

ACOUSTIC ANALYSIS OF VARIOUS BASSOON FINGERINGS IN MOZART'S INTROITUS

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Abstract: The work contains the analysis of selected bassoon fingerings, namely the first four bars of the Introitus part from W. A. Mozart's Requiem. The takes were recorded in the anechoic room at the BUT Brno. The loudness curves, formants, spectral qualities using FFT are evaluated, and brightness, sharpness, spectral centroid are also measured. The duty cycles of the wave, including a pulse with a constant width, are taken into account, in connection with other double reed instruments. The analysis was performed both for entire phrases and for isolated tones. The fingering data are compared with each other (strengths and weaknesses) and evaluated from the point of view of aesthetics, i.e. how suitable the given fingering is for a different style and various interpretations.

Keywords: acoustic, analysis, bassoon, brightness, constant width pulse, double reed, FFT, fingering, formants, loudness, LPC, Mozart W.A., music, timbre, sharpness, spectral centroid, spectrum, Requiem.

MOTIVATION OF THE WORK

The bassoon is a woodwind instrument and "the total length of its bore is about 254 cm, flaring from a width of 4 mm at the narrow end of the crook to 39 mm at the bell" [8], and thus a very wide tonal range usually from B₁($f_0 = 58$ Hz) to D₅ ($f_0 = 622$ Hz) [8], 3.3 octaves. It covers not only bass parts in chamber and orchestral music, but also baritone and tenor parts. In terms of timbre, it combines well with other woodwinds, but also with all strings. Compared to brass instruments, it has a lower acoustic output, but also a narrower, gentler spectrum, which is why it is often masked by them. Its character is suitable for figures and ostinatos, homophonic chord passages or tutti, but also for solo melodies.

The timbre of the instrument depends largely on the quality of the so-called double reeds consisting of two "slices". Like the oboe, the bassoon uses a double reed made of a type of cane (*arundo donax*) [8], today also of substitute (artificial) materials. The position of both lips on the area of the double reed plays an im-

portant role, i.e. whether the player's lips touch the tip, middle or base (close to the bocal) of the double reeds and how much the surface of the reeds is damped. The bassoon has 19 standard tone holes and up to 9 other tone holes, which serve to regulate the intonation and playability of the instrument [21]. Thanks to this, the player can choose different fingerings on the holes with their different areas and depths [11]. The more or less open space on the pipe then becomes the second factor that affects the timbre. The rule is that if the player uses holes that have a similar diameter and depth and are close to each other, the resulting timbre of the passage will be more homogeneous. However, for easier fingerings, or better unification of dynamics or even special timbre, the player can use fingerings with holes that are more distant and different in size. How much will the timbre and dynamics change among individual notes? Will different fingering also be reflected in other acoustic parameters, such as the ADSR envelope, uniformity or spectral refraction (flux), sharpness, brightness, etc.? Recording takes and analysing them should answer these questions to some extent. The motivation was

not only to measure the acoustic parameters of the excerpt, but also to consider their aesthetic impact on the composition itself.

CONTEMPORARY INVESTIGATIONS AND EXPERIMENTS WITH THE BASSOON ACOUSTICS

The bassoon has been extensively studied in the recent past by musicians, instrument makers, and acousticians. In addition to analyses of the players' practical musical experiences, a number of mechanical measurements, experiments and computer simulations have been carried out. The double reed, as the oscillator, is of course the most interesting: experiments using the artificial mouth and the stroboscope have provided new information about closing the "reed (top) and demonstrating the splitting issue of the reed opening region into several subregions" [1]. „Phase-space trajectory for a double-reed instrument with reed mass and damping (circles)" [2] was identified together with the outgoing pulse waveform sounds. A new theory has emerged about the "variation of the detected reed opening area as a function of the binarisation threshold" [2]. The oscillator, the double reed, has of course been subjected to experiments and simulations in coordination with the exciter – the air, where "the dimensionless acoustic pressure $p_e(t)$ and the dimensionless acoustic flow $u_e(t)$ " [9] are measured. Research and experiments have been described, „the phase-space trajectory with reed mass and damping and the analytical curve for zero mass and damping" [2]. Actions of "the reed opening area and of the lower part at the beginning of the bore" and phenomena such as "the jet formation at the entry of the double reed, reattaching the flow to the walls, movement of streamlines, turbulent mixing" [3] and others are also investigated. The model was proposed, where air pressure at the inlet of a double reed channel and at the input of the bore are linked by a nonlinear relation. [3]

We can also benefit from research related to other double reed instruments, especially the oboes, but also bagpipes with a double reed in the pipe. Valuable research includes the "Piezoelectric Excitation Method" used in the case of "Fingerings for F4 and forked F4 on the oboe" [14]. The principles of "a dou-

ble-reed exciter linked to an acoustic resonator" [4] studied in the case of the Greek aulos can also be applied to the bassoon. Here we obtain useful data related to parameters such as "bore's length, mouthpiece's length, bore's inner diameter, bore's material thickness, tone holes' curvature radius, etc." [4]

The main work on physical properties is "The Experimental Investigation of Bassoon Acoustics" by Timo Grothe" [8]. It contains detailed graphs and tables on "mouth pressure, lip force, dynamic levels in dB SPL, in sones, spectrograms, spectral centroids, formant centre frequencies F1, F2, F3, F4, the radiated sound" [8] with polar patterns and others. We most often compare the data from these studies with ours.

THE INTROITUS

The introductory part of Wolfgang Amadeus Mozart's *Requiem* (KV 626), specifically the *Introitus: Requiem aeternam*, contains bassoon solo passages that have a very specific function and character. The bassoon solo appears right in the opening bars of the piece in the key of D minor (see Fig. 1). The bassoon, as a deep woodwind instrument, often has a complementary and harmonic role in the orchestra, but in this part, it also participates in conveying the melody and underlining the overall atmosphere. "The instrumental overture is a lament for death (basset-horns and bassoons), to which the deep and high string instruments play sobbing figures, which in Mozart's music represent weeping. This peaceful grief is interrupted in the seventh bar by the forte blows of trombones, trumpets and timpani: death is not only a kind friend, but also a step towards the dreaded judgment" [10]. These solo places high demands on the bassoonist's interpretative skills, especially in the areas of tonal culture and expression.

From an instrumentation perspective, it is interesting that Mozart chose the bassoon, whose dark timbre perfectly captures the somber atmosphere of the piece. "Because of its wide compass and its range of characteristic tone-timbres, from richly sonorous at the bottom to expressively plaintive at the top, it is one of the most versatile and useful members of the orchestra" [21]

The main melody in *The Requiem aeternam* is melodious and lyrical, and the bassoon supports it with its rich, singing tone. It contributes to the dark and mournful tone of the piece. Its tonal timbre gives the work a sense of depth, humility and sadness, which is absolutely essential for the spiritual effect of this composition. In combination with the other wind instruments (especially the basset-horns and trombones), the bassoon adds fullness and emotional intensity to the harmony. From a musical technical point of view, the bassoon solo part requires careful control of breathing, intonation and phrasing. The instrument must be perfectly in tune with the orchestra and choir, especially in the dynamic

character places high intonation demands on the precise intonation of chromatic progressions, the purity of large interval jumps, the stability of tuning in various dynamics and intonation adaptation to the string section.

TECHNICAL PARAMETERS OF THE MEASUREMENT

The recording took place on November 18, 2024, from 5:30 p.m. to 7:00 p.m. The bassoonist sat on a standard chair and the microphone was placed on the zero-horizontal axis (in the listener or audience position) at a dis-

Requiem.

Adagio.

Componiert in Wien 1791.

The musical score is for the first four bars of the Introitus of *The Requiem aeternam*. It is in G major (one sharp) and 4/4 time. The tempo is Adagio. The score includes parts for Corni di Bassetto in F, Fagotti, Violino I, Violino II, Viola, and Violoncello/Basso ed Organo. A red box highlights the first four bars of the Fagotti part, which is a solo. The Fagotti part starts with a piano (p) dynamic and features a melodic line with chromatic progressions. The other instruments provide harmonic support, with the strings playing a rhythmic pattern of eighth notes.

Fig.1: *The Introitus, the first 4 bars* [12]

contrasts and sensitive transitions between the individual parts of the piece. Tone culture requires a perfectly balanced tone across the entire range. The ability to produce subtle dynamic shades and the need to maintain the quality of the tone even in pianissimos is important. At the same time, a full and rich sound typical of the bassoon is needed. The solo emphasizes the softness of the tone and the ability to capture the tragic character of the composition. Capturing the prayer-like

tance of 1.5 m from the centre of the instrument and a height of 1.2 m. Similarly to concerts, the directional lobes coming from the holes in the front were stronger than the rear ones; moreover, in the anechoic room they were not reflected by the back wall but were absorbed.

