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Acoustic pulse reflectometry for the measurement of horn crooks

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The echo-based technique of acoustic pulse reflectometry can be used to measure tubular objects to determine the bore profile. In this paper, measurements of historic orchestral horn crooks are presented showing how the technique can help to determine the method of construction of historic crooks and can provide valuable information to manufacturers of reproduction period instruments. Comparison of the bore profile measured by pulse reflectometry and the known exit radius of the crook can be used to determine the presence of leaks. The technique is shown to be sensitive enough to find a leak in a horn crook that behaves reasonably under playing conditions and was not suspected of having a leak prior to testing.

1 Introduction

Acoustic Pulse Reflectometry (APR) is a non-invasive technique that can be used for the measurement of the input impulse response of a tubular object. From this the input impedance and the internal profile can be deduced. In conventional APR a loudspeaker produces as closely as possible an acoustic impulse (click) which travels down the air contained in a cylindrical source tube and into the object under test.

When the bore contracts a positive reflection coefficient is experienced by the wave, and expansions cause a negative reflection coefficient. The multiple reflections within the object under test then result in backward going waves travelling back down the source tube to be measured by a microphone mounted in the source tube wall. As long as the dimensions of the source tube are long enough then the forward going impulse and the backward going reflections are separated physically in the time domain.

A measurement with the source tube closed by a cap is then performed and a deconvolution procedure is used to calculate the input impulse response. The bore profile (as a plot of internal diameter versus axial distance) of the object under test can then be deduced using the layer peeling bore reconstruction algorithm [1].

This paper describes recent developments in the technique which include use of Maximum Length Sequences, the importance of DC and low frequency information in determining slow trends in the resulting reconstruction, and the method of calibration of the apparatus. Application of the technique is demonstrated via an investigation into the bore profiles of a selection of crooks from orchestral horns.

2 Maximum Length Sequences

Using impulsive excitation is not an efficient method of getting energy into the system. If impulses are to be used then averaging of repeated measurements must be performed to give a good signal to noise ratio. A more time efficient technique is to use signal maximum length sequences (or MLS). Swept sine wave techniques are also popular but in this case the experiment tends to take a little longer to perform if convincing results are to be obtained.

A maximum length sequence (MLS) signal is a pseudo random sequence of 0's and 1's that has a flat frequency spectrum. The sequence is used as the input to the loudspeaker and the signal is measured at the microphone. The loudspeaker should produce two repetitions of the MLS with the microphone signal recorded during the second play as the reflections of the end of the MLS are just as important as the reflections from the start of the MLS. The input impulse response of the system is then extracted by cross-correlation of the original MLS with the microphone signal. This method of excitation has been employed frequently in measuring the input impulse response of rooms for reverberation measurement [2] and more recently for APR.

The easiest method of programming the cross-correlation is to use frequency domain multiplication:

$$H(\omega) = MLS^{*}(\omega) \times P(\omega) \qquad (1)$$

where $H(\omega)$ is the Discrete Fourier Transform of the system impulse response, $P(\omega)$ is the Discrete Fourier Transform of the measured microphone signal and $MLS^{*}(\omega)$ is the complex conjugate of the Discrete Fourier Transform of the original MLS sequence that was fed to the loudspeaker. A computationally much faster technique is to use the Fast Hadamard Transform for cross-correlation [3] but with modern computer power the Discrete Fourier Transform approach is perfectly adequate.

3 Experimental Setup

3.1 Single Microphone Apparatus

Single microphones have been used for most pulse reflectometry in the past [4,5,6]. The schematic of the experimental apparatus is shown in figure 1.

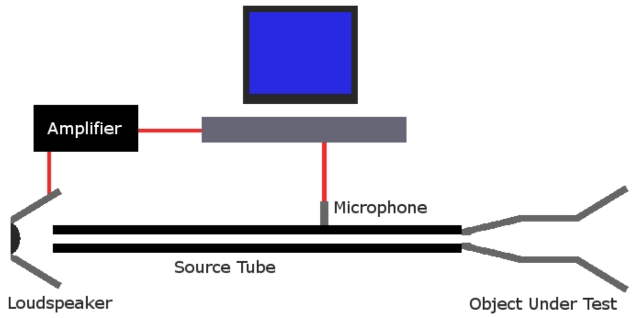


Fig.1 Acoustic Pulse Reflectometry Apparatus.

