Measurement Techniques and the Playability of Terminal Horn Crooks

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ABSTRACT
Before the invention of valves, orchestral horns were generally equipped with a number of crooks of differing effective lengths to facilitate the use of the instrument in music of different tonalities. Even after the introduction of valves, some horns continued to be provided with detachable crooks. The experience of players is that the choice of crook critically affects the response of a horn, and that different crooks providing the same nominal pitch can have appreciably different playing properties. The bore profiles of a sizeable sample of terminally-fitting crooks with effective lengths up to 3.5m were derived from wide-band input impedance measurements using a multiple microphone technique. Bore profiles were also derived from time domain pulse reflectometry measurements for comparison. The correspondence between the bore profile of a crook and the intonation and ease of note initiation when played by appropriately experienced horn players was explored in a series of playing tests.

INTRODUCTION
The modern orchestral French horn is fully chromatic and can play in any key through the use of valves which add or subtract lengths of tubing to or from the air column. Prior to the invention of valves, the “natural horn”, however, had no valves and could only play one key at a time through oscillating the lips at the different harmonic resonances of the air column. Natural horn players will therefore have a number of separate pipes called crooks which are of different lengths to set the instrument into different keys. These are normally designed such that the players mouthpiece fits into one end and a tapered tenon at the other end is inserted into a socket on the main body, or corpus, of the instrument as shown in figure 1.
The crooks vary in length from tens of millimetres to more than three metres. For practical reasons, all but the shortest crooks are coiled with between 1 and 4 hoops.

The playing qualities of a natural horn are dependent on the design of the crooks and the corpus. In particular the resonances of the instrument’s air column must be tuned close to a harmonic series for the instrument to have a satisfactory timbre, but also the bore profile can have an effect on the ease of starting a note, the intonation of the resonant modes and the ease with which the pitch can be “bent” by the players lips for fine tuning. For example, when a note is started, the reflections of the pressure oscillations produced by the players lips take several cycles to reflect from the bell of the instrument and return to the lips [1][2]. If the lips are vibrating close to a resonance frequency of the instrument then the reflections from the bell will arrive in phase to reinforce the resonances of the lips and the note should sound cleanly.

Variations in design exist between different crooks made by different manufacturers and those made in different eras. Typically, British instruments built in the 18th century would have used a relatively short tapered “master crook” to which could be added one or more cylindrical couplers between the crook and corpus to achieve the desired length of horn. By the start of the 19th century there was a certain level of standardisation amongst instrument makers and it had become more common to have separate crooks for almost all keys with the possible exception of Bb-basso which was normally achieved by adding a cylindrical coupler to the C-basso crook. Although there seems to be no standard taper for the tenon and socket joints on orchestral horns of the period, in many cases the crooks were interchangeable from one instrument to another, and it is likely that players would “mix and match” the crooks to best meet their playing requirements.

Dents in crooks also lead to variations in their internal profile. It is reasonable to assume that the small reflections from these discontinuities in the internal bore profile will lead to small discrete reflections in the initial pressure oscillations and this may affect the playability of the instrument. This also applies to discontinuities at the tenon and socket joint or joints.

The current paper will explore various techniques for measuring the internal profile of horn crooks and how sound reflects within them. Approximate measurements of the bore profile of crooks can be achieved by taking external measurements with callipers and then subtracting an estimate of the wall thickness. Internal measurements with callipers are only achievable near the open ends of coiled tubing in the instrument. Pulse reflectometry is a non-invasive echo based method for determining the impulse response (the pressure reflections resulting from inputting a pressure pulse into an instrument). This method is effective for crooks up to about 1.4 metres in length. The internal bore profile can then be reconstructed from this data. Recently multiple microphones have been used meaning that experiments may also be done in the frequency domain (by measuring the response of instruments to sine waves) and using this data to deduce the time domain response and bore profile. In this paper crooks of different length and of different ages (recent and historical) will be measured and conclusions drawn on their construction, condition and playability.

The experiments in this paper were performed using two methods: “time domain” pulse reflectometry [3][4] and a “frequency domain” method known as TMFC (Two-Microphone-Four-Calibration) [5].

