THE PROBLEM OF DC OFFSET IN THE MEASUREMENT OF IMPULSE RESPONSE USING ACOUSTIC PULSE REFLECTOMETRY

A. Li Open University, Faculty of Technology, Milton Keynes, UK
D.B. Sharp Open University, Faculty of Technology, Milton Keynes, UK
B.J. Forbes Open University, Faculty of Technology, Milton Keynes, UK
J. Kemp University of Edinburgh, Dept of Physics and Astronomy, Edinburgh, UK

1. INTRODUCTION

Acoustic pulse reflectometry has become established as a useful non-invasive technique for measuring the input impulse response, input impedance and internal dimensions of tubular objects (e.g. musical wind instruments or lengths of pipework). A sound pulse is injected into the duct under investigation and the resultant reflections are recorded. The input impulse response of the duct is then calculated by deconvolving the reflected signal with the input pulse shape. Application of suitable algorithms to the input impulse response yields the input impedance and bore profile of the duct.

An input impulse response measurement made using acoustic pulse reflectometry will generally contain an unwanted DC offset. Unless removed, this offset causes the calculated bore profile to expand or contract too rapidly. In this paper, the origin of the DC offset in the input impulse response is examined and methods for determining its value are reviewed. The possibility of preventing the introduction of the DC offset is also investigated.

2. ACOUSTIC PULSE REFLECTOMETER

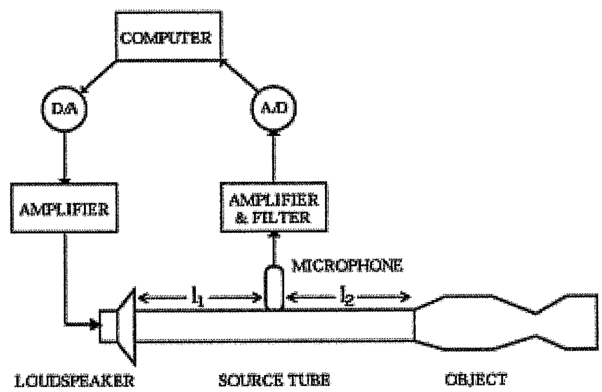

Figure 1: Schematic diagram of pulse reflectometer

A schematic diagram of a pulse reflectometer is shown in Figure 1. An electrical pulse produced by a D/A converter is amplified and used to drive a loudspeaker. The resultant sound pulse travels along a source tube into the duct under test. A microphone in the source tube wall records the reflections returning from the duct. The microphone output is then amplified and low-pass filtered to prevent aliasing. The resultant signal is sampled by an A/D converter and stored on a PC.

To obtain the input impulse response of the duct, the recorded 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 performing a complex division of the duct reflections by the input pulse in the frequency domain [1]:

$$IIR(\omega) = \frac{R(\omega)}{I(\omega)} \tag{1}$$

where ω is the angular frequency, $R(\omega)$ is the transformed duct reflections, $I(\omega)$ is the transformed input pulse, and $IIR(\omega)$ is the transformed input impulse response of duct. By inverse Fourier transforming $IIR(\omega)$, the input impulse response $iir(n)$ of the duct under test is obtained (where n is the discretised time). Application of a suitable algorithm to the input impulse response enables the duct profile to be reconstructed [2].

Generally, the input impulse response of a duct measured using acoustic pulse reflectometry will contain a DC offset. The presence of this DC offset causes the calculated duct profile to expand or contract spuriously and therefore must either be prevented from occurring or removed prior to application of the reconstruction algorithm.

To determine and remove the DC offset, a 50 cm long cylindrical tube can be inserted between the source tube and the duct under investigation [3]. Since there should be no signal reflected back from this 'DC tube', the average value over the first millisecond of the input impulse response is the DC offset. This value can then be subtracted from the whole input impulse response. Alternatively, instead of the 50 cm long cylinder, the last section of the source tube can be used as a 'virtual DC tube' [4].

