimately, the thesis should provide an interpretation of the main differences and advantages of the Helder Tenor compared to other, older recorder models.

Zusammenfassung

Diese Arbeit setzt sich mit der akustischen Analyse moderner Blockflöten auseinander. Da der Helder Tenor ein neues und noch weitgehend unerforschtes Instrument ist, liegt der Fokus der Arbeit auf dem Verlauf des Frequenzganges der Flöte, sowie deren Teiltonverhalten. Um aussagekräftige Aussagen treffen zu können, wurden drei weitere Tenorblockflöten analysiert. Dies ermöglicht einen Vergleich des neuen, "modernen" Modells zu den herkömmlichen, altbewährten Modellen. Letztendlich enthält die Arbeit eine Interpretation der Unterschiede und Vorteile des Helder Tenor gegenüber herkömmlichen Tenorblockflöten.

Contents

1 Introduction

1.1 Motivation

Nowadays, recorder playing is often fraught with prejudices like boring and simple, which limits the recorder to its original form. When digging deeper into this subject matter, one realises that this is wrongly claimed. Modern recorder models enable the player to play not only renaissance or baroque literature, which is most commonly associated with this instrument, but also contemporary, exciting literature using a big variance in timbre and loudness or special effects like glissandi, multiphonics and so on.
Since the modern recorder is still rather underexplored, in this study the focus lies on the analysis of the Helder Tenor, a particular new recorder model, which is still in progress. Aims including a wider pitch range and dynamic range are analysed in order to be proofed.

1.2 The recorder

It is known that one of the earliest instruments [1] was some kind of flute. In the Middle Ages, every conceivable form or size, talking about traverse flutes and fipple flutes, were being played. The earliest surviving ’block-flute’ is dated about 1400 or even some decades earlier. However, in the eighteenth century playing the flute became disdained because you had to stick one end of it in your mouth. It took until the invention of primary schools before it gained more popularity again.
The early recorders were small sized, generally made in one piece and had a more or less cylindrical bore. More than two octaves were possible so that the instrument could be used for virtuoso divisions as well as for polyphonic music, which required the production of a ’consort’, smaller and larger sizes of the recorder. Because of the larger sizes still having to fit the player’s hand, the conical bore was invented. These models, now known as the ’renaissance’ instruments were available from about 15 centimetres to about two metres.
In the 17th century the recorder was redesigned. The conical bore, as known before, was varied in order to extend to a range of two and a half octaves and the tone became more expressive. Furthermore it was now made in three sections. On this familiar shape of the new ’baroque’ model most of the modern instruments are based.
During the 18th century the flute had been redesigned again. The classical orchestra was developed and therefore a wider range of dynamics was needed. That’s why instead of the recorder the traverse flute became the ’orchestral’ instrument.
At the end of the 19th century the recorder gained its popularity again. In 1919 the first

models of the 'modern' recorder were being made and composers like Berkeley or Britten began writing for it. The most exciting literature has come during the last 20 years basically from German, Dutch and Japanese composers using special effects such as glissandi, flutter-tonguing and multiphonics.

1.2.1 Helder Tenor

Inspired by a recorder from the 1930s, the so-called Herwiga Rex, the Helder Tenor was developed in the early 1990s. The outstanding quality of its quite balanced first and third octave is based on the principle of pure harmonics. It immediately can be noticed that compared to a 18th century recorder pretty much every part of it got reinvented: bore, length, weight, key work, embouchure and the additional piano key. It finally has got a well-balanced sound through the whole instrument, especially in the first and third octave, which cannot be achieved with older models. The reason therefore is the cylindrical foot joint and the new and more complex key system. Additionally, the player is able to play organic dynamics by using the piano key. The Sound Unit, a flexible block system consisting of four parts, makes an organic dynamical playing possible as well as a lot of variation in sound. The Lip control is a mechanism which enables the player to exert influence on the sound while playing. The moveable block can be tilted with the lips and therefore the width of the wind channel can be changed. By doing so, both timbre and pitch can be influenced. Further advantages of the Sound Unit are the variable exchangeable wind channel plates, the adjustable block and the adjustable height of the wind channel.
The interested reader is referred to related literature [2].

