Comparison of perceived sound qualities of five clarinets of different makes

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In this paper, the perceived sound qualities of five clarinets from different manufacturers are compared. An attempt is made to relate differences in the timbres of the instruments to variations in their designs. A series of psychoacoustical listening tests is discussed. The listening tests are designed to investigate perceived differences between single notes played on the five clarinets. Recordings of four note pitches (E3, F3, F4 and B4 clarinet transposed notes), played at two different dynamic levels, are used to populate the tests. Each listening test is either made up of notes produced by a human player or notes produced by an artificial mouth. In the tests, participants are presented with 60 pairs of sounds and asked to rate the overall difference between the notes of each pair and also to indicate which has the brighter timbre. A selection of results from the listening tests is presented and analysed via comparison with geometrical, spectral centroid and input impedance measurements.

1 Introduction

Forward-thinking instrument manufacturers are always keen to find new ways of optimising the designs of musical instruments according to musicians' needs.

This paper reports part of a larger study that attempts to correlate the geometrical and acoustical properties of five clarinets, made by different manufacturers, with their qualities as perceived by listeners and players. The five clarinets under investigation are a Boosey & Hawkes Regent instrument, a Buffet Crampon B12 instrument, a Jazzo instrument, a Corton instrument and a Yamaha 34IIS instrument. The clarinets are in used condition and were all serviced before starting the study.

For each of the five clarinets, the bore profiles and the dimensions and locations of the tone holes have been measured. Input impedance measurements have also been carried out on all five instruments for note fingerings across the playing range, using a bespoke capillary-based impedance set up described previously in [1]. This measurement system allows the impedance of a complete clarinet (including the mouthpiece) to be measured.

In the current paper, we report a series of pyschoacoustical tests, designed to investigate the timbres of the clarinets as perceived by listeners. Four notes - written pitches E3, F3, F4 and B4 - played by a semi-professional clarinettist (P.K., one of the authors) at *mezzo piano* and *forte* dynamic levels, were recorded. The same set of notes at *forte* dynamic level was produced by an artificial playing device (Figure 1).

Figure 1: Artificial playing device with a clarinet

From these sounds, three listening tests were constructed, each having the same structure but respectively containing the *mezzo piano* sounds produced by the human player (Test 1), the *forte* sounds played by the human player (Test 2), and the *forte* sounds produced by the artificial playing device (Test 3). Each test presents pairs of sounds, asking the listener (i) to rate on a scale 0-4 the overall difference in timbre between the members of each pair, and (ii) to specify which (if either) of the two sounds has the brighter timbre.

Preliminary results from these listening tests are presented here together with some initial analysis of the results. In particular, attempts are made to relate some of the findings to the geometrical and acoustical measurements made on the clarinets, and also to spectral centroid values obtained from sounds produced by the instruments, with a particular focus on the notes E3 and B4.

2 Listening tests

2.1 Test stimuli preparation

The sounds used in the listening tests were recorded in a semi-anechoic chamber, at a room temperature of about 22ºC. The recordings were made using a B&K ½" microphone with Type 5935 power supply connected to a Marantz solid-state recorder.

To enable investigation of the timbre of the clarinets across the playing range, four notes were chosen. Firstly E3 was selected as it is the lowest note on the clarinet. To produce this note all the tone holes need to be closed and therefore the resonance properties are mainly determined by the shape of the bore. Secondly, note F3 was recorded. For this note fingering, only one tone hole is open, providing the opportunity to investigate the influence of the size and location of the tone hole on the sound produced. Note F4, which is near the top of the first register, was also recorded. Lastly, note B4 was chosen. To produce B4 on the clarinet, all of the tone holes are closed, with the exception of the register key. This provides an opportunity to investigate the effect of the register key on the timbre of the notes produced by the different models of clarinet.

Each note was recorded five times, with the pitch detection functionality of Adobe Audition 1.0 used to ensure that all the recorded notes were within 10 cents of their expected equally tempered frequency values. Then, for each note pitch, the two recordings that were closest in frequency to each other were selected for use in the listening tests (using two recordings of each note enabled control pairs to be included as well as comparison pairs, described further in Section 2.2).

Following this, one second duration steady-state sections of the recorded sounds were selected and normalized to 0 dB peak level. For each sound a 10ms fade–in and fade-out was applied.

