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A clarinetist's exploration of clarinet tone through advanced technique, instrument configuration and acoustic impedance

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In this work, sound, pitch and spectral production/control is explored on the clarinet with reference to the measured impedance of different standard/advanced fingerings and instrument configurations used in the author's performance practice. Instrument configurations include the mouthpiece with barrel, with barrel and upper joint (upper demi-clarinet), with lower joint and bell (lower demi-clarinet) and the complete clarinet. Sound spectra of select pitches produced by the author using advanced techniques and above configurations (and several non-standard fingerings) are analyzed next to the magnitude of the corresponding measured impedance. The alignment of peaks in spectral and impedance magnitudes are studied and used to better understand the tone's spectral varieties and possible difficulties in its steady sound production and tuning. This study is a means of informing the performer's musical performance practice, highlighting sound production possibilities and limitations. As this study also involved producing a significant increase in available impedance measurements for the clarinet, it is hoped that it will also serve to inform future research and de-velopment in clarinet synthesis (while further enhancing the performer's tools for live performance). This study allows acoustic effects/principles to be observed and heard from the perspective of an accomplished performer—considering both the player and the instrument.

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1. INTRODUCTION

In instrumental performance practice for contemporary music, extended techniques and instrument modifications/preparations are often used by composers and instrumentalists to add sonic variety to a performance. When used effectively, these techniques can allow the performer to craft a distinct sound world for the audience to experience. Each instrument has its own unique possibilities for idiomatic extended techniques and modifications/preparations.

In contemporary clarinet performance practice, common extended techniques include multiphonics, microtones, overblowing, glissando, flutter tongue, slap tongue, and growling, among others.[1,2] While these techniques rely on the player's ability to manipulate the vocal tract and control blowing/mouthpiece pressure through embouchure adjustment,[3–7] they are often facilitated by an extensive range of fingerings specific to the possible pitches and/or sounds that may be generated by their use,[1,2,8] each one changing the clarinet's acoustic response (or *acoustic impedance* as discussed in Section 2).

Modifying the instrument itself is another way to enable sonic variety. The B-flat soprano clarinet, the most commonly used clarinet type, is made with five separate interlocking parts: the mouthpiece, the barrel, the upper joint, the lower joint and the bell, allowing for the following partially assembled (incomplete) clarinet configurations in addition to the full instrument (see Figure 1. Since configurations consisting of approximately half of the instrument are known in the clarinet community as *demi-clarinets*, a term coined by composer and clarinetist William O. Smith, configurations with upper and lower joints are henceforth referred to as upper and lower demi-clarinets, respectively. Clarinet configurations considered herein are further discussed in Section 3.

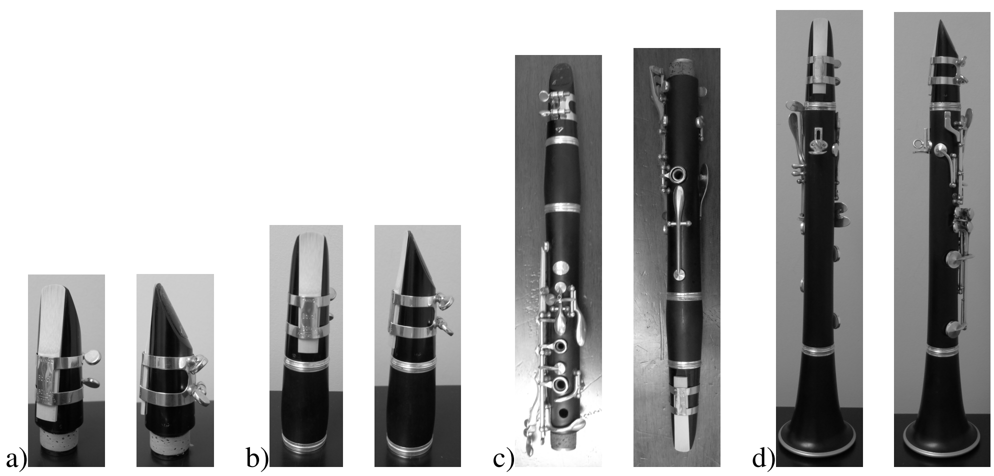

Figure 1: Two views of each of four (4) clarinet configurations: a) mouthpiece alone, b) mouthpiece with barrel, c) mouthpiece with upper joint (upper demi-clarinet) and d) mouthpiece with lower joint and bell (lower demi-clarinet).

