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Low frequency acoustic and ultrasound waves to characterise layered media

P.B. Wilkinson [a], D.A. Gunn [a,*], S. Holyoake [a], B.A.J. Dashwood [a], C.R. Brett [b], J.G. Rees [a]

[a] British Geological Survey, Environmental Science Centre, Keyworth, Nottingham, NG12 5GG, UK
[b] Uniper Technologies Ltd, Ratcliffe-on-Soar, Nottingham, NG11 0EE, UK

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ABSTRACT

Poor penetration and excessive absorption of high frequencies limit spectroscopic approaches using fast rise pulses for inspecting many engineered structures. So, this study focused on the alternative application of low frequency acoustic and ultrasound waves for the characterisation of challenging structures in airborne and waterborne environments. A simple, transfer matrix model approach was developed for the simulation of 1D sound propagation through layered media that comprise many engineered structures. This model was used to test the feasibility of using sound waves for non-destructive characterisation of an articulated lorry transported trailer and offshore foundation infrastructure. The targets were not in contact with the sound sensors and incorporated highly attenuating layers with acoustic contrasts to the surrounding medium that result in over 90% reflection of incident wave pressure. In both cases, resonances controlled by the thicknesses and interval velocities of component layers modulated sound reflection from, and transmission through the whole structure. These effects were observed as local maxima and minima in the spectra of the transmission and reflection coefficients. These spectral coefficients also determined the modulation to the temporal envelope of a linear frequency modulated pulse used to insonify the targets. In the acoustic study, which comprised only theoretical modelling, discrimination of differing cargo widths and between solid versus empty cargo trailers was possible using the transmission coefficient. In the ultrasound study, which comprised theoretical modelling and experimental testing, discrimination of differing steel and concrete substructure thicknesses and also of gaps between them was possible using the reflection coefficient. The model outcomes indicated while an acoustic system would require around 90–100 dB of dynamic range, an ultrasound system would only require around 40 dB to be effective.

1. Introduction

Many established non-destructive tests (NDT) are based upon analysis of one-dimensional propagation of ultrasound waves through layered media. Ultrasound sonography involving the analysis of the arrival times and temporal characteristics of echo pulses is commonplace in materials NDT [1] and medical physics [2]. Ultrasound spectroscopy involves additional analysis of the spectral characteristics of echoes and has traditionally used fast rise, broadband pulses of MHz frequencies or above [2–5]. While ultrasound spectroscopy is widely used for material property and structural inspection, its use at high frequencies can be limited in materials with very high attenuation. Because of their greater penetration, acoustics and low frequency ultrasound (<200 kHz) offer alternative inspection approaches in materials where higher frequencies are scattered or absorbed. But the resolution of normal sonographic approaches is limited when applied to lower frequency evaluation due to relatively long wavelengths. However, several animal studies indicated that bats and dolphins [6–8] have discriminated thickness differences (of 0.5 mm), which are beyond the limit of their spatial or temporal resolving capabilities (1/20th wavelength & 0.7 μs for a dolphin) by detecting shifts in the echo spectra of around 3 kHz. Moreso, they appear to achieve these performance levels not with high frequency, fast-rise time pulses used in sonography, but only by generating (ultra)sound frequencies from 10 kHz to 150 kHz using long duration pulses, in the case of dolphins to 70 μs and bats to 25 ms [6–8].

Long duration, frequency modulated (FM) signals have been utilised successfully to extract the attenuation, velocity and thickness of non-metallic composites via spectral decomposition of echoes from single layers [9–12] and also in low frequency seismic applications [13]. In this paper, we use a simple 1-D wave propagation model to demonstrate simple tomography or echo sensor arrangements required to extend these applications to evaluate two challenging multi-layered systems. We scope the bandwidth and potential sensitivity required of practical measuring systems, and hence establish the potential feasibility of either case. These

* Corresponding author.
E-mail address: dgu@bgs.ac.uk (D.A. Gunn).

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studies include representation of each layered system by an equivalent numerical model, through which the propagation of a linear frequency modulated chirp is simulated. The dependence of notches in the frequency spectrum of the reflection coefficient, or peaks in the transmission coefficient, on key structural elements within each layered system are analysed to demonstrate how these features could be used as system condition diagnostics. The first study relates to a non-harmful, non-contact, acoustic method for screening of soft-sided, articulated cargo trailers at ferry ports. The second study relates to the evaluation of the foundation condition of offshore renewable energy infrastructure using ultrasound. Ultrasound echo spectra from equivalent laboratory scaled physical models are used to verify the numerical results from the second study to demonstrate the specific application to offshore foundation evaluation.

2. Layered media characterisation:

2.1. General principle

Reverberation of incident sound wave energy, which penetrates a finite thickness layer and is partially transmitted and reflected at the interfaces between the layer and bounding media, is shown in Fig. 1. At a frequency where the sound wavelength is approximately twice the host layer thickness, the reflection coefficient reduces to a minimum (controlled by the losses in the materials). This first minimum is equivalent to the fundamental half-wavelength resonance [14,1] and occurs at a frequency f_r that can be estimated by the ratio of the sound velocity, V_s to thickness, L, of the layer, given by,

$$f_r = V_s/(2L) \tag{1}$$

Further minima or notches appear in the reflection spectra of the echoes from single layered targets insonified with broadband, low frequency modulated signals where the reflection coefficient diminishes to local minima at frequencies where the thickness is equivalent to integer multiples of the fundamental half-wavelength resonance (Fig. 1). In the absence of attenuation, each layer has a reflection and transmission coefficient described by Ref. [14] as,