This technique relies on the assumption that an impulse emitted by the loudspeaker will completely pass the microphone before any reflections arrive from the end of the source tube. The length of the source tube between the microphone and the end of the tube is chosen to meet this condition. Also the last of the reflections from the object under test must completely die away before the first of those reflections bounce off the loudspeaker and reach the microphone. The distance between the loudspeaker and microphone is also chosen to meet this condition.

This technique is effective for short objects. Measuring longer objects is possible but high frequency accuracy suffers. The reason for this is that the length of an impulse measured in a cylindrical tube depends on the visco-thermal losses experience by the wave as it travels down the source tube. These losses increase with frequency, causing the impulse to be low pass filtered, so rounding the corners and making it longer in length. Increasing the source tube dimensions in principle allows longer objects to be measured but also increases the width of the impulses, necessitating further increases of source dimensions so creating a vicious cycle.

3.2 Multiple Microphones

While single microphones have been used for most pulse reflectometry in the past, using multiple microphones has a major advantage in terms of separating forward and backward going waves making shorter source tubes possible (which in turn leads to much smaller visco-thermal losses within the source tube). Recent work in this area has included very high accuracy impedance measurement using swept sine excitation using four calibrations and precisely machined dimensions [7, 8].

Separation of forward and backward going waves using two microphones has also been attempted by Louis et al. [9]. The main problem with these techniques is that wavelengths that have certain integer relationships with the microphone separation distance are not measured accurately. This can be solved by taking measurements with microphones at various separations. Another problem was with the sensitivity of the experiments to the machining or knowledge of the distances between microphones and calibration objects. Future work may involve discussion of solutions to these problems.

4 Calibration

Calibration is performed by deconvolving the reflections from a cap used to terminate the source tube from the object reflections. This can be been done by frequency domain division:

$$IIR(\omega) = \frac{OBJ(\omega)}{CAP(\omega)} \qquad (2)$$

where *CAP* is the FFT of the cap reflections, *OBJ* is the FFT of the object reflections and *IIR* is the FFT of the input impulse response (and an inverse FFT is used to calculate the time domain input impulse response). This process removes the effect of the frequency responses of the microphone, loudspeaker, soundcard and source tube propagation. The only limitation is that the signal to noise ratio is very poor at frequencies outside the bandwidth of the above responses.

No signal is measured above around 15 kHz for most pulse reflectometry measurements (depending on the length of the reflectometer source tube) due to visco-thermal losses. For similar reasons and due to the laws of diffraction the reflection coefficients of most musical instruments to these high frequencies are minimal. In practice the random noise outside the measurement bandwidth can cause certain frequencies in the *IIR* have very large values for the division. These singularities in the measurement have often been corrected by using a small constraining factor, *q*, added to the denominator of the frequency domain deconvolution [4,5,6]:

$$IIR(\omega) = \frac{OBJ(\omega)}{CAP(\omega) + q} \qquad (3)$$

This forces the impulse response to zero outside the bandwidth of the cap measurement. The disadvantage of this technique is that it has a small effect on frequencies within the measurement bandwidth. The current experiments use a new version of this processing which can be described as a constraining vector:

$$IIR(\omega) = \frac{OBJ(\omega)}{CAP(\omega)(1 + q(\omega))} \qquad (4)$$

with $q(\omega)$ being a vector equal to zero for low frequencies and then increasing exponentially at high frequencies to set the impulse response to zero outside the bandwidth. The cut-off must be fine tuned depending mainly on the losses (which in turn depend on the radius and length of the source tube). Figure 2 shows the results of a frequency domain division with and without a constraining vector. An alternative technique developed by Forbes at al [10] is that of Truncated singular value decomposition (TSVD).