Determining and removing the DC offset using a DC tube is essentially a calibration measurement. Ideally, the introduction of DC offset into the input impulse response should be prevented in the first place. In order to be able to do this it is first necessary to establish the origin of the DC offset.

3. DC OFFSET IN THE INPUT PULSE AND REFLECTIONS

Originally, it was thought that the DC offset in the input impulse response was caused by small DC offsets in the input pulse and reflections. The most likely cause of such offsets is a slight inaccuracy in the calibration of the data acquisition card which contains the D/A and A/D converters.

Figure 2 shows a typical input pulse measured on a pulse reflectometer as described above. The inset shows the first 6 milliseconds of the pulse in more detail. A small DC offset of approximately 5 mV is clearly visible.

The DC offset introduced by the data acquisition card can be removed by performing two reflectometry measurements. In the first measurement, a positive electrical pulse is used to drive the loudspeaker. The resultant positive pressure pulse is recorded by the microphone. In the second measurement, a negative electrical pulse is used to drive the loudspeaker. This time a negative pressure pulse is produced and is recorded by the microphone. The negative pressure pulse is then inverted and averaged with the positive pressure pulse.

Figures 2 and 3 show a positive pressure pulse and a negative pressure pulse after inversion. Figure 4 shows the result of averaging the pulses of Figures 2 and 3. The insets show the start of the pulses in more detail. Both the positive and negative pressure pulses contain a systematic DC offset of approximately 5 mV. When the negative pressure pulse is inverted, the DC offset becomes –5 mV. Hence, averaging this inverted pulse with the positive pressure pulse gives a pulse with no DC offset.

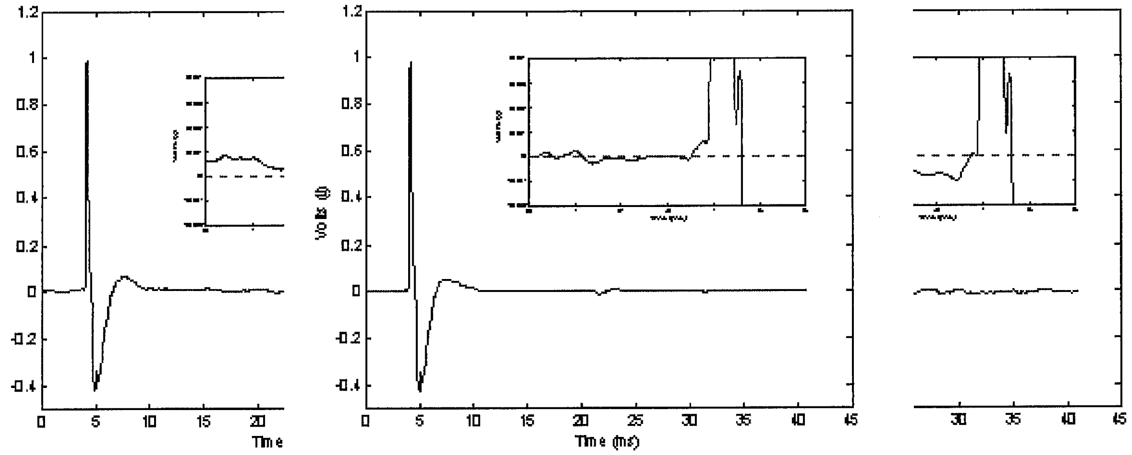

Figure 2: Input pulse   Figure 4: The averaged input pulse   3: The inverted pulse

Figures 5 and 6 show the reflections which return from a 306 mm long stepped tube (whose radius expands from 6.2 mm to 9.45 mm) when positive and negative electrical pulses are used to drive the loudspeaker. Figure 7 shows the result of averaging the signals of Figures 5 and 6. Again, the averaged reflections have no DC offset.