As mentioned earlier, the sounds for Test 1 (*mezzo piano*) and Test 2 (*forte*) were produced by a human player, while an artificial blowing device was used to produce the sounds for Test 3. The design of the artificial mouth is approximately based on that described in [2]. It includes a plastic airtight chamber, into which a clarinet mouthpiece is inserted. A moveable bar covered by a rectangular piece of rubber, imitating the lower human lip, is positioned inside the chamber. By adjusting this, the pressure of the "lip" on the clarinet reed can be altered. The mouthpiece is sealed into the box by a rubber gasket. Compressed air is supplied via an input pipe. For each note fingering on each instrument, the air pressure within the artificial mouth was adjusted and the pressure of the "lip" was altered until a stable note was produced. Due to the limitations of the artificial mouth design it was not possible to produce certain notes on one or more of the clarinets. Consequently, the notes E3 on the Jazzo clarinet, and B4 on the Buffet, Corton and Jazzo clarinets were not recorded.

2.2 Structure of the listening tests

Tests 1 and 2 consisted of 40 comparison and 20 control pairs of sounds. By 'comparison pairs' we mean pairs of sounds in which a note recorded on one of the instruments is paired with the same note produced on a different clarinet. There are five clarinets, resulting in ten pairs of sounds for each of the four note pitches tested, giving 40 comparison pairs in total. The 'control pairs' comprise two repeats of the same note produced on the same instrument. There are five clarinets and so five pairs of sounds for each of the four note pitches, totalling 20 control pairs of sounds.

For each of the 60 pairs of sounds making up the test, two questions were asked. First, the participants were asked to rate on a scale from zero to four (0 = no difference, 4 = very large difference), the overall difference between the timbres of the two sounds. Second, the participants were asked which of the two sounds has the brighter timbre (possible answers: "A", "B", or "no difference"). If a particular sound was chosen as being brighter, the corresponding instrument was given a score of 1 and the other instrument a score of 0. If no difference was perceived, both instruments were given a score of 0.5.

Examples were provided prior to the start of the test to give the participants an idea of the range of differences in the sounds (both in terms of overall timbre and in terms of brightness) that they might encounter during the test.

(Test 3 had the same structure as Tests 1 and 2, but due to the limitations of the artificial playing machine design described previously, it only included 16 control pairs of sound and 27 comparison pairs.)

The listening tests were conducted in a quiet room, using the same computer and the same pair of Sennheiser HD-380 pro headphones for each participant. Each test took approximately 20-30 minutes.

3 Results

In total 105 individual tests were carried out, with 40 responses for Test 1 (18 males, 22 females), 35 responses for Test 2 (19 males, 16 females) and 30 responses for Test 3 (16 males, 14 females). Of the contributors to Test 1, 24 participants had no or only basic musical training, and 16 participants had an intermediate (Grade 5-7) to an advanced (grade 8 and over) level of musical training. Meanwhile, the Test 2 participants comprised 27 non-musicians, and 8 intermediate to advanced level musicians. The Test 3 participants consisted of 19 non-musicians and 11 intermediate to advanced level musicians.

Over the rest of this section, a selection of the listening test results are presented, focussing mainly on Test 1 but giving some detail for Tests 2 and 3. Firstly, an overview is provided, looking across all four notes included in the tests. Then specific attention is given to the listening test results for the notes E3 and B4.

3.1 Overview of listening test results

The first question in all three listening tests was designed to investigate the perceived difference in overall timbre between the sounds of each note pair.

For Test 1, the mean ratings (averaged across the 40 participants) for the 20 control pairs range in value from 0.025 (F4, Regent) up to 0.625 (B4, Buffet). Further averaging across all 20 control pairs gives an overall mean rating for the 20 control pairs of 0.288. These results indicate that, in general, participants perceived no difference or negligible difference between the timbres of the control pairs.

In contrast, the mean ratings (averaged across the 40 participants) for the 40 comparison pairs range in value from 0.375 (F3, Buffet-Regent) to 3.5 (B4, Jazzo-Regent). Again, further averaging across all 40 comparison pairs gives an overall mean rating for the comparison pairs of 1.587. These results show that for most of the comparison pairs, participants were able to perceive a significant difference between the constituent sounds.

For Tests 2 and 3, the results follow the same pattern. The overall mean ratings for all the pairs (control and comparison) making up the three different tests can be seen in Table 1, together with the associated standard deviations.

Table 1: Overall mean ratings for control and comparison sound pairs for all responses to Tests 1, 2 and 3.

	Control pairs	Comparison pairs
Test	Average values (std. dev.)	Average values (std. dev.)
1	0.288 (±0.472)	1.587 (±0.776)
2	0.369 (±0.469)	1.556 (±0.845)
3	0.231 (±0.330)	1.738 (±0.840)

The 40 comparison pairs in Test 1 are made up of 10 comparison pairs at each note pitch. Sounds from a given instrument feature in four of these ten comparison pairs. For example, the Buffet clarinet is compared with each of the four other instruments, resulting in four comparison pairs. By summing the mean ratings of the four comparison pairs featuring a given instrument, an aggregate score for that instrument can be found for a particular note pitch. Figure 2 shows the aggregate scores for the five clarinets for note pitches E3, F3, F4 and B4, determined from the Test 1 results.

It can be seen from Figure 2 that, for notes F4 and B4, the aggregate scores for the Jazzo clarinet are significantly higher than the scores for the other clarinets. This implies that, at these two note pitches, the Jazzo clarinet was perceived as having a noticeably different timbre in comparison with the other clarinets.

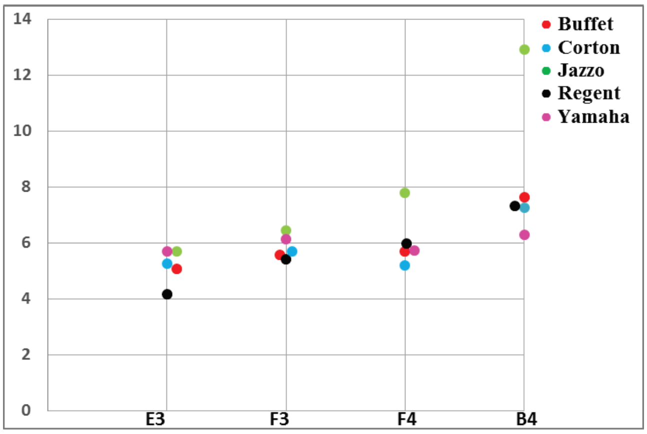

Figure 2: Aggregate scores for each of the clarinets

The Jazzo clarinet's aggregate score at note pitch B4 is particularly high, with a value of 12.9 (the maximum aggregate score possible is 16). At this pitch, nearly all participants judged the difference between the timbre of the Jazzo clarinet and that of each of the other four instruments as being either large (assigning a rating of 3) or very large (assigning a rating of 4).

The second question in the listening tests was designed to investigate the perceived differences in brightness between the sounds of each pair. It has previously been noted that Test 1 comprises 10 comparison pairs at each of four different note pitches and that sounds from a given instrument feature in four of these ten comparison pairs. By summing the brightness ratings (0, 0.5 or 1) for the four comparison pairs featuring a given instrument across all forty participants, a quantitative measure of how many times that instrument was chosen as having the brighter timbre can be found for each particular note (see Figure 3).

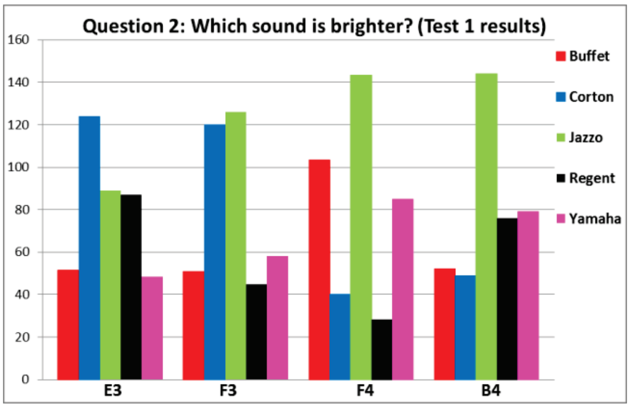

Figure 3: Summed brightness ratings for the clarinets.

For three of the four notes presented in the listening test, it can be seen from Figure 3 that the Jazzo instrument was generally considered to have the brightest timbre (the exception is at note pitch E3, where the Corton has the highest summed brightness rating). For B4, the summed brightness rating for the Jazzo clarinet is nearly twice as large as for any of the other clarinets.

The large perceived differences in overall timbre and in brightness between the Jazzo clarinet and the other instruments at note pitch B4 are explored further in Section 3.3. First, though, we look in more detail at the listening test results for the note E3.

3.2 Note E3 (Test 1) result analysis

In this section, we focus on the note pitch E3 and draw on the results of Test 1.