$$R = \frac{\left[\frac{1}{4}\left(\nu - \frac{1}{\nu}\right)^2 \sin^2\left(\frac{2\pi L}{\lambda}\right)\right]}{\left[1 + \left(\frac{1}{4}\left(\nu - \frac{1}{\nu}\right)^2 \sin^2\left(\frac{2\pi L}{\lambda}\right)\right)\right]} \tag{2}$$

$$T = \frac{1}{\left[1 + \left(\frac{1}{4}\left(\nu - \frac{1}{\nu}\right)^2 \sin^2\left(\frac{2\pi L}{\lambda}\right)\right)\right]} \tag{3}$$

where $\pi \cong 3.142 \ldots$, λ = wavelength of sound within the layer, $\lambda = Vs/f$, where f = frequency and $\nu = Z_{BL}/Z_0$, the ratio of the bounded layer and bounding media acoustic impedances. Similarly, echoes backscattered from a multi-layered sequence are the result of the superposition of the incident wave that has been modulated by partial reflection and transmission, and delayed via multiple transits across the thickness of the bound layers within the sequence. Hence, it is possible that the reflection spectra of such backscattered echoes will exhibit notch characteristics

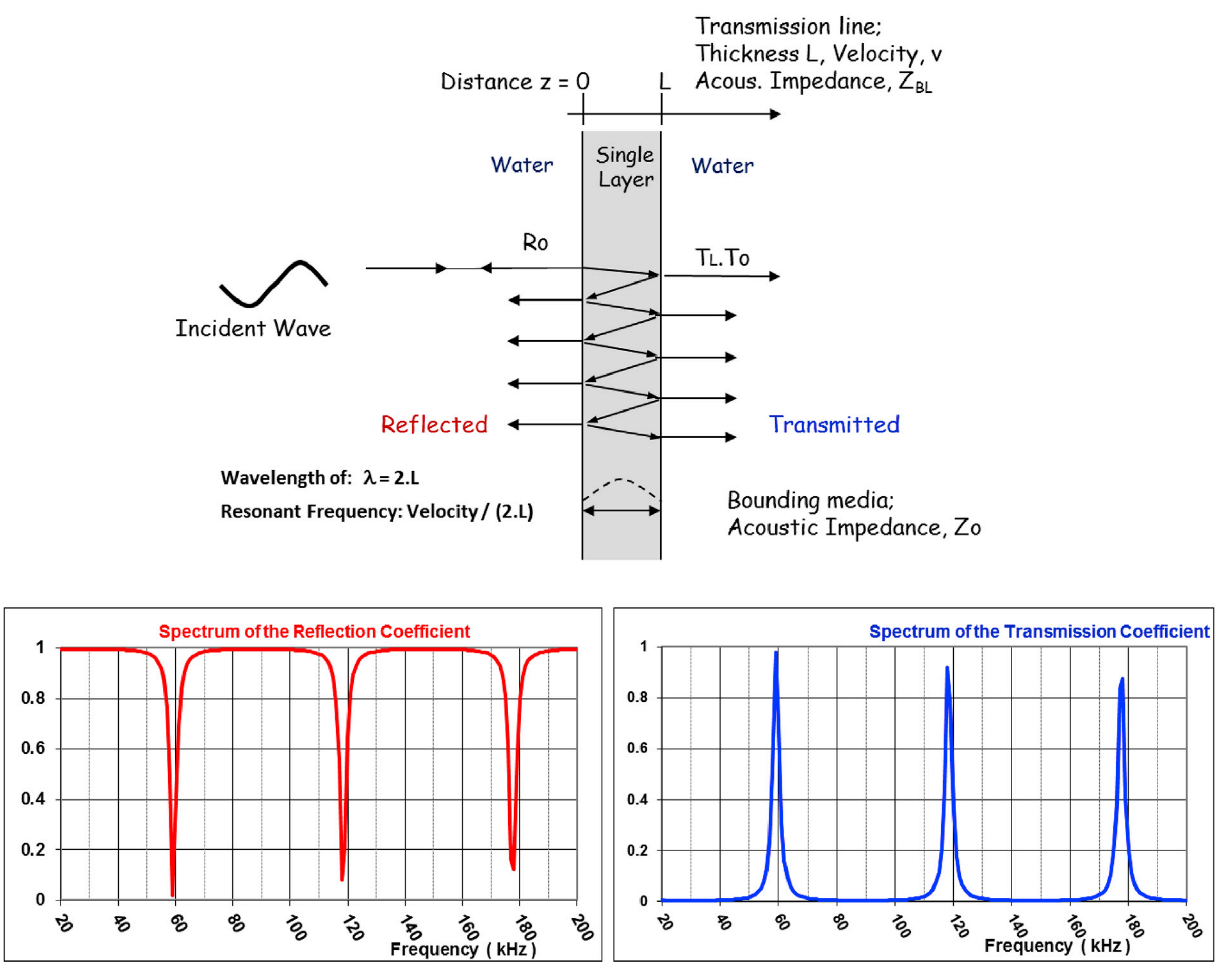

Fig. 1. Reverberation of incident sound wave energy that penetrates a finite thickness layer and is partially reflected at the interfaces between the layer and bounding media; example shows a single layer bounded by water. The spectra of the reflection and transmission coefficients relate to amplitudes of the reflected and transmitted sound. Examples show notches for a fundamental frequency of 59 kHz, such as produced by a 50 mm mild steel plate.