An Acoustical Approach to the Question of Early Horn Technique

Lisa Norman

Introduction

Horn players interested in performing music from the early eighteenth century are often faced with the dilemma of whether or not it is authentic to play with the hand in the bell of the instrument. Placing the hand in the bell allows the performer greater security in the high register[1] and also provides the opportunity for the player to manipulate wayward pitches inherent in natural brass instruments. However, in addition to these more practical issues of hand technique, there is also a significant difference in timbre between the bright sound from a fully open, uncovered bell and the warmer, darker sound from a partially covered bell. Composers writing for the horn would most likely have had one or the other tone quality in mind, depending on the practice at the time, but doubt remains as to exactly when hand technique became established in different regions of Europe.[2]

Documentation on horn technique from this era is scarce, with only a few methods and treatises surviving, but in these we find little if any discussion of what to do with the hand.[3] The famous Bohemian horn player Anton Joseph Hampel is thought to have played an important role in promoting and codifying the "hand-in-the-bell" technique about 1750, but unfortunately there is no specific reference to this new technique in the horn methods he left behind. Analysis of musical sources such as manuscripts can provide an insight into what performers were capable of playing; chromatic passages and non-series tones might indicate whether a certain technique was used,[4] but it is the coupling of performer and instrument that essentially creates the music. Original early horns provide a wealth of hidden information, not immediately apparent from initial observation. Robert Pyle has carried out some interesting acoustical experiments, comparing the responsiveness of French- and German-style horns to hand technique.[5] He found that the smaller throat of the French-style instrument does appear to be more sensitive to hand technique. But this is still an area of research that has not yet fully been explored. The work presented here focuses on the design of eighteenth- and early nineteenth-century instruments and what we can infer by way of playing properties from physical and acoustical measurements with the hand both in and out of the bell.[6]

Early horn technique

The natural horn is capable of producing a number of notes that are approximate to a harmonic series. Understanding and becoming completely familiar with this series is essential for the natural horn player because the series is also fundamental to the acoustics

DOI: 10.2153/0120110011004

of the instrument. These notes are referred to as the natural resonances, or resonant modes of the air column. The length of the horn determines the key of the approximate harmonic series—hence the need to change crooks to play in different keys. On a horn crooked in E♭ or D, it is quite possible to play up to the twenty-fourth resonant mode,[7] but playing in the extremes of the high register is physically demanding. Also, because the notes become increasingly closer together, it is much easier to miss the target note (split a note) and land on the wrong resonance. On the other hand, the high register was very attractive to composers, because the greater variety of notes meant there was more potential for the development of melodic lines.

Some of the resonant modes on a natural brass instrument do not fit comfortably with tempered scale tunings: the seventh, eleventh, and thirteenth in particular can be quite "out of tune," at least to our modern ears. On the assumption that musicians would have wanted to alter these wayward notes (at least to some extent), horn players have two possibilities open to them: the first is to "bend" the note in tune with the lips, a technique that is generally thought to have preceded the second option, which is to use the right hand in the bell of the instrument.[8] Some horns are more suited to hand technique than others, and it is interesting to explore whether these differences can be observed through current techniques in acoustical analysis.

Acoustical and physical measurements

It can be argued that human playing tests are the best way of assessing the playing characteristics of an instrument, but for reasons of preservation this is often not an option when studying surviving early brass instruments. In addition, many eighteenth-century horns are no longer in playing condition due to large dents, leaks, or cracks. A thick layer of dust inside the tubing or a trapped foreign object could also alter the acoustics of the instrument. Another issue concerns the subjectivity of player tests as a result of individual preferences—consistency is not always achievable. Acoustical tests offer an alternative approach; this method is very useful in terms of the objectivity of results, but it does not solve the problem of instruments in poor condition. In these cases, another option is to take physical measurements of the bore profile of the instrument and use computational models to predict the acoustical properties. This approach will be discussed briefly at the end of the article.

Acoustical tests were carried out using a well-known echo-based technique to measure the instruments' acoustic impedance, providing information about the natural modes of resonance of the instrument. The same mouthpiece was used for all experiments. The physical bore profile was measured in detail using equipment such as calipers and measuring rods.

Horns examined

The instruments included in this survey are drawn mainly from three museum collections, in Basel, Kremsegg, and Edinburgh.[9] A total of twenty-three horns from the eighteenth and early nineteenth century were examined, covering a range of design developments from fixed-pitch, wide-coiled hunting horns (Figure 1) to more compact crooked orchestral horns (Figure 10). A full listing of the details of all of these instruments can be found in the appendix.

Figure 1: Hunting horn by Michael Leichamschneider, 1718.
Historisches Museum Basel, inv. 1878.22.

In order to expand the data set, and for the sake of comparison, three modern copies of early eighteenth-century horns have also been included in this study, as well as a modern double horn.

Input Impedance

Measuring the input impedance of an instrument is a useful starting point when considering the acoustical properties of any instrument with a resonating air column. The graph in Figure 2 shows an example of an impedance curve for an instrument by Andreas Barth, measured using the commercially available Brass Instrument Analysis System (BIAS).[10] Each peak on the graph corresponds to a note or resonant mode on the horn and provides information about its position and strength. The peaks are evenly spaced in terms of frequency, as one would expect given that the modes are very close to forming a harmonic series. The overall shape, or envelope, of the impedance curve is strong in the low to middle registers, getting weaker as the pitch increases, with no significant peaks after about mode sixteen;[11] this typically corresponds to what the player perceives.

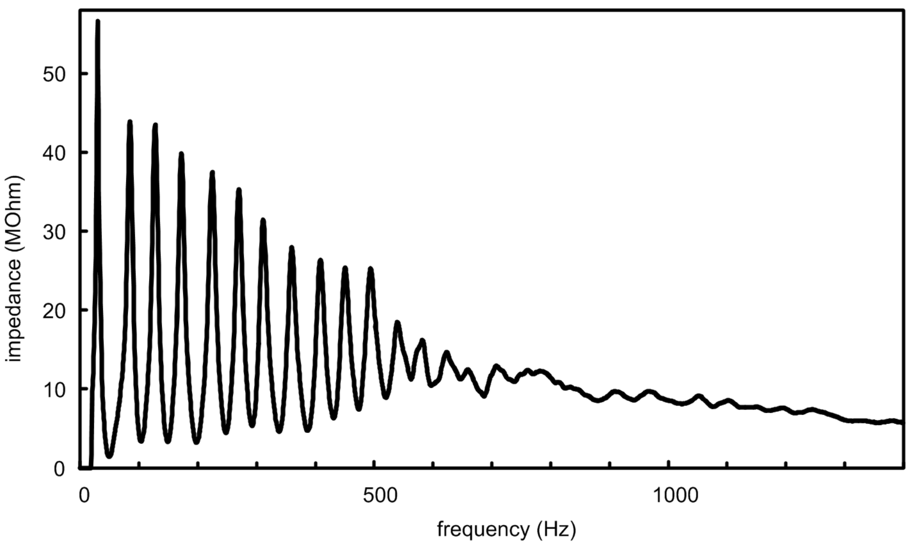

Figure 2: Input impedance curve for a horn by Andreas Barth, mid-nineteenth century, measured without the hand in the bell.

