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STUDY OF INFLUENCE OF TEMPERATURE ON ACOUSTIC PROPERTIES OF MATERIALS FOR ULTRASOUND THERMOMETRY

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Abstract

In life sciences as well as in manufacturing processes the problem of non-intrusive internal temperature monitoring is yet to have a satisfactory solution. As temperature changes, like physical properties, acoustic properties also change. More attention has been paid to the estimation of attenuation coefficient as the preliminary work indicate higher thermal sensitivity. Attempt has been made to compute layer impulse response h(t) using multiple narrowband transducers. The technique employes only reflected ultrasound signals from layer boundaries and appropriate curve filling technique to minimize errors. The technique also eliminates the dependence of attenuation coefficient on reflection coefficient.

Introduction

Various types of sensors are used to monitor temperature. The response of the conventional thermal sensors is independent of the medium to which such sensors are exposed. The introduction of such conventional sensors at the site of heating perturbs the heating process and affects the temperature distribution. In processes like material moulding, tissue heating, spot welding it is not possible to introduce temperature sensors. A non-contact measurement technique has to be resorted to for determining temperature of inaccessible layers in such cases. The non-contact methods like optical pyrometry and infrared thermometry are useful only in measuring surface layer temperature while acoustic methods could be useful in probing the inaccessible layers.

Temperature affects some of the properties of materials like acoustic properties. Properties like velocity, impedance, attenuation, etc. are investigated with a view to find a method to estimate the temperature of the material under test (MUT). For qualitative characterization of materials ultrasound has been in use for more than two decades, however, temperature effects on acoustic properties have not been studied from the view point of thermometry. Information available is very little on ultrasound thermometry. Some researchers are actively engaged in trying ultrasound in biological applications like hyperthermia. [1] The main interest of researchers centres on the acoustic velocity in solids as it has great practical importance in measuring thickness, mixing ratio in composite, internal and external stresses, etc. The percentile changes in propagation velocity for the temperature changes of the order of room temperature to 50°C are very small for materials like PVC, Perspex, Polypropelene (0.1-0.2% per °C). For a wide variety of biological tissues, the ultrasound propagation velocities are approximately the same and their variation with temperature is small. On the other hand, attenuation coefficient changes by a factor of five and its variation with temperature is also large. The latter needs to be explored for ultrasound thermometry. The values reported by different researchers for attenuation coefficient showed considerable variation depending on the transducer, excitation voltage, frequency, etc. It is necessary to develop techniques to get accurate and repeatable values of attenuation coefficient and to estimate the effect of temperature on them.

Considering layer inaccessibility in a multilayered medium the layer impulse response technique [2] is proposed and implemented to obtain accurate values of attenuation coefficient. The MUT is modelled as a linear time invariant system which can be completely characterized in time domain by its impulse response or equivalently in frequency domain by its transfer function. [3]

Experimental Model

The Fig. 1 describes a multilayered model comprising of N layers. At each interface the incident ultrasound signal is partially reflected and N such reflections are received by the same transducer which produced the excitation signal $P_0(t)$ normal to the surfaces of the layers of the model. Only the first order reflections are considered in the analysis.

$$R_1(f) = r_1\, P_0(f)\; e^{-\alpha_1(f)\, 2L_1}\; e^{-j2\pi f\,(2L_1/c_1)}$$

$$R_2(f) = r_2\,(1 - r_1^{\,2})\, P_0(f)\; e^{-[\alpha_1(f)\, 2L_1 + \alpha_2(f)\, 2L_2]}\; e^{-j2\pi f\,[(2L_1/c_1) + (2L_2/c_2)]}$$

:

$$R_N(f) = r_N \prod_{m=1}^{N-1} (1 - r_m^{\,2})\, P_0(f)\; e^{-\sum_{n=1}^{N} \alpha_n(f)\, 2L_n}\; e^{-\sum_{n=1}^{N} j2\pi f(2L_n/c_n)}$$