Playing in an anechoic chamber may be unusual for a bassoonist, but for an experienced professional musician it is not a major problem. The practice of an orchestral, chamber and

solo player has brought the performer recording measured samples, Roman Novozámský, to a large number of different acoustics. Without an immediate flexible response, his performance would be significantly affected. The environment of an anechoic chamber forces the player to play completely naturally, with proper wind support, but with a pronounced harmonic imagination. This allows the instrument to vibrate freely with a natural sound and intonation. The perception of tone timbre is changed compared to conventional acoustics with reverberation, but the nuances in the difference in tone timbre and width are even more obvious. The length of stay in such acoustics does not play a significant role, the professional tries to adapt very quickly and reacts adequately to external conditions. He would play everything essentially the same in acoustics with reverberation of 2-2.5 sec. The reverberation itself creates harmonies during solo interpretation that facilitate and support natural sound and intonation.

The parameters of the anechoic chamber were volume 87 m^3 , critical frequency 105 Hz, reverberation time 0.18 s in the octave band 125 Hz, <0.08 in the octave bands 250 Hz to 8 kHz. The Earthworks Audio M23 measuring microphone was used for recording: frequency response 3 Hz to 23 kHz ± 1 -3 dB, polar pattern omnidirectional, sensitivity 34 mV/Pa, acoustic input 140 dB SPL and self-noise 20 dB SPL.

The signal from the microphone was fed into RME Micstasy microphone preamplifiers, from there into the A/D converter A/D – D/A Interface ADI-2, which transmitted digital information to the DAW (Cubase 10) at a sampling frequency of 48 kHz with a depth of 24 bits. The recorded takes were normalized to the calibration signal level of 94 dB SPL. The dynamic range of the phrase recorded from 1.5 meters thus ranged between 75 and 90 dB (from *mf* to *ff*), i.e. roughly 26 and 75 sones. The bassoon dynamics requirement in *The Introitus* of the *Requiem* is piano (i.e. approx. 50 dB) [17]. If we use *The Sound Propagation Level Calculator* [18] to calculate the signal loss over another 15 meters (the centre of the auditorium of a medium-sized concert hall), we obtain a dynamic range between 43 and 58 dB [18], i.e. 3.2 and 8 sones [20], i.e. the musical dynamics bands between *ppp* and *p*. This roughly corresponds to the dynam-

ics required by W. A. Mozart. However, we will analyse the normalized signal recorded from a distance of 1.5 meters.

The double reed chosen for this demonstration was professionally made from high-quality cane from Georg Rieger (Germany). The reed is of rather lower hardness, providing a soft and darker sound with good flexibility, responding well to the player's requirements. In addition to the wind support, fine pressure corrections were also used, which an experienced player accustomed to his own instrument uses more or less automatically. The Fox bassoon, model 680, on which the demonstrations were played, is a professional instrument that is excellently crafted, with natural ergonomics and a balanced sound. Nevertheless, it exhibits a certain timbre, sound and intonation instability, given the design of the instrument, despite many years of improving the original Heckel design.

SWITCHING OF DOUBLE REEDS, THE DUTY CYCLE

The constant pulse signal (a periodic sequence of impulses, whether of a "rectangular, triangular, or with a rounded peak amplitude" [19] shape) is used to digitally imitate "double reed instruments". Important parameter in its creation is the so-called duty cycle and within it "constant opening times" [13], when the two reeds are opened, so air flows into the pipe, and the "constant closing times" [13], when both reeds are closed, air stops flowing into the instrument. The ratio of the pulse length (τ) to the entire period (T) is called the width of the pulse [13] ($\tau/T = 1/10$). We digitally created an artificial positive pulse with the length of 14% of the period, i.e. rounded a ratio of $1/7$, when every main seventh partial in the spectra is silenced (spectral gaps see Fig. 2). The graph on the top left will always contain a wave with its amplitude, the graph on the top right is created by the cube root autocorrelation and informs us about the most common pulse width ratio, the graph on the bottom is a periodogram showing the spectrum.

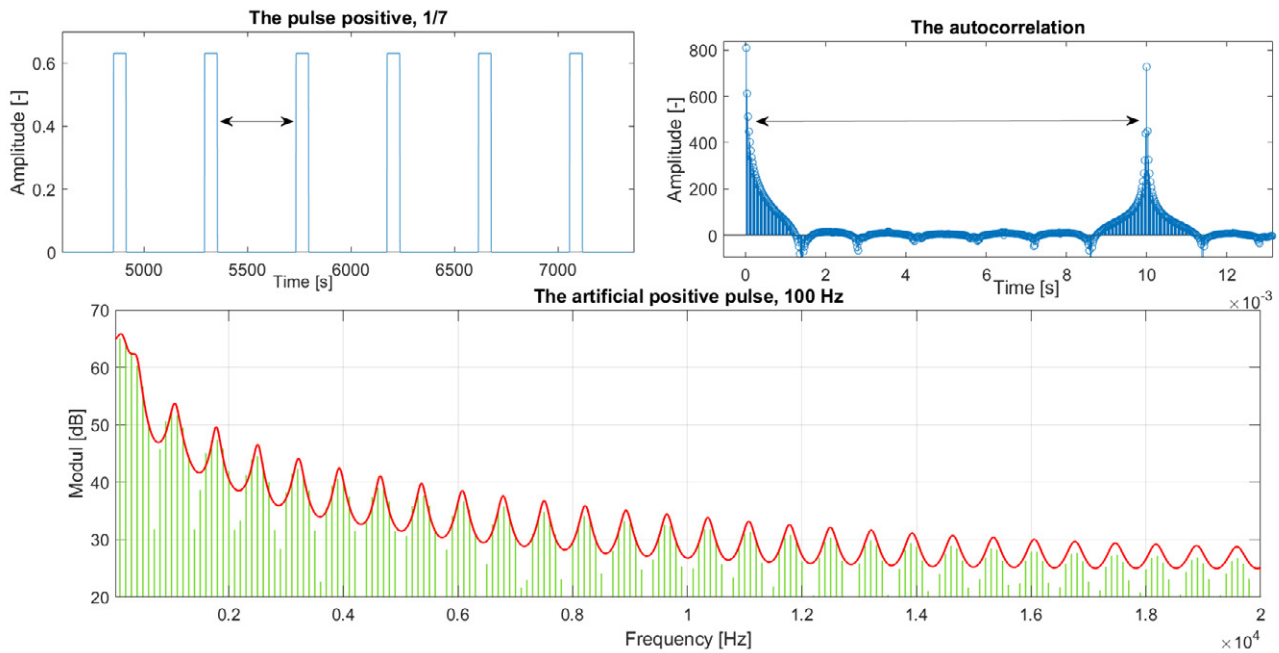


Fig.2: The artificial pulse 1/6, D4

As already mentioned, a real reed does not open and close completely perpendicularly or linearly obliquely in time, but the open part formed by the lips during the reeds closing

small partial waves. These are caused by the tips and reed not closing over the entire surface. Partial surfaces open on the tips and on the so-called heart during the closed phase.

The example is the G5 oboe tone recorded also in the anechoic room at the BUT Brno.