Figure 1: Helder Tenor

1.2.2 Functionality and sound generation

In a recorder sound is produced by radiating energy from the vibrating air in its bore [3]. Much of the energy, which is basically the player's breath, is then lost as heat through viscosity. Most of the sound is radiated through the openings in the bore: the window, the open finger holes and the open end at the foot.
Pitch control is provided by opening or closing the so-called finger holes, various openings, along the length of the tube. When all finger holes are closed, the recorder appears to

be a slightly tapered cylinder, obviously open at one end or perhaps even both. Standing waves in the air column occur for wavelengths such that a pressure minimum occurs at an open end or a pressure maximum at a closed end. The lowest mode of an open tube corresponds to a half-wavelength with a pressure maximum in the middle of the tube length, while the lowest mode of a tube closed at one end corresponds to a quarter-wavelength with a pressure maximum at the closed end. The open/open and open/closed cases can be easily distinguished by noting the pattern of harmonics.

The effective length of the vibrating air column of a pipe is longer than the physical length of the tube because the standing wave can extend beyond an open end. The effective length of a pipe can be chosen to match the fundamental frequency to any musical note, but it is not generally convenient to provide one pipe for each note in a portable instrument. The solution is to acoustically shorten the tube by opening a hole in the side, thereby releasing pressure before the end. If the hole is big enough, there will be a pressure node at the hole position effectively terminating the standing wave. Smaller holes should have a less drastic effect, but would still tend to suppress part of the standing wave and raise the fundamental frequency. By opening several holes in succession up the tube it is possible for a musician to play all or most of the notes of a chosen scale. Of course the size and position of the holes evidently determine the ability to play in tune. This is why there is still being experimented a lot with the bore when building new recorders.

2 Recording of the recorder

The recording took place on December 6th and 7th 2016 at the production studios of the University of Performing Arts in Graz. In two days we recorded four flutes:

- Voice-flute in D on 415 Hz, a baroque model after P. Bressan
- Herwiga Rex (1930s) of M. König & Söhne , which is an inspiration for the Helder Tenor
- modern Yamaha model (end of the 1980s)
- Helder Tenor

In order to keep the results objective, we recorded every tone ten times. Afterwards the recorder player picked the three best versions out of ten of every recording in order to get a best possible result by making the average of them later on in the analysis.

2.1 Setting

For the recording we used three Schoeps MK 4 cardioid microphones in three different distances to the player. Markers on the floor should prevent the player from moving too much while recording in order to keep the distance to the microphones as stable as possible.

The reason for using three different microphone positions is the highly complex radiation of the recorder. As in chapter 1.2.2 mentioned, the air jet comes through the window as well as through the open end and finger holes.

Microphone	distance to player	height
near	0.45 m	1.45 m
middle	0.8 m	1.4 m
far	1.25 m	1.4 m

Table 1: Microphone positions

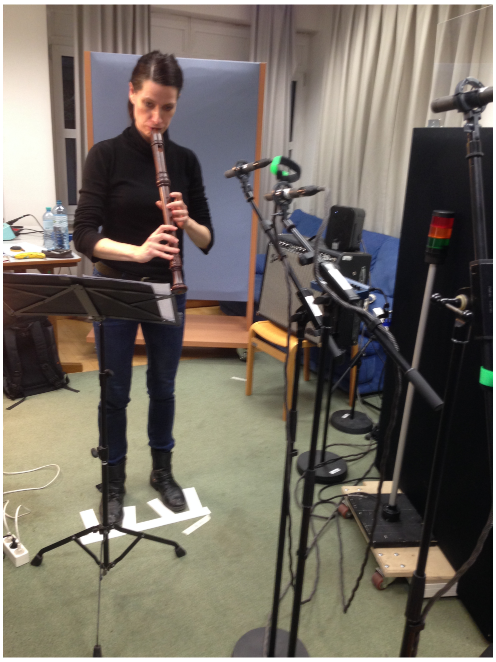

Figure 2: Setting - The player on her position during the recording session

A note being produced of a recorder is like a set of variously spaced point sources, considering the window, open finger holes and the open end at the foot. This means that a set of harmonics will be radiated by each source and there will be an interference pattern for each harmonic in the surrounding air. Since the recording hasn't been done in an anechoic room, room reflections and the presence of the player have an impact on these patterns. For measuring sound properties such as loudness and harmonic content, the position of the microphone is of great importance [4]. Because of that the microphone has to be outside the diffuse-field distance and therefore the nearest one was too close to the player. The one in the middle was already placed outside the diffuse-field distance and so it could be used for the analysis. The distance between the second and the third one was too small to make any difference in the recording so it was not necessary to use both of them. Hence the second microphone with a distance of 0.8 m to the player has been chosen.