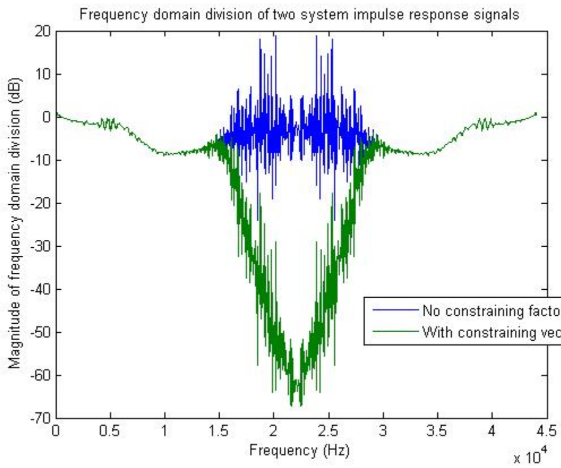


Fig.2 Frequency domain division.

5 Results

The following results show the accuracy of the current technique. The green line in figure 3 shows the internal profile of an early 20th century (possibly 1930s) Boosey and Hawkes orchestral horn in F (with valves open) measured by pulse reflectometry. Also shown is the blue line which shows the internal profile of the same crook removed from the rest of the horn. Figure 4 shows the same plot but focussing in on just the crook section.

Physical measurements of the very end of the crook reveal an internal diameter of between 10.8 and 10.6 mm. There is a tenon joint at the end of the crook which is strongly tapered to allow a snug fit with a socket on the corpus of the instrument. At a distance of 5mm in from the open end of the tenon, the diameter is measured to be between 11.4 and 11.5 mm. These measurements agree quite closely with the internal profile shown according to pulse reflectometry. It is likely that the error is of the order of 0.2 mm. The bandwidth of the experiment extends to 15 kHz and this corresponds to a wavelength of 23 mm. Steps in the bore will therefore not be resolved perfectly but will suffer from a Gibbs phenomenon ripple in the internal profile. This explains the imperfections of the reconstruction near the open end of the crook.

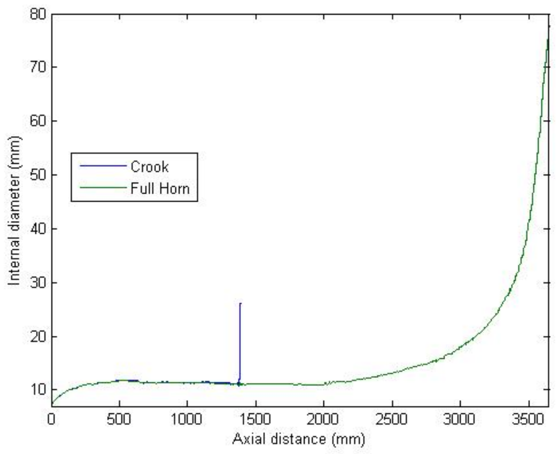


Fig.3 Boosey and Hawkes piston valve horn in F (circa 1938).

The crook is constructed from two sections of tubing, one roughly parabolic in shape and the other roughly cylindrical. These are joined by a sleeve joint at approximately 600 mm along the crook as measured along the center line of the tubing starting from the mouthpiece receiver. It is possible to join two tubes with very little discontinuity in cross section using a sleeve joint. One particularly interesting feature of this crook is the expansion in diameter between 500 mm and 600 mm along the crook (i.e. at the end of the first section of tubing). It seems likely that this was not a design feature but is the result of a repair.

If a dent occurs in a brass instrument then the instrument may be disassembled at the soldered joints and then a hard appropriately shaped object (a mandrel or dent ball) is inserted to the appropriate location inside the horn and supported on a vice. The dented tubing is then pressed down so that the depressed area is raised by the hard object within. This can lead to thinning of the metal and an expanded bore diameter as may have happened in this case.

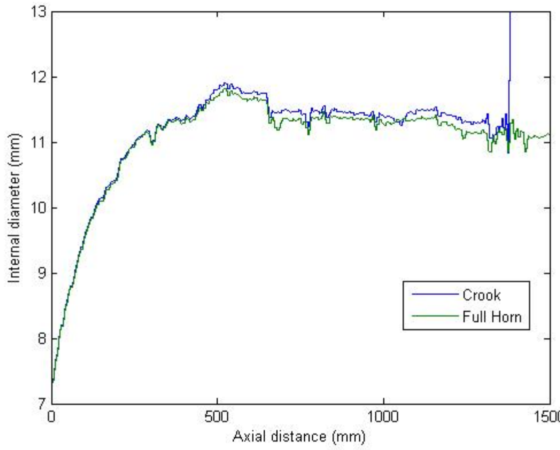


Fig.4 Valved Boosey and Hawkes (detail).

