IMPROVING THE MEASUREMENT OF THE LOW FREQUENCY CONTENT OF THE IMPULSE RESPONSE USING ACOUSTIC PULSE REFLECTOMETRY

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ABSTRACT

Acoustic pulse reflectometry is a useful non-invasive technique for measuring duct properties. A sound pulse is injected into the duct under investigation. Suitable analysis of the resultant reflections yields the input impulse response from which the input impedance and duct dimensions can be calculated. In this paper, the importance of both the DC level and the low frequency content of the input pulse to the measurement of input impulse response is demonstrated.

INTRODUCTION

Acoustic pulse reflectometry has become established as a useful non-invasive technique for measuring the input impulse response and internal dimensions of tubular objects (e.g. musical wind instruments or lengths of pipework) and for the detection of leaks in pipes [1][2].

ACOUSTIC PULSE REFLECTOMETRY TECHNIQUE

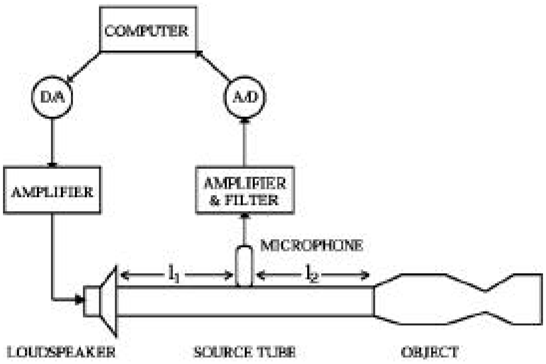

Figure 1: Schematic diagram of pulse reflectometer

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 [3]:

$$IIR(w) = \frac{R(w)}{I(w)} \qquad (1)$$

where w is the angular frequency, $R(w)$ is the transformed duct reflections, $I(w)$ is the transformed input pulse, and $IIR(w)$ is the transformed impulse response of duct. By inverse Fourier transforming $IIR(w)$, the input impulse response $iir(n)$ of the duct under test is obtained (where n is the discrete time). Application of a suitable algorithm to the impulse response enables the duct profile to be reconstructed [4].

DC PROBLEM IN THE INPUT IMPULSE RESPONSE

The input impulse response of a duct measured using acoustic pulse reflectometry generally contains 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 bore reconstruction algorithm.

Figure 2 shows the impulse response of a 806 mm stepped tube (comprising cylindrical sections of radii 4.8 mm, 6.2 mm and 9.45 mm) with and without a DC offset present. Figure 3 shows the result of applying a bore reconstruction algorithm to the impulse responses of Figure 2. The reconstruction calculated from the impulse response with no DC offset compares well with the directly measured duct profile whereas the reconstruction calculated from the impulse response which contains a DC offset can be seen to contract spuriously.

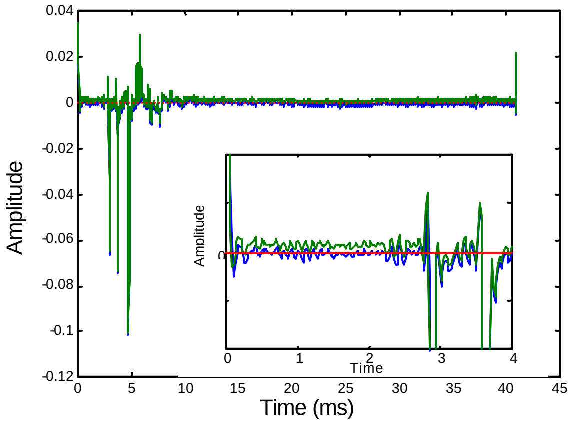

Figure 2: Input impulse response of stepped tube

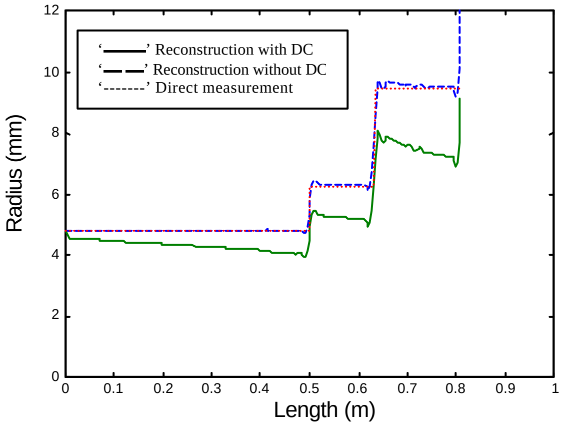

Figure 3: Reconstructions of stepped tube

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 4 shows a typical input pulse measured on a pulse reflectometer. The inset shows the first 6 milliseconds of the pulse in 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. Figure 5 shows the result of averaging the pulses. 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.