3 Analysis of the recorder

The first part of the analysis is the trend of the tones being played on each recorder over its entire range measured in dB(A).
The second part is the analysis of the partial harmonics. For this part only the Helder Tenor is used since the focus of this thesis is on this particular recorder.
The third part lays focus on the piano- and forte-fingerings compared to piano and forte being played with standard-fingerings. In addition to the Helder Tenor the baroque model has been chosen for analysis, since it is the most common played instrument of the recorders. So a comparison from the Helder Tenor, the 'modern' recorder model, to the baroque Tenor, the most 'popular' model can be drawn in order to show the difference and further development.
The fourth part is again a spectral analysis, but this time using different fingerings and the Lip control function of the Helder Tenor to study the potential difference in loudness of the recorder.

3.1 MATLAB functions

The analysis of the recorders, which has been done in MATLAB, basically consists of two parts. On the one hand the integrated loudness of the instruments and on the other hand the harmonics. Both parts will be discussed into more detail later on.
This chapter lays focus on the MATLAB functions being used for the analysis. In order to analyse the integrated loudness, the built-in `integratedLoudness` function, which is part of the Audio System Toolbox, was used. The standards of integrated loudness are defined by the ITU-R BS.1770-4 [5] and the EBU R 128 [6], [7], [8] standards. The output argument ot this function is integrated loudness in loudness units relative to full scale (LUFS), returned as a scalar. This is the result of the algorithm breaking down the audio signal into 0.4-second segments with 75% overlap. It calculates the acoustic power of the sound relative to 20μPa and also weights it. I decided to use this function because it already has got a weighting approximated to the human ear and additionally relates the value to 20μPa.
For the spectral analysis the fast Fourier transform, or FFT has been used. It is a fast method of calculation of the discrete Fourier transform, the DFT. It would not make sense to use a continuous transformation on an audio signal because the size of the data being edited or transformed is simply too big. The DFT evaluates the signal on several points. The number of points being sampled depends on the sampling rate. In my analysis I use a sampling rate of 88200 Hz, which means that there are 88200 sampling points per

second. This is rather inconvenient, but since the recording was made with 88200 Hz I decided not to downsample because it means a higher resolution and does not come with any disadvantages. As already mentioned, with the ordinary Fourier transform it is only possible to detect the frequency parts of the sound, the chronological trend is not considered.

3.2 Trend of tones over the recorders' entire range

At first, the four recorder models are analysed on their integrated loudness, as in the above section already explained. Because we did not calibrate the loudness of the instruments during the recording, this had to be done afterwards. Therefore, I measured the instrument with a sound level meter in the same environment and under the same conditions the recording took place and could then calibrate its loudness by adding the difference of the value received from the sound level meter to the value measured during the recording to get the results as sound pressure level in dB(A). Further, the linear regression of each instrument has been calculated:

$$y = ax + b \tag{1}$$

with

$$a = \frac{Cov(x, y)}{V(x)} \tag{2}$$

and

$$b = \bar{y} - a\bar{x} \tag{3}$$

The following figure shows the trend of tones being played on each flute over its entire range. The circles depict the average of the three recordings, the vertical error bars the standard deviation of each tone. There it is remarkable that the player is able to reproduce the same tone three times with a fluctuation in sound pressure level less than 3 dB, exceptions neglected. Finally there is the regression line so that the trend over the entire possible range is easier to be seen.
As expected, the trend of the baroque model is the steepest with a sound pressure level of 66 dB(A) reaching up to 98 db(A), which makes a difference of 37 dB(A). The Yamaha is already more balanced with a difference of 27 db(A) in sound pressure level. Additionally, it is louder than the baroque recorder, naming a difference of 9 dB(A), regarding its regression lines. Taking a closer look at the linear regression of the Herwiga-Rex with its sound pressure level reaching from 67 dB(A) up to 106 dB(A), speaking of 39 db(A) difference, as well as the line of the Helder Tenor, those two are likewise well-balanced. This is because the Herwiga-Rex is skipping a lot more than the Helder Tenor, which is rather continuously becoming louder over its range. It goes from 70 dB(A) up to 96

dB(A), which leads to a difference of 26 dB(A). Hence it can be said that the balance of the instruments got improved a lot throughout the years and the aim of an even more balanced course of the Helder Tenor in the first octave as well as the third got well achieved.

