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Directional wave separation in tubular acoustic systems – The development and evaluation of two industrially applicable techniques

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A R T I C L E   I N F O

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A B S T R A C T

An acoustic device is used to evaluate internal features and defects within tubes by determination of the acoustic impulse response. This paper concerns methods of separating the total pressure wave measured in the device into its forward and backward travelling components, which facilitates computation of the acoustic impulse response. The device comprises a tube that has a speaker at one end and is axially instrumented with microphones. Unlike similar works, the methods presented in this paper were designed to be applied in an industrial context, they allow simple calibration and implementation using readily transportable equipment. Two wave separation algorithms are presented; the first is a known method that has been improved to provide simplified calibration and the second is a computationally inexpensive technique that has been adapted to improve its operational bandwidth. The techniques are critically evaluated using a custom built test rig, designed to simulate realistic tube features and defects such as constrictions, holes and corrosion. It is demonstrated that, although inter-microphone attenuation is not accounted for in the second algorithm, both algorithms function well and give similar results. It is concluded that the added sophistication of the first method means that it is less affected by low frequency interference and is capable of yielding more accurate results. However, in practical use as an evaluation tool, the benefits of including inter-microphone attenuation are outweighed by the additional calibration and computational requirements. Finally the output of the wave separation techniques is validated by showing agreement between experimental impulse response measurements and those obtained from a theoretically derived acoustic tube simulator.

1. Introduction

Acoustic pulse reflectometry (APR) is a proven method of characterising features and profiles within tubular objects. APR has various applications, including measurement of the bore profile of musical instruments [1–3], determination of features of the vocal tract [4,5] and, as is the focus here, non destructive evaluation (NDE) of industrial tubes and pipelines [6–8]. Not only is APR an effective method for the detection, location and characterisation of features and defects within tubes and pipelines, it is non-invasive as nothing is physically inserted in the tube. Testing on single tubes can be performed in a matter of seconds, and APR is deployable on live pipelines as it is tolerant to static pressure, flow and a wide variety of gas compositions. On this basis APR is highly suited to industrial use; however, much of the relevant literature [2,4,9–12] is focused on laboratory based experiments where little attention is focused on the industrial applicability of the methods. The present paper offers two methods of APR testing that can be readily deployed in an industrial context.

A common shortcoming of APR systems is that the impulse response of an object can be difficult to interpret due to the presence of re-reflected waveforms. With reference to Fig. 1, sound is injected into the gas (air) within the source-tube by the speaker, travels forwards into the test object and is reflected back towards the speaker wherever it encounters a change in acoustic impedance; returning pressure waves are then re-reflected at the manifold/speaker location and again travel forwards through the source-tube and into the test object. If there is an overlap of forward and backward propagating waves at the microphone location then the response of the test object cannot be isolated from the response of the system to the left of the microphone, i.e. the speaker and manifold. This problem can be overcome by separating the total pressure wave into its forward and backward travelling components. If wave separation is implemented and the forward and backward travelling waves are isolated at a given axial location within the source-tube, backward travelling waves (the output)

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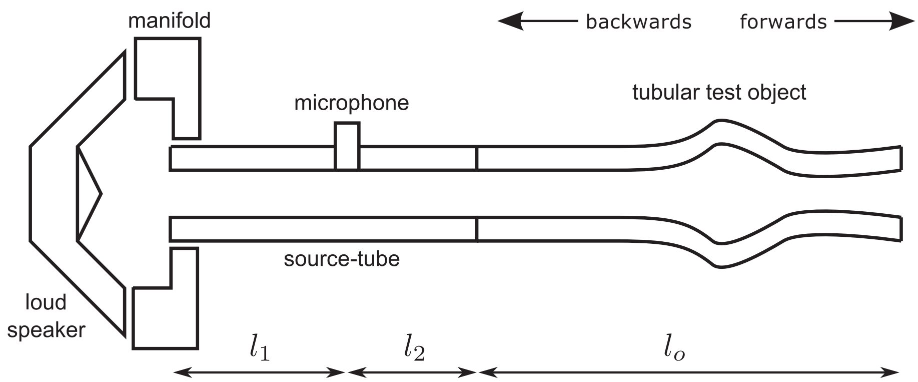

Fig. 1. Typical APR testing arrangement.

may be deconvolved with respect to forward travelling waves (the input) to achieve the impulse response of the system to the right of the given location, i.e. the acoustic impulse response of the test object.