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 (Figure 6 shows the reflections from the stepped tube 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 7 shows the impulse response calculated from the input pulse and stepped tube reflections of Figures 5 and 6. The impulse response can be seen to contain a DC offset of approximately –0.0017 (note that this is a dimensionless quantity). The cause of the DC offset in the calculated input impulse response is investigated in the next section.

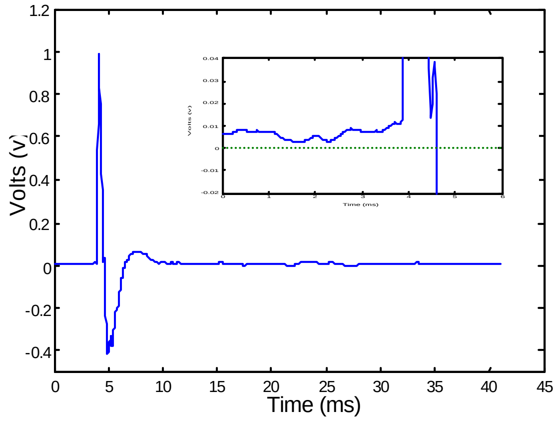

Figure 4: Input pulse

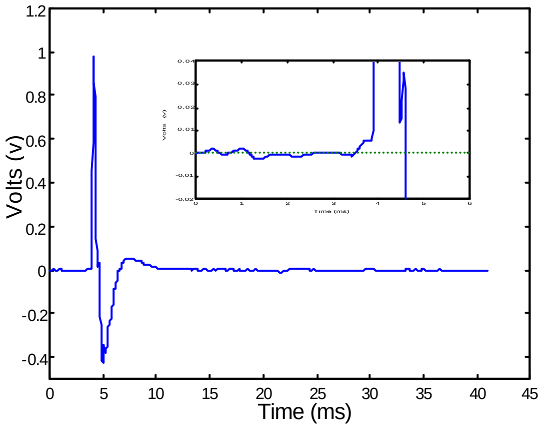

Figure 5: The averaged input pulse

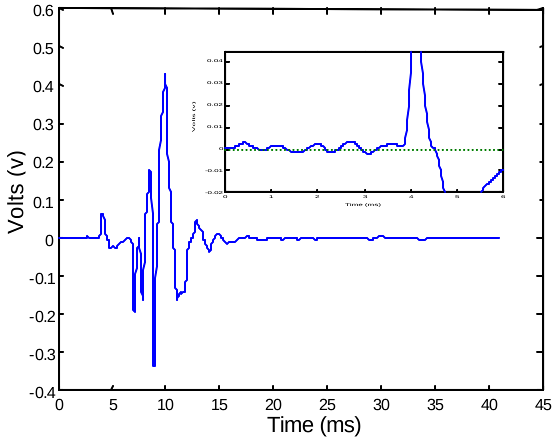

Figure 6: The averaged stepped tube reflections

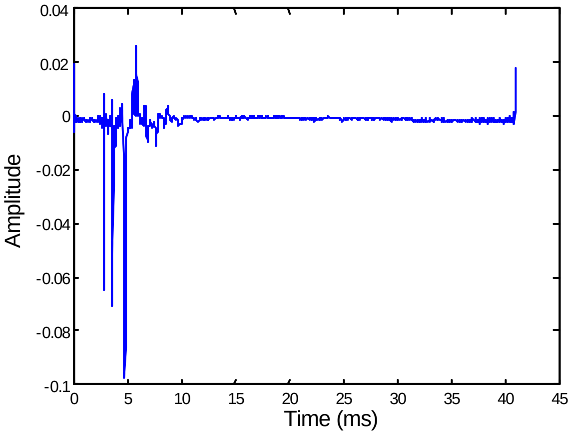

Figure 7: Input impulse response of stepped tube, DC =-0.0017

Origin Of DC Offset In The Input Impulse Response

According to Discrete Fourier transform (DFT) theory, the first elements of the input pulse and the duct reflections in the frequency domain are given respectively by