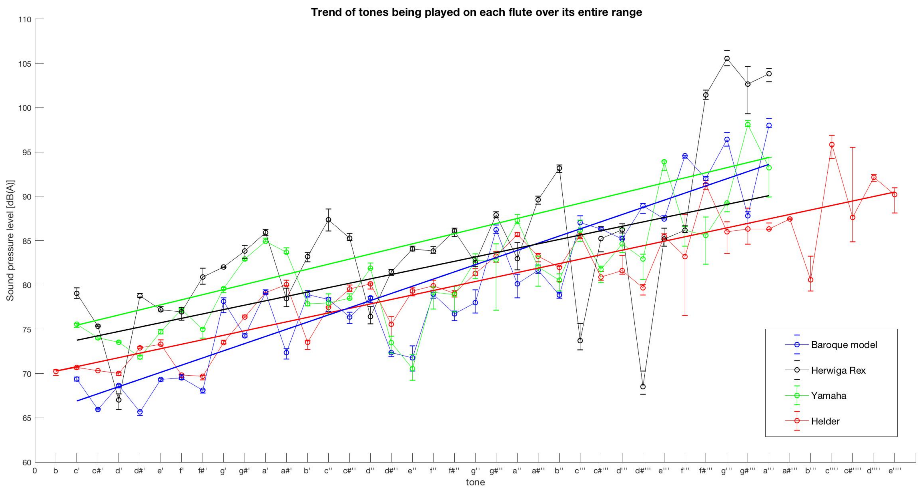

Figure 3: Trend of tones being played on each flute over its entire range

3.3 Partial harmonics

The second part of the analysis, as already mentioned, is focussed on the partial harmonics. Basically, only the fundamental plus the first six overtones have been chosen because any other harmonics are already too low in amplitude to be heard by the human ear and therefore not decisive in the analysis. Thus a decrease of down to -40 dB is shown in the graph.

For the first and second register the partial harmonics are shown once for the lower part, containing the average of the first three tones of the register (b, c', c#' for the first and d#", e", f" for the second register), and once for the upper part, containing the average of the last three tones of the register (c", c#", d" for the first and g", g#", a" for the second register). The third (a#", b", c"'), fourth (c#"', d"', d#"') and fifth register (e"', f"', f#"') only contain three tones each, the sixth (g"', g#"') and seventh (a"', a#"') only two tones, wherefore these registers are depicted only once each, again showing the mean of the particular tones. For the three highest tones (c#"", d"", e"") are not defined any registers any more, thus the mean of them is shown.

It is remarkable that especially the lower part of the first register, but as well the lower part of the second, are richer in overtones than the upper parts. The third register has got very few overtones and the following registers are rather poor in overtones, too. What is noticeable is that the seventh register again is very rich in overtones. Knowing that the properties of partial harmonics depend on the fingering, the individual graphs can be explained easily. The first two octaves hardly contain any fork fingering whereas in the upper registers, especially from a#” to d#”’, meaning third, fourth and half of the fifth register, only fork fingering is used. Fork fingering causes a loss in overtones, which is shown to advantage very well. The seventh register has got a relatively closed fingering, which explains the exceeding richness in overtones, which can be said for the three highest tones as well.