The envelope of an impedance curve varies from instrument to instrument, depending on the shape of the respective bore profile. In Figure 3, a very different impedance curve to that of the Barth is shown. This measurement is from a horn by William Shaw. A possible reason for this difference is that the two horns use different crooking systems and as a result, have quite different bore profiles in the first meter of tubing, as measured from the mouthpiece receiver (see Figure 4).

There is a much more rapid expansion in the initial section of tubing on the horn by Shaw than on that of Barth, and this can be explained by the fact that a crook-and-coupler

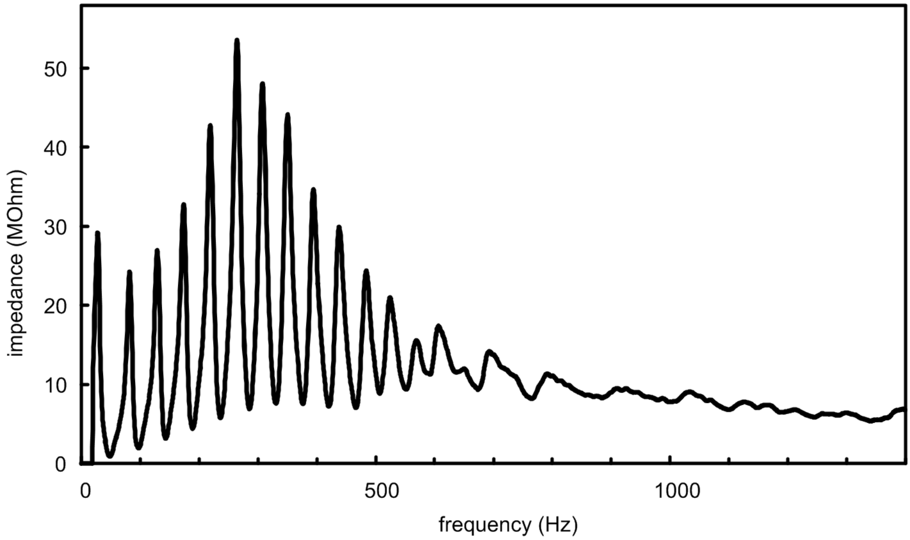

Figure 3: Input impedance curve for a horn by William Shaw, late eighteenth century, measured without the hand in the bell.

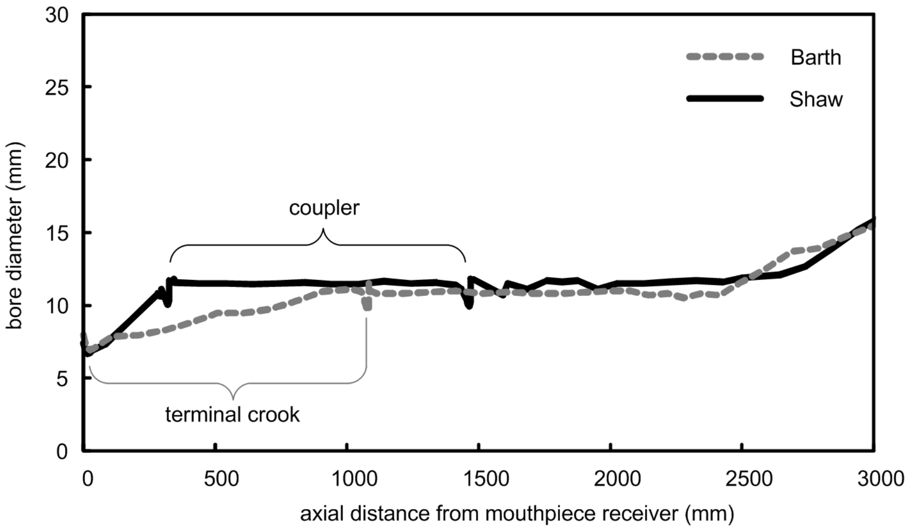

Figure 4: Bore profiles, showing the first three meters of tubing measured from the mouthpiece receiver, for a horn by Barth (one terminal crook inserted) and a horn by Shaw (one crook and one coupler inserted).

system is used on the former instrument—i.e., both a master crook and a coupler are employed (the cylindrical coupler section is annotated on the graph in Figure 4), whereas the Barth horn requires only one terminal crook to achieve the same pitch. The seven different terminal crooks for the horn by Barth can be seen in Figure 5.

Figure 5: (left) seven terminal crooks for a horn by Barth, with two additional couplers in the middle; (right) only one master crook, seen here on a horn by Shaw, with four additional couplers.

The master-crook-and-coupler system is most commonly associated with horns from England,[12] and it is interesting, but perhaps not surprising, that the use of such a system has a significant influence on the acoustics of the horn. The mouthpipe of a brass instrument is crucial to the behavior of the acoustics of the instrument. It can be predicted from these measurements that response in the very low register on the horn by Shaw would be quite unstable and weak at low dynamic levels. It should be noted however that with increasing loudness, higher harmonics are excited, providing positive reinforcement from the stronger upper resonances, and the tone becomes more stable.[13] Similar patterns in the shape of impedance curves can also be observed for other horns in this study with either master-crook-and-coupler or terminal-crooking systems.

Another pattern becomes apparent when comparing the impedance curves of early eighteenth-century horns to those from the late eighteenth century: this concerns the difference in the strength of the upper resonances. It was common for composers to use modes higher than the twelfth and often as high as the sixteenth in their horn writing throughout the period of the eighteenth century, and yet the impedance curves for a number of instruments (measured without the hand in the bell) show extremely weak resonances in this region. Notable instruments where this is the case are horns by the makers Michael Saurle (Figure 6), Josef Wenzel Lausmann, and Shaw (see Figure 5 for a

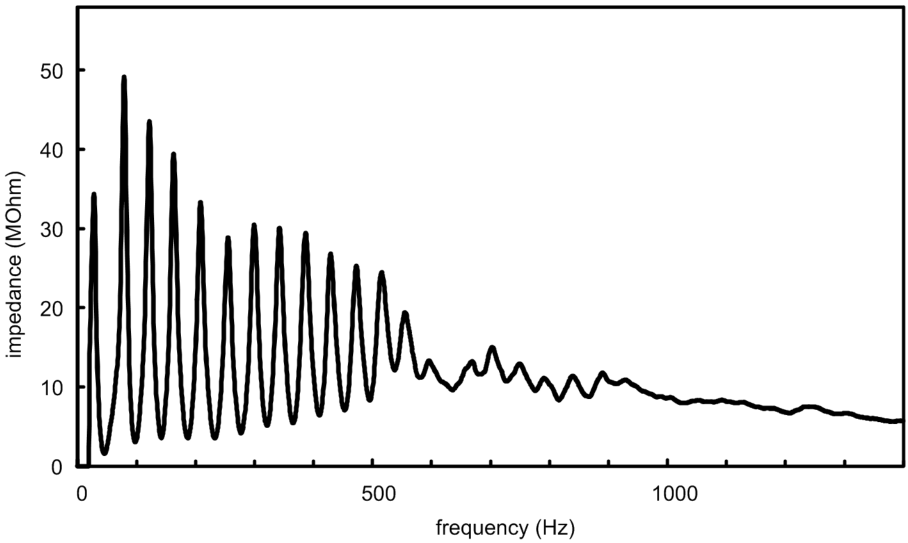

Figure 6: Input impedance curve for a horn by Michael Saurle, late eighteenth century, measured without the hand in the bell.