Successfully composing and performing with extended techniques requires a deep sensitivity of the musician to the response of the instrument. While a clarinetist, with a great deal of practice, can gain an intuitive understanding of how to control the instrument, the teachings of extended techniques can sometimes seem subjective, making them difficult to learn, let alone to master. Drawing connections between a player's experience and the acoustic characteristics of the clarinet (its response at different frequencies) can provide a greater understanding of the instrument's physical possibilities and limitations, possibly making the practice of extended techniques more intuitive and/or even providing insight into the development of pedagogical methods.

In this work, the authors initially collect impedance measurements for standard fingerings of a Bbclarinet (Yamaha Custom CX) made freely available online[9] (data referred to by UNSW) and then take significant additional measurements of extended non-standard fingerings and configurations of the author's own clarinet (Buffet Festival b-flat) at the Centre for Interdisciplinary Research on Music Media and Technology (CIRMMT) which is housed at the Schulich School of Music of McGill University (data referred to by "McGill"). In addition, sound examples are recorded by the author/clarinetist and the spectral magnitudes are observed and analysed next to the magnitude of the corresponding measured impedance, with the aim of gaining a better understanding of the impedance's effect on the production of more novel sonorities produced by extended/advanced playing techniques, possibly better informing musical practice and further discovery and production of new sounds.

In Section 2, two sets of impedance measurements of a standard fingering (UNSW and McGill) are compared and shown next to the sound spectra made by the author by playing (and overblowing) the fingering for pitch E3. In Section 3, additional measurements of more non-standard fingerings and instrument configurations (McGill) used in extended/advanced playing techniques are considered, with comparisons made to sound recordings at several pitches. Finally, in Section 4, conclusions and possible future work is briefly discussed.

2. MEASURED IMPEDANCE OF STANDARDIZED FINGERINGS

It is well know that the ease and limitation of producing a particular tone on a clarinet with an applied fingering and/or configuration may be described, at least in part, by its corresponding acoustic impedance Z.[10–13] The impedance, defined as the ratio of acoustic pressure p to the volume flow U as functions of frequency, is a physical property of the instrument that is dependent on its configuration and/or the applied fingering and may be measured in isolation of the player blowing into the mouthpiece (though, of course, the presence of the player applying fingerings during measurement is essential).[14] The change of Z as a function of frequency, the magnitude of which is displayed using impedance curves, yields the acoustic response of the instrument at all measured frequencies: that is, a peak in the magnitude of Z at a particular frequency implies that an input of acoustic flow at that frequency will produce a corresponding strong pressure response at the same frequency —a favorable region in the spectrum for efficient sound production. The clarinet has many unique fingerings, and each fingering has a corresponding impedance curve, an important factor in determining the stability, intonation and timbre of sounds produced with that fingering.[9]

Initially the authors' study relied on an online collection of such impedance curves (UNSW), graciously made available by UNSW for mostly standardized fingerings of the B-flat clarinet (Yamaha Custom CX including mouthpiece), with a smaller number of multiphonic and A clarinet fingerings also included.[15] Impedance measurements of the author's own clarinet (Buffet Festival B-flat) were later taken at McGill University, with a theoretical mouthpiece prepended (McGill). As shown in Fig. 2, the two separate measurements of different B-flat clarinets align very closely for the first five (and most significant) peaks. The differences observed above approximately 1400 Hz may be due to the fact of the different instruments, the inclusion of a mouthpiece in the measurement (UNSW) versus prepending a theoretical mouthpiece to the measurement (McGill), normalization differences and/or differences in the measurement technique/apparatus/location.