PULSE REFLECTOMETRY AND TMFC

In conventional acoustic pulse reflectometry [3] an acoustic pulse (click) is played from a loudspeaker into a cylindrical source tube (in this case of length 16 metres) and the reflections from an object under test coupled to the other end of the source tube are recorded by a microphone mounted in the source tube wall. As long as the source tube is significantly longer than the object under test and the microphone is placed appropriately the reflections from the object do not overlap the incoming pulse or reflections from the source (loudspeaker). While the pulse is not perfectly sharp in shape a band limited impulse response can be calculated by deconvolution by dividing the Fourier transform of the measurement by the Fourier transform of a measurement of the tube closed in a cap and then performing an inverse Fourier transform to the result. This impulse response is then used to calculate the internal bore profile of the object under test using a lossy layer peeling algorithm [6].
Background noise can be a problem. To combat this, “maximum length sequences” (MLS) [7] are used for the pulse reflectometry measurements in this paper. A maximum length sequence is a signal consisting of an overlapping sequence of windows each of which contains a unique binary number. The order of the MLS for these experiments was chosen to be 18 meaning that the windows were 18 samples long and the total MLS sequence consisted of $2^{18} - 1$ binary numbers. When the signal is played twice from the loudspeaker the recorded signal during the second playing of the signal is measured and the response of the system is calculated by auto-correlation with the measured signal. It takes almost 12 seconds to play the (repeated) MLS sequence at 44,100 Hz sample rate and a few seconds to perform the auto-correlation by (using the discrete Fourier transform method). Deconvolution with a cap measurement is still necessary to derive the impulse response. Care must be taken not to drive the loudspeaker into harmonic distortion as this leads to spurious alias peaks in the time domain impulse response.

A further improvement to pulse reflectometry is in the calculation of the loudspeaker transfer function from the cap measurement enabling the reflections from the source to be predicted and removed from the measurement of the object under test [4]. This was required for accurate measurements of the horn crooks due to the long lengths of some of the examples and the fact that many reflections occur within the pipe due to the poor radiation characteristic of a crook with no bell attached.

The most significant limitation of the technique relates to the very low frequency components of the measurement. These are responsible for slow drifts in the derived bore reconstruction and are therefore required accurately, but the more low frequency that is fed into the source tube, the wider the pulse and the poorer the separation of the forward going and backward going waves in the source tube. To improve on this a non-calibrated version of the TMFC method described below was incorporated and was used to replace only the bottom two non-zero frequency bins in the frequency domain version of the impulse response. At these low frequencies the propagation constant is known accurately according to theory so no calibration was necessary. In turn this meant that the MLS sequence used for the main time domain measurement could be filtered (using a digital high pass filter) before being fed into the loudspeaker amplifier to minimize the pulse width without sacrificing low frequency accuracy in the final impulse response. With these steps carried out it was found that no DC offset removal was necessary other than setting the zero frequency bin in the reflectance to -1. At high frequencies the impulse response was filtered out gradually to zero around 5 kHz after which the experimental data was poor due to losses in the long source tube. This means that sharp steps are not reconstructed with perfect resolution but the results show that the accuracy is acceptable for bore reconstruction.

The TMFC Method

The Two-Microphone-Four-Calibration method [5] uses a driver to generates a plane sine wave which traverses a relatively short measurement duct (typically 12.8cm). The object to be studied is placed on the far end. By using two microphones situated in the measurement duct the reflectance (frequency domain version of the impulse response) of the object under test can be calculated from the ratio of the microphone signals as long as the frequency domain propagation factor (which characterizes the wavelength and losses) and relative frequency domain microphone transfer sensitivities are known. In the current paper the sine waves of frequency 50 Hz, 100 Hz, 150 Hz and so on up to 20 kHz are used enabling the discrete frequency domain input impedance to be calculated.

The system is calibrated by measuring the impedance of four closed tubes of known length yielding three complex calibration coefficients. These parameters can also be derived using plane wave theory. This is necessary for the low frequencies since unfeasibly long calibration tubes would be needed for a “full calibration”. From the measured impedance the impulse response can be calculated using an inverse Fourier transform hence a reconstruction can be obtained.

One complication is that different microphone distances are required for different frequency ranges and an even longer measurement duct for low frequencies. This is because singular frequencies exist where there is effectively no difference between the signals if the distance...
between the microphones is a multiple of half a wavelength. The advantage of the technique is that very good signal to noise ratios are possible including at very high frequencies due to the short length of the source tube. A major disadvantage is that the measurements take a long time as each frequency bin must be measured for a time longer than the length of the impulse response which may be up to around a twentieth of a second. If long impulse responses are to be measured accurately then the frequency resolution must be equal to roughly the inverse of the impulse response length. For the current study the frequency resolution is 50 Hz meaning that the impulse response is deduced for a fiftieth of a second. This is shorter than the length of the impulse response of the very longest of the objects we wish to study so while we expect good results for short crooks, the longest will not be reconstructed accurately due to time domain aliasing.

RESULTS

All the horn crooks measured were designed to fit a standard horn mouthpiece at the input end and hence had internal diameters of roughly 6 to 8 mm at the input. The tenons all had a standard internal diameter of around 11 mm making them interchangeable, although there was some small variation in the length of nominally similar crooks depending on manufacturer and variation in (historical) tuning systems. In some cases the crook sets different pitches were produced by the player piecing together up to four pieces of tubing by hand whereas others were built in one piece. All crooks were measured without the corpus so their lengths were clearly demonstrated.