Fig.3: Double reeds (from the left): duduk, oboe, bassoon, bagpipe

has a more rounded wave shape. The “closed time” of a mechanical double reed (Fig. 3) is not completely silent, flat, but is filled with

The sample shows a ratio of 1/6.5, the quasi-closed phase is filled with 7 positive and 7 negative half-waves. The spectrum contains 15 stronger partials (see Fig. 3). The shapes of the main wave and partials are smooth, i.e.

each creating one harmonic component. The samples were recorded with the French oboe Marigaux model 901, R.A.M.O. wood, vintage 2014, bore diameter 10-10.5 mm, hardness medium soft.

band 7-14 kHz (see Fig. 5). The Fossati Paris instrument was used for the measurements. For the Armenian instrument duduk, we recorded the tone D4, the width pulse is on $1/3$, the closed phase contains readable 3 positive

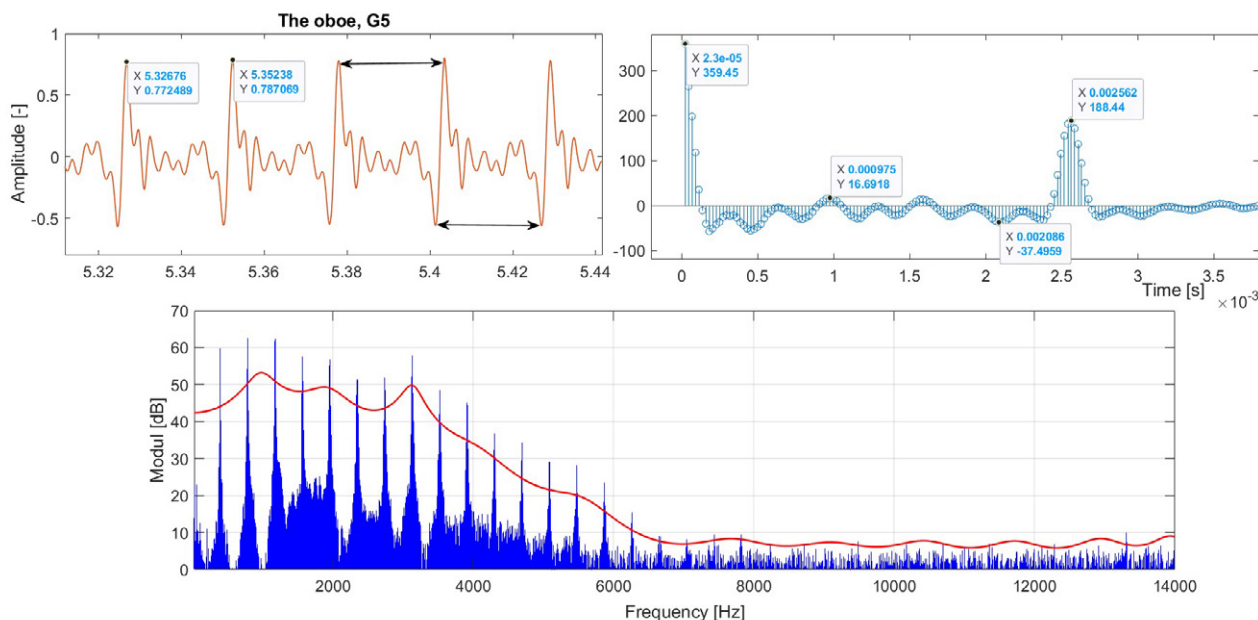


Fig.4: The oboe, G5

The F4 tone played by the Cor Anglais (English horn) also exhibits smooth partial waves, the ratio is numerically based on $1/7$, the quasi-closed time contains only less intensive

and 3 negative massive half-waves, nevertheless with quieter 20 smaller waves inside them (see Fig. 5). The “aggressive” spectrum is therefore completely filled with dozens of

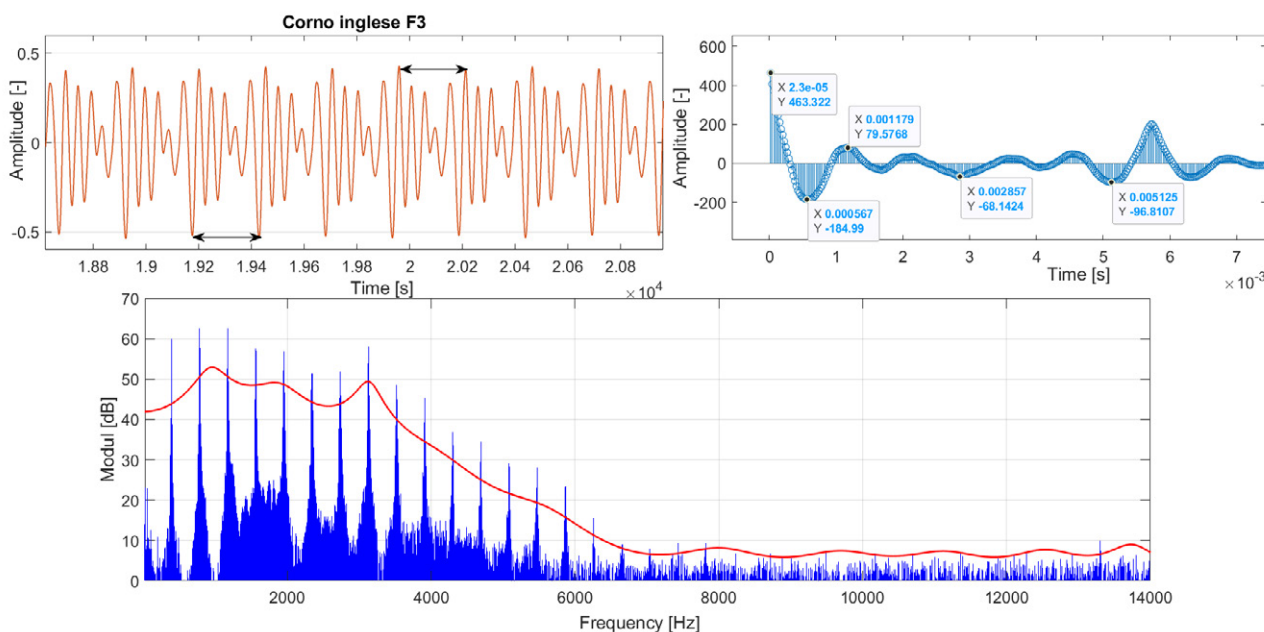


Fig.5: The cor anglais, F3

4 positive and 4 negative half-waves. In the spectrum we find 15 louder partials with 3 formants and the fading higher partials on the

partials. Such a wide spectrum was created with high probability thanks to the massive double reed, where the lips usually touch it

with their larger surface near the tips and where very strong breath is needed to vibrate it. The recording was done using the Armenian Duduk made of Professional Apricot Wood from the manufacturer Pro Duduk clé A, Balaban, Musical Instrument Doudouk.

very quiet half-waves. The spectrum contains a lot of formants (see Fig. 7). The samples were recorded with the German type Püchner instrument, Rieger reed, 1.2 mm thickness of the bassoon reed blank, Rieger 1a template.

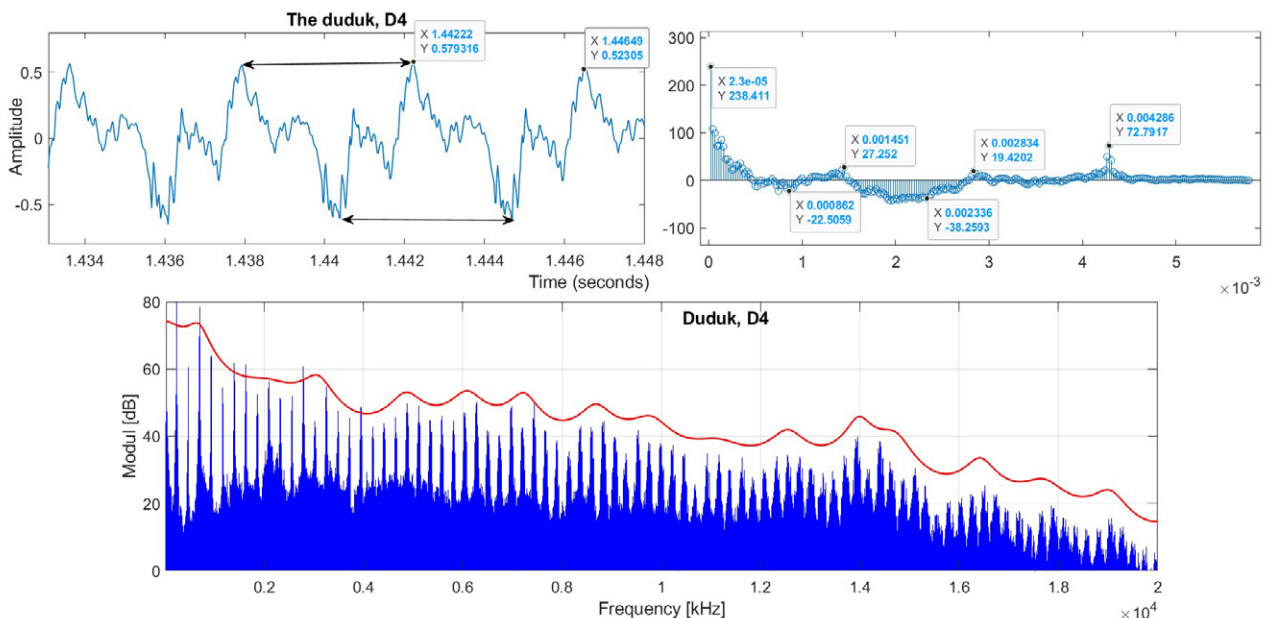


Fig.6: The duduk, D4

Bassoon tones in the lower position show a much wider (e.g. $1/10$, $1/8$), than tones in the higher registers ($1/3$, $1/2$). The C2 sample thus shows the width pulse $1/9$, in the quasi-closed phase there are 6 weaker negative and 5 positive half-waves, then 4 positive and 3 negative

In contrast, the bassoon C#4 played by the same instrument in the upper register shows a relatively slender spectrum with pronounced formants (see Fig. 8). The wave vibrates in the rhythm of the width pulse $1/4$, T. Grothe gives the switching tip $1/2$ for the same tone.