By alternating the pulse polarity in this way, it is possible to obtain measurements of both the input pulse and the duct reflections with no DC offset. However, when such measurements are used to calculate an input impulse response, the response generally still contains a DC offset. Figure 8 shows the input impulse response calculated from the input pulse and stepped tube reflections of Figures 4 and 7. The input impulse response can be seen to contain a DC offset of approximately –0.017 (note that this is a dimensionless quantity). In section 4, the cause of the DC offset in the calculated input impulse response is investigated.

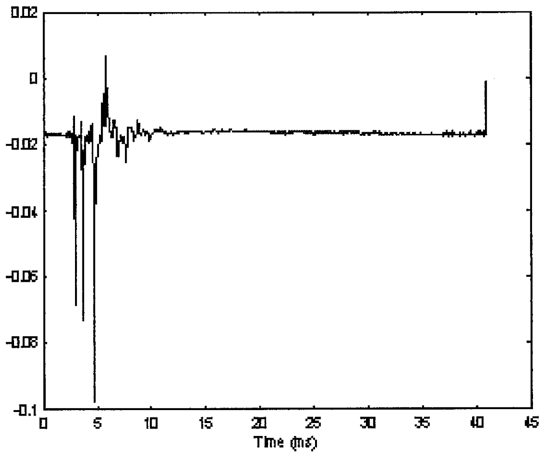

Figure 8: Input impulse response of stepped tube, DC =-0.017

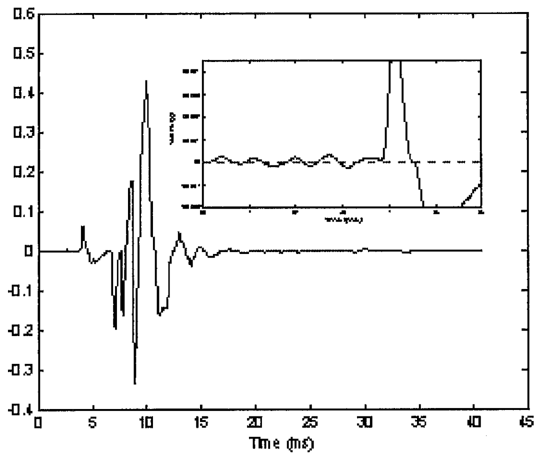

Figure 7: The averaged reflections

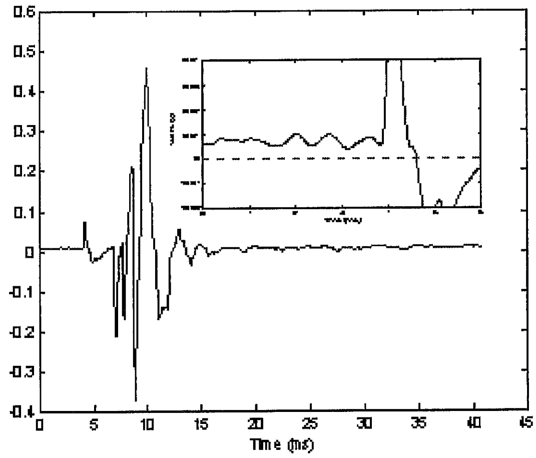

Figure 5: The positive reflections

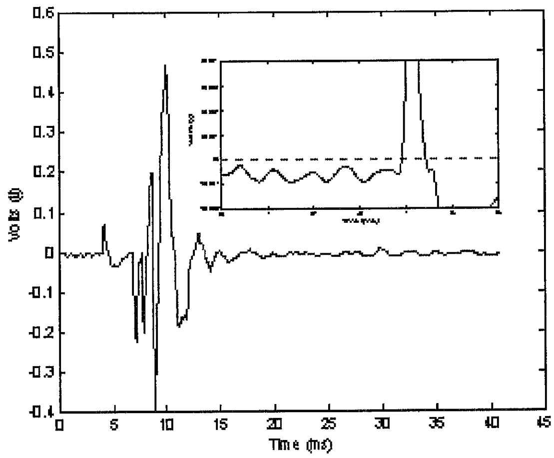

Figure 6: The inverted reflections

4. DC OFFSET IN THE INPUT IMPULSE RESPONSE

4.1 Theoretical origin of DC offset in the input impulse response

According to Discrete Fourier transform (DFT) theory, for an input vector x of length N, the DFT is a vector X also of length N defined by