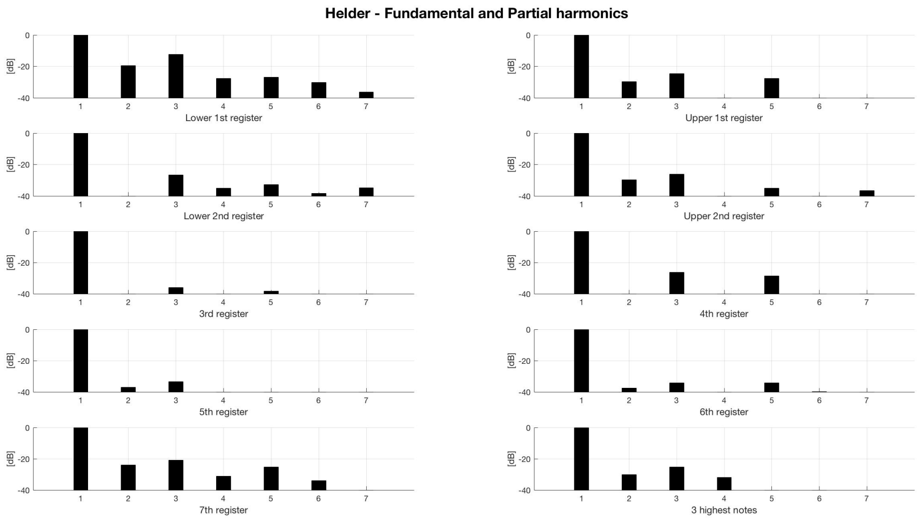

Figure 4: Fundamental and partial harmonics of the Helder Tenor

3.4 Piano-, forte-fingerings and dynamics

In order to simplify the variation in dynamics while playing the musician has got the opportunity to use so-called piano-fingerings and forte-fingerings. This part of the analysis is about the comparison of those two types. It shows several tones in forte, once being played with forte-fingering and once a dynamic forte being played with standard-fingering and the same tones in piano, this time once with piano-fingering and once a dynamic piano being played with standard-fingering. Dynamic forte in this case means reaching the loudest point when playing dal niente and dynamic piano means reaching the lowest point when playing al niente.

It has to be said that there are no piano-fingerings on the baroque model for f”’-a”’ and on the Helder for a#"'. Forte-fingerings are missing on the baroque model for c'-f#', g#', a#', g#", g#"', a"' and on the Helder Tenor for b, c', d#' and b"'. These missing piano- and forte-fingerings are replaced by standard-fingerings because in these cases standard-fingering is either the softest or the loudest possible variety.

Figure 5 shows the comparison of piano and forte being played on the baroque model. This time, instead of sound pressure level in dB(A) loudness in sone was used as unit.

$$sone = 2^{\frac{dB(A)-40}{10}} \tag{4}$$

In this way it is easier to compare loudness in relation to one another because it is a psychoacoustic unit of loudness and describes the subjective perception of sound pressure. Doubling the perceived loudness doubles the sone value. (E.g. 10 sones are twice as loud as 5 sones, wheras when calculating in dB double sound pressure level means +6 dB).

Both times the trend of loudness of the piano tones is quite stable, whereas the trend of loudness of the forte tones is highly increasing. Against expectations, the piano-fingering is louder than a piano played with standard-fingering and the forte-fingering is lower that a forte played with standard-fingering. Although the player has got the feeling to achieve a louder or softer sound by using forte- or piano-fingerings, with standard-fingerings it is still possible to play with a greater variety in dynamics.

By taking a closer look at the piano-fingerings it can be seen that despite the highest tone (d#"') every other is louder than the piano played with standard-fingering. The a", for example, almost has got the same loudness at both types of fingering with only one sone difference. On the contrary, the g' with piano-fingering is twice as loud as with standard-fingering.

The forte-fingerings don't show that a big difference in loudness. c' and g' have got almost the same loudness with less than one sone difference and c"' is one sone lower with forte-fingering than with standard-fingering. In comparison to piano-fingerings, forte-fingerings are sometimes louder than standard-fingerings, as can be seen at c', d", a" and c"'.

Taking a look at the difference in loudness from the lowest tone, the c', to the highest one depicted, a d#"', the d#"' is in forte about five times and in piano only about three times as loud as the c'. This shows the increase in loudness in the higher octaves, which was desired to be reduced with the Helder Tenor.

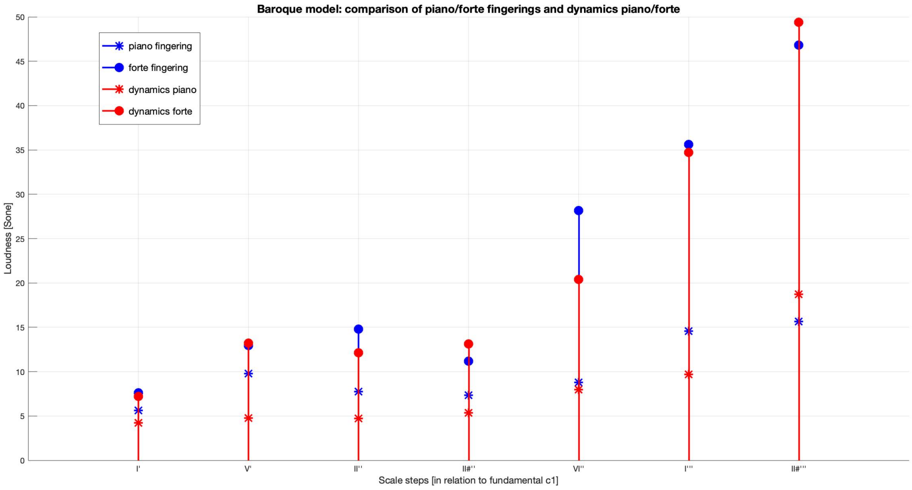

Figure 5: Comparison of piano/forte fingerings and dynamics piano/forte of the baroque model

