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Simulation of Laser Ultrasonic Surface Wave Dispersion In a Multilayered Skin Model

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Abstract

The need for a sensitive method of the non-destructive evaluation of skin layer properties is highly desirable in a number of medical applications. The use of laser-generated surface acoustic waves (SAW) for the characterisation of multi-layered materials is widely used in industrial applications. In this paper we present research expanding this principle for the use of generated SAW for the characterisation of skin layer properties. The SAW dispersion relations are calculated for Finite Element simulated SAW displacement waveforms over a range of source-detector separations in three-layered models of human skin. The simulations show that SAWs are extremely sensitive to changes in layer properties and will be able to be utilised to quantitively characterise the layer properties of human skin by the development of an inverse algorithm.

Introduction

When a material is illuminated with a laser pulse, absorption of the laser irradiation leads to a rapid increase in the temperature of the irradiated area which causes rapid thermal expansion and results in the generation and propagation of ultrasonic waves. In the non-destructive thermoelastic regime various ultrasonic waves can be generated including longitudinal and transverse waves, surface waves and lamb waves. The characteristic of these waves is dependent on the thermal, optical, elastic and geometrical features of the material and on the parameters of the exciting laser pulse [1].

The use of laser generated SAWs for the non-destructive evaluation of layered materials has been extensively studied. Research has been carried out on the use of photoacoustic surface waves for the characterisation of thin films [2,3], and a recent study on a bonded copper-aluminium layered sample shows that there is a clear influence of bonding layer thickness of surface wave dispersion and by the use of an inverse algorithm, thickness and elastic properties of the bonding layer can be determined from the measured velocity dispersion relation [4].

SAWs propagate parallel to the investigated surface and interact with layers as thin a 100th of there wavelength, this makes them ideal for use in the characterisation of layered materials.

This paper discusses a study into the suitability of using laser generated surface acoustic waves for the characterisation of skin properties without causing any damage to the skin thermally or by mechanical disruption. The technique described in this paper involves measuring the propagation velocity of SAWs, which are directly related to the material properties, and thickness of layers, this is done over a wide frequency range in order to obtain maximum information regarding the material under test.

This research develops a finite element modelling technique to model the generation and propagation of laser generated waves in order to study the surface wave dispersion in skin models, this is the initial step in the development of a non-destructive technique to characterise the skin layers using SAWs.

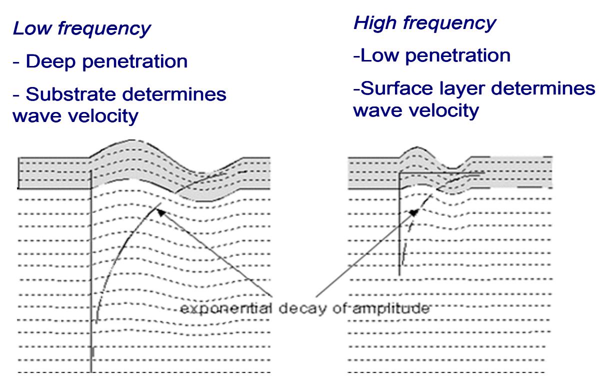


Figure 1. Schematic diagram showing surface waves in layered media [2]

Surface Acoustic Waves

Laser generated SAWs can be described as an additive superposition of ultrasonic wave of various frequencies. The surface waves act as oscillations that propagate along the target with amplitude that decays exponentially with depth. Every wave component propagates with it own velocity, and the impulse is deformed as it propagates along the material. It is the concentration of the wave energy at the surface that makes surface waves sensitive to layered media like skin, in layered material the velocity of SAWs depend on frequency, which is known as dispersion. The phase velocity of SAW is a wave parameter that is very sensitive to layered media. For a homogeneous and isotropic material described by Young's modulus E, Poisson's ratio ν and density ρ the phase velocity of the SAW can be described by Equation 1.

$$c = \frac{0.87 + 1.12\nu}{1+\nu}\sqrt{\frac{E}{2\rho(1+\nu)}} \qquad [1]$$

In a multilayered material where the elastic properties of the layers are different, the effect of all these layers affects the propagation velocity of the surface waves, with the phase velocity dispersion curves dependent on the elastic parameters, density and layer thickness. Longer wavelength (lower frequency) surface waves have deep penetration depth and propagate with a velocity dependent on the deeper layers, while the shorter wavelength (higher frequency) layers have low penetration depth and propagate with a velocity dependent on the surface layers as shown in Figure 1. The behaviour of the generated surface waves depend on the properties of each of the layers and can be divided into two distinct cases: 1/ a slower layer (lower Young's modulus) on a faster layer (higher Young's modulus) and 2/ a faster layer on a slower layer. In the case of a slow layer on a fast layer the top layer decreases the surface wave velocity of the substrate and leads to what is known as normal dispersion where the lower frequency components arrive earlier. In the case of a fast layer on a slow layer the opposite occurs and what is known as anomalous dispersion is observed where the higher frequency waves arrive earlier.

Finite Element Simulation

A finite element simulation (FE) of the thermoelastic laser generated surface waves in a 3-layered models of human skin is performed using commercial FE code ANSYS. The simulation procedure used is an