ACOUSTIC PULSE REFLECTOMETRY FOR THE NON-INVASIVE MONITORING OF DUCTS

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1. INTRODUCTION

Acoustic pulse reflectometry is a non-invasive measurement technique which can be used to determine the internal profiles of ducts of varying cross-section. The technique involves probing the duct under investigation with a sound pulse and recording the resultant reflections. Suitable analysis of the reflections gives the input impulse response of the duct, from which the cross-sectional area as a function of axial distance can be calculated. The presence of any small blockages or leaks in the duct can be identified from the calculated bore profile.

In this paper, the historical development of acoustic pulse reflectometry is discussed and the basic reflectometry technique is described. Finally, some of the established applications, such as leak detection in pipe sections and the profiling of historical wind instruments, are reported.

2. HISTORICAL DEVELOPMENT

Acoustic pulse reflectometry was originally developed as a seismological technique for the observation of stratifications in the earth's crust. The earth's crust is made up of layers of different types of rock. When an approximately impulsive pressure wave is produced by a source such as dynamite and used to probe the crust, reflections are generated due to impedance differences between the layers. These reflections return to the surface where they are recorded and, because of the impulsive nature of the excitation, termed the input impulse response. Ware and Aki [1] developed a solution to the inverse problem of calculating the reflection coefficients of the layer boundaries from the input impulse response. The solution assumed lossless propagation through the layers. From the boundary reflection coefficients and the impedance of the surface layer of rock, the impedances of deeper layers could be calculated.

In the early seventies, the medical research team led by Sondhi noted the potential of acoustic pulse reflectometry as a method for measuring airway dimensions. In an essentially theoretical paper, Sondhi and Gopinath [2] described how, by applying a sound pulse to the airway under test and recording the reflections at the lips, the area profile of the airway could be calculated. In their treatment, as in the Ware-Aki treatment, losses in the airway were not taken into account.

Jackson et al [3] published area profiles of excised dog tracheas and lungs measured using a pulse reflectometer. They modelled the airway as a series of discontinuously joined cylindrical segments of equal lengths but differing cross-sectional areas (and, hence, differing impedances). The problem of measuring the airway dimensions was thus reduced to one of finding the areas of the individual segments (an analagous problem to that of determining the impedances of the layers of rock in the earth's crust). The design of the reflectometer was such that a sound pulse created by a spark discharge was applied to the airway via a source tube. Reflections generated at the boundaries between the cylindrical segments returned from the airway and were recorded by a microphone embedded in the wall of the source tube part of the way along its length. The input impulse response of the airway was determined by deconvolving the airway reflections with the input pulse shape. The algorithm developed by Ware and Aki was used to calculate the reflection coefficients of the inter-segment boundaries, from which the segment areas were calculated. Although the Ware-Aki algorithm did not take into account losses in the airway, good area profiles were still achieved because the airways measured were short enough for attenuation to be insignificant.

The first measurements on human patients were carried out by Fredberg et al [4]. The reflectometer used to make the measurements was a substantially more complicated version of the one used by Jackson et al. A sound pulse was again applied to the airway via a source tube. However, in this case both the tube and the subject's lungs were filled with He/O_2 gas. The resultant reflections returned from the airway and were measured by a microphone in the wall of the source tube. The reflections were processed as before and an area profile was calculated using the Ware-Aki algorithm. The reason for filling the apparatus and the subject's lungs with He/O_2 was to increase the speed of sound thereby increasing the bandwidth of the input pulse. With more information from the frequency range in which airway wall non-rigidity could be neglected (i.e. above approximately 1kHz), Fredberg argued that more accurate results should be achieved. On the whole, profile reconstructions made using the He/O_2-filled reflectometer appeared to compare more favourably with X-ray results than those made using an air-filled reflectometer, although the results were not conclusive.

