INTRODUCTION

Measurement of the strength of adhesive bonds in multi-layered structures is of increasing importance. Ultrasonic NDE methods do not directly determine the strength of a bond but indicate characteristics of a bond which may be related to bond strength through empirical relationships. One such bond characteristic is its acoustic impedance. Impedance profiling methods have long been studied in the field of geophysics and medical ultrasonics [1,2]. In this paper the development of an inversion algorithm based on the so called Goupillaud equal travel-time method is described [3], with the aim of applying it to the NDE of adhesive bonds.

The algorithm is evaluated using both synthetic and real data to establish the effects of noisy data and material attenuation on the accuracy of the reconstructed profiles. Since the media of interest can be highly attenuating, a simple loss-correction model has been developed which reduces the inaccuracies introduced by material attenuation.

The impedance profiling algorithm uses the impulse response of the layered structure, calculated through deconvolution of the pulse-echo data with a reference signal. The performances of three different deconvolution techniques, namely the autoregressive spectral extrapolation (ASE) method, the L1-norm spike extraction method and the frequency domain Wiener filter methods, have been compared.

Finally, in order to establish the relationship between the impedance jump at the bond line and the bond strength, calculated impedance values for real samples have been correlated with the peel strengths of the bonds obtained through destructive peel tests.

DESCRIPTION OF METHOD

Detailed mathematical treatments of the Goupillaud inversion algorithm have been described in several other publications [1,2,3,4]. Here a brief outline of the method is given.

In the Goupillaud model, the heterogeneous medium is divided into N discrete homogeneous layers of equal travel-time \( \Delta t \), where \( \Delta t \) equals the signal sampling interval. The assumed boundary conditions are that the downgoing wave is an impulsive source \( R=1 \) plus the reflection from the free surface \( R(0) \), and the upcoming wave is the reflection sequence.
The impulse response $R(z)$ is written in terms of its $z$-transforms. Here $z = \exp(i\omega \Delta t)$. The reflection and transmission coefficients at each interface are

$$r_k = \frac{\rho_k v_k - \rho_{k+1} v_{k+1}}{\rho_k v_k + \rho_{k+1} v_{k+1}} \quad (2)$$

$$t_k = \left(1 - r_k^2\right)^{1/2} \quad (3)$$

where $\rho_k$ and $v_k$ are the density and acoustic velocity of the $k$th layer. The impulse response amplitudes can thus be written as

$$R_0 = r_0$$
$$R_1 = r_1 (1 - r_0^2)$$
$$R_2 = r_2 (1 - r_0^2)(1 - r_1^2) - r_0 r_1 r_2^2 (1 - r_0^2)$$

which leads to the relationship

$$r_k = \frac{R_k + F_1(t) R_{k-1} + F_2(t) R_{k-2} + \ldots + r_0 r_{k-1} R_1}{\prod_{i=0}^{k-1} \left(1 - r_i^2\right)} \quad (4)$$

The solution of equation (4) has been given by Claerbout [4] in the form of a recursive algorithm that gives the reflection coefficient at any layer $r_k$ in terms of the known impulse amplitudes up to $R_k$ and the coefficients up to the previous layer $r_{k-1}$. This is in the form of a symmetric Toeplitz matrix equation

$$\begin{pmatrix}
1 & R_1 & R_2 & \ldots & R_{k-1} \\
R_1 & 1 & R_1 & \ldots & . \\
R_2 & R_1 & 1 & \ldots & . \\
\vdots & \vdots & \ddots & \ddots & \vdots \\
R_{k-1} & \ldots & R_1 & 1 & .
\end{pmatrix}
\begin{pmatrix}
r_1 \\
r_2 \\
r_3 \\
. \\
r_k
\end{pmatrix}
= \begin{pmatrix}
R_1 \\
R_2 \\
R_3 \\
. \\
R_k
\end{pmatrix} \quad (5)$$

Starting with $k=1$ and solving for $r_k$ recursively, the whole reflection coefficient $r_1$ is recovered. A fast method of solution for equation (5) is employed which is after Levinson [5].

The first stage of the computations is thus the calculation of the impulse responses $R_k$ from the acoustic pulse-echo signal by deconvolution. Then equation (5) is solved recursively using the Levinson method. Having computed the reflection coefficients, starting from a known impedance value another recursive relationship recovers the impedance as a function of $i$ (or travel time):

$$\rho_{i+1} v_{i+1} = \frac{1 - r_i}{1 + r_i} \rho_i v_i \quad (6)$$

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