Measurements (UNSW and McGill) are plotted against the spectral magnitude of several sound recordings made by the author using corresponding fingerings and employing advanced overblowing techniques. A comparison is shown for the E3 fingering (the clarinet's lowest note) in Fig. 2. The recording was made using an omnidirectional condenser microphone placed approximately 10 cm from the bell.

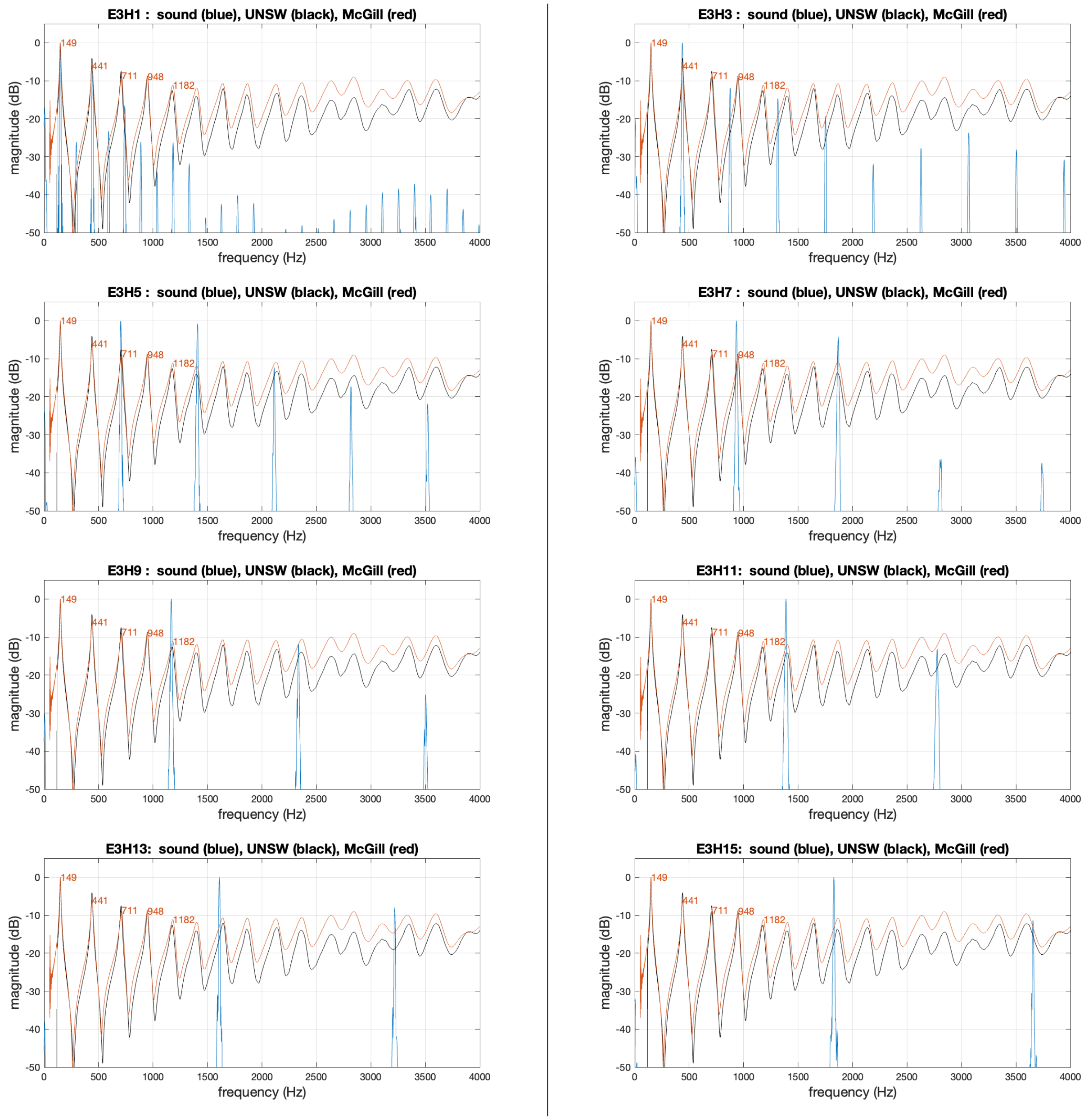

Figure 2: The spectrum of a note played using an E3 fingering, overblowing each of eight (8) impedance peaks, labeled H1, H3, . . . , H15 for the near odd-harmonic relationship with the first peak. The sound spectrum is plotted against measured impedance curves of a different clarinet (Yamaha Custom CX) from UNSW (black) and the same clarinet (Buffet Festival B-flat) measured at McGill University (red).

A. OBSERVATIONS ON E3

Notice in Fig. 2 that, while the first peaks of the sound spectrum align with impedance peaks, greater misalignment can be observed with an increase in frequency, the result of juxtaposing a harmonic sound spectrum with impedance curves that have a more "compressed" spectral distribution of peaks with frequency (the bell effectively increasing the clarinet length with frequency[16]). Notice also that, as expected, peaks in the sound spectrum tend to have a greater relative magnitude when they align with peaks in the impedance. While this is most obvious in the first and third harmonics (see Fig. 2, E3H1), increased magnitude can also be observed in the sound's 5th harmonic (as compared to the neighboring 4th and 6th harmonics), and the 8th harmonic (as compared to neighboring 7th and 9th harmonics), showing that the clarinet's "odd harmonic spectra" is only valid up to a certain frequency.

For most notes overblown on E3, the fundamental (sounding) frequency aligns with a peak in the impedance curve (though greater misalignment occurs in examples E3H13 and E3H15). Several upper harmonics of the sound spectrum, however, have less magnitude because of their relative misalignment with peaks in the impedance: see harmonics 3, 4 and 5 (E3H5), harmonics 