Figure 6 now shows the comparison of nine tones in piano and forte being played on the Helder Tenor. This time, the trend of loudness of the forte tones as well as of the piano tones is increasing a lot more than with the baroque model. The f#''' in forte with standard-fingering is, for example, four and a half times as loud as the b, whereas with forte-fingering the same tone is not even four times as loud. This shows that with standard-fingerings a greater variety in loudness is possible than with forte-fingerings. In the first two octaves the difference in forte of standard-fingering and forte-fingering is between three sones and eight sones. The biggest difference is at d#''' with 41 sones. This means that the standard-fingering is more than one-third louder than the forte-fingering.
Taking a look at the piano one can see that compared to the baroque model, the piano-fingerings work better with the Helder Tenor. Five times out of nine the piano-fingering is lower than the standard-fingering. d'' has got almost the same level of loudness in both versions, the biggest difference is at g''' with 20 sones, which means that the piano-fingering is one and a half time louder than the standard-fingering. Against expectations, b has got almost the same level of loudness with less than one sone difference in piano- and forte-fingering.

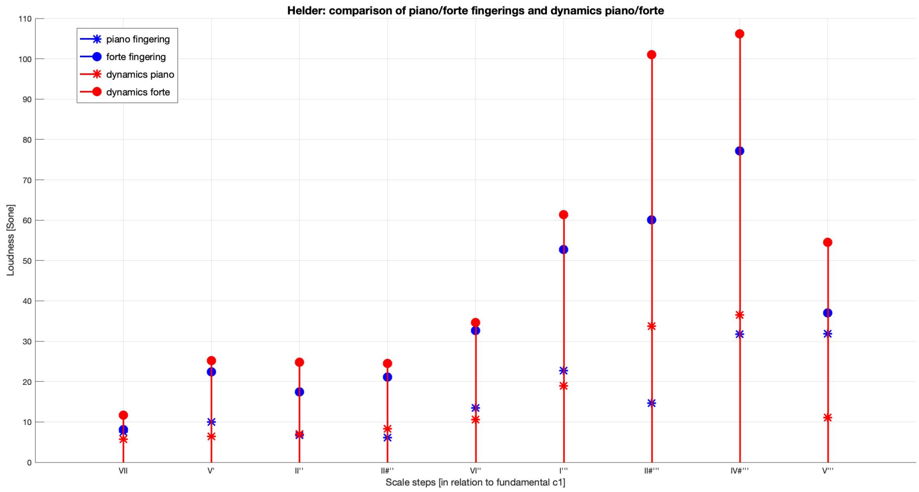

Figure 6: Comparison of piano-/forte-fingerings and dynamics piano/forte of the Helder Tenor

In Figure 7 the comparison of piano- and forte-fingerings of both models, the baroque and the Helder Tenor, is shown. For some tones don't exist piano- and forte-fingerings, that's why standard-fingerings are used in these cases. For the Helder Tenor there is a missing piano-fingering for a#''' and missing forte-fingerings for b, c', d#' and b'''. For the baroque model piano-fingerings have to be replaced for f''', f#''' and g''' and forte-fingerings have to be replaced for c'-f#', g#', a#' and g#''.

It is remarkable that the baroque model is rather stable in loudness in the first register. Another thing that is noticeable is that the piano-fingering of the Helder Tenor is, against expectations, until a#' louder than the baroque recorder. From b'-e'' it is lower and then from f''-d''', despite a few exceptions, louder again. Simplistically, in the second register the piano-fingering of the Helder Tenor is lower, in the other registers it is the opposite way. Besides, it has to be marked out that the difference in loudness sometimes is so high that one piano-fingering is twice as loud as the other, talking about extrema like d#', e' and a#', for example. Taking a look at the forte-fingering, the Helder Tenor is despite g''' always louder than the baroque recorder, often even almost twice as loud.