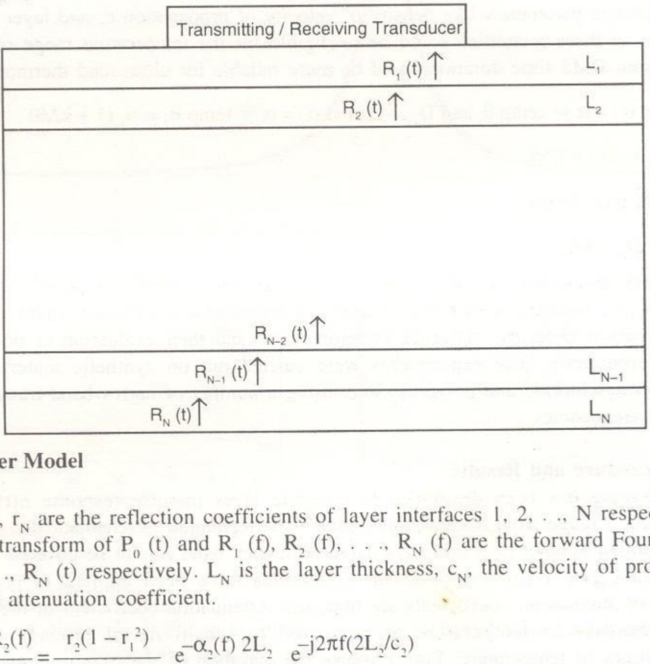

Fig. 1 : Multilayer Model

where $r_1, r_2, \ldots, r_N$ are the reflection coefficients of layer interfaces 1, 2, . ., N respectively, P_0 (f) the forward Fourier transform of P_0 (t) and R_1 (f), R_2 (f), . . ., R_N (f) are the forward Fourier transforms of R_1 (t), R_2 (t), . . ., R_N (t) respectively. L_N is the layer thickness, c_N, the velocity of propagation through L_N and α_N is the attenuation coefficient.

$$H_{21}(f) = \frac{R_2(f)}{R_1(f)} = \frac{r_2(1 - r_1^{\,2})}{r_1}\; e^{-\alpha_2(f)\, 2L_2}\; e^{-j2\pi f(2L_2/c_2)}$$

$$H_{N,\,N-1}(f) = \frac{r_N\,(1 - r_{N-1}^{\,2})}{r_{N-1}}\; e^{-\alpha_N(f)\, 2L_N}\; e^{-j2\pi f(2L_N/c_N)}$$

The impulse response can be obtained as

$$h_{N,N-1}(t) = \frac{r_N(1 - r_{N-1}{}^2)}{r_{N-1}\,\pi} \left\{ \frac{[\alpha_N L_N/\pi]}{[\alpha_N L_N/\pi]^2 + [t - (2L_N/c_N)]^2} \right\}$$

From layer transfer function or layer impulse response it is possible to compute RMS time duration D_t and RMS bandwidth D_f. Attenuation coefficient of the layer of interest in MUT can be estimated using D_t and D_f as,

$$\alpha_N = \frac{\pi D_t}{L_N} \quad \text{and} \quad \alpha_N = \frac{\pi}{\sqrt{2}\, D_f L_N}$$

It is possible to obtain attenuation coefficient of the layer of interest without knowing the reflection coefficients at layer boundaries. It is necessary from the experimental view point to have the sufficient strength in the excitation so as to have measurable reflected signals with a higher S/N ratios. A number of narrowband transducers have been used to cover the frequency range of interest rather than using a single wideband transducer.

Effect of Temperature

Temperature affects the parameters like density ρ, velocity of propagation c, and layer thickness L. For solids the changes in these quantities could be negligible for the temperature range of interest. Hence estimation of α from RMS time duration could be more reliable for ultrasound thermometry.

$$D_{t1} = D_t \text{ and } \alpha_1 = \alpha \text{ @ temp } \theta_1 \text{ and } D_{t2} = D_t \text{ and } \alpha_2 = \alpha \text{ @ temp } \theta_2 = \alpha_1(1 + k\Delta\theta)$$

$$\therefore (D_{t2} - D_{t1}) / D_{t1} = k\Delta\theta$$

Similarly, for RMS bandwidth,

$$(D_{f1} - D_{f2}) / D_{f2} = k\Delta\theta$$

where 'k' represents temperature variation constant for attenuation coefficient of MUT.
The present work is concerned with the estimation of attenuation coefficient, layer impulse response and RMS time duration under the influence of temperature and their evaluation as potential parameter for ultrasound thermometry. The experiments were carried out on synthetic materials, polymethylmethacrylate, polyvinylchloride and polypropylene, using a number of narrowband transducers operating at different centre frequencies.