Concentrating on the perceived difference in overall timbre, Table 2 shows the mean ratings in descending order (averaged across the 40 participants) for the 10 comparison pairs at note pitch E3. It can be seen that the largest perceived difference in overall timbre was between the sounds produced by the Jazzo and Yamaha instruments (with a mean rating of 2.03). Meanwhile, the smallest perceived difference in overall timbre was between the sounds produced by the Buffet and Regent clarinets (with a mean rating of 0.78).

Table 2: Mean ratings of difference in overall timbre between pairs of sounds for note E3 (Test 1 results).

Instrument pair (Note E3)	Mean rating (on scale 0-4)
Jazzo-Yamaha	2.03
Buffet-Corton	1.78
Buffet-Jazzo	1.50
Corton-Yamaha	1.40
Regent-Yamaha	1.25
Jazzo-Regent	1.25
Corton-Jazzo	1.05
Buffet-Yamaha	1.03
Corton-Regent	1.03
Buffet-Regent	0.78

The reason that listeners found it difficult to perceive a difference in timbre between the Buffet and Regent clarinets can be understood through inspection of Figure 4. This figure shows input impedance magnitude curves for the five clarinets with the E3 note fingering applied. It can be seen that the curves for the Buffet and Regent instruments are in close agreement, particularly over the first few resonance peaks. Indeed, the magnitude of the first resonance peak for the Regent clarinet is 57.6 MΩ compared with a magnitude of 58.5 MΩ for the Buffet instrument, while the peak frequencies are identical at 150.8 Hz. Meanwhile, the magnitude of the second resonance peak is 43.6 MΩ for the Regent clarinet and 40.1 MΩ for the Buffet instrument, with the peak frequencies 442.9 Hz and 440.7 Hz respectively.

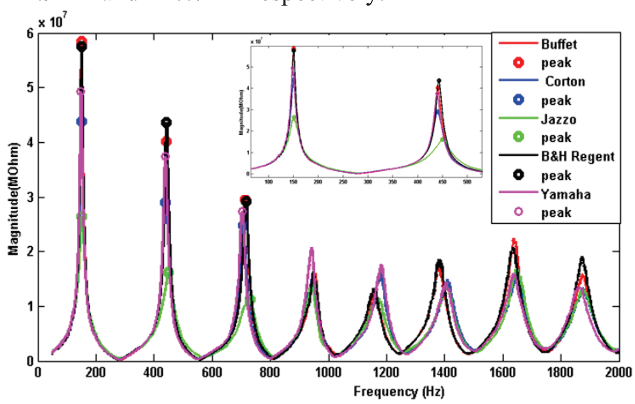

Figure 4: Input impedance magnitude curves for five clarinets for note E3.

Conversely, the large difference in timbre perceived between the Jazzo and Yamaha clarinets at the note pitch E3 is partly explained by the differences observed between their impedance curves. Examination of Figure 4 reveals that, out of the five instruments, the Jazzo clarinet has the highest first and second resonance frequencies (151.2 Hz and 450.1 Hz) while the Yamaha clarinet has the lowest first and second resonance frequencies (148.2 Hz and 438.8 Hz). Large differences can also be seen with respect to the magnitudes of these resonances, with the Jazzo clarinet having first and second peak heights of 26.4 MΩ and 16.2 MΩ compared with respectively 49.4 MΩ and 37.4 MΩ for the Yamaha instrument.

As the note E3 is produced by closing all the tone holes, the frequencies and magnitudes of a clarinet's resonances with this fingering applied (and consequently the timbre of the sound produced) are predominantly determined by the geometry of the bore. Figure 5 shows the bore profiles of the five clarinets used in this study, measured using a set of high precision measurement discs with rod attachments.

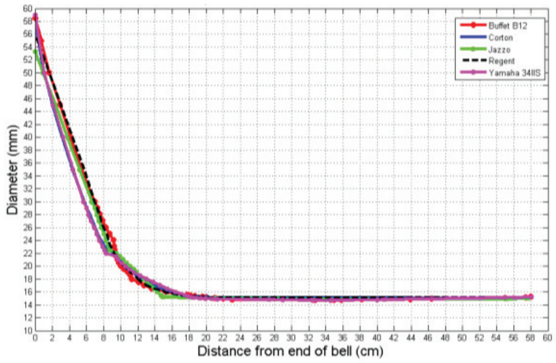

Figure 5: Bore profiles of five clarinets.

The close agreement seen between the impedance curves for the Buffet and Regent clarinets (and which led to listeners finding it difficult to perceive a difference in timbre between these two instruments when playing E3) can be explained through inspection of their bore profiles. Within the bell and the expanding section of the lower joint, the Buffet and Regent instruments have virtually identical bore profiles. Even within the cylindrical section of the lower joint and within the upper joint their bore profiles are very similar.