$$X(k) = \sum_{n=1}^{N} x(n) * e^{-2\pi j(k-1)(n-1)/N} \qquad 1<=k<=N \qquad (2)$$

$$X(1) = \sum_{n=1}^{N} x(n) \qquad (3)$$

The Inverse Discrete Fourier transform (IDFT) is similarly defined by

$$x(n) = \frac{1}{N}\sum_{k=1}^{N} X(k) * e^{2\pi j(k-1)(n-1)/N} \qquad 1<=n<=N \qquad (4)$$

or

$$x(n) = \frac{X(1)}{N} + \frac{1}{N}\sum_{k=2}^{N} X(k) * e^{2\pi j(k-1)(n-1)/N} \qquad 1<=n<=N \qquad (5)$$

In acoustic pulse reflectometry analysis, according to equation (3), the first elements of the input pulse and the duct reflections in the frequency domain are given respectively by

$$I(1) = \sum_{n=1}^{N} i(n) \qquad (6)$$

(7)

where represents the input pulse and represents the duct reflections in the time domain.

That is, the first element of the input pulse in the frequency domain is the sum over all sample points of the input pulse in the time domain. Similarly, the first element of the duct reflections in the frequency domain is the sum over all sample points of the duct reflections in the time domain.

From equations (1), (6) and (7)

(8)

Using equation (5) to perform an IDFT on the input impulse response yields:

(9)

The first term in equation (9) is the DC level of the input impulse response. It depends on *IIR(1)* which, according to equation (8), is equal to the sum of all the sample points which make up the duct reflections divided by the sum of all the sample points which make up the input pulse (all in the time domain).

4.2 The elimination of DC offset from the input impulse response

Close examination of Figures 4 and 7 reveals that neither the input pulse nor the duct reflections exhibit strong polarity. That is, the sum of the sample points which make up the input pulse and the sum of the sample points which make up the duct reflections are both close to zero. Consequently, the calculation of *IIR(1)* can result in a division by zero or near-zero causing numerical instability.

Work is currently being carried out to produce an input pulse of greater polarity. The duct reflections resulting from using such an input pulse will also show a greater degree of polarity. Thus division by zero problems should be removed allowing the DC level to be accurately determined and input impulse responses to be determined with no DC offset.

5. CONCLUSIONS

Although DC offset in input impulse response measurements can be removed by calibration using a DC tube, it is more desirable to prevent the introduction of DC offset in the first place. Removing small DC offsets from the input pulse and duct reflections has little or no effect on the presence of DC offset in the input impulse response. The presence of DC offset in the input impulse response appears to depend on the shape of the input pulse and its lack of polarity. Improving the polarity of the pulse should enable the DC level to be calculated more accurately.

6. REFERENCES

[1] Marshall, I., "The production of acoustic impulses in air", *Meas.Sci.Technol.*, **1,** pp.413-418, 1990.
[2] Amir, N., Rosenhouse, G., Shimony, U., "A discrete model for tubular acoustic systems wit varying cross section - The direct and inverse problems. Part 1 and Part 2: Theory an

Experiment", *Acustica*, **81**(5), pp.450-474, 1995.
[3] Sharp, D.B., *PhD Thesis*, University of Edinburgh, UK, 1996.
[4] Kemp, J., "Practical improvement to acoustic pulse reflectometry: the virtual DC tube method an source reflection cancellation", *Proceedings of the International Symposium on Musical Acoustic* Volume **2**, pp387-390.