$$I(1) = \sum_{n=1}^{N} i(n) \tag{2}$$

$$R(1) = \sum_{n=1}^{N} r(n) \tag{3}$$

where $i(n)$ represents the input pulse and $r(n)$ 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), (2) and (3)

$$IIR(1) = \frac{R(1)}{I(1)} = \frac{\sum_{n=1}^{N} r(n)}{\sum_{n=1}^{N} i(n)} \tag{4}$$

where *IIR(1),* is the first element (0 Hz value) of the input impulse response in the frequency domain.

The input impulse response *iir(n)* of the duct is obtained by calculating the Inverse Discrete Fourier Transform of *IIR(w)*:

$$iir\,(n) = \frac{IIR\,(1)}{N} + \frac{1}{N} \sum_{k=2}^{N} IIR\,(k) * e^{2pj\,(k-1)(n-1)/N} \tag{5}$$

Examination of equation (5) reveals that *iir(n)* is the sum of a DC component and N-1 sinusoidal components. The DC component depends on *IIR(1)* which, according to equation (4), 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). Close examination of Figures 5 and 6 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 [5]. The incorrect evaluation of *IIR(1)*, and thus of the DC component *IIR(1)/N*, is the cause of the DC offset in the impulse response.

DC Tube Method Of DC Offset Removal

For accurate bore reconstruction, the DC offset in the input impulse response must be either prevented from occurring or removed prior to application of the reconstruction algorithm. In this section, details are given of a calibration procedure for removing the DC offset.

To determine and remove the DC offset, a 50cm long cylindrical tube is inserted between the source tube and the duct under investigation [6]. Alternatively, instead of introducing an extra cylindrical tube, the last section of the source tube can be used [7]. Since there should be no signal reflected back from this 'DC tube', the first millisecond of the impulse response should be zero. Referring back to equation (5), this means that the sum of the DC component and all the sinusoidal components should be zero over this time period. Assuming that the sinusoidal components are calculated correctly, finding the average value over the first millisecond of the measured impulse response gives the DC offset (the amount by which the DC component *IIR(1)/N* is incorrectly calculated). This value can then be subtracted from the whole input impulse response.

In general, using the ‘DC tube' method of removing DC offset results in accurately reconstructed duct profiles (as shown in Figure 3). However, in some cases, bore reconstructions are still seen to expand and contract spuriously. The reasons for this are explored in the next section.

LOW FREQUENCY PROBLEM IN THE INPUT IMPULSE RESPONSE

The 'DC tube' method of DC offset removal works on the assumption that all the sinusoidal components which make up the impulse response are calculated correctly. This is not always the case. Figure 8 shows the magnitude spectrum *IIR(w)* of a stepped tube impulse response measurement. Since *IIR(w)* is a reflection coefficient, its magnitude should not exceed 1 at any frequency. However, examination of Figure 8 reveals that at 25 Hz the magnitude of the measured *IIR(w)* is equal to 1.48. This incorrect evaluation is due to the poor response of the loudspeaker at low frequencies. From equation (1), it can be seen that if the input pulse doesn't contain significant energy at 25 Hz then division by noise will occur resulting in the incorrect calculation of *IIR(w)*.