In contrast, the bores of the Jazzo and Yamaha clarinets have quite different profiles. While both instruments are cylindrical over the upper joint and the first part of the lower joint, the second part of the lower joint of the Jazzo clarinet is essentially conical in nature and is then followed by the bell which is also conical but with a more rapid taper. Meanwhile, the bore of the Yamaha clarinet expands in a smooth exponential fashion over the second section of the lower joint and over the bell. These geometrical differences lead to the observed differences in the two instruments' impedance curves at note pitch E3 and, in turn, to the large perceived differences in their overall timbre.

3.3 Note B4 (Test 1) result analysis

In this section, we focus on the note pitch B4, again drawing on the results of Test 1.

Concentrating first on the perceived difference in overall timbre, Table 3 shows the mean ratings (averaged across the 40 participants) for the 10 comparison pairs at note pitch B4, presented in descending order. It is immediately apparent that the largest perceived differences in overall timbre were for all four sound pairs involving the Jazzo clarinet. This leads to the significantly higher aggregate score for the Jazzo clarinet at note pitch B4 seen previously in Figure 2.

Table 3: Mean ratings of difference in overall timbre between pairs of sounds for note B4 (Test 1 results).

Instrument pair (Note B4)	Mean rating (on scale 0-4)
Jazzo-Regent	3.5
Corton-Jazzo	3.3
Buffet-Jazzo	3.25
Jazzo-Yamaha	2.85
Buffet-Regent	1.6
Buffet-Yamaha	1.4
Regent-Corton	1.375
Buffet-Corton	1.375
Yamaha-Corton	1.2
Yamaha-Regent	0.85

To try to understand why the overall timbre of the Jazzo clarinet is noticeably different from all the other clarinets at this note pitch, it is worth examining the impedance magnitude curves for the five clarinets with this note fingering applied (Figure 6).

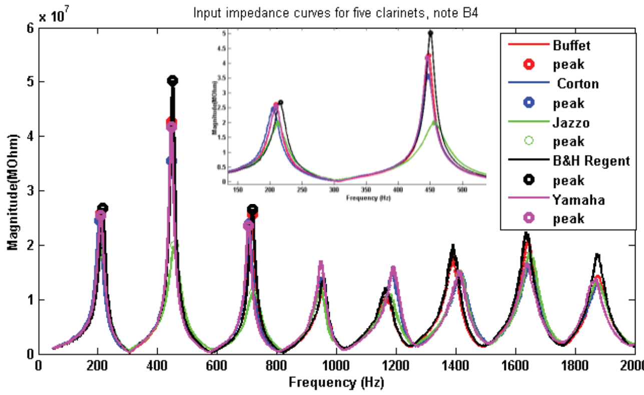

Figure 6: Input impedance magnitude curves for five clarinets for note B4.

The note B4 is in the second register of the clarinet, therefore the pitch is based on the second resonance. Examination of Figure 6 reveals that the magnitude of the second resonance peak for the Jazzo clarinet is significantly lower than for the other clarinets. Indeed, the amplitude of this peak is 20.0 MΩ for the Jazzo clarinet, whereas the amplitudes for the other four clarinets range from 35.6 MΩ to 50.2 MΩ. In addition, the Jazzo clarinet has a second resonance frequency of 457.7 Hz, whereas the frequencies of the second resonances of the other clarinets are lower, ranging from 445.6 Hz to 450.4 Hz. Similarly, the magnitude of the third resonance peak for the Jazzo clarinet (with an amplitude of 11.2 MΩ) is also markedly lower than for the other clarinets (with amplitudes ranging from 23.5 MΩ to 26.6 MΩ). Meanwhile, the Jazzo clarinet has a third resonance frequency of 721.5 Hz, whereas the third resonance frequencies of the other clarinets are a little lower, ranging from 704.9 Hz to 718.1 Hz.

The significant differences, both in terms of the magnitudes and frequencies of the second and third resonances, between the Jazzo clarinet and the other instruments, go some way to explaining the perceived differences in overall timbre revealed by the listening tests.