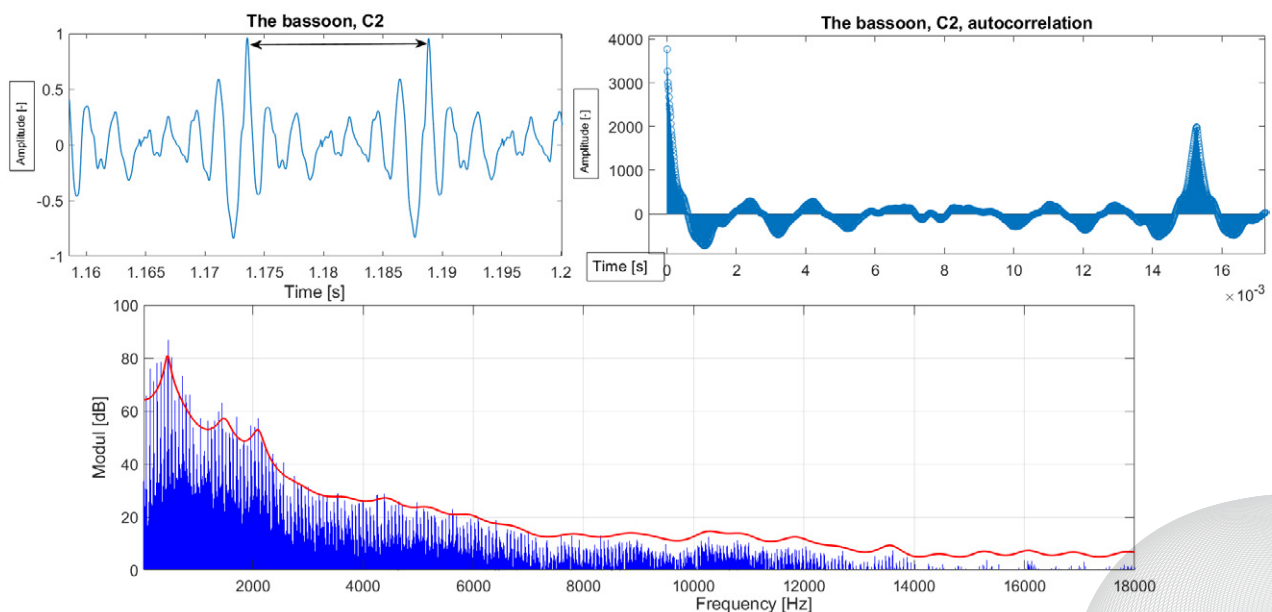


Fig.7: The bassoon, C2

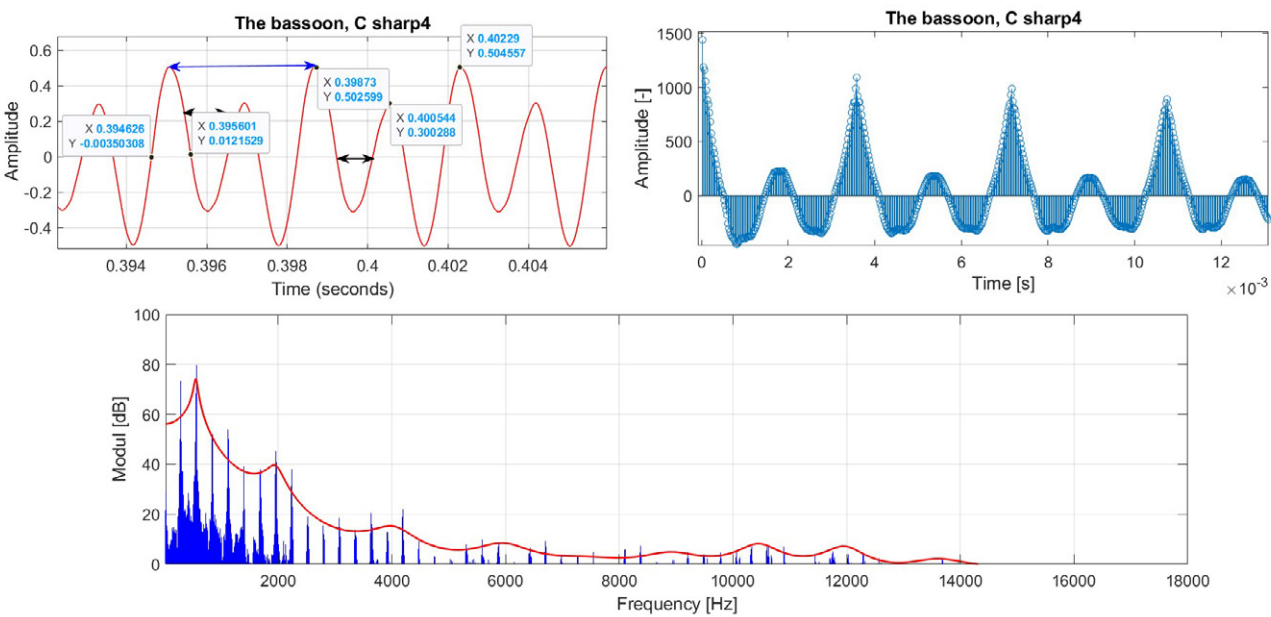
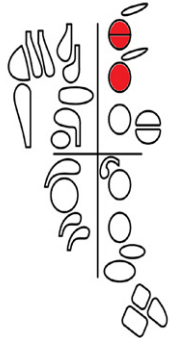


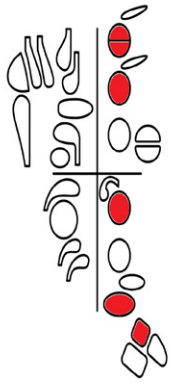
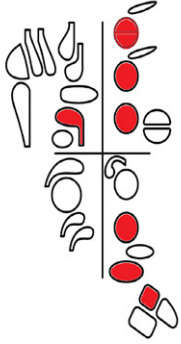
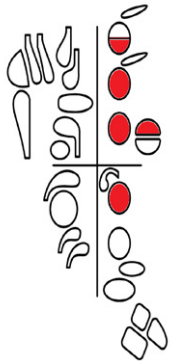
Fig.8: The bassoon, C#4

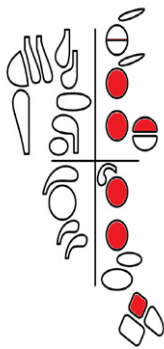
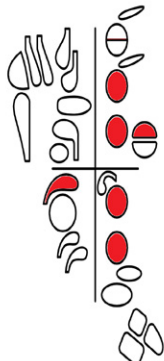
THE INVESTIGATED FINGERING

The sample from the *Introitus* contains a total of five notes, of which at least three allow for timbre correction, namely C#4, D4 and F#4. The note E4 can also be worked with, but it was not the subject of the study. The bassoon-

ist used basic fingerings for these notes, but also so-called alternative fingerings, where smaller hole areas create stronger resistance to breathing. A lot of takes were recorded with various fingering combinations, but in the end only takes 2, 3, 4, 7, 8 and 9 were selected. The individual tones that were cut out were also named accordingly to them, see a summary Tab. 1.

name	fingering	experience of bassoonists	played in events (takes)
basic D4		softer and darker in timbre	2

name	fingering	experience of bassoonists	played in events (takes)
alternative D4 with more resistance		fuller and brighter sound	8, 9
basic C#4		softer and darker in timbre	2
alternative C#4 with more resistance		fuller and brighter sound	7, 8, 9
basic F#4		rather narrower, weaker and brighter	2

name	fingering	experience of bassoonists	played in events (takes)
alternative F#4 with more resistance		fuller, the timbre blends better	3, 8
alternative F#4 with less resistance		lower dynamics and narrower sound	4, 9

Tab. 1: Fingerings

ANALYSIS OF THE COMPLETE PHRASE

To analyse the entire excerpt, versions 2, 8 and 9 were recorded, every with different fingerings. From several recordings of the same fingering, the best played one was selected. The complete phrase was analysed in terms of dynamics and timbre afterwards, with special attention paid to notes D4, C#4 and F#4. Phrases (takes) 8 and 9 were played at approximately the same tempo, take No. 2 slightly slower. Even so, the takes can be compared objectively – see Figure 9.