3 and 4 (E3H7), harmonic 3 (E3H9) and harmonic 2 (E3H9) in Fig. 2. For E3H7 and above, the author/clarinetist experiences more difficulty sustaining a steady tone and the pitch begins to waiver (likely due to fewer supporting harmonics helping to establish and sustain the pitch). The misalignment with the fundamental is particularly noticeable in E3H13 and E3H15 and overblowing these notes produces considerable strain on the embouchure, with the pitch becoming increasingly flat. Finally, note that all overblown notes (above E3H1 in Fig. 2) do not have and "odd harmonic spectra" for which the clarinet sound is sometimes known.

3. NON-STANDARDIZED FINGERINGS AND NEW IMPEDANCE MEASUREMENTS

Following the analysis of sound spectra and impedance measurements for standardized fingerings (UNSW), the authors further expanded the collection to include possible non-standard fingering measurements for extended playing techniques (McGill). Measurements at McGill University were taken using the CapteurZ impedance measurement system from CTTM, Le Mans, France (designed by Jean-Christophe Le Roux and Jean-Pierre Dalmont) with a prepended theoretical mouthpiece using the Transfer Matrix Method (TMM). In addition, measurements were also made of instrument configurations as it is a practice of the author to play on deconstructed partial instruments during performance. Figure 1 shows the four (4) clarinet configurations for which additional impedance curves were obtained:

1. mouthpiece with the barrel,
2. mouthpiece with the barrel and the upper joint or *upper demi-clarinet* and
3. mouthpiece with the lower joint and bell or *lower demi-clarinet*.

Each demi-clarinet has its own collection of numerous possible fingerings, a selection of measurements for which is shown for the upper demi-clarinet in Fig. 3.

Recorded sound examples are made for several clarinet pitches: Ab4, C#5, D#6, G#5 and C7 (concert pitch being a full tone lower), each with 2 or more possible extended techniques and fingerings and/or configurations used to generate the tone. The spectra are compared to corresponding impedance curves in Fig. 4.

A. DISCUSSION ON PITCHES WITH EXTENDED FINGERINGS/CONFIGURATIONS

Pitch Ab4 from Fig. 4 was recorded on the complete clarinet using the normal fingering for this note (impedance Z:g#4b) as well as on the lower demi-clarinet using a non-traditional fingering (Z:ld4). In the impedance curves, the positions of the first two peaks are similar, and the fundamental of both recorded

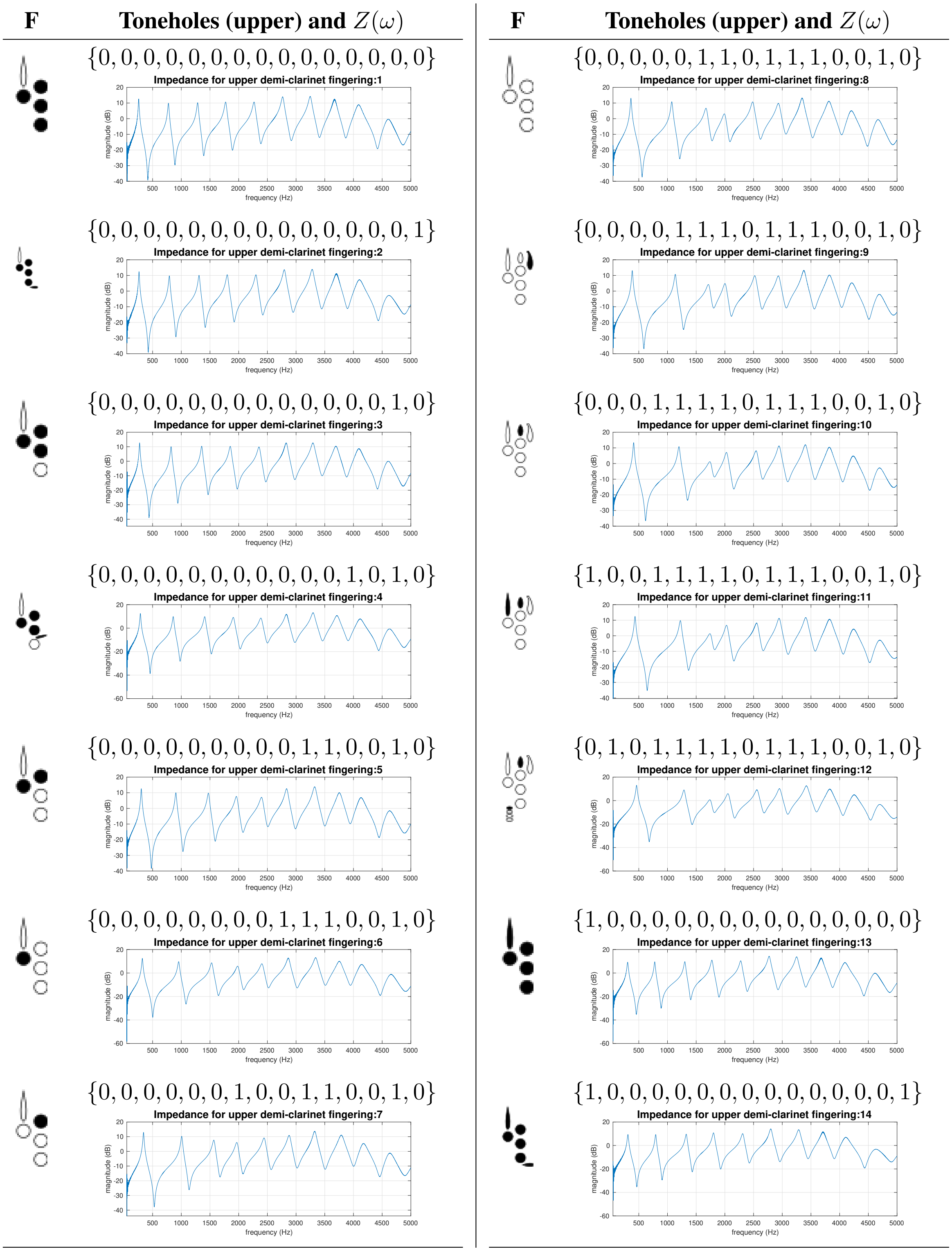

Figure 3: Example upper demi-clarinet measured impedance curves for fourteen (14) fingerings (F) with vectors showing corresponding open ('1') and closed ('0') states for all fifteen (15) toneholes of the clarinet's upper joint.

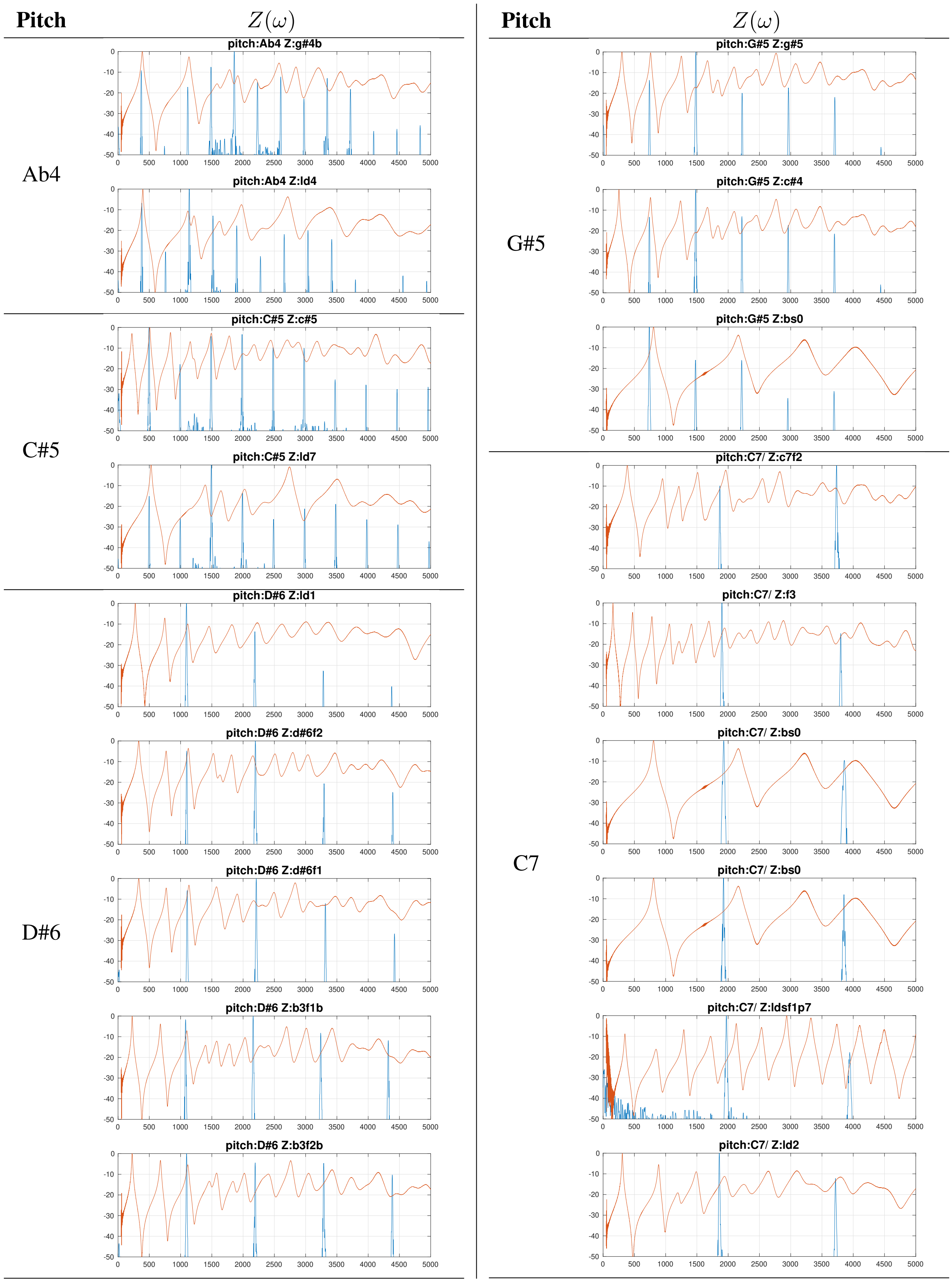

Figure 4: Recorded sound examples (blue) of several pitches are juxtaposed with impedance curves of corresponding configuration/fingerings that were used to generate the tone.

sounds align well with corresponding impedance peaks, with the pitch of the demi-clarinet appearing slightly higher and its second harmonic more prominent (in spite of the split peak in the impedance with which it is most aligned). The impedance curve of the complete clarinet has two (roughly) harmonic peaks, with the higher peaks being closer together and irregularly spaced. In contrast, the demi-clarinet impedance does not have any obvious well-defined peaks that are (even roughly) harmonic to the first peak, with the higher frequency peaks being broader and undefined.

Pitch C#5 from Fig. 4 was also recorded on the complete clarinet using the normal fingering (impedance Z:c#5) and on the lower demi-clarinet using a non-traditional fingering (Z:ld7). When played on the complete clarinet, C#5 is in the second register (aka the clarion register). It is played with the same fingering as F#3 with the addition of the register key. Playing any note above the fundamental/chalumeau register can be thought of as overblowing, although clarinetists do not regularly speak of it in this way. Furthermore, for inexperienced players just learning to play in the clarion register, it is common to hear a presence of the corresponding chalumeau register tone. Notice that the recorded sound fundamental aligns with the second peak in the impedance curve. In contrast, for the lower demi-clarinet the recorded sound fundamental aligns most closely with the first peak in the impedance curve, and this indeed is the lowest pitch that can be produced with this demi-clarinet fingering. Both recordings have about the same fundamental frequency. Interestingly, the most prominent partial in the complete clarinet recording is the fundamental, which makes sense given that it aligns with the strongest peak in the impedance curve. The most prominent partial in the lower demi-clarinet recording is the third partial, which does not align with an impedance curve peak (leading to speculation that it might possibly be supported by the vocal tract).

Pitch D#6 from Fig. 4 was recorded on the lower demi-clarinet and on the complete clarinet using four different fingerings. Two of these fingerings were traditional altissimo register fingerings (impedances Z:d#6f1 and Z:d#6f2) and two were similar fingerings normally used to play B3 in the chalumeau register with the register key removed and the first left-hand tone hole closed (Z:b3f1b, Z:b3f2b). In normal altissimo fingerings, the register key is open and the top left-hand tone hole is typically open. The lower demi-clarinet fingering had all tone holes closed, and the pitch was produced through overblowing (Z:ld1). In all five plots for this pitch, the fundamental of the recorded sound aligns with the third peak in the impedance curve. In the recorded sound spectra, the fundamental is the strongest frequency for the lower demi-clarinet recording (Z:ld1) and one of the overblown fundamental register fingerings (Z:b3f2b). In contrast, in the two recordings produced with traditional altissimo fingerings (Z:d#6f1 and Z:d#6f2) and the other overblown fundamental register fingering (b3f1b) the second partial has the greatest magnitude.

Pitch G#5 from Fig. 4 was recorded on the complete clarinet using two different fingerings and the mouthpiece with barrel. One of the complete clarinet fingerings was the traditional G#5 fingering (impedance Z:g#5) used in the clarion register and the other was the traditional C#4 fingering (Z:c#4) used in the chalumeau register. The only difference between these fingerings is that the G#5 fingering has the register key depressed and the C#4 fingering does not. It is possible to play G#5 with either fingering, but it is more strenuous to play it without the register key. The impedance curves make it clear why adding the register key makes G#5 easier to play with its normal fingering since the second peak has a greater magnitude for the normal G#5 fingering. Overall, the high frequency content in the regular G#5 fingering is shifted upwards in magnitude compared to the regular C#4 fingering. However, the played sound spectra for these two fingerings look very similar. The impedance curve and played sound spectrum for the mouthpiece with barrel both look much different than the complete clarinet impedance curves and spectra. The impedance curve peaks are much broader and spaced farther apart. In the played sound spectrum, the fundamental peak is positioned slightly below the first impedance peak's center frequency. In the complete clarinet recording spectra, the second partial has the greatest magnitude. In the mouthpiece with barrel recording spectrum, the fundamental has the greatest magnitude. Notice that in the mouthpiece plus barrel recording spectrum, the fundamental is closest to the first impedance peak, but in the complete clarinet recordings the fundamental aligns with the second impedance peak.

Pitch C7 from Fig. 4 was recorded on the complete clarinet using two fingerings, the lower demi-clarinet using two fingerings (one stopped and one open), and the mouthpiece with barrel. Interestingly, none of the recorded sound spectra align accurately with an impedance curve peak. They all are positioned either slightly (or significantly) below an impedance curve peak (again leading to speculation that the sound's harmonic peak may possibly be supported by a tuned vocal tract resonance). In this extremely high frequency range for the B-flat clarinet, there are many possible fingerings for C7, one of which for the complete clarinet (impedance Z:c7f2), has the register key depressed, the thumb and first finger tone holes closed in the upper joint, and the first finger tone hole and Ab/Eb key depressed in the lower joint. The other complete clarinet fingering is the normal fingering for F3 (Z:f3). The impedance curve reveals why the more traditional C7 fingering is more effective since the peak that the fundamental of the recorded sound aligns with best is higher in magnitude than the peak at roughly the same frequency for the F3 fingering. The impedance curve used for the mouthpiece with barrel for C7 is the same as that used for G-sharp 5 (Z:bs0). To produce C7 on the mouthpiece with barrel, the clarinetist used overblowing, but in this case, had great difficulty since she has less experience overblowing on just the mouthpiece with barrel. Perhaps this difficulty is also because the peaks in the mouthpiece plus barrel impedance curve are very far apart compared to complete clarinet fingerings. The fundamental for the mouthpiece with barrel is significantly lower in frequency than the point in the second peak with the greatest magnitude. However, the fundamental does lie approximately halfway between the minima that define the boundaries of this very broad peak. For the lower demi-clarinet C7 recordings, impedance Z:ldsf1p7 was made with a fingering where all the tone holes and keys were closed and the bell was mostly *stopped* (i.e. the hand is used to cover most of the bell). For the other lower demi-clarinet C7 recording (Z:ld2), all but one of the tone holes and keys were closed and the bell was open. Both lower demi-clarinet sounds were produced through overblowing. The peaks for the lower demi-clarinet stopped fingering are much more well defined than for the open fingering with clearer maxima and minima throughout the entire frequency range. The fundamental frequency for the open lower demi-clarinet recording (Z:ld2) is noticeably lower than for the other recordings. For all recordings except the one made with the complete clarinet and the normal fingering for C7 (Z:c7f2), the fundamental has the highest magnitude. However, for the normal C7 fingering, the second partial has the highest magnitude.

4. CONCLUSION AND FUTURE WORK

This work has been largely concentrated on expanding the availability of acoustic impedance measurements for extended clarinet fingerings and instrument configurations used by the author and clarinetist in her performance practice. Observing and comparing peaks in both the spectra of her produced sound and in the impedance curves can provide a visual feedback to inform her performance practice. This work will endeavor to continue expanding the sound examples of the corresponding measured impedance, making data readily available online.

Further, impedance measurements will have tremendous value when they are applied to future research in physical modeling synthesis and parameter estimation of waveguide components. Finally, it is hoped that this data will inform the development of a tool for real-time (live) performance that allows the performer to *virtually* change the configurations of the instrument more continuously during performance, without necessarily requiring solely discrete physical events of (dis)assembling the instrument and/or using multiple instruments.

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