Wave separation may be achieved by using a long source-tube [11]. Setting l_2 greater than half the length of the excitation waveform; $l_2 > c/2\lambda$, (where c is the speed of sound in the tube and λ is the length of the waveform) and l_1 greater than l_o, (Fig. 1) ensures firstly, that the outgoing wave fully passes the microphone before the reflection from the test object is received; and secondly, that reflections from any feature in the test object pass the microphone before the recorded signal is corrupted by forward travelling re-reflections. However, the use of long source-tubes is unfavourable because of the added acoustic attenuation, limitations on the length of the excitation signal and general impracticality of transporting and connecting a long tube. An alternative is to decompose overlapping pressure waves into their forward and backward travelling components using two or more axially spaced microphones within the source-tube [2,4,13,14]. While using just two microphones is advantageous for its simplicity and minimal interruption within the source-tube, the fundamental drawback of any two microphone wave separation technique is that a singularity occurs when an acoustic wavelength within the tube is equal to twice the inter-microphone distance, or integer multiples thereof [14]. It is critical to note that one of the singularities is at zero frequency. The frequency band (from zero upwards) over which the first singularity is dominant reduces with increasing microphone spacing. Therefore a trade off is made between overall bandwidth and loss of signal to noise at low frequencies. Combining the results of more than one microphone pairs can significantly alleviate this trade-off [2,14,15].

For a wave separation technique to be deployed as part of an NDE tool in an industrial context three key issues must be considered.

1. Frequency content; for APR to be beneficial in the NDE sector it must be possible for long tubes (5 m and above) to be tested, as such low frequency content must be measured and included in subsequent processing. There are two key reasons for this; first, low frequencies are less affected by attenuation and so can travel greater distances without significant loss of signal; second, long test objects have resonances at lower frequencies than short objects and if an undistorted time domain impulse response is to be achieved all resonances must be captured by the system. Within the relevant literature, test object lengths are rarely greater than 1 m [2,4,9–12] and as such frequencies below $\approx$100 Hz are commonly neglected since they contain no resonances. Kemp et al. [2] fitted a straight line to the frequency response below 100 Hz, this was valid since the longest object tested was less than 250 mm in length. If for example a 5 m object is to be tested, resonances could be expected at frequencies as low as 17 Hz, based on a quarter wavelength resonance and assuming a speed of sound of 342 m/s; so the interpolated straight line could only be applied in the sub 10 Hz range. This means that for wave separation to be implemented in longer tubes, frequency range of the measurements must be extended as close to zero as possible.
2. The system output should be a time domain impulse response of the object under test. The acoustic response of tubular objects is often determined in terms of an object's planar mode complex input impedance [16]. Although the acoustic impedance is closely related to the impulse response [14], the impulse response is most appropriate as this gives the clearest indication of defect location and associated feature shape.
3. Calibration must be simple, fast and not reliant on the use of numerous or long calibration load tubes. For example, in [12] a high accuracy acoustic impedance measurement technique is presented that uses three calibration loads, one of which is a 97 m pipe. Such a calibration would be inappropriate in an industrial context due to the requirement to have on hand a 97 m tube and sensitivity of the method of [12] to the quality of connection with the source-tube.

In the present work two methods of multi-microphone wave separation are developed to make them suitable for use in an industrial NDE tool. A rigorous high accuracy technique that requires some on-site calibration is compared to a faster, less rigorous method that requires no on-site calibration. The two wave separation techniques used are both known methods; however, in their raw form neither method is suitable for deployment in an industrial APR system. As such, modifications are made to both techniques to improve their accuracy and usability. The first technique, introduced by Kemp et al. [2], is a time domain multi-microphone technique that includes the effects of inter-microphone attenuation. Modifications made to this technique simplify the on-site calibration procedure and remove restrictions on microphone spacing while maintaining its salient benefits. The second technique, developed by Louis et al. [4], is analogous to the first although inter-microphone attenuation is not included. In fact, the methods may be shown to be equivalent for a two microphone system where Kemp's multi-microphone transfer functions are replaced by pure delays. The benefits of the method of Louis et al. [4] is that its mathematical formulation allows for fast processing and, by not including inter-microphone attenuation, calibration requirements are minimal. The technique given by Louis et al. [4] is modified in the present work so that it is applicable to multi-microphone systems, therefore expanding the frequency band over which it may be applied.