In a conference paper presented at a meeting of the Acoustical Society of America, Benade and Smith [5] described an early attempt to measure the input impulse response of a musical wind instrument using acoustic pulse reflectometry. An input sound pulse was produced by a spark discharge at the mouthpiece of a tuba. The tuba reflections, recorded by a microphone also positioned at the mouthpiece, were considered to be the input impulse response of the tuba. No attempt to remove the effects of the input pulse shape by deconvolution was reported. Ayers et al [6] presented similar work but used a piezoelectric transducer as the sound source instead of a spark discharge.

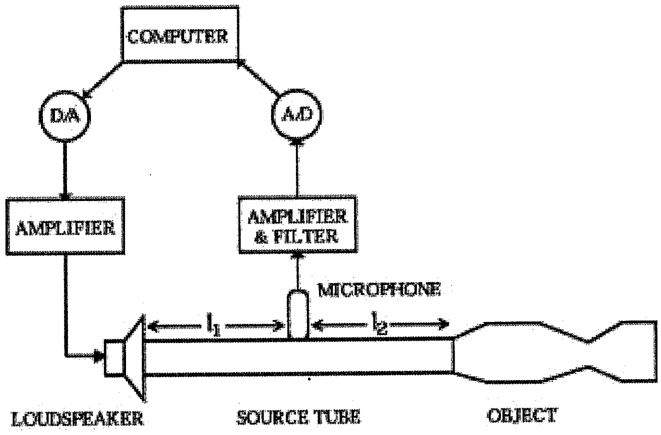
A large amount of research into the use of acoustic pulse reflectometry for measuring the acoustical properties of musical wind instruments was carried out at the University of Surrey under the supervision of Bowsher. The group's earliest work was undertaken by Goodwin [7] who developed a reflectometer whose design was very similar to the clinical reflectometer of Jackson et al and again used a spark discharge to produce the sound pulse. Deane [8] replaced this inconsistent spark source with a loudspeaker. The consistency of the loudspeaker generated pulses allowed averaging of both the input pulse and the instrument reflections to improve the signal-to-noise ratio. Deconvolution then gave the input impulse response.

The research was continued by Smith [9] and Watson and Bowsher [10]. They presented bore reconstructions of various brass instruments calculated from input impulse responses measured using a pulse reflectometer. Cylindrical symmetry was assumed and, instead of the area, the radius was calculated as a function of axial distance. The reconstruction algorithms employed were the Sondhi and Gopinath algorithm and a non-comprehensive version of the Ware-Aki algorithm (a version which did not take into account all of the multiple reflections within the instrument).

Until recently, none of the algorithms used to calculate the bore profile of an object from its measured input impulse response took into account the effect of losses in the object. This had not proved significant when reconstructing a short object such as an airway but when a longer object such as a brass instrument was reconstructed it became more important. Amir et al [11] suggested the use of a layer-peeling algorithm which was modified to include the effect of losses. The algorithm resulted in reconstructed profiles whose radii were correctly predicted at all axial distances. The trumpet and trombone profiles presented were in very good agreement with direct measurements.

3. BASIC REFLECTOMETRY TECHNIQUE

3.1



Experimental measurement

Figure 1: Schematic diagram of pulse reflectometer

Figure 1 shows a schematic diagram of a pulse reflectometer. An electrical pulse produced by a D/A converter is amplified and used to drive a loudspeaker. The resultant sound pressure pulse travels along a copper source tube into the duct under test. A microphone embedded part of the way along the source tube records the reflections returning from the duct. The microphone output is amplified and low-pass filtered to prevent aliasing. The resultant signal is then sampled by an A/D converter and stored on a PC. This procedure is repeated 1000 times and the samples are averaged to improve the signal-to-noise ratio.

3.2 Physical constraints on source tube

The source tube section l_2 is necessary to ensure that the input pulse has fully passed the microphone before the first of the returning duct reflections reaches it. The minimum duration of the input pulse is in practice limited by the requirement that the pulse carries sufficient energy to ensure a good signal-to-noise ratio in the measured reflections.

After the duct reflections pass the microphone they are further reflected by the loudspeaker. The source tube section l_1 is necessary to separate the duct reflections from these source reflections. It ensures that once the duct reflections reach the microphone, they can be recorded for up to $2l_1/c$ seconds (the time taken to travel the distance from the microphone to the loudspeaker and back, where c is the speed of sound) before the source reflections return and contaminate the signal.