Although the chapter on the motivation of the research mentioned the intonation related to the fingerings used as one of the key criteria, our analysis of the entire excerpt and

the tones subsequently isolated from it is focused on only two parameters: dynamics and timbre. Not on tuning. However, tuning was also checked throughout the project, right at the beginning of the recording. The bassoonist tried to play intonation as cleanly as possible and as many recordings of a given fingering variant were made so that the intonation-solid, best one could be selected. We can check up the differences in intonation on Fig. 9, where the curves from phrases 2, 8 and 9 are plotted. We see that the differences in pitch are only minimal and only slightly arise, especially at the first tone D4, i.e. when the melody is introduced.

In the case of dynamics (Fig .10), the curves were plotted in units of psychoacoustic

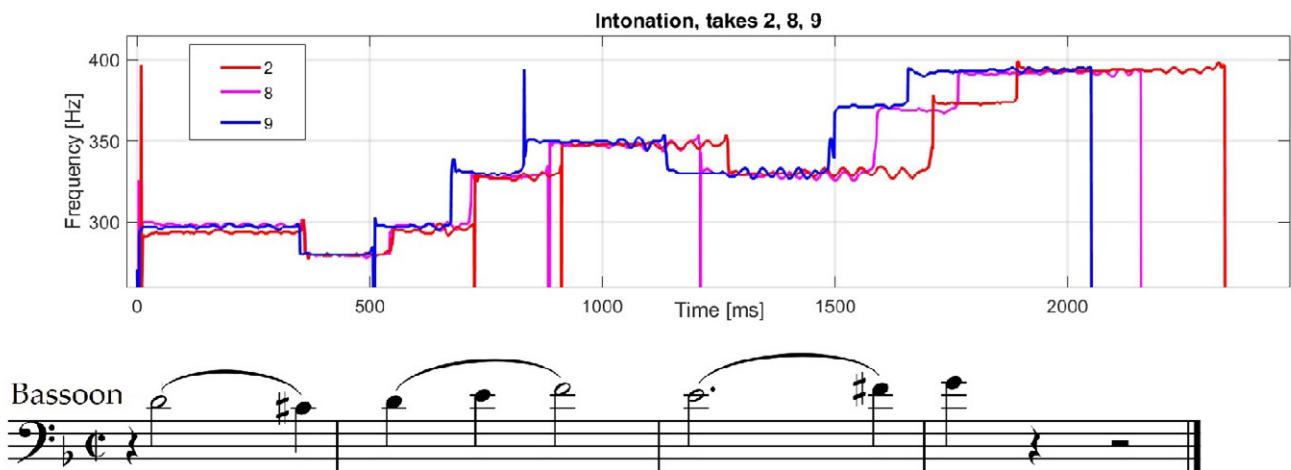


Fig.9: The intonation of takes 2, 8, 9

sones, i.e. how the intensity is perceived by the listener as the signal passes through the chain from the source, through air vibrations, through the outer, middle and inner ear to the brain. The curves are mostly identical, the biggest difference is found in the already mentioned tone C#4 in the take No. 2 compared to the almost dynamically identical takes 8 and 9. The difference is an average of 18 sones, which when converted to musical dynamics is an increase of one to one and a half dynamic levels (e.g. forte). Also worth noting in take No. 2 is the jump between the tones D4 and C#4, when C#4 drops to a level of up to 30 sones and then rises to 58 sones with sforzato articulation. The difference in the dynamics of the C#4 between takes No. 2 and takes 8 and 9 can also be expressed in terms of dynamic range of tone (its dynamic fluctuation). In the case of take No. 2, it can be calculated as 30 sones and in takes 8 and 9 only 20 sones. As for the examined tone F#4, the loudest was identified in take No. 9 at an average level of 74 sones and with a flat dynamic range (sforzato articulation) of only 18 sones. Dynamical-

ly, take No. 8 is the lowest with an average dynamic level of 49 sones and a wider average dynamic range of approximately 15 sones. Compared to the other two takes, take No. 2 generally shows the most dynamic sforzato in most tones.

If we compare our curves of sound pressure level and loudness with the graphs in the publication *Experimental Investigation of Bassoon Acoustics*, in figure 5.14 *Dynamic levels of the radiated sound in sound pressure level SPL and loudness* [8], the dynamic range for tones from D4 to G4 measured for five instruments is stated to be in the range of 73 to 84 dB SPL, i.e. from 18 to 49 sones. These takes were recorded at the same distance of 1.5 meters as ours and on average they also roughly correspond to our calculations. The investigated C#4 is at a level of 84 dB SPL (49 sones) for Timo Grothe and F#4 at the dynamic level of 82 dB SPL (43 sones). This fact also justifies the goal of our research – to optimize the fingering dynamic level of these "critical" bassoon tones.

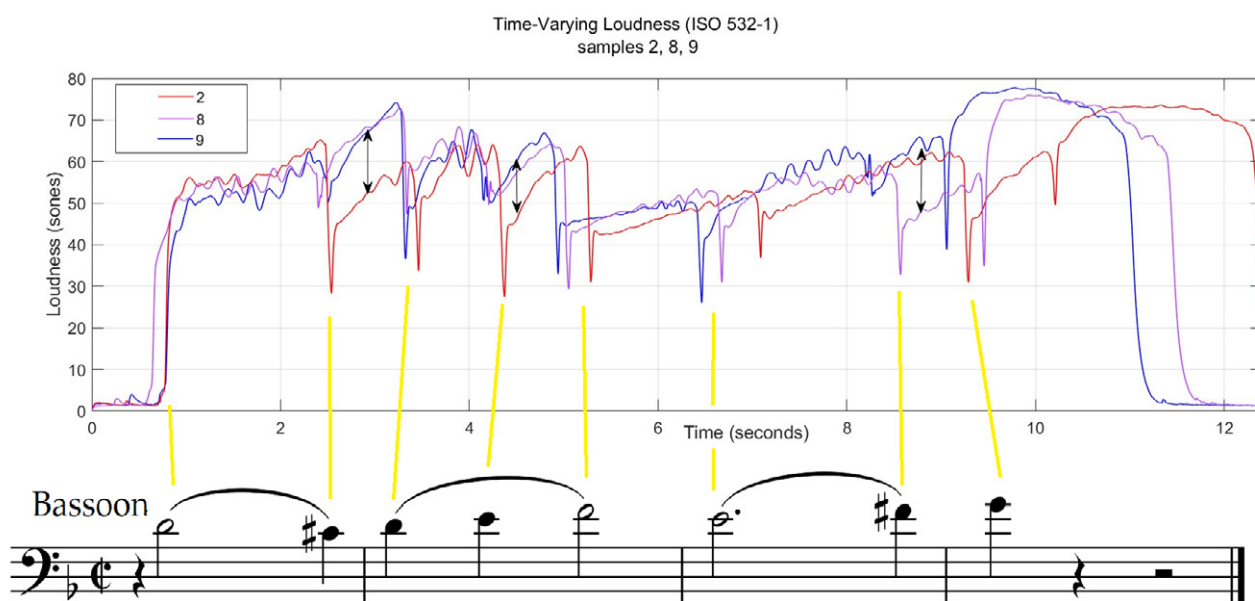


Fig.10: The loudness of takes 2, 8, 9

In order to compare the timbre, we cut out the individual tones C#4 and F#4 from the phrase and displayed the so-called periodograms using the FFT spectrum analysis [7]. For all takes, the calculation with the same parameters, including the Hanning window, was constantly used. Next, we estimated the outline of the spectrum and the formants in it using linear predictive coding (LPC) [16]. Here too, the same LPC order was observed for all takes. The three curves of takes 2, 8 and 9 were then plotted in a common graph – see Fig. 11, bottom image. As already mentioned in part “*The switching of double reeds*”, the formants – local maxima of the spectrum in the case of the bassoon, the cor anglais and the oboe are related to the switching of the double reed and their duty cycles, i.e. “the width of the pulse τ/T ” [13].