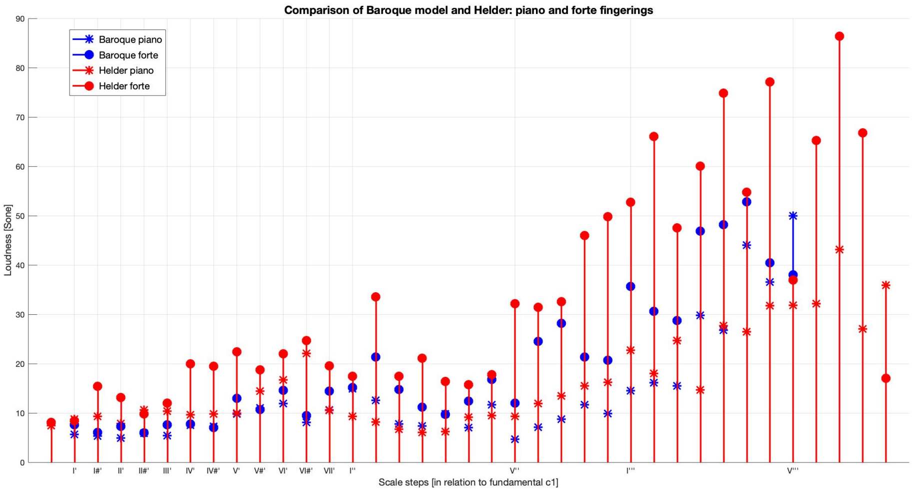

Figure 7: Comparison of piano-/forte-fingerings of the baroque model and the Helder Tenor

3.5 Lip control

The fourth part of the analysis, as above mentioned, is focussed on the loudness difference of the Helder Tenor. On a common recorder, a forte sound has got a different pitch than a piano sound. This difference can be slightly corrected by the player, but normally occurs to be a problem in intonation. This is the reason why the Lip control function was created on the Helder Tenor. By using this function, it is possible to play the same tone in piano without any difference in pitch. Thus intonation has come up to a new level.

In order to see how much of a difference in loudness from piano to forte is possible, a spectral analysis of the tones being played with Lip control has been done. The following graph shows the outcome. There are depicted three levels of loudness for each sound. A forte being played with forte-fingering and two times piano, once with piano-fingering and once using Lip control.

What can be seen easily is that the piano being played using Lip control is even lower in loudness than when using piano-fingerings. The minimum of reduced loudness is one sone, as for d#”, piano-fingerings of d” and g#” are even twice as loud as with Lip control.

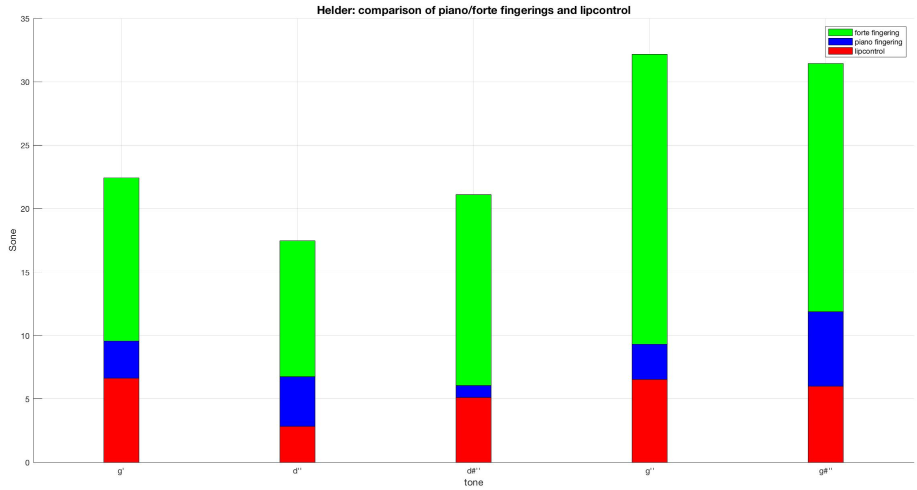

Figure 8: Comparison of piano-/forte-fingerings and Lip control of the Helder Tenor

By now, we know that Lip control is a way to play a piano that cannot be achieved with any other technique. Of course this must have an impact on the overtones. The following figure 9 depicts the five tones, which have already been analysed above, now with their fundamental and partial harmonics.