Experimental Procedure and Results

Experimental technique has been developed to compute layer impulse response h(t) using multiple transducers covering a range from 0.8 to about 8MHz. The technique is schematically shown in Fig. 2. With the use of limited number of transducers, large frequency band cannot be covered. Obviously there could be some truncation errors. Appropriate corrections have been applied to reduce the errors. Consistent values of attenuation coefficients are obtained. Attenuation coefficient of the materials tested is found more sensitive to temperature as compared to sensitivity of propagation velocity for corresponding changes in temperature. Fig. 3 shows the variation of the impulse response obtained at various temperatures. Knowledge of reference temperature is however essential for calibration. Fig. 4 and Fig. 5 depict the dependence of attenuation coefficient and velocity of propagation on temperature. The estimation of impulse response, RMS time duration and attenuation coefficient could be correlated to temperature of the material under test.

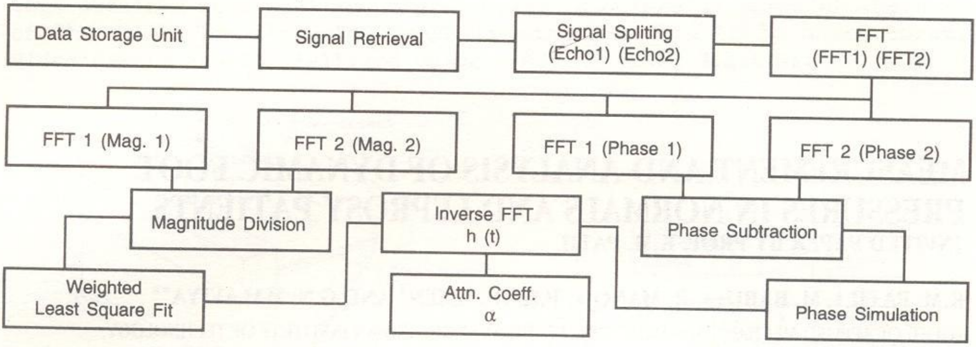

Fig. 2 : Signal Processing Schematic

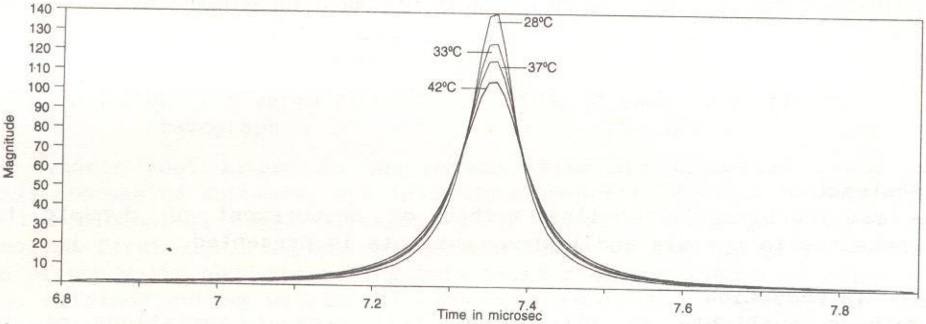

Fig. 3 : Effect of Temperature on Impulse Response

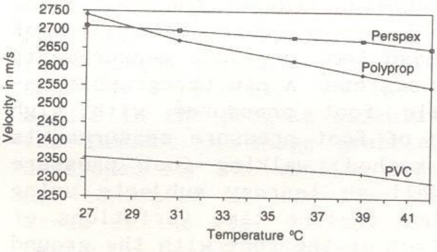

Fig. 4 : Effect of Temp. on Velocity

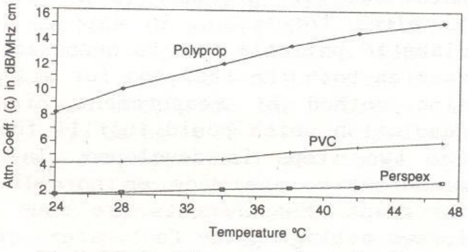

Fig.5: Effect of Temp. on Attn. Coeff.

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