3.3 Input impulse response evaluation

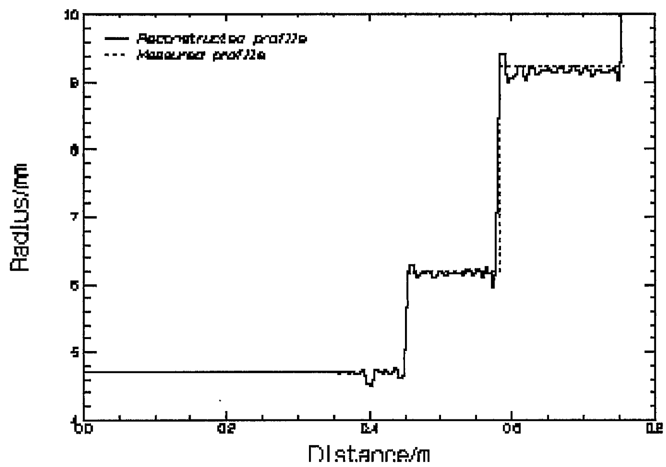
To obtain the input impulse response of the duct, the sampled reflections are deconvolved with the input pulse shape. The input pulse shape is measured by rigidly terminating the source tube and recording the reflected pulse. This ensures that both the duct reflections and the input pulse have travelled the same path in the source tube and have therefore experienced the same source tube losses. The deconvolution is carried out by Fourier transforming both the sample containing the duct reflections and the sample containing the input pulse. To prevent leakage in the frequency domain, both samples must be self-windowing; i.e. the signal must have decayed to zero by the end of the sample. A complex division of the duct reflections by the input pulse is then carried out in the frequency domain. A constraining factor q is added to the denominator to prevent division by zero.

$$IIR(\omega) = \frac{R(\omega)I^*(\omega)}{I(\omega)I^*(\omega)+q}$$

where ω is the angular frequency, $R(\omega)$ is the transformed duct reflections measured at the microphone, $I(\omega)$ is the transformed input pulse measured at the microphone, $I^*(\omega)$ is the complex conjugate of $I(\omega)$ and $IIR(\omega)$ is the transformed input impulse response. $IIR(\omega)$ is then Inverse Fourier transformed to give the input impulse response $iir(t)$ of the duct.

3.4 Bore reconstruction

The reflections returning from the duct occur at changes in impedance, such as expansions or contractions. A suitable algorithm (such as the layer-peeling algorithm developed by Amir et al, which compensates for attenuation due to losses) allows the reflection coefficients arising from these impedance changes to be evaluated from the input impulse response. It is then a small step to calculate the changes in area along the bore. If the duct is assumed to have cylindrical symmetry, the changes in radius can also be calculated.

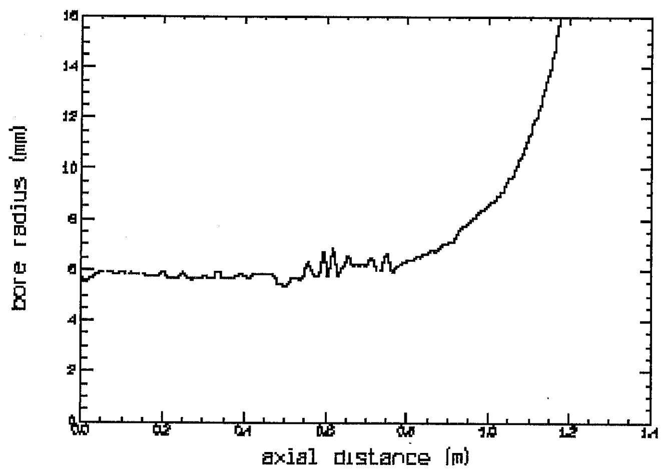


However, DC offsets in the input pulse and the duct reflections generally cause a small DC offset in the input impulse response. This offset manifests itself by causing the reconstruction to expand or contract too rapidly. To determine the DC offset, a cylindrical section of tubing is inserted between the source tube and the duct under investigation. Since there should be no signal reflected from this cylindrical connector (as it contains no expansions or contractions) the input impulse response should be zero. The average value of the measured input impulse response over this range thus gives the DC offset value. Removing this value from the input impulse response before the algorithm is applied ensures the bore profile is accurately reconstructed.