The next set of results, in figure 5, shows bore profiles from three crooks: a Boosey and Hawkes crook (London, circa 1938), a Boosey & Co crook (London, circa 1900), and a mid 19th century crook by F. Besson, Paris. The figure illustrates a general trend observed by the authors, that more recent instruments tend to have larger internal diameters for the cylindrical section of the crook than more historic instruments. Interestingly the reconstructions for both the B&H and Bossey & Co crooks show dents at the same point (around 785 mm along the length of the tube) and by visual inspection of the instruments it is clear that this has been caused by difficulties players may have had inserting and removing the crook into and from the corpus, causing some damage to the section of the coiled crook tube adjacent to the tenon joint which joins the crook to the corpus.

Unlike the 'London' crooks, the older Besson crook was constructed from two sections of tubing using an overlapping or terrace joint. In these, the tubing is joined by expanding the internal diameter of one tube so that it mates with the other tube, or two different tube diameters are used. It is clear from pulse reflectometry and from external observation that the join is located around 700 mm from the mouthpiece end. This crook, although quite playable, is so significantly dented and depressed in the initial section of tubing that it is not clear what bore profile was initially created by the maker. It is, however, clear that the terrace joint construction did originally imply the large jump in the profile observed at 700 mm.

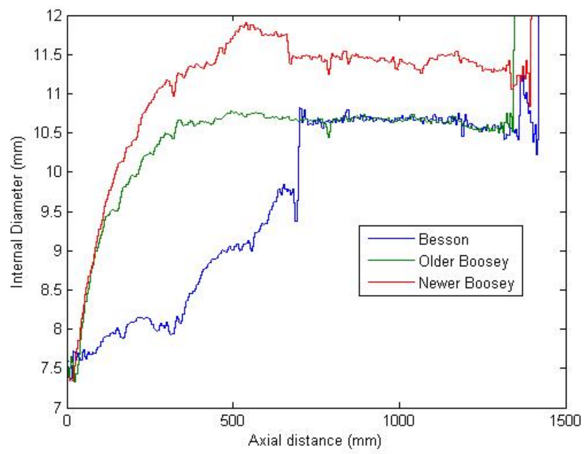
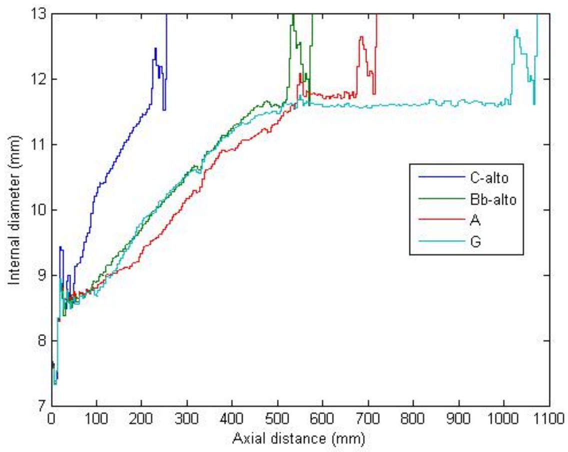


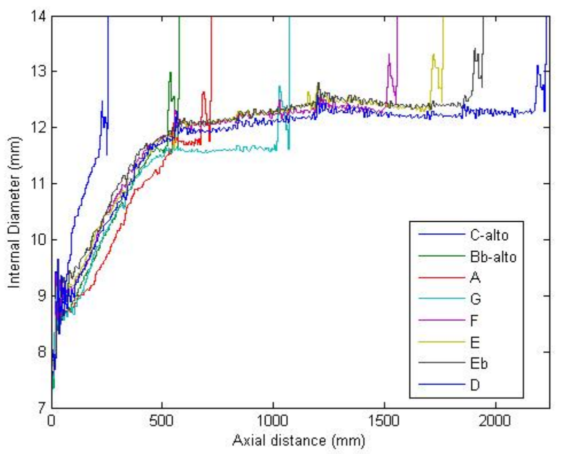
Fig.5 19th century Besson crook (significantly dented) and crooks by Boosey & Hawkes, and Boosey & Co.

In figure 6 and 7 we see bore reconstructions for a set of crooks in current production, and made by M. Jiracek & sons of the Czech Republic. These crooks are in very good condition. The C-alto and B flat-alto crooks are constructed using single almost conical sections of tubing. The A and G crooks are constructed from two sections of tubing, one roughly conical and one cylindrical. It is clear from the reconstructions and from observation of the outside of the crooks that the sleeve joint is at a position 565 mm from the mouthpiece end. The discontinuity in the bore at this position is not great so the joints were well constructed and soldered. Measurement of the internal diameters of the exits of the crooks revealed a value of 11.7 mm. This agrees well with the measurements of the C-alto, Bb-alto, A and G crooks.



.Fig.6 Modern crooks (C to G) by M. Jiracek & sons (Czech Republic).

The F and E crooks have been constructed using three pieces of tubing, the second two of which are cylindrical with socket joints at 565 mm and 1200 mm. Four pieces of tubing have been used to construct the E flat and D crooks and these have joints at 565 mm, 1200 mm and 1865 mm. The maker appears to have used a single conical mandrel to construct the first section of tubing for all but the shortest of the crooks (C-alto). Varying lengths of up to 465 mm (1.5 feet) of cylindrical pipe of internal diameter 11.7 mm have then been carefully joined to create the correct acoustic length for the instrument. The bore reconstructions shown in figure 7 show a 0.5 mm over-prediction of the internal profile at the end for the F, E, and D crooks. This is due to the sensitivity of the bore reconstruction algorithm to very low frequency components in the impulse response measurement for test objects over a meter in length.

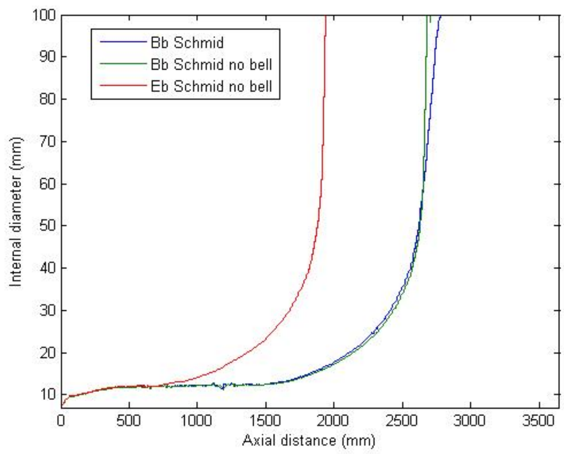


.Fig.7 Crooks by M.Jiracek & sons (Czech Republic).

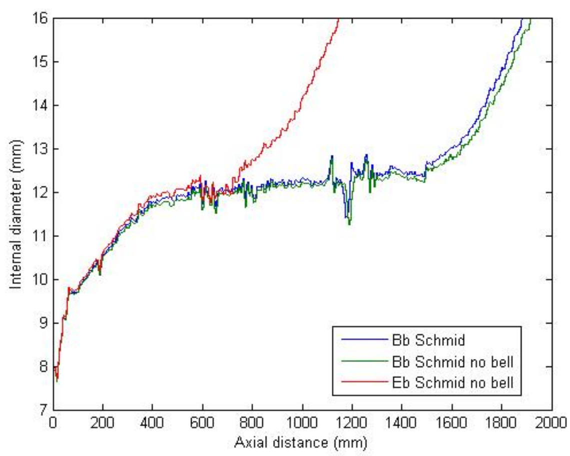
Figures 8 and 9 show a modern Bb/Eb-alto double horn with rotary valves made by Engelbert Schmid of Germany. The term double horn refers to the fact that in addition to the usual valves for chromatic playing, a valve is provided which can be used to bypass a section of tubing to change the length from that for a Bb horn to that for an Eb horn. Measurements were performed with this change valve depressed and not depressed (the main valves were not depressed).

The five valves are positioned side by side starting at around 580 mm along the length of the bore. The first change valve for changing between the Bb and Eb sounding lengths is positioned at 580 mm. Next the air column continues through the three main valves followed by the second change valve which is present at 720 mm. The bore profiles then deviate with the Eb valve position setting the start of the bell section at this point as can be seen from the deviation of the graphs in figure 9. The section of tubing added by the second change valve for the Bb sounding length finishes at 1495 mm. The total length of tubing added is therefore around 770 mm.

Figure 9 also shows that the extra section of tubing used for the Bb sounding length features discontinuities at 1200 mm along the instrument length. These may correspond to the main tuning slide and the two water release keys either side. The internal bore diameter at the tuning slide is 11.9 mm and this expands to 12.5 mm where sections are partially pulled out to set the tuning. The mean diameter around this point is shown as 12.2 mm on the bore reconstructions, showing an over prediction in internal diameter by 0.3 mm. It is possible that the slight constriction by 0.5 mm in internal diameter at 1180 mm along the bore corresponds to a mild distortion in cross-section at the bend in the tuning slide.



.Fig.8 Modern double horn by with rotary valves by Schmid (Germany).



.Fig.9 Valved Schmid horn (detail).

The Schmid instrument also features a removable screw on bell and figure 8 shows clearly that the measurements of the Bb horn diverge from each other at a diameter of around 60 mm. The diameter of the screw connection between the removable bell and the main corpus of the instrument is 70 mm exactly, showing that the technique is reasonably accurate for the whole length of the instrument. Plane wave propagation is assumed in the bore reconstruction algorithm which means that better accuracy at the bell is not currently achievable but the study of multimodal decomposition [11] may be used to solve this problem in the future.

The crooks measured in the bore reconstructions in figure 10 were constructed by Gautrot of Paris in around 1875. These were made using overlapping or terraced joints. The close agreement in profile for the crooks shown in Figure 10 suggests that the tapered parts of these crooks have been drawn from the same mandrel. However, at approximately 700 mm from the mouthpiece receiver end, the C-basso crook appears to have a more rapid expansion in bore profile. A trivial examination of the crooks indicated that there was an anomaly in the results: either there was an error in the measurements or some other cause. This was evidenced by the fact that the measured internal diameter of the cylindrical tubing was, in fact, larger than the external diameter.

One possible cause for this apparent expansion would be a small leak at the point where measured results expands rapidly, diverging from the profile of the other Gautrot crooks. The effect of the leak is to cause a negative reflection in the impulse response which in turn is interpreted as a spurious expansion in the bore profile [4]. A test was performed by blowing through the crook while it was partly submerged in water. Bubbles were observed to be coming from a point 700 mm along the bore proving the existence of the leak at this position. The exact position of the leak was obscured from detection from the naked eye beneath adjacent coils of tubing. . In playing tests, although the crook felt "stuffy", it was not apparent that this stuffiness was caused by a leak.

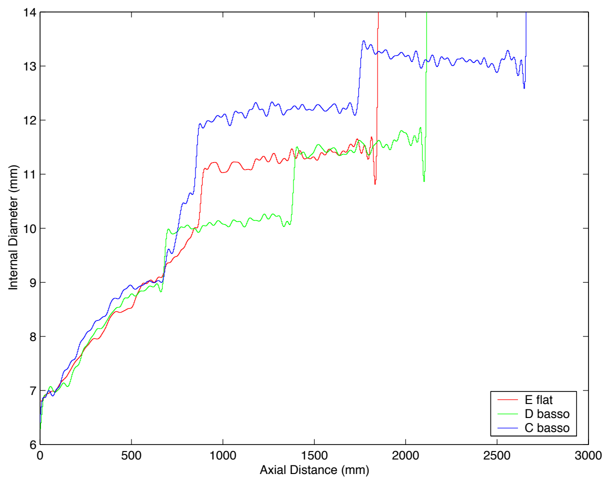


Fig.10 Crooks by Gautrot (Paris, circa 1875).

5 Conclusion

Pulse reflectometry has proved to be very useful in determining the construction methods used by manufacturers. In addition to this the leaks, dents and imperfections in manufacture can be readily identified and located. The error bound for internal diameter measurements for tubular objects of relatively gradual flare and of length 1 m of the current apparatus is around ±0.1 mm and around ±0.8 mm objects in excess of 2 m in length.

Its ability to find these features is far in advance of the human eye, or indeed ear! Pulse reflectometry could be used by manufacturers and repairers as part of a quality control process. It should also be noted that the technique has wider application than just that of musical instruments, but would be of value for any industry interested in detecting imperfections in tubular objects, finding leaks in pipework for example.

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