If we focus on the spectrum variants for the tone C#4, the most formant areas (approx. 7), and therefore the most typical double reed timbre, are found in the otherwise dynamically quietest take No. 2. Takes 8 and 9

lack the formants above 2 kHz (see black arrow), the partials here drop evenly, similar to the sawtooth signal, and the formants above 10.5 and 12 kHz are significantly weaker (see the second arrow). This means that the reed was probably already springy due to the lower air impedance in the bore, the low air pressure escaping from the larger area of wider or more numerous holes only moved the tip of the double reed and was not enough to vibrate the inner surfaces of the reed (heart). The sound of takes 8 and 9 will thus be closer to the timbre of string instruments (e.g. violin on the D string [17]) or brass instruments (the softer tone of the trumpet [17]).

If we compare our periodograms of the C#4 tone with the tables in T. Grothe’s publication (*Figure 5.15 Spectral metrics of the bassoon sound* [8]), we find confirmation for formants with centers above 0.6, 2, and 4 kHz, but in our analysis, we miss the formant above 1.3 kHz, and T. Grothe apparently did not include silent formants from 6 kHz (F5) and above.

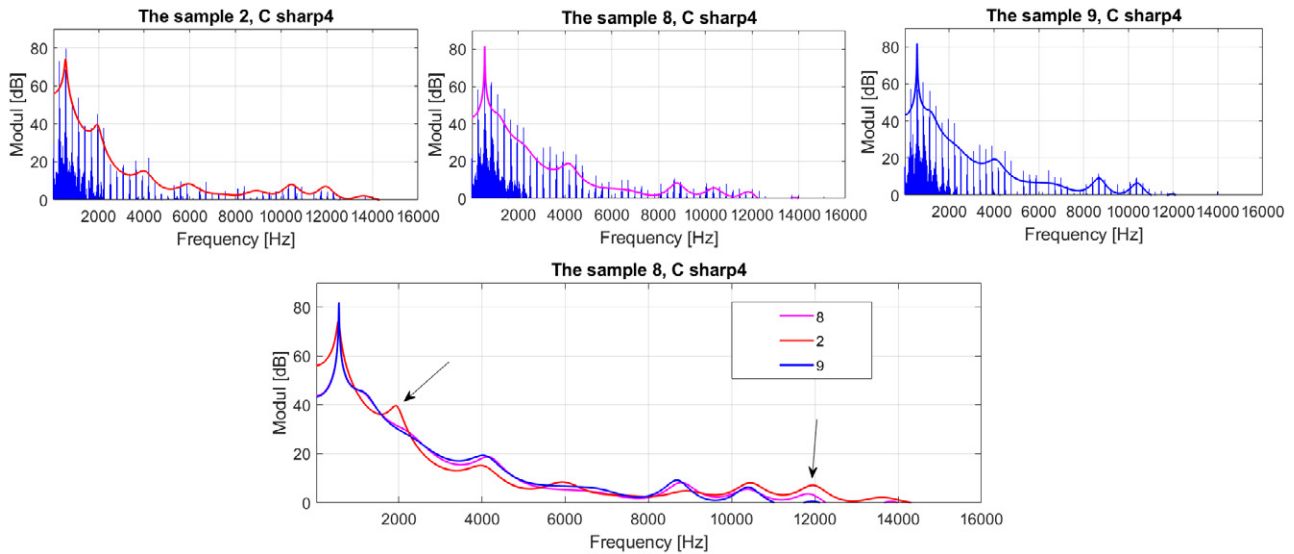


Fig.11: FFT and LPC of Cis 4, samples 2, 8, 9

In three samples of the F#4 tone, we find a similarity with the C#4 samples. The F#4 from sample 2 contains 8 to 9 more clearly drawn formant regions, while in sample 8 we find only about 7 of them and in sample 9 only

ing the center of mass of the (tonal) spectrum" [5]. How much higher the spectral centroid curve of the same tone will be placed, the wider the entire spectrum should be, the tone should sound fuller, and its brightness should be more pronounced (on the contrary, it will be darker). On the graph in Fig. 13, we notice that the samples differ mainly in the case of

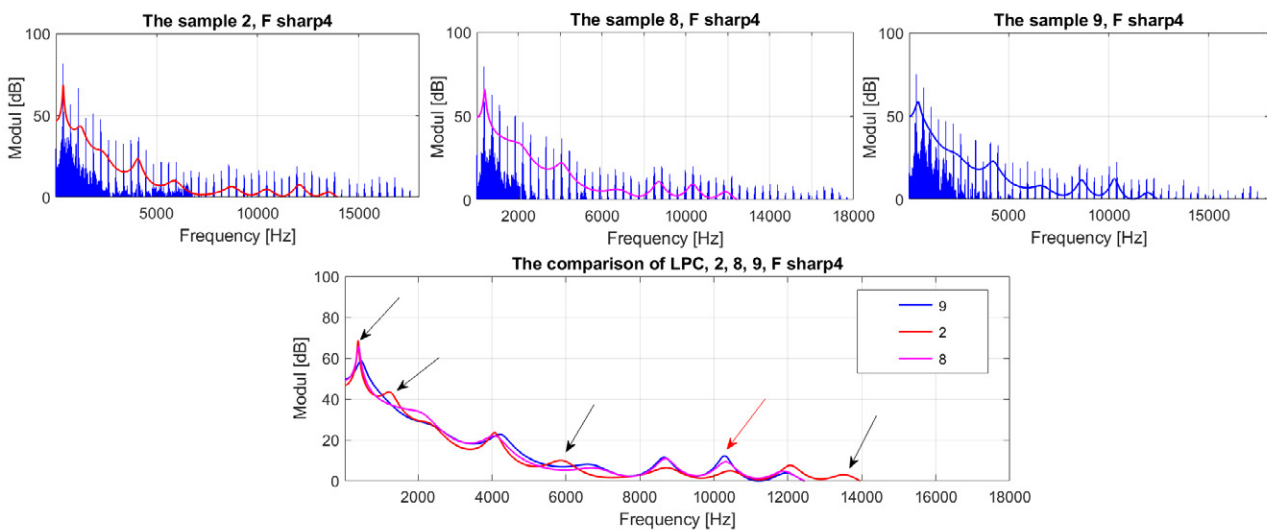


Fig.12: FFT and LPC of Fis 4, samples 2, 8,

6, see Fig. 12 black arrows. They mainly lack the first formant rise above 1 200 Hz (see red arrow), and especially in sample 9 the band from the first to about the eighth linearly decreasing partials again creates a timbre more corresponding to a sawtooth than a pulse (two-reed) signal. The measured spectrum also corresponds to listening by ear. Variants of the entire phrase and the cut-out tones C#4 and F#4 can be compared using the spectral centroid "consisting of estimat-

D4, C#4 and F#4, namely by the lower-placed curve of sample number 8. Its spectral centroid in the case of C#4 is located at about 100 Hz (G2 tones) lower than in samples 2 and 9 (see Fig. 13 double black arrow), and in case of F#4 the curve lays about 60 Hz (B1) lower than in samples 2 and 9 (see Fig. 13 double black arrow). It can therefore be said that although this sample No. 8 does not show a typical bassoon timbre, it is significantly darker than the other two (F#4, however, is here one dynamic level quieter here).

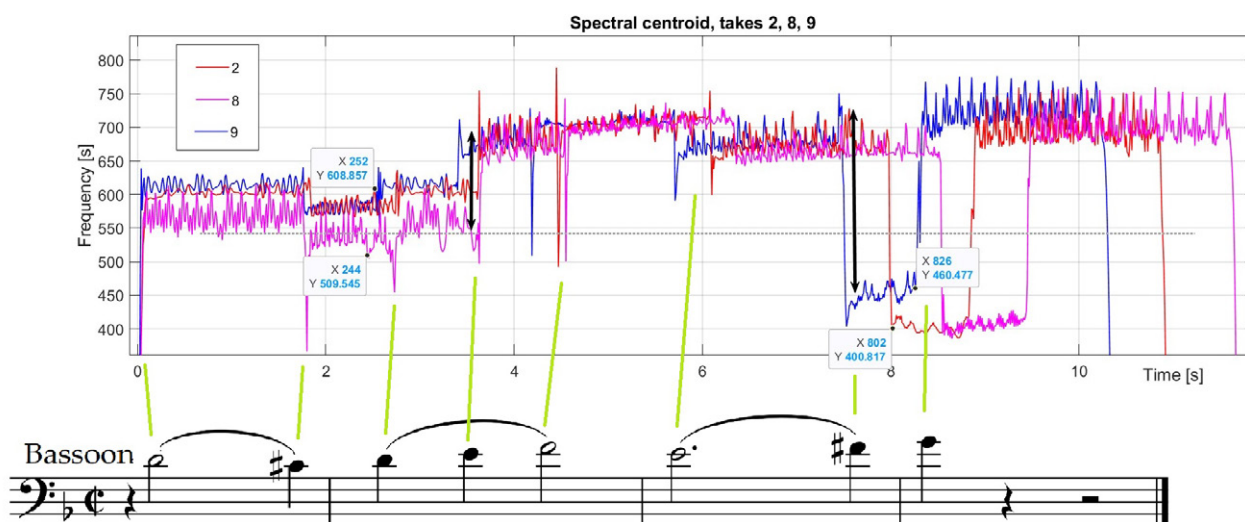


Fig.13 The spectral centroid of takes 2, 8, 9

It is worth noting the spectral centroid of F#4, which drops significantly down compared to the melody contour, up to 300 Hz. This indicates that in all three cases (takes 2, 8, 9) the spectrum of F#4 is significantly narrowed and the tone pales within the surroundings of others.

Analysis of Single Tones

To verify the dynamics and timbre of C#4 played with other fingerings, they were cut out from complete phrases and this time only displayed as a periodogram and LPC in samples number 3 and 4 (see Fig. 14). Sample 3 with about eight formants shows a similar, slightly softer timbre as sample no. 2 and sample no. 3 with six drawn formants has a timbre similar to the sample 9.

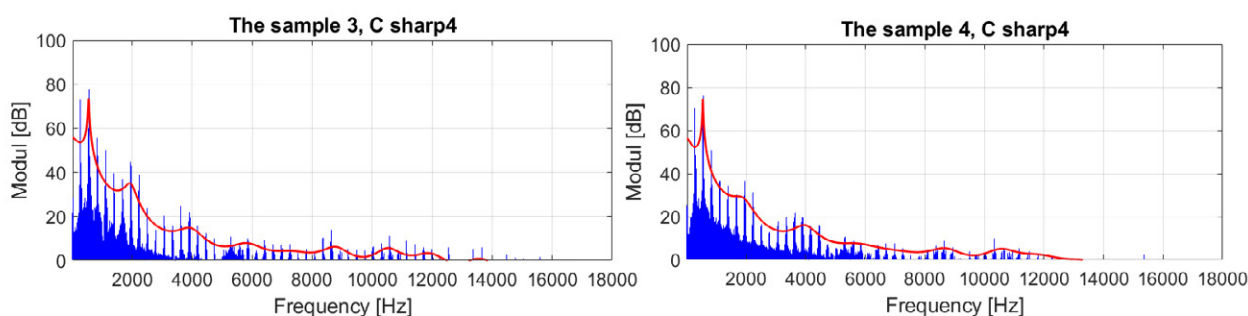


Fig.14: FFT and LPC of C#4, samples 3, 4

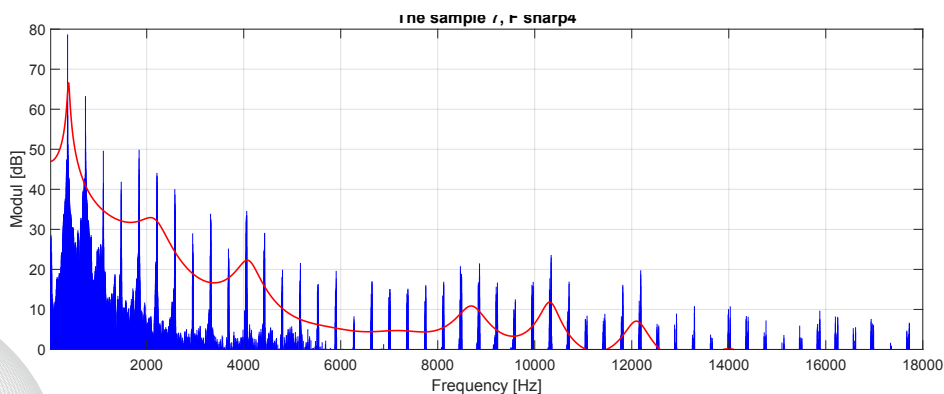


Fig.15: FFT and LPC of F#4, sample 7

All five (2, 3, 4, 8, 9) cut samples of the C#4 tone can be found compared to each other below, in the sharpness and clarity graphs and the parameter table. The sharpness parameter is based on a different calculation methodology than the already mentioned spectral centroid, or brightness. The 24 bark bands play an important role here, each with its own sharpness coefficient in connection with the sensitivity of the cochlea in the inner ear. Not only harmonic but also noise components are included in the measurement and "Von Bis-

sample 2, the highest level 1.85 acum is shown in sample 3 (every sample begins on whole second). The evaluation of these samples is supplemented by brightness measurements [17], where samples 2 and 4 are identically the darkest (see Fig. 16, the bottom graph).

For selected samples Cis4, D4, Fis4 from takes 2, 3, 4, 8 and 9, the average values of acoustic pressure, loudness, spectral centroid, sharpness and brightness were calculated. These were then arranged in Tab. 2 below for com-

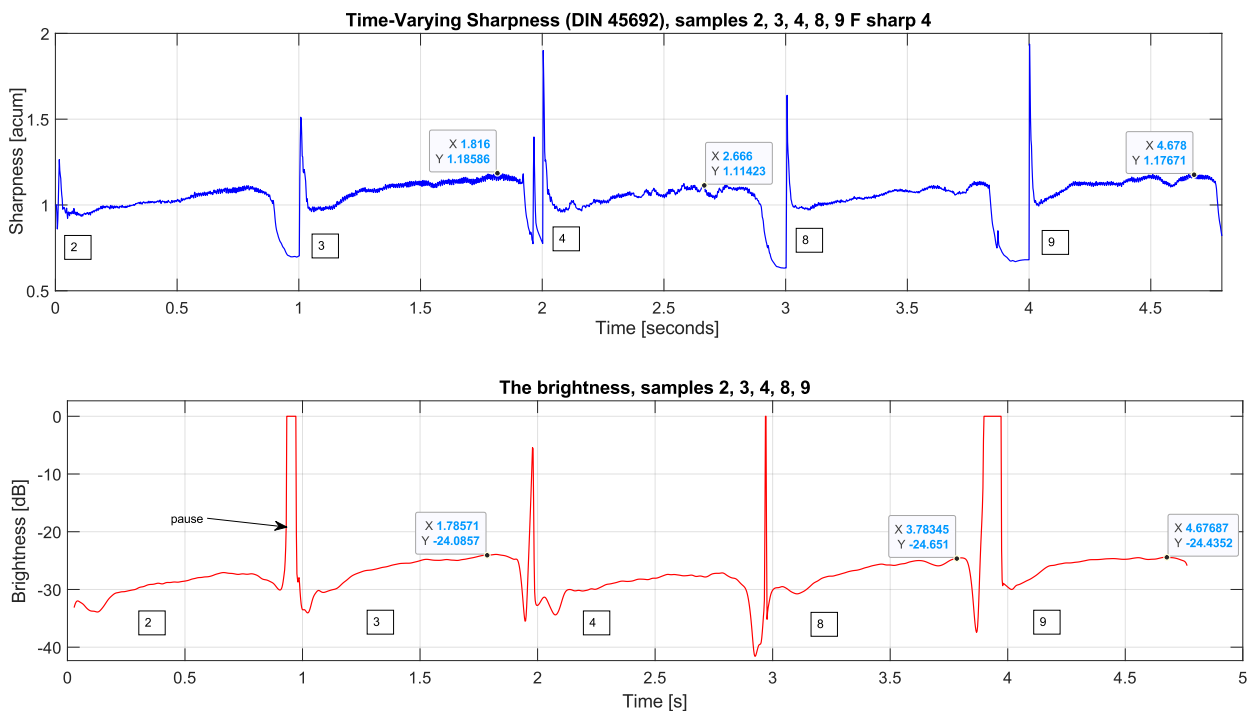


Fig.16: The sharpness and brightness of F#4 samples 2, 3, 4, 8, 9

marck's and Aures's methods of weighting curve" [6] complement the calculation. The unit is 1 acum, "a narrow-band noise centred at 1 kHz" [8] with a level of 60 dB. In graph in Fig. 16, we see that the lowest sharpness of around 0.85 acum is shown by beginning of

parison. Tab. 3 with a simple verbal description describing the character of each sample (tone) is also attached to it. The measured "hard" data can thus be compared with the experiences of bassoonists and verify how well they match.

fingering	SPL (dB SPL)	Loudness (son)	No of formants	spectr. centroid (Hz)	sharpness (acum)	brightness (dBFS)
basic D4	86.04	55.68	7	568.9	0.8789	-41.05
alternative D4 with more resistance	84	48.76	6	603.7	0.9089	-29.46
basic C#4	84.6	50.68	7	535.1	0.8702	-38.95
alternative C#4 with more resistance	87.8	63.12	5	581	0.9668	-37.49
basic F#4	85.12	52.56	8	406.8	1.03	-29.34

fingering	SPL (dB SPL)	Loudness (son)	No of formants	spectr. centroid (Hz)	sharpness (acum)	brightness (dBFS)
alternative F#4 with more resistance	83.82	47.84	7	406.2	1.053	-26.8
alternative F#4 with less resistance	81	39.57	6	385	1,05	-29.02

Tab. 2: The comparison

fingering	characteristics according to measurements
basic D4	stronger in volume, timbre of pulse, wider spectrum, sharper and brighter
alternative D4 with more resistance	medium volume, inclining to timbre of saw, wider spectrum, sharper, darker
basic C#4	medium strong, timbre of pulse, wider spectrum, less sharp, bright
alternative C#4 with more resistance	stronger, more timbre of saw, wider spectrum, less sharp and bright
basic F#4	medium strong, timbre of pulse, narrower spectrum, slightly sharp, darker
alternative F#4 with more resistance	quiet, more timbre of saw, narrower spectrum, slightly sharp, dark
alternative F#4 with less resistance	quiet, timbre of saw, narrower spectrum, slightly sharp, darker

Tab. 3: Characteristics according to measurements

DISCUSSION

The question is how much it bothers that, due to the timbre-suitable fingerings, the melody has dynamic gaps of one and a half levels down (i.e. from mf to mp). The reverberation of the hall, for which the *Requiem* is intended by its instrumentation, evens out the dynamic contour of the melody by making the reflections extend all the notes in the melody. The louder notes grow lengthwise into the tone of the quieter ones and cover the dynamic gaps that arise there. The *Introitus* has a prescribed Adagio, i.e. about 50-60 BPM, and the chamber-type reverberation with a reverb phase of 500 to 850 ms will turn quarter notes into quarter notes with a half or even half dotted (but with a fading release phase). And what about the hall-type reverberation of 2 -2.5 seconds? Of course, the louder notes will partially mask the following quieter ones.

Of course, both brightness and sharpness are subsequently influenced in the acoustic chain by the frequency characteristics of the halls. However, we were interested in these parameters as dry signal, i.e. the pure timbre of the instrument. Subsequently, it is possible to es-

timate how the hall acoustics will be changing this original timbre.

So which combination of fingerings was the most suitable for the opening entry of the *Introitus* section? The optimal approach seems to be the use of basic fingering in combination with appropriate wind technique and imagination, i.e. preferably at lower dynamics. These fingerings are also closest to the timbre of the original instruments and with a soft and darker timbre they guarantee excellent results. In general, with double reeds, the softer and darker timbre of the sound of the mechanism combines better in timbre and intonation, especially with other wind instruments.

Although we have measured the now standard psycho-acoustic parameters, it would be appropriate for our analysis to be supplemented with listening tests that would determine where the boundaries are within which the timbres that make up the mixtures (the *Introitus* entry) can move. Generally, a narrower pulse timbre will indicate a two-reed instrument more, and conversely, a fuller and sharper sawtooth signal will indicate strings or brass. And here, a fuller bassoon could be

similar in timbre to a French horn and not create the appropriate timbre contrast or even be confusing. However, the tone of a bassoon is not only formed by the quality of the static spectrum, but transients also play an important role here, slight vibrato and other processes occurring in the tone. In other words, these elements can then compensate for the atypical bassoon spectrum.

Listening tests can thus indicate to a certain extent which timbre/touch is more suitable for the *Requiem* within a given instrumentation, or more appealing to the listener in the context of other instruments. Listening should also indicate how, for example, different samples of C# and D# connect with the basset-horn and strings. Although players and sources state that the basset-horn sounds like a softer clarinet, in its higher "clarine" register, where it complements the bassoon in a fugue in the *Introitus*, it may not resemble the clarinet timbre with its predominant odd partials (see Fig. 17). As a result, the difference between single and double reed can be erased and the semantic meanings of the two different timbres (understood, for example, as hollow and soft) can be lost.

esting recordings can be evaluated using both acoustic and psycho-acoustic metrics and supplemented with experimental listening.

CONCLUSIONS

An excerpt of the first four bars of the *Introitus* part from W. A. Mozart's *Requiem* was chosen for the study, which lies in the higher register of the instrument, i.e. the 4th octave. The takes were recorded on the Fox instrument in an anechoic room at the BUT Brno. The numerical calculation was performed using the Matlab program. Algorithms evaluating loudness in sones units and supplemented with dB SPL levels were used for the analysis, LPC was used to plot formants, FFT periodograms were calculated to evaluate the quality of the spectrum, and brightness, sharpness, spectral centroid were also measured. The duty cycle of the wave, including the constant width pulse in connection with other double reed instruments, was taken into account.

The data obtained from various fingerings were compared and evaluated in this way, and

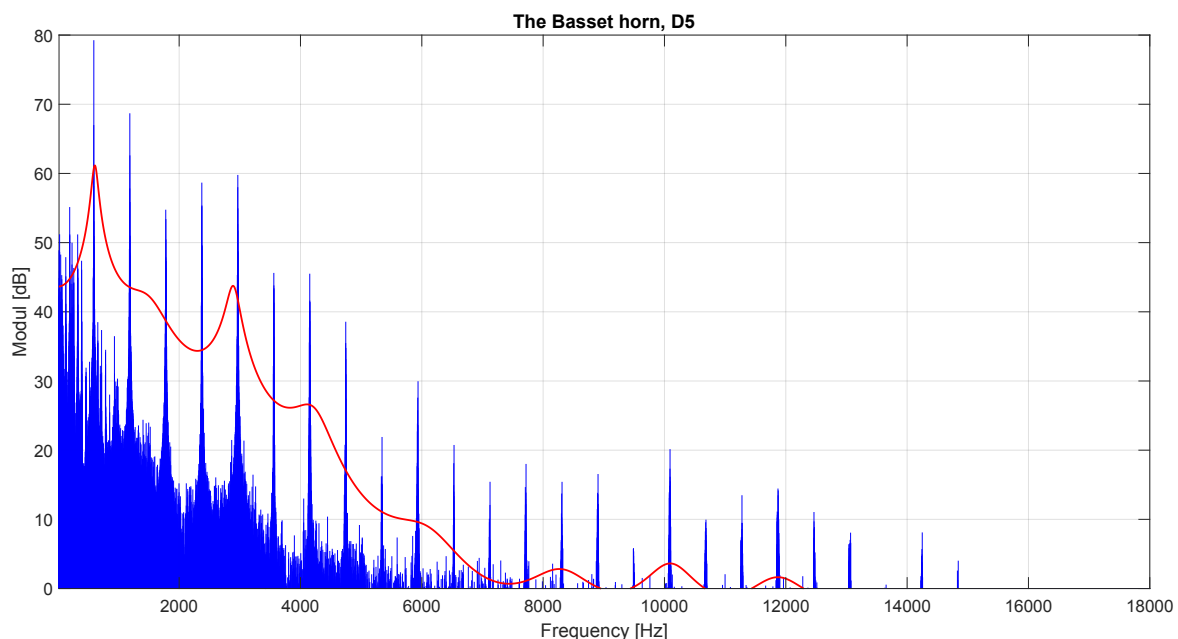


Fig.17: The basset-horn, D5

And of course, nowadays there is an exposed interdisciplinary discipline – the analysis of music performances, where the most inter-

also from the point of view of aesthetics, i.e. how suitable each fingering is for the given style and various interpretations, what are its strengths and weaknesses. New information was verified within the works of research

concerning mainly the mechanical-acoustic properties of the bassoon, but also numeric simulations of the double reed signal. The discussion states what other research should further verify and supplement this analysis.

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