While the internal dimensions of the bell of and instrument can be estimated directly using conventional techniques [8] the internal dimension of tubing is much harder to determine, especially in coiled sections. Traditional techniques for estimating the bore profile involve measuring the external dimension, estimating the wall thickness and subtracting this from the external dimension. This generally works quite well but there will occasionally be uncertainties, for instance at overlapping joints and in the first section of the crook where there may be a reinforcing chemise at the mouthpiece receiver.

The set of crooks made by Courtois consist of 8 crooks (giving nominal horn lengths for B flat, A, G, F, E, E flat, D, C-basso) and one coupler for extending the C-basso crook to Bb-basso. By way of comparing and validating the measurement techniques the Courtois A, F and D crooks were measured externally using callipers and internally using pulse reflectometry and the TMFC method. The results are shown in figures 2a, 3a and 4a, together with bore profiles for A, F and D crooks from six different makers, in figures 2b, 3b, and 4b. We can see that the pulse reflectometry measurements look convincing in terms of the overall trend of the air column diameter for the A and F crook measurements and look perhaps a fraction of a millimetre too large for the D crook (longest). The taper at the end of the crook is not reconstructed accurately in pulse reflectometry due to the limited (roughly 5 kHz) frequency bandwidth meaning that the sharp steps in the bore are not reconstructed with full precision but rather are smoothed out in the manner known as the Gibb's phenomenon.

Figure 2 Comparison between measuring techniques for a Courtois A crook (figure 2a, left), and A crooks from six different makers (figure 2b, right).
The TMF technique in contrast reconstructs the sharp changes in diameter very accurately due to the technique boasting large (20 kHz) bandwidth. On the downside, the overall trend in the reconstruction (determined by the low frequency accuracy) is not quite so convincing with the longest crook (the D crook) measurement showing that the TMF technique is clearly over predicting the air column diameter to the point of exceeding the known external diameter by one millimetre. It is clear that the TMF technique shows significant promise but that it requires to be carried out with more frequency resolution if it is to be applied to the longer horn crooks. This would, however, make the measurement process even longer as currently only one frequency can be measured at once.

Looking at the external measurements, the cylindrical chemise, approximately 140mm in length, at the start of the crook can clearly be seen. The bore profile in this section of the instrument is generally believed to be critical in determining some of the playing characteristics. As can the obvious steps in the outside diameter of the overlapping joints at 700mm for the Courtois F crook, and 710 and 1430 for the Courtois D crook.

In figure 5(a) we see the bore profile of the shortest five in the Courtois set. The figure shows that the shortest two crooks are basically conical while the third begins to have a more parabolic design. The fourth and fifth crooks (for nominal pitches F and E) appear top have very similar profiles and may well be made from same mandril. Going on to consider the longer members of the Courtois set in figure 5(b) we see that they also seem to be close enough in shape to have been made from the same mandril. Looking closely at a point around 800 mm into the bore of the instrument we can see that there is a characteristic bump in the bore profile. This is probably due to the manufacturer having a common design for the first 800 mm of the crooks (with a roughly parabolic shape increasing from around 7.5 mm internal diameter to around 10 mm) and then joining on another section of tubing increasing from an internal diameter of 10
mm to around 11 mm in the next 600 mm and cylindrical there after to give the desired pitch. We can see an illustration of the accuracy of the technique by comparing the C basso and B flat basso plots which actually are reconstructions of the same piece of tube as the cylindrical coupler section added at the end of the crook is the only difference between the horn used at a nominal pitches of B flat and C basso.

During playing tests it was noted that the mouthpiece sat quite far into the mouthpiece receiver of the D crook from the Courtois set and that it wobbled slightly. Visual inspection suggested that the receiver had been crimped in an attempt to reduce the diameter and make it a better fit for the mouthpiece. It can be seen from figure 5(b) that the receiver diameter is larger and the profile different from that of the other Courtois crooks.

CONCLUSIONS AND FURTHER WORK
The bore reconstruction for various sets of crooks has been obtained via two different measurement techniques: the time-domain method of acoustic pulse reflectometry; and the frequency-domain “Two-Microphone-Four-Calibration” method. From crook measurements of lengths less than 1.4 m the TMFC system has delivered accurate and promising results. Above 1.4 m however, the “missing” low frequency data causes the reconstructions to over-predict the profile radii. Theoretically, the relatively new TMFC method should give better results than the well established APR method as the TMFC system measures over a much larger bandwidth than does APR. We hope to improve the results obtained via the TMFC method by reducing the lowest measured frequency from 50 Hz down to 10 Hz. We also hope to increase the frequency resolution of the data from 50 Hz intervals to 10 Hz intervals.

References: