Modeling of Acoustic Wave Propagation in Layered Solids and Its Application in Heat Assisted Magnetic Recording

Wei Peng, Yiao-Tee Hsia, Julius Hohlfeld

Seagate Technology

Abstract

In multi-layered solids, an acoustic wave is partially reflected and partially transmitted at boundaries where the acoustic impedance changes. With a large number of layers, an acoustic wave propagates by splitting and re-merging at each layer interface, which renders a too complex wave pattern to be predicted with analytical models. A Finite Element Method (FEM) based numerical model is developed to predict the acoustic wave propagation in multi-layered solids, where an ANSYS acoustic fluid element is adopted to solve this problem. This element was originally designed for homogeneous solids, and includes an assumption of negligible density gradients across the boundaries. To overcome this limitation, equivalent acoustic speed c_i' and density ρ_i' are derived to capture the density variation, i.e., $c_i' = c_i \rho_i$, $\rho_i' = 1$; and in order to keep the travel time constant inside each layer, the layer thickness h_i' is changed accordingly to compensate the acoustic speed c_i', i.e., $h_i' = h_i \rho_i$.

The numerical results are benchmarked with analytical computation for both a homogenous case and a two-layer solid case. The model is applied to study the pump-probe transient reflectivity measurements on Heat Assisted Magnetic Recording (HAMR) media, where the thermo-elastic waves are isolated and then subtracted from the composite reflectivity change measurement. As a result, the reflectivity change caused by the thermal decay is separated from the thermo-elastic waves, allowing a more accurate prediction and measurement of the thermal properties of HAMR media.

Nomenclature

c, Z	acoustic velocity, impedance
h	thickness
P	pressure
R_{Dis}, R_{Pre}, R_{Eng}	reflection coefficients for displacement, pressure, and energy, respectively
T_{Dis}, T_{Pre}, T_{Eng}	transmission coefficients for displacement, pressure, and energy, respectively
ρ	density

Introduction

A sudden thermal exposure to a laser pulse generates a transient thermo-elastic surface expansion-contraction. Since atoms of a solid are bound elastically, this transient surface expansion-contraction results in a thermo-elastic stress / strain wave, which propagates through the whole solid at the speed of sound (Fig. 1). This acoustic wave propagation is generally applied in pulse-echo ultra-sonic measurement for thickness metrology to characterize multi-layer structures.

The acoustic impedance (Z) of a material, which affects the acoustic wave propagation, is defined as the product of density (ρ) and acoustic velocity (c) of that material, i.e., $Z = \rho c$. The governing Navier-Stokes equation for acoustic wave propagation is derived from Hooke's law, Newton's law and the continuum hypothesis:

$$\frac{1}{c^2 \rho}\frac{\partial^2 P}{\partial t^2} - \nabla \cdot \left(\frac{1}{\rho}\nabla P\right) = 0 \qquad (1)$$

where P is the pressure.

In multi-layered solids, bonded layers may have different impedance. The acoustic waves are partially reflected and partially transmitted at boundaries where the acoustic impedance changes. This is commonly referred to as impedance mismatch. Enforcing continuous particle velocity and local particle pressures across the boundary between materials, the fractions of the incident-wave intensity are [1]:

$$R_{\mathrm{Pre}} = \frac{Z_2 - Z_1}{Z_1 + Z_2}, T_{\mathrm{Pre}} = \frac{2Z_2}{Z_1 + Z_2} \quad (2)$$

where R_{Pre} and T_{Pre} denote the reflection and transmission coefficients for pressure, respectively. The reflected energy is square of the difference divided by sum of acoustic impedances of the two materials, i.e.,

$$R_{Eng} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2, T_{Eng} = 1 - \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 \quad (3)$$

where R_{Eng} and T_{Eng} denote the reflection and transmission coefficients for energy, respectively. Note that the sum of the transmitted wave energy and the reflected wave energy remains constant following the energy conservation law.

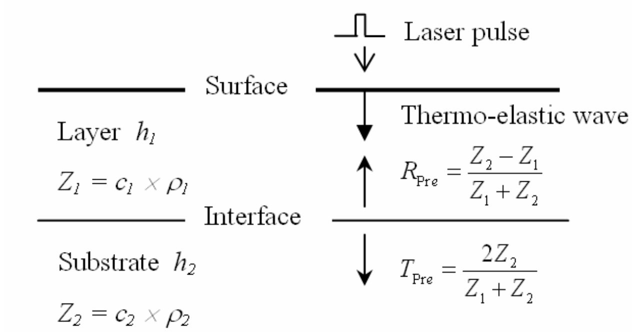

Figure 1. Schematic of acoustic wave propagation in a bi-layered solid

FEM Modeling of Acoustic Wave Propagation in Layered Solids

With a large number of layers, an acoustic wave propagates by splitting and re-merging at each layer interface, which renders a too complex wave pattern to be predicted with analytical models. A Finite Element Method (FEM) based numerical model is developed to predict the acoustic wave propagation in multi-layered solids. This model adopts the ANSYS acoustic fluid element (FLUID 29), which was originally designed to solve the acoustical fluid-structure interaction problems [2]. The fluid element is assumed to be compressible, inviscid with no mean flow, same as the solid material.

The governing equation used in ANSYS acoustic analysis is the traditional acoustic wave equation:

$$\frac{1}{c_i^2}\frac{\partial^2 P}{\partial t^2} - \nabla^2 P = 0 \quad (4)$$

where i is the index of each layer. Equation (4) assumes negligible density gradients across the boundaries, i.e., $\rho_i = \rho_j$, and thereby is only valid for homogeneous solid. To include the density difference-induced impedance, equivalent acoustic speed c_i' and density ρ_i' are derived to capture the density variation, i.e.,

$$Z_i' = Z_i, c_i' = c_i \rho_i, \ \rho_i' = 1 \quad (5)$$

Substituting Eq. (5) into Eq. (1) and Eq. (4), both governing equations converge; and enforcing the continuous velocity and pressures across the boundary yields Eq. (2).

In order to keep the travel time constant inside each layer, the layer thickness h_i' is modified accordingly to compensate for the acoustic speed change:

$$h_i' / c_i' = h_i \,/\, c_i \qquad \Rightarrow \qquad h_i' = \rho_i h_i \tag{6}$$

Benchmark of the FEM Based Acoustic Model

A benchmark case is designed to verify the FEM acoustic model (Fig. 2), where two top layers with the same thickness h, acoustic speed c_1 and c_2, density ρ_1 and ρ_2, are fully bonded and deposited on a substrate. Three locations of interest are investigated: *a* - middle of the top layer; *b* - interface between top layer and bottom layer, and *c* - middle of the bottom layer. The top surface is a free end, i.e., 100% reflection with inversion ($Z_0 = 0$). The thickness of the substrate is much larger compared to h and assumed to be infinite, i.e, the acoustic wave transmitted into the substrate is omitted. The reflection is assumed to be 50% without inversion, i.e., $Z_3 = 3Z_2$.

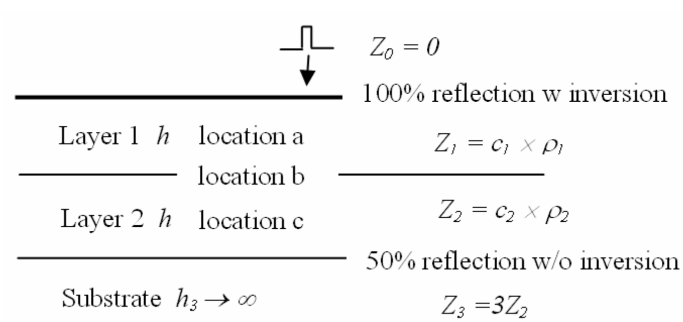

Figure 2. Benchmark of acoustic wave propagation in a three layered solid

Analytical Solution

Spatial and temporal histories of the acoustic wave are calculated based on Eq. (1). The acoustic waves are shown in Fig. 3, where the error bar length represents the magnitude of the pressure and the flip between plus and minus signs represents an inversion. Both homogeneous and layered cases are calculated, where the homogeneous case is obtained by assigning both top layers the same material properties, thereby eliminating the impedance mismatch. As shown in Fig. 3(a), the acoustic wave transmits through two identical top layers and reflects at the substrate surface with 50% pressure magnitude loss. No pressure sign change occurs until the acoustic wave hit the free end. For the layered case ($c_1 = ½\, c_2$), the acoustic wave partially reflects /transmits at the layer interfaces (Fig. 3(b)).

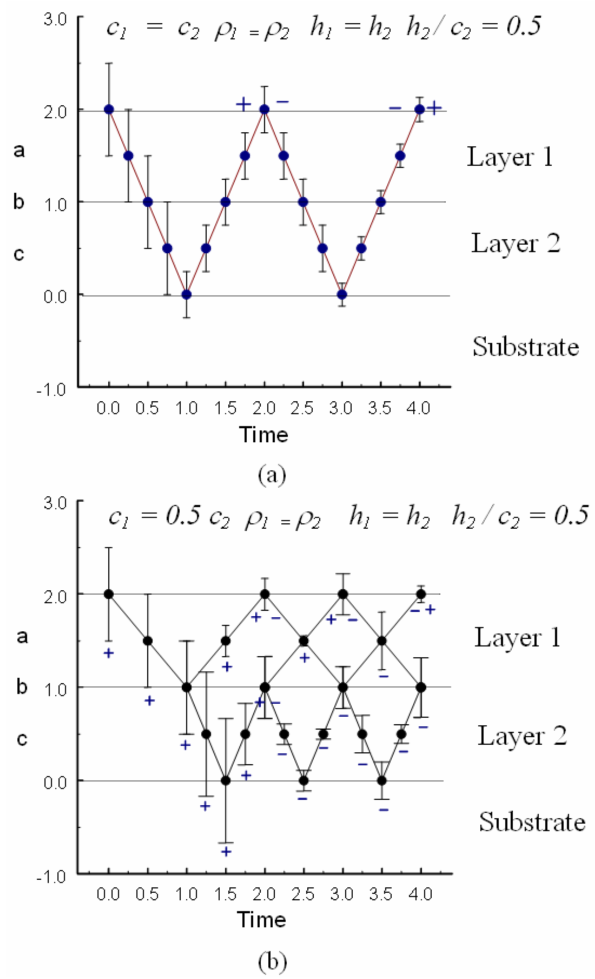

Figure 3. Analytical solution of acoustic wave propagation for (a) homogeneous and (b) layered case

FEM Solutions

The benchmark case has been tested with the FEM acoustic model. Only the two top layers are simulated. The free boundary $Z_0 = 0$ is obtained by constraining the top surface (zero pressure except the initial pressure pulse). The infinitely thick substrate with 50% reflection ($h_3 = \infty, Z_3 = 3Z_2$) is obtained by assigning the boundary of the bottom layer an impedance of 0.5 (ANSYS: *SF, all, impd, 1; MP, mu, , 0.5*). The equivalent acoustic speeds, densities, and thicknesses for layer 1 and 2 are obtained following Eqs (5) and (6).

The simulation results, as shown in Fig. 4, track down the acoustic wave at three locations as defined in Fig. 2: *a, b* and *c*. They match perfectly with the analytical computation results. Take location *a* in homogeneous case (Fig. 4(a)) as an example, the stress wave passes through this location at time 0.25, 1.75, 2.25, 3.75, with decreasing magnitude of 1, 0.5, 0.5, 0.25. There is one inversion that occurs at time 2.0 and switches the sign.

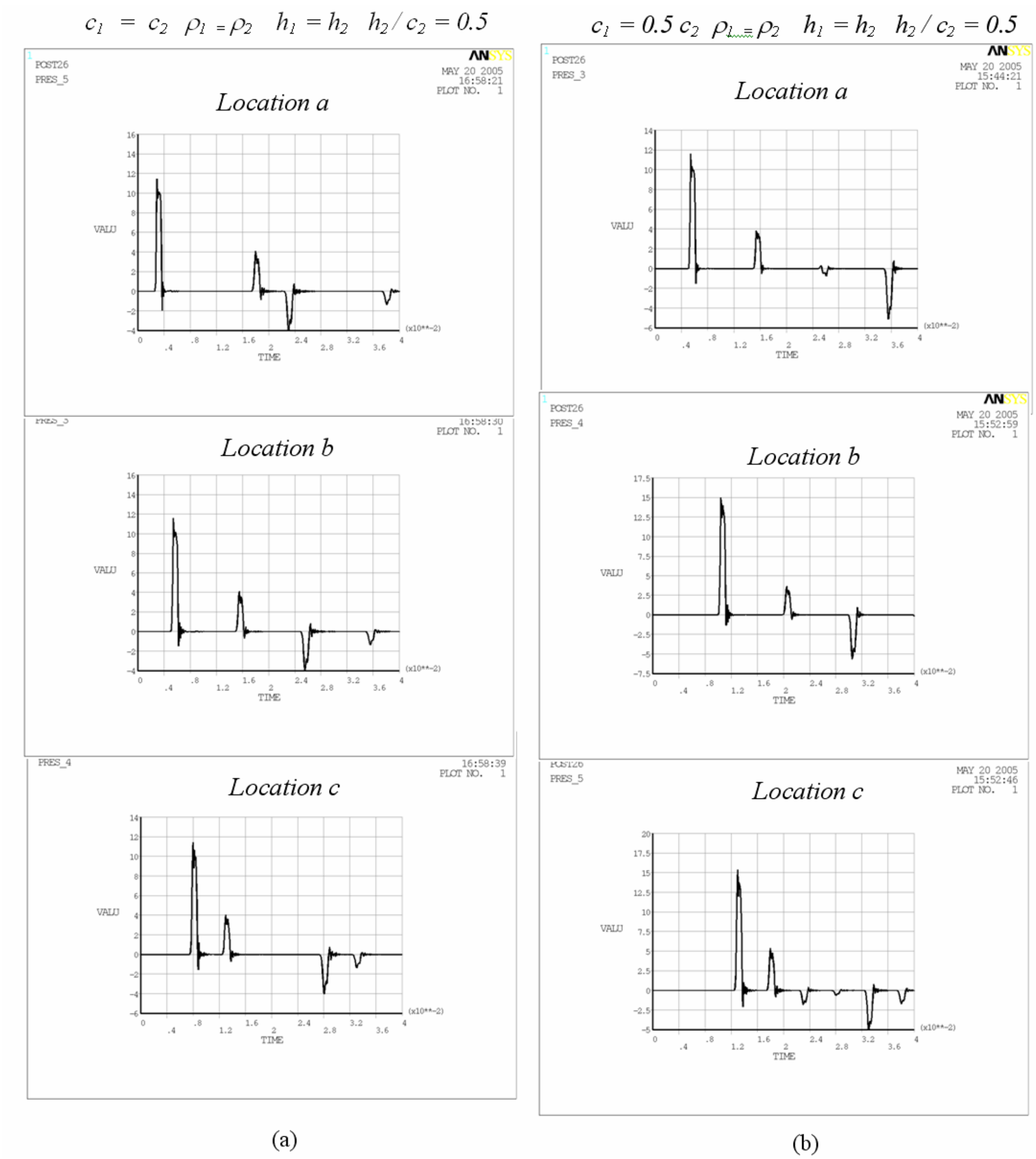

Figure 4. FEM solution of acoustic wave propagation for (a) homogeneous and (b) layered case

Application Case

Laser pump-probe transient reflectivity measurements are conducted on Heat Assisted Magnetic Recording (HAMR) media, where femto-second surface transient reflectivity is measured in order to characterize the thermal conductivities [3] However, thermal decay induced reflectivity change usually is contaminated with the thermo-elastic waves. The acoustic wave propagation model can be readily used to isolate the thermal-elastic sources.

Pump-probe Measurement on HAMR Disk Samples

Three multi-layered (8 layers) HAMR disk samples, with three different heat sink material, have been studied. Inside each sample, these layers are fully bonded together. The top surface is a free end, i.e., 100% reflection with inversion ($Z_0 = 0$). The thickness of the substrate is much larger compared to h, thereby the acoustic wave transmitted into the substrate is omitted. This is obtained by assigning the bottom of the finite thick ($h_3 = c$) glass substrate an impedance of 1 (ANSYS: *SF, all, impd, 1; MP, mu, , 1*); c can be of any value.

As shown in Fig. 5(a), the disk surface transient temperature, represented by the surface reflectivity, gradually decayed with time after being heated by a laser pulse. The relaxation times of the temperature-induced reflectivity are similar for all three samples. However, thermo-elastic acoustic waves induced by the laser pulse also show up as reflectivity change and is superposed on the thermal decay. For the samples with Au and Cu heat sink, the acoustic waves appear periodically and can be easily distinguished from the temperature induced reflectivity change. On the contrary, for the sample with 200 nm Al heat sink, the acoustic waves do not show a clear periodicity, thereby is hard to be separated from the temperature induced reflectivity change.

FEM Solutions

To separate the reflectivity changes caused by the thermal decay from the thermo-elastic wave, FEM acoustic wave propagation model is used. Since the pump-probe measurement is based on the surface displacement induced reflectivity change, it is necessary to extract the displacements from the model output. Assuming a harmonic plane wave traveling towards positive x, it is noted that the overpressure and condensation are in phase, and lead the displacement by 90° for a wave traveling towards +x, but lag by 90° for a wave in the opposite direction, which leads to

$$R_{Dis} = \frac{Z_1 - Z_2}{Z_1 + Z_2}, T_{Dis} = \frac{2Z_1}{Z_1 + Z_2} \qquad (7)$$

where R_{Dis} and T_{Dis} denote the displacement reflection and transmission coefficients, respectively. In order to directly apply the pressure based FEM model to obtain the surface displacement, equivalent impedances are applied as follows:

$$Z_i^{"} = \frac{1}{Z_i}, c_i^{"} = \frac{1}{\rho_i c_i}, \rho_i^{"} = 1, h_i^{"} = \frac{h_i}{\rho_i c_i^2} \qquad (8)$$

As shown in Fig. 5(b), by applying the FEM acoustic wave propagation model, normalized surface displacements induced by the thermo-elastic waves are extracted for these HAMR disk samples. It is confirmed from the model that for the Al substrate, the period of the acoustic wave is much shorter. The thermo-elastic waves are then subtracted from the composite reflectivity change. As a result, the reflectivity changes caused by the thermal decay are separated from the thermo-elastic waves, allowing an accurate prediction of the thermal properties of HAMR media.

Conclusion

A FEM model is developed to predict the pressure and displacement propagation of elastic acoustic wave. It is benchmarked with analytical computation for both a homogenous and a layered solid case. The model is successfully applied to the pump-probe transient reflectivity measurements on HAMR media, where the thermo-elastic waves are isolated and subtracted from the composite reflectivity change measurement.

Acknowledgement

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