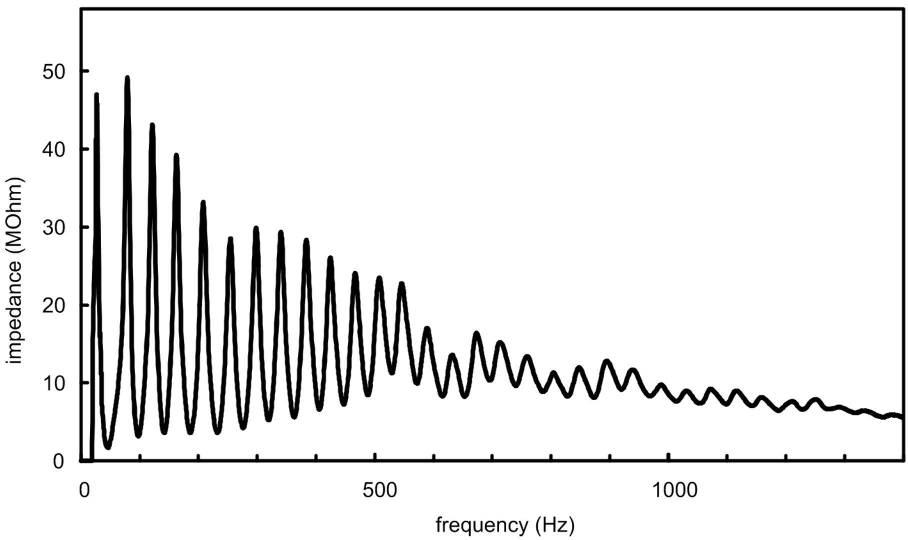

Figure 7: Input impedance curve for a horn by Saurle, measured with the hand in the bell.

photograph). Indeed, these are all instruments from around the late eighteenth century, when it is very likely that hand technique would have been used, but nevertheless it is interesting to observe such strong evidence to support the fact that without the hand in the bell, some of these notes in the high register would be almost impossible to play, and certainly extremely unstable. In the case of the horn by Saurle, the fifteenth and sixteenth resonances are also extremely sharp, but with the hand placed within the bell, the peaks not only become stronger, but the frequency also drops, bringing the notes more in tune (Figure 7). This will be discussed in more detail below.

Quality factor

Baroque horn players were adept at playing in the very highest register of the horn and they would most likely have preferred or favored instruments that provided as much security in this region as possible. This is one area where the interpretation of the acoustical data from the input impedance curve can give a relatively unambiguous indication of playing characteristics, as demonstrated in the previous example (Figures 6 and 7). The presence or absence of resonant peaks on an impedance curve of a particular horn gives a good idea of how easy it is to play in this register, but there is another factor worth considering: a peak's narrowness, also known as its quality factor.

The quality factor (Q factor) is an indication of the bandwidth of a particular resonance and provides information about the strength of a particular resonant peak on an input impedance curve. From the player's perspective, this might be perceived as how well-centered a note is to play. The following equation shows how Q can be calculated for a symmetric resonance curve,[14] where ω_0 is the resonant frequency and $\omega_u - \omega_l$ is the bandwidth (difference between the upper and lower frequency values) at half the peak power:[15]

$$Q = \frac{\omega_0}{\omega_u - \omega_l}$$

It has been shown that narrow resonant peaks, resulting in high values of Q, make pitching notes on a brass instrument easier than wider resonant peaks with lower values of Q.[16] The positioning of the hand in the bell of the horn changes this aspect of the acoustics of the instrument significantly; not only do the magnitudes of resonances in the upper register increase, but so too does the Q factor. The reason why this is so relevant to the following discussion is that an objective study of how the Q factor varies on these original instruments over the course of the eighteenth century may help to provide a new perspective on the question of early horn technique. In the following investigation, the focus will be the analysis of modes eight to sixteen—commonly used notes in horn writing from this period and the region where a diatonic scale is almost possible.

The average Q values for the same two groups of resonances were measured on each instrument: modes eight to twelve and modes twelve to sixteen. Taking average values rather than the values of specific resonances was found to be more useful in looking for general trends because small perturbations (such as a crook fitting) can often affect specific resonances. It is over this range that a rapid decrease in the amplitude of peaks on the impedance curve can be seen without the hand in the bell, but it is also the range where the introduction of the hand in the bell strengthens the resonances significantly, as was observed in Figures 6 and 7. The Q values for each individual resonant peak from the impedance curves of the Saurle instrument, measured with hand in and hand out of the bell, are shown in Figure 8; the increase in Q value in the high register, due to the hand, is clearly evident.

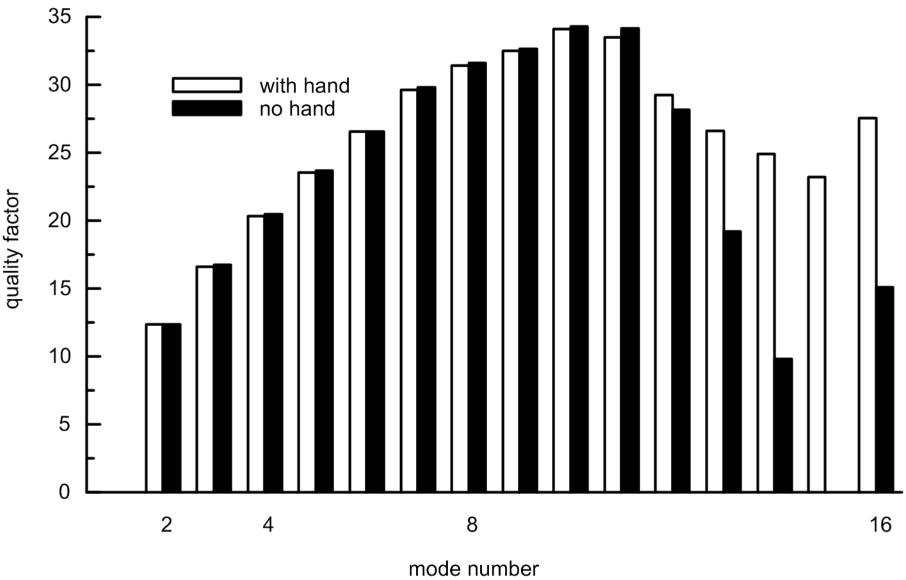

Figure 8: Q factor values up to the sixteenth mode, taken from the graphs in Figures 6 and 7 for a horn by Saurle, measured with hand in and out of the bell.

When comparing the playing characteristics and acoustics of different early horns, there arises the issue of comparing instruments of differing lengths; the various fixed-pitched instruments and crook combinations all have unique playing and tonal qualities, and indeed this is one of the attractions of the early instrument. Figure 9 shows how the average Q factor of modes twelve to sixteen varies in relation to the fundamental pitch of the horn.[17]

There is clearly a trend that the higher the pitch of the instrument (or the shorter the horn), the lower the Q value for modes twelve to sixteen. Therefore, for the purposes of this study, an acoustical comparison will be made only between instruments of similar length.

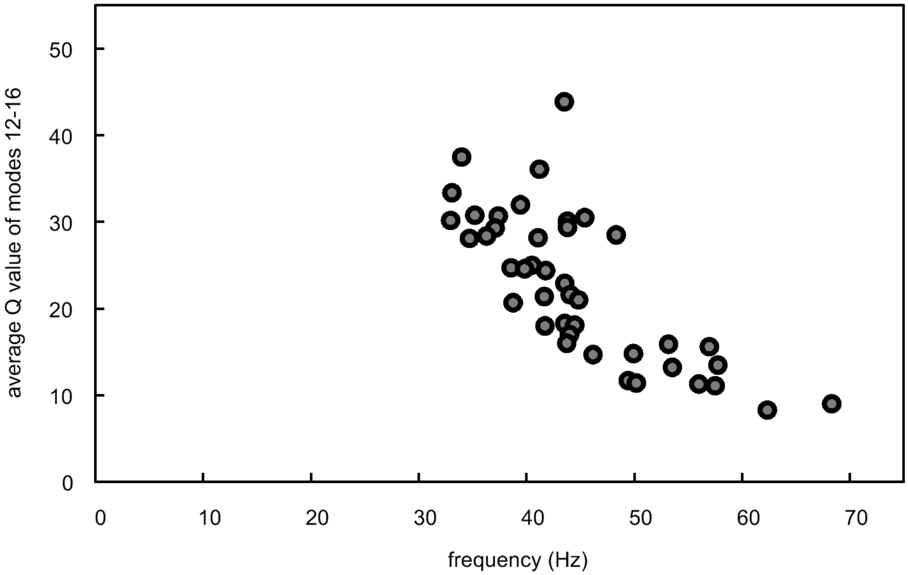

Figure 9: Spread of average Q values for modes 12–16 plotted against nominal fundamental frequency for all horns.

Initially the instruments were ranked according to the average Q values of only modes twelve to sixteen with no hand in the bell; Tables 1, 2 and 3 below show a sample of the results.

From these tables it is apparent that instruments from the earlier part of the eighteenth century tend to have higher average values of Q for modes twelve to sixteen than those from later in the century, which would imply that the earlier horns are also easier to play in this range without the aid of the hand. Some of the instruments made more recently, including the modern double horn by Paxman, seem to have comparatively high values of Q across their complete set of resonances, and this may be due to the "cleaner" internal condition of these instruments compared to older ones. Dust, dents, and corrosion on the inner walls of the tubing are thought to reduce the Q factor of brass instruments.[18]

Instrument maker	**Q value: average of modes 12–16**	**Fundamental frequency (Hz)**	**Date of manufac-ture**
Buchschwinder	32	39.4	1742
Shaw	25	38.6	ca. 1790
Barth	21	38.8	ca. 1840

Table 1: Horns with frequencies between 38 and 40 Hz (modern pitch E♭) ranked in descending order of average Q value, modes 12–16 (no hand in the bell).

Instrument maker	Q value: average of modes 12–16	Fundamental frequency (Hz)	Date of manufacture
Meinl Baroque copy	30	43.8	2004
Seraphinoff Baroque copy	29	43.8	2008
anonymous	23	43.5	ca. 1790
Paxman modern	22	44.1	2002
Werner	21	44.8	ca. 1770
Saurle	18	44.5	ca. 1790
Shaw	18	43.6	ca. 1790
Barth	17	44.0	ca. 1840

Table 2: Horns with frequencies between 43 and 45 Hz (modern pitch F) ranked in descending order of average Q value, modes 12-16 (no hand in the bell).

Instrument maker	Q value: average of modes 12–16	Fundamental frequency (Hz)	Date of manufacture
Eichentopf	31	45.4	1735
Werner	29	48.3	1735
Saurle	15	49.9	ca. 1790
Lausmann	15	46.2	ca. 1840
Shaw	12	49.4	ca. 1790
Barth	11	50.2	ca. 1840

Table 3: Horns with frequencies between 45 and 51 Hz (modern pitch F-sharp/G) ranked in descending order of average Q value, modes 12–16 (no hand in the bell).

An alternative way of interpreting the data is to compare the average Q values of modes twelve to sixteen with those immediately lower—modes eight to twelve. This gives a general indication of how quickly the Q values decrease (if at all) across this range. Table 4 shows the instruments ranked according to the difference between the average of modes eight to twelve and of modes twelve to sixteen.

A similar order to that of the previous tables can be seen, but with a few rearrangements; in general, the difference in Q value over the full range of modes eight to sixteen is more pronounced for the later than for the earlier instruments. In terms of the effect on the response of the instrument, the greater the difference in Q value, the less secure the notes will feel to the player when ascending in this region. Concerning the instruments in Table 4, there appears to be a slight divide between those with a Q difference of 12 or 13 and those with a lower value of Q, perhaps an indication that the horns in the latter group would perform better without the hand in the bell. On a few of the very early horns, modes twelve to sixteen even appeared stronger than the lower range of modes eight to twelve,

Instrument maker	Q difference between: average of modes 8–12 and 12–16	Fundamental frequency (Hz)	Date of manufacture
anonymous	6	43.8	ca. 1790
Seraphinoff Baroque copy	8	43.8	2008
Meinl Baroque copy	9	43.6	2004
Werner	12	44.1	ca. 1770
Saurle	13	44.8	ca. 1790
Shaw	13	43.6	ca. 1790
Barth	13	44.5	ca. 1840
Paxman	15	44.0	2002

Table 4: Horns with frequencies between 43 and 45 Hz (modern pitch F) ranked in ascending order of Q difference between the average of modes 8–12 and 12–16 (no hand in the bell).

suggesting greater security in this very high register. Figure 10 shows photographs of two of the horns, one with low and one with high values of "Q difference," from Table 5.

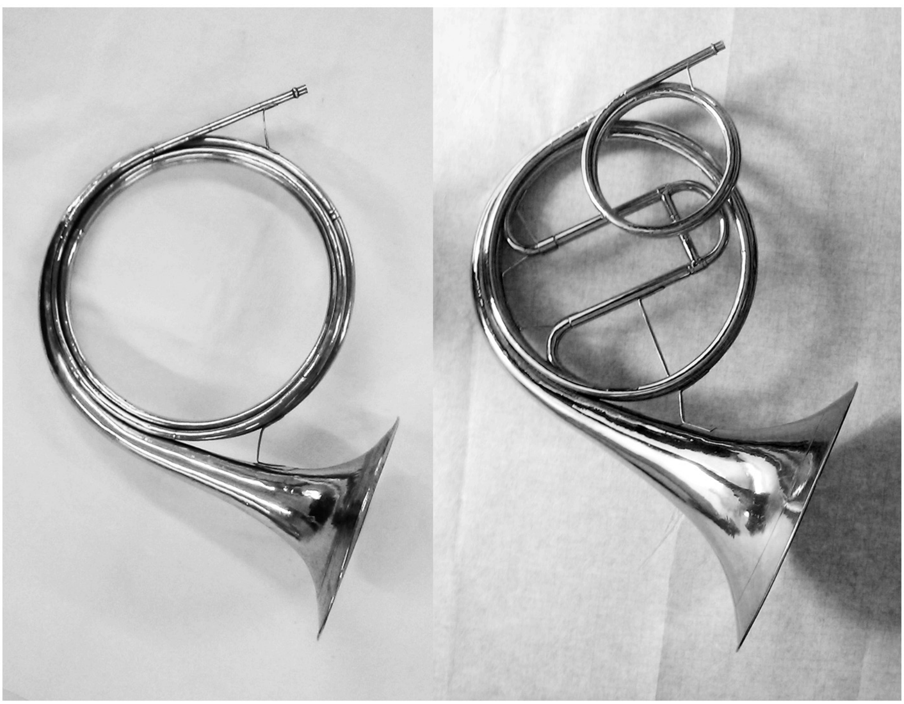

Figure 10: (left) fixed pitch horn by Johann Heinrich Eichentopf, 1735, "Q difference" – 4; (right) crooked horn by Barth, mid-nineteenth century, "Q difference" – 18.

Instrument maker	Q difference between: average of modes 8–12 and 12–16	Fundamental frequency (Hz)	Date of manufacture
Eichentopf	4	45.4	1735
Werner	6	48.3	1735
Saurle	13	49.9	ca. 1790
Shaw	13	49.4	ca. 1790
Lausmann	18	46.2	ca. 1840
Barth	18	50.2	ca. 1840

Table 5: Horns with frequencies between 45 and 51 Hz (modern pitch F-sharp/G) ranked in ascending order of Q difference between the average of modes 8–12 and 12–16 (no hand in the bell).

Many of the instruments in this data set were clearly made with hand technique in mind and so it is useful and important to examine systematically the effect on the Q factor of placing the hand in the bell. The average of modes twelve to sixteen were compared with hand in and out of the bell; the subsequent ranking based on this parameter produced results very similar to those in Tables 3–5. For example, instruments in which there was very little difference in the average Q factor over modes eight to sixteen (from Tables 3–5) also showed very little difference after the introduction of the hand into the bell of the horn. Again, this supports the theory that the designs of horns from the early eighteenth century are more suited to hand-out-of-the-bell technique than those made later in the century.

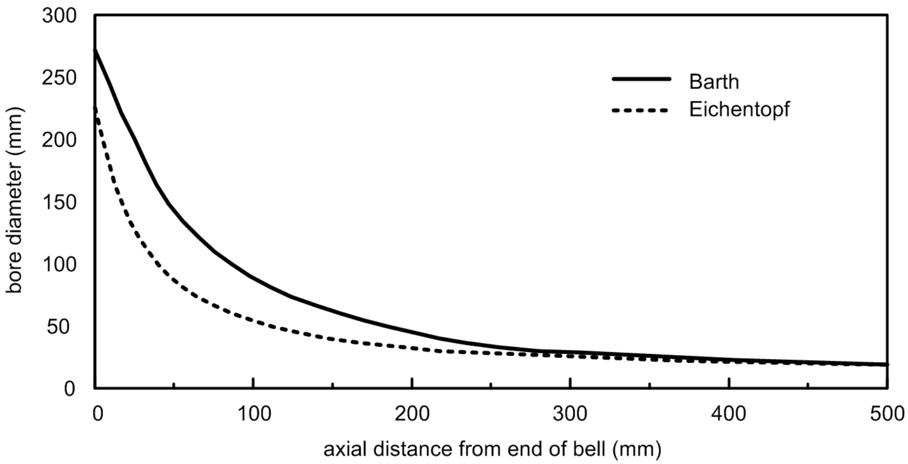

Figure 11: Comparison of the bell profiles for a horn by Eichentopf and a horn by Barth.

The instrument by Barth from the mid-nineteenth century showed the greatest increase in average Q after the introduction of the hand in the bell, an increase of about 10, whereas average Q factor for the horn by maker Johann Heinrich Eichentopf, dated 1735, rose by only 2. It is interesting to compare the bore profiles of these two instruments, in particular that of the bell, in order to see the difference between a horn bell designed with hand technique in mind (the horn by Barth), and one most likely without (the horn by Eichentopf, Figure 11). The horn by Eichentopf has a more delayed and rapid bell expansion than that by Barth, a common distinction in horns from the respective periods.

Intonation

The hand positioned within the bell not only has the potential to help with pitching in the high register of the horn by increasing the Q factor and amplitude of resonances, but also to alter the tuning. The effect on intonation is more pronounced on some instruments than on others. Figures 12 and 13 show harmonicity plots for two very different horns—a simple coiled hunting horn dated 1718 by the maker Michael Leichamschneider (see

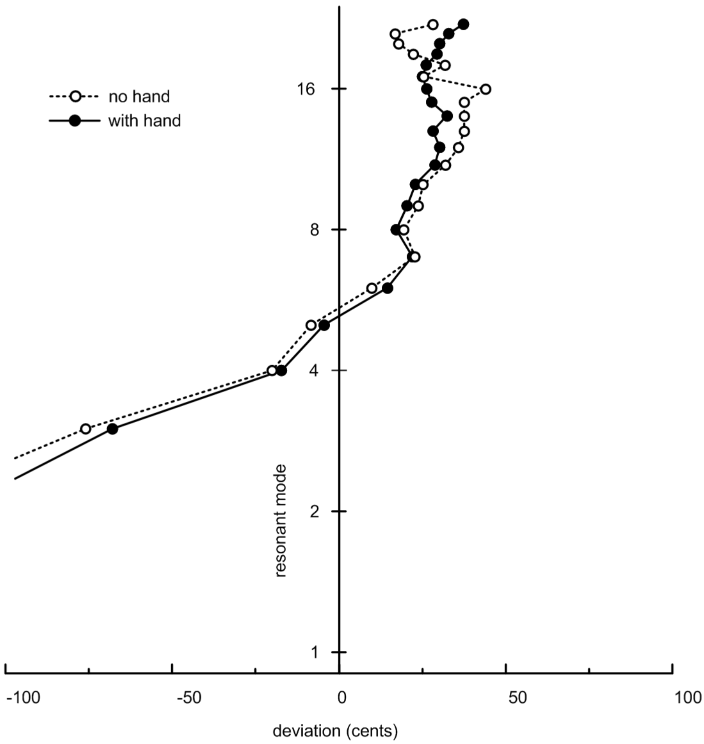

Figure 12: Harmonicity plot for a horn by Leichamschneider, 1718, measured with hand in and hand out of the bell.

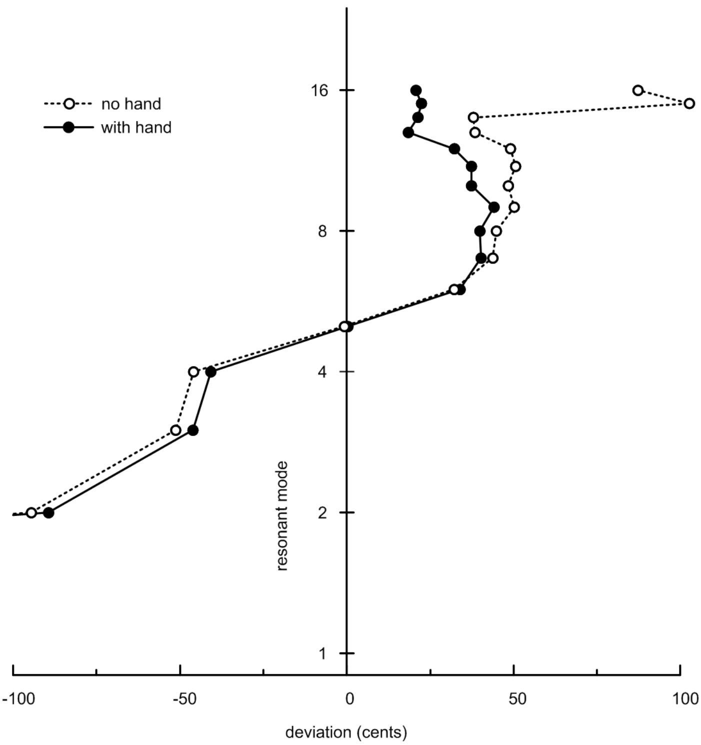

Figure 13: Harmonicity plot for a horn by Saurle, late eighteenth century, measured with hand in and hand out of the bell.

Figure 1 for a photograph), and a crooked horn from the late eighteenth century by Saurle (Figure 14). The harmonicity plots provide a visual representation of how closely the natural resonances of an instrument are aligned to a harmonic series (for a fundamental pitch based on the average of modes four and eight). A perfect harmonic series would produce a straight vertical line. Deviation from the line is measured in cents.

In these examples the very lowest modes are not visible as they are more than 100 cents (a semitone) flat; this is a feature of many brass instruments.[19] In practice, however, at all but the quietest dynamic levels, low notes rely on support from upper resonances (the multiples of the pitch played). This effect often helps to bring lower resonances more in tune whereas higher notes are largely left unsupported. Also, as mentioned previously, it is not necessarily desirable for every note to fall within a harmonic series, notably the seventh, eleventh, and thirteenth modes, which are not compatible with tempered tuning systems; the pure eleventh harmonic, for example, falls somewhere between a written (for horn) f^2 and $f\#^2$. Nevertheless, a horn that is considered to play well and have good intonation will normally produce a harmonicity plot with points that closely match a harmonic series.

Figure 14: Horn by Saurle, late eighteenth century.

The main difference between the two graphs (Figures 12 and 13) concerns the high register, modes eight to sixteen. There is less deviation here in the horn by Leichamschneider than in that by Saurle. In the latter plot, the fifteenth and sixteenth resonances are not only extremely weak with low Q factors (see Figure 6), but they are also noticeably sharp, and at this pitch there is no extra support from upper resonances. The placement of the hand in the bell of the Saurle brings the sixteenth mode much more in line with the modes directly below. On the Leichamschneider, the effect of the hand in the bell on the intonation is much less pronounced. In general, horns from the late eighteenth century were found to have a greater deviation in the range of modes four to sixteen than many of the horns from the first half of the century. This deviation from the harmonic series was reduced for the later instruments when the hand was inserted into the bell, particularly in the high register. Without the hand in the bell, there was a general tendency for the upper resonances of these horns to become increasingly sharp, but with the hand in the bell, the intonation was greatly improved due to the hand's flattening effect.

Further exploration through modeling

The input impedance curve has been described as the "acoustical fingerprint" of an instrument,[20] and indeed it is very useful for identifying instruments with similar acoustical characteristics based on the shape of the curves, as discussed earlier with reference to the different crooking systems. Analysis of the impedance curve can also be used to identify irregularities in the acoustics of an instrument. One such instrument, which appears to have an atypical acoustic response, is the horn by Eichentopf. The unusually undulating impedance curve for this instrument can be seen below in Figure 15.

Initial thoughts when analyzing this graph were that perhaps there was a leak or even a foreign body lodged inside the tubing. In order to explore this further, computer modeling proved to be very useful as a comparison to the measured data. The modeling

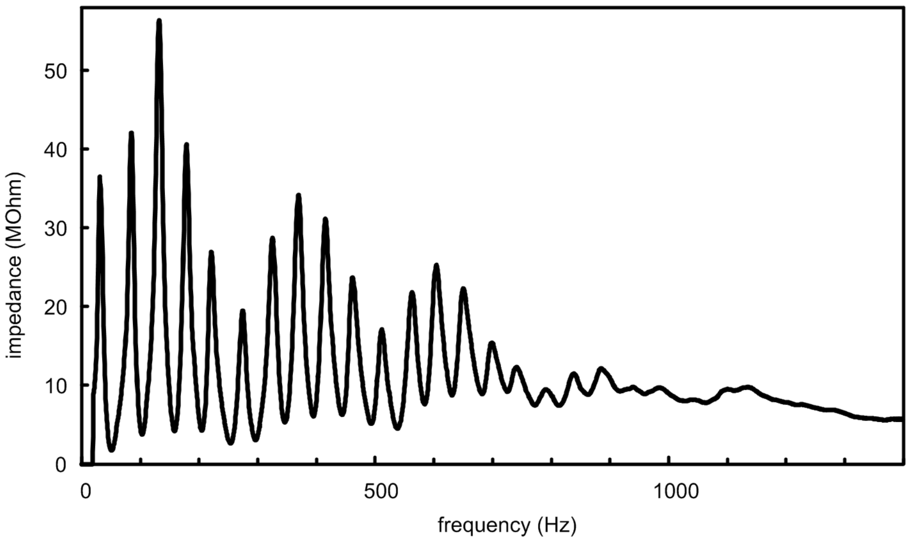

Figure 15: Input impedance curve for the horn by Eichentopf, 1735, measured without hand in the bell.

program used was developed at the University of Edinburgh by Alistair Braden.[21] The input data requires a detailed measurement of the bore profile of an instrument in order to output an impedance curve.

In Figure 16, both the measured and the modeled impedance results are displayed on the graph. Surprisingly, the curves are very similar, which would imply that the internal surface of the tubing is in good condition and that there are no unexpected energy losses. The bore profile itself must then provide a clue as to what is causing this irregular impedance curve; Figure 17 shows the initial section of the Eichentopf horn, measured from the mouthpiece receiver.

Here we can see that at about 700mm from the start of the mouthpipe, there is quite a sudden flared expansion and then a step before the tubing becomes narrower again; these are features that are likely to contribute to the unusual impedance curve.[22] It is uncertain whether the initial section of this bore profile would have originally followed this shape or whether it is the result of one or more repairs over the course of time.

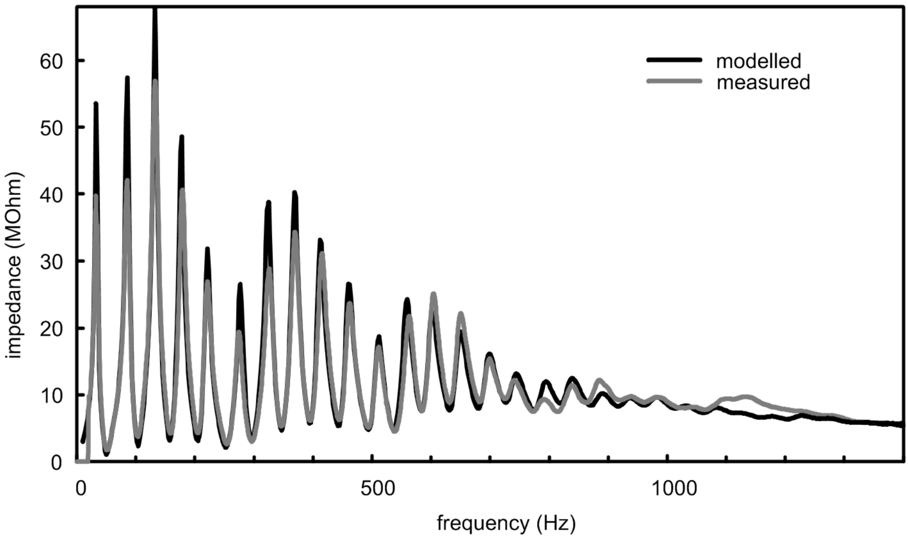

Figure 16: Comparison of the measured (Figure 15) input impedance curve for the horn by Eichentopf, with the input impedance curve produced by a computer model, based on bore profile measurements.

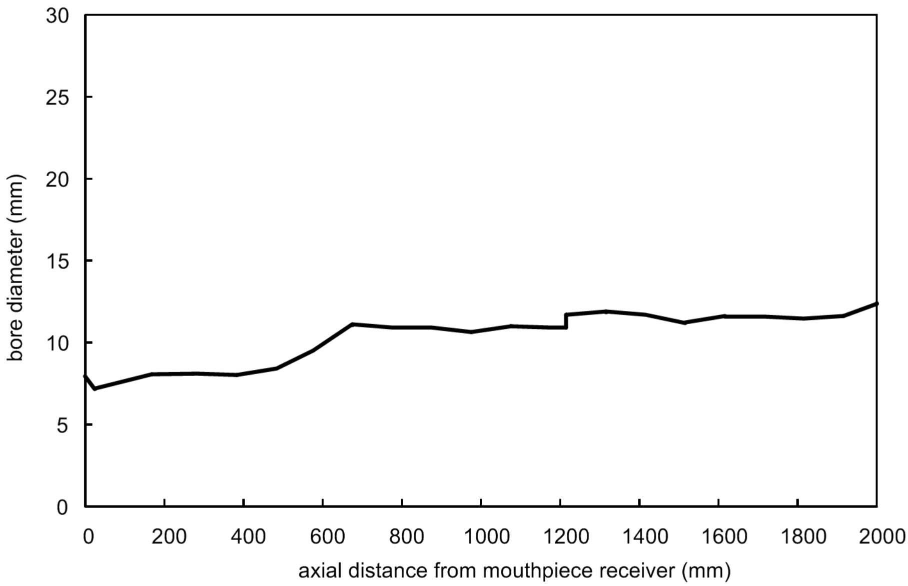

Figure 17: Bore profile, showing the first two meters of tubing measured from the mouthpiece receiver, for the horn by Eichentopf.

Conclusions

The effects of playing with the hand in or out of the bell are not only keenly felt by the player and apparent to the listener, but can be measured and analyzed objectively from an acoustical point of view too, as demonstrated by these results. The input impedance curve provides an indication of the unique acoustical response of each instrument, but among the horns examined, many shared similar shapes of curves; interesting groupings emerged between horns that used the crook and coupler system, and those which employed terminal crooks. The acoustical implications of the crook-and-coupler system seems to indicate weaker resonances in the lower register, certainly at quiet dynamic levels, but stronger towards the middle register. Given that this system was strongly associated with horns from England, this is an interesting geographical characteristic which it would be interesting to explore further by expanding the data set. Analysis of the impedance curves for late eighteenth-century horns, with and without the hand in the bell, revealed just how vital the hand is in increasing the strength of upper resonances, particularly in the region of the sixteenth resonant mode.

Interesting results were observed through analysis of the Q factor: horns from the early part of the eighteenth century showed the least decline in Q values over the range of modes eight to sixteen, and the introduction of the hand in the bell proved to have the least effect for these earlier instruments too. This is perhaps largely due to the shape of the bell profile. There appears to be some correlation between date of manufacture and Q factor, but measurements from more instruments will be needed to explore geographical trends.

The effect of the hand in the bell of the horn was also found to have a greater influence on the intonation of late eighteenth-century instruments, compared to those from earlier in the century. Earlier instruments were generally found to produce a set of resonances more closely aligned to the harmonic series, particularly in the high register, than those of a later date.

The results suggest that the evolution of horn design was a gradual process and that the transition to hand in the bell also occurred gradually, with player technique and instrument design evolving simultaneously. One advantage of systematical analysis of instruments in this way is to observe general trends, but it can also prove useful for singling out horns with unusual or uncharacteristic acoustical response, or may even help to identify anonymous instruments. The potential for this will increase as more horns are examined and measured—this is an ongoing project.

Computer modeling has not yet been fully exploited in the field of early instrument research. It can be used not only to provide confirmation for instruments with seemingly irregular acoustical measurements, but it is hoped that it will also prove useful in exploring the acoustical response of damaged instruments and those no longer in playing condition.

Lisa Norman was awarded an MSc by Research (with Distinction) from the University of Edinburgh in 2009 and is currently undertaking a PhD focusing on the organology of eighteenth-century horns. She was awarded the Frederick R. Selch Award for the best student paper presented at the 2010 American Musical Instrument Society meeting in Washington, DC. In her spare time she enjoys playing and teaching the horn and recorder.

Acknowledgements

I would like to thank Andrea Fornaro (Basel, Historisches Museum), Arnold Myers (Edinburgh University Collection of Historic Musical Instruments), John Chick (private collection), and Michael Söllner (Schloss Kremsegg, Musical Instrument Museum) for kindly allowing me access to measure the instruments included in this article, and also for their knowledge, aid, and most helpful assistance.

Notes

1 Arthur H. Benade, *Fundamentals of Musical Acoustics* (New York: Dover, 1990; 2nd rev. edn), 427–28.

2 Horace Fitzpatrick was one of the first scholars to tackle the subject of early horn technique in relation to the growing trend for historically informed performance practice in his article, "The Valveless Horn in Modern Performances of Eighteenth-Century Music," *Proceedings of the Royal Musical Association* 91 (1964): 45–60.

3 For example, *The Compleat Tutor for the French Horn*, attrib. Christopher Winch (London: John Simpson, 1746) and *Méthodes & Traités 21: Série I France 1600–1800: Cor*, ed. Jean Saint-Arroman (Courlay: Fuzeau, 2003).

4 Thomas Hiebert has looked at this issue in two very interesting articles: "Virtuosity, Experimentation, and Innovation in Horn Writing fromEearly 18th-century Dresden," *Historic Brass Society Journal* 4 (1992): 112–59; and "Extraordinary Horn Writing in 'The Egerton Manuscript Collection': A Contribution to the History of the Horn in Mid-eighteenth Century England," in *Jagd- und Waldhörner: Geschichte und musikalische Nutzung*, ed. Boje E. Hans Schmuhl and Monika Lustig (Augsburg: Wißner, 2006) 239–46.

5 Robert Pyle, "An Acoustical Comparison of Typical French and German Hand Horns," in *Jagd- und Waldhörner*, 391–410.

6 Throughout this article, references are made to measurements with the hand in the bell. The same player's hand was used for all measurements and the position of the hand within the bell was determined by the player as the most comfortable for the employment of hand technique. An "open" hand position was adopted for all measurements, i.e., no attempt was made to explore the effects of varying the closure of the bell.

7 Examples of music where this can be found include: Peter Fux (1753–1831), Concerto in E♭; Josef Fiala (1748–1811), Concerto in E♭; and Jan Dismas Zelenka, (1679–1745) *Capriccio I* in D.

8 Arnold Fromme, "Performance Technique on Brass Instruments during the Seventeenth Century," *Journal of Research in Music Education* 20, No. 3 (Autumn, 1972): 329–43.

9 Historisches Museum Basel: Musikmuseum; Schloss Kremsegg: Musical Instrument Museum;

Edinburgh University Collection of Historic Musical Instruments.
[10] Gregor Widholm, "Brass Wind Instruments Quality Measured and Evaluated by a New Computer System," in *Proceedings of the 15th International Congress on Acoustics, Trondheim, Norway, 26–30 June 1995*, ed. Mike Newman, vol. III (Trondheim: ICA, 1995), 517–20.
[11] Mode 4 is equivalent to a written "middle C" (c^1) and mode 16 is equivalent to a written "high C" on the horn (c^3).
[12] John Humphries, *The Early Horn: A Practical Guide* (Cambridge: Cambridge University Press, 2000), 28.
[13] Benade, *Fundamentals of Musical Acoustics,* 402–03.
[14] It should be noted that the peaks of resonance curves concerning musical instruments are not absolutely symmetrical, and so for the purpose of this analysis, a Lorentzian curve-fitting computer program was used to determine the Q factors.
[15] Lawrence E. Kinsler, Austin R. Frey, Alan B. Coppens, and James V. Sanders, *Fundamentals of Acoustics* (John Wiley & Sons, 2000), 16.
[16] Fang-Chu Chen and Gabriel Weinreich, "Nature of the Lip Reed," *Journal of the Acoustical Society of America* 99 (1996), 1219–26.
[17] The fundamental pitch was calculated based on an average of the fundamental of modes four and eight.
[18] John Chick, D. Murray Campbell, and Arnold Myers, "The Effects of the Internal Condition of the Bore on the Acoustic Properties of Brass Instruments: What Can We Tell about the Playing Condition of Historic Brass Instruments without Playing Them?," in *Musical Acoustics Network, Edinburgh* (July, 2009).
[19] D. Murray Campbell and Clive Greated, *The Musician's Guide to Acoustics* (Oxford University Press, 2001), 343–45.
[20] Matthias Bertsch, "Bridging Instrument Control Aspects of Brass Instruments with Physics-based Parameters," *Proceedings of the Stockholm Music Acoustics Conference, August 6–9, 2003 (Stockholm: KTH Speech, Music and Hearing, 2003),* 193–96.
[21] Alistair C. P. Braden, Michael J. Newton, and D. Murray Campbell, "Trombone Bore Optimization based on Input Impedance Targets," *Journal of the Acoustical Society of America* 125 (2009), 2404–12.
[22] Wilfred Kausel, "Computer Optimization of Brass Wind Instruments," *Diderot Forum on Mathematics and Music* (Vienna, 1999), 227–42.

Appendix

Twenty-three horns were examined in total, predominantly from the eighteenth century. Earlier and later instruments were also included for the sake of comparison.

Abbreviations:

EUCHMI	Edinburgh University Collection of Historic Musical Instruments
Kremsegg	Kremsegg, Musical Instrument Museum
Basel	Musikmuseum, Historisches Museum Basel
JC	Edinburgh, private collection – John Chick

maker	**inv. no.**	**collection**	**date of manufacture**
anonymous	2888	EUCHMI	late eighteenth century
anonymous	Söl.011	Kremsegg	early nineteenth century
Barth	Piz.003	Kremsegg	mid-nineteenth century
Buchschwinder	1980.2123	Basel	1742
Ehe	1956.617	Basel	early eighteenth century
Eichentopf	1980.2134	Basel	1735
Graf	1980.2182	Basel	1745
Haas	1880.72	Basel	1682
Hofmaster	3296	EUCHMI	ca. 1760
Kretzschmann	531	EUCHMI	ca. 1830
Lausmann	Piz.006	Kremsegg	mid-nineteenth century
Le Brun	2161	EUCHMI	1721
Leichamschneider	1878.22	Basel	1718
Meinl	JC - 1	JC	2004 (baroque model)
Nagel	Piz.002	Kremsegg	1663
Paxman	JC - 2	JC	2002 (modern 23E)
Sandbach	203	EUCHMI	ca. 1810–30
Saurle	Piz.005	Kremsegg	late eighteenth century
Seraphinoff	JC - 3	JC	2008 (baroque model)
Shaw	216	Kremsegg	late eighteenth century
Werner	1980.2098	Basel	1735
Werner	Piz.001	Kremsegg	ca. 1770
Winkings	2492	EUCHMI	ca. 1760