The observed differences in impedance must arise as a result of geometrical differences between the Jazzo clarinet and the other instruments. In the fingering for the note B4 on the clarinet, only the register key is open. Measurements have been made of the diameters and the locations (in terms of distance from the tip of the mouthpiece) of the register holes on the five clarinets. Figure 7 plots these values for all five instruments in terms of percentage difference from the average register key diameter ("Percentage diameter difference") and percentage difference from the average location ("Percentage spatial difference"). Examination of Figure 7 reveals that, although the diameter of the register key on the Jazzo clarinet is approximately 3.5% larger than the average register key diameter, it is actually comparable in size to the register keys of the Corton and Regent instruments. However, the Jazzo register key can be seen to be located higher up the instrument (closer to the mouthpiece tip) than the register keys on all the other clarinets. Indeed, the distance from mouthpiece tip to register key for the Jazzo clarinet is 3.7% less than average. This geometrical difference is the most likely explanation for the differences observed in the second and third peaks of the impedance magnitude curves and the perceived differences in the overall timbre of the Jazzo clarinet at note pitch B4 established by the listening tests.

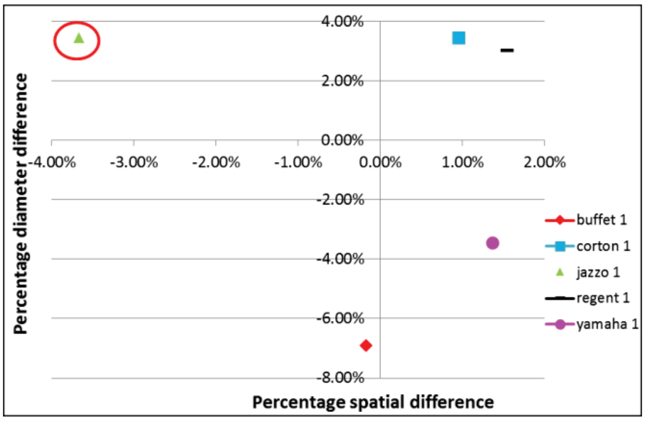

Figure 7: Locations and sizes of clarinets' register keys.

Moving on to the perceived difference in brightness at note pitch B4, it was noted earlier from inspection of Figure 3 that the summed brightness rating for the sound produced by the Jazzo clarinet was significantly greater than the equivalent ratings for the sounds of the other clarinets.

The spectral centroid of a sound is acknowledged to be a good predictor of the timbral brightness of that sound. Table 4 shows the values of the spectral centroids of the sounds used in Test 1 (at note pitch B4), in descending order of frequency. It can be seen that the sound produced by the Jazzo clarinet has the highest spectral centroid frequency, with a value of 1454.6 Hz. Consistent with the summed brightness ratings, the spectral centroid frequencies of the sounds produced by the Corton, Yamaha and Buffet clarinets are much lower in value (ranging from 1209.5 Hz to 1375.9 Hz). However, slightly unexpectedly, the spectral centroid frequency of 1449.2 Hz for the sound produced by the Regent instrument is only slightly lower than that for the Jazzo instrument.

The high spectral centroid frequency (in relation to three out of the four other clarinets) of the B4 note produced on the Jazzo can, to a large extent, be explained by reference to the impedance curves of Figure 6.

Table 4: Spectral centroid for note B4

Instrument (Note B4)	Spectral centroid (Hz)
Jazzo	1454.6
Regent	1449.2
Corton	1375.9
Yamaha	1296.5
Buffet	1209.5

For the Jazzo clarinet, the second and third resonance peaks, are smaller in magnitude than the corresponding peaks in the other clarinets' impedance curves. As a result, when the note B4 is played, there will be less energy in the sound radiated by the Jazzo clarinet at these frequencies than there will be in the sound radiated by the other clarinets. The magnitudes of the higher resonance peaks are much more similar across all five clarinets, so the energy in their radiated sound at these higher frequencies will be comparable. The consequence is that in the sound radiated by the Jazzo clarinet there will be more energy at higher frequencies (relative to the lower frequencies) than there will be in the sound radiated by the other instruments. That is, it will have a higher spectral centroid frequency.

4 Conclusion

This paper has presented an initial analysis of selected results from tests designed to establish listeners' perceptions of differences in timbre between clarinets from five different makers. It has been demonstrated that perceived differences in timbre between the clarinets can be explained in terms of geometrical and acoustical differences between the instruments.

The next stage of the work is to carry out a much more detailed statistical analysis of the listening test results. In addition, playing tests are currently being conducted to establish musicians' perceptions of the relative playing properties of the instruments. An in depth attempt will then be made to correlate measured geometrical and acoustical differences between the instruments with the perceived differences in their musical qualities.

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