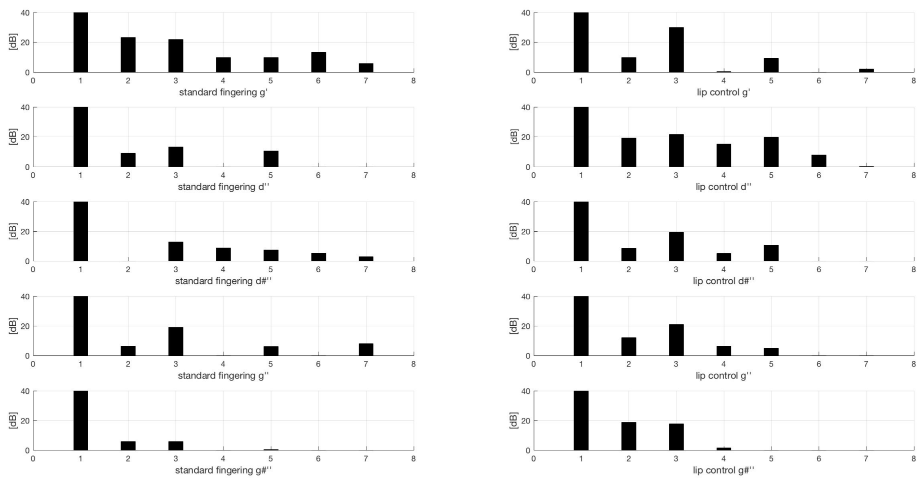

Figure 9: Comparison of standard-fingerings and Lip control - Fundamental and partial harmonics of the Helder Tenor

At first sight one would say that the Lip control function provides the tone with less overtones. Still, the first few harmonics are therefore higher developed, in comparison to standard-fingerings. What is conspicuous is that the second overtone is higher developed with Lip control than with standard-fingerings. Furthermore, the third and the fifth are louder than the second and the fourth, so it can be said that all odd harmonics are higher developed, which leads to a hollower and warmer sound.

4 Conclusion and Discussion

The aim of this thesis was to analyse the Helder Tenor so as to show the sound properties of this special recorder, for it is still a very new and poorly studied instrument.

Therefore, a closer look was taken at the trend of tones over the recorder's entire range. Three other recorder models were used for the analysis, too, in order to show the difference from the modern recorder to conventional models. The first remarkable feature of the Helder Tenor is its bigger range. It starts at b, a half-tone lower than other recorder models, and reaches up to e"". Thus the range of the Helder Tenor is a major sixth bigger than the one of other models. Another advantage that could be discovered is its well-balanced trend of tones over its entire range, the three other models analysed did not appear likewise.

Further, the partial harmonics of the Helder Tenor were part of the analysis. There it could be showed that it has got mainly odd harmonics. According to this, the recorder is not quite rich in overtones. An alternative to cross-fingering could improve this fact.

Another part was to show up the differences and advantages of the Helder Tenor to common recorder models, in this thesis a baroque model. It could be shown that when using dynamic fingering on the Helder Tenor it is possible to play up to twice as loud as with the baroque model.

Due to the Lip control function on the Helder Tenor it is now possible to play a even softer piano without any difference in pitch. As a consequence, its volume expands once more.

List of Figures

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References

[1] John Martin. *The Acoustics of the Recorder*. Moeck Verlag Celle, Ed. Moeck Nr. 4054, 1999, 3-5.

[2] Susanne Fröhlich: recorder 2.1. `https://susannefroehlichrecorder.wordpress.com/2016/01/03/introducing-the-helder-tenor/`, 30/10/2018

[3] John Martin. *The Acoustics of the Recorder*. Moeck Verlag Celle, Ed. Moeck Nr. 4054, 1999, 14.

[4] John Martin. *The Acoustics of the Recorder*. Moeck Verlag Celle, Ed. Moeck Nr. 4054, 1999, 16-18.

[5] International Telecommunication Union; Radiocommunication Sector. *Algorithms to Measure Audio Programme Loudness and True-Peak Audio Level*. ITU-R BS.1770-4, 2015.

[6] European Broadcasting Union. *Loudness Normalisation and Permitted Maximum Level of Audio Signals*. EBU R 128, 2014.

[7] European Broadcasting Union. *Loudness Metering: 'EBU Mode' Metering to Supplement EBU R 128 Loudness Normalization*. EBU R 128 Tech 3341, 2014.

[8] European Broadcasting Union. *Loudness Range: A Measure to Supplement EBU R 128 Loudness Normalization*. EBU R 128 Tech 3342, 2016.

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Erklärung

Hiermit bestätige ich, dass mir der *Leitfaden für schriftliche Arbeiten an der KUG* bekannt ist und ich diese Richtlinien eingehalten habe.

Graz, den 25.01.2019

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Unterschrift der Verfasserin/des Verfassers