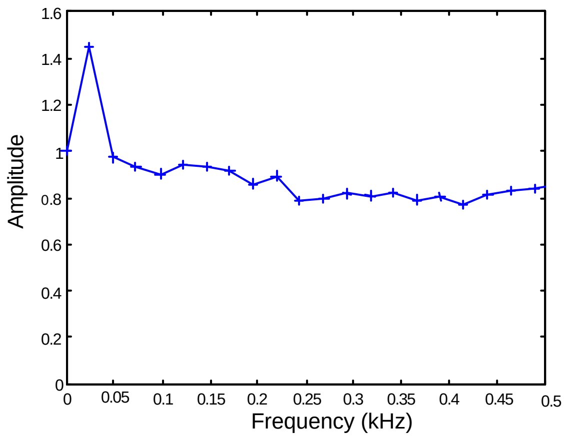

Figure 8: Magnitude of Input impulse Response

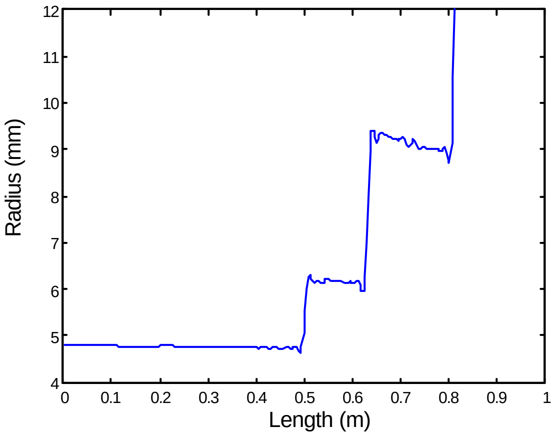

Figure 9: Reconstruction of stepped tube

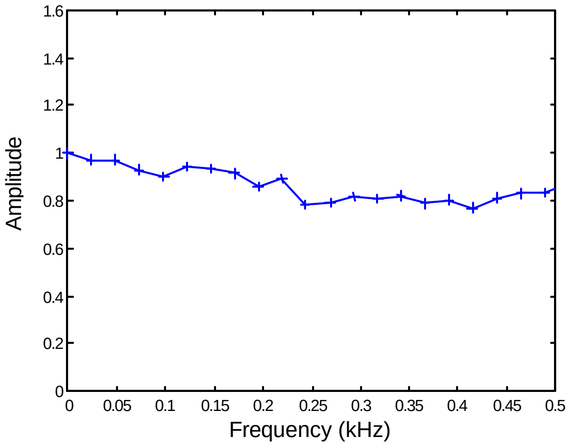

Figure 10: Magnitude of input impulse response (measured 25 Hz value replaced by theoretical value)

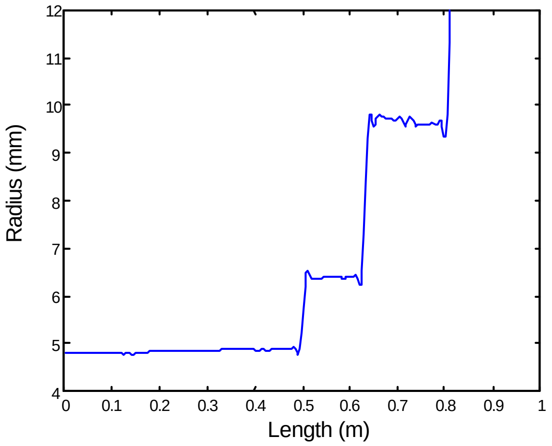

Figure 11: Reconstruction of stepped tube using altered input impulse response

The average value over the first millisecond of this impulse response will therefore be equal to the amount by which both the DC component and the 25 Hz sinusoidal component are incorrectly calculated. Therefore the 'DC tube' method will not only find and remove the DC offset but also an offset due to the 25 Hz component. Figure 9 shows the calculated duct profile resulting from applying the reconstruction algorithm to the impulse response of Figure 8 (after the 'DC tube' method has been implemented). The radius of the last section of the reconstructed stepped tube profile can be seen to decrease with distance.

In Figure 10, the 25 Hz value of $IIR(w)$ has been replaced with a theoretically determined value. Figure 11 shows the calculated duct profile resulting from applying the reconstruction algorithm to the impulse response of Figure 10 (again, after implementing the 'DC tube' method). The radius of the last section of the reconstructed stepped tube profile now remains constant with distance.

CONCLUSIONS

To ensure consistently accurate bore reconstructions, it is necessary to improve the low frequency content of the input pulse used in acoustic pulse reflectometry. Once this has been achieved, it should be possible to use the 'DC tube' method to remove the DC offset from input impulse response measurements. Alternatively, by improving the polarity of the input pulse, it may be possible to prevent the introduction of DC offset in the first place by measuring the DC component of the input impulse response correctly.

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