Figure 2: Bore reconstruction of a stepped tube

Figure 2 shows a bore reconstruction of a stepped tube calculated from measurements made using a pulse reflectometer. The directly measured profile is also plotted for comparison purposes.

4. APPLICATIONS



One of the fields in which acoustic pulse reflectometry has become established as a useful measurement tool is musical acoustics. In particular, the technique has proved invaluable in the analysis of historical wind instruments [12] which, due to their precious nature, cannot be played.

Figure 3: Bore reconstruction of a Cornopean in BI (Glen, c 1840)

As an example, Figure 3 shows the bore profile of an early British cornet of the model sometimes known as a ``cornopean". This instrument employed an early form of valve called the Stölzel valve. The abrupt bends in the valve passages result in noticeable irregularities in the windway around 0.6m along the instrument. The overall topography is very similar to that of the modern trumpet.

Another application for which acoustic pulse reflectometry has shown great potential is that of leak detection in pipes [13]. A small leak in the wall of a duct presents a reduction in the impedance seen by the incoming pulse. This change is similar to the change in impedance caused by a widening of the duct. Hence, the leak appears as a spurious expansion in the bore reconstruction.

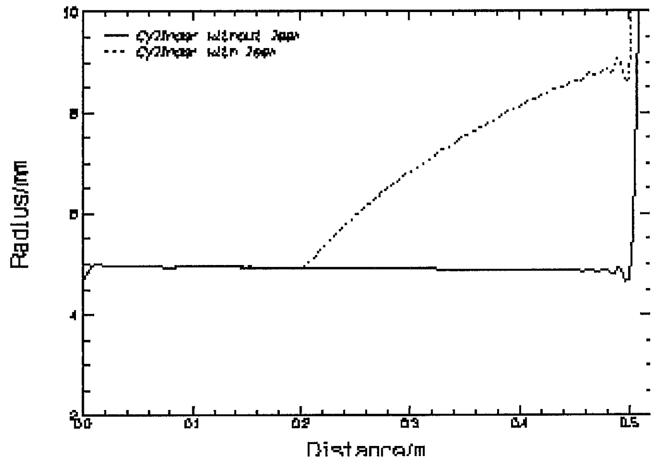


Figure 4: Bore reconstruction of cylindrical pipe with and without sidehole

As an example, Figure 4 shows bore reconstructions of a 501mm long cylindrical pipe (of internal radius 5mm) both with and without a 0.5mm radius sidehole. The two reconstructions coincide until the position of the leak, 200 mm from the start of the pipe. From this point onwards, the reconstruction of the leaking pipe expands, whilst the reconstruction of the airtight pipe continues at the correct radius of 5.0mm.

For the case of a cylinder, it is quite obvious that this expansion is caused by the leak because the radius at the end of the reconstruction should be equal to the radius at the beginning. However, for a duct whose profile is not known in advance, an expansion in the reconstruction due to a leak may be indistinguishable from an actual widening of the bore. Hence, the position of a leak may be difficult to determine. However, the presence of the leak can still be confirmed by observing a discrepancy between the radius of the reconstructed bore and the directly measured radius at the output end of the tube.

5. CONCLUSIONS

Over the past thirty years, acoustic pulse reflectometry has become established in the fields of medicine and musical acoustics as a useful non-invasive method of measuring duct dimensions. Interest is now also being shown by manufacturing industry in the possibility of using reflectometry as a method of quality control in monitoring parts containing ducts throughout the various stages of production. The technique should allow defects such as blockages and corrosion to be detected during the manufacturing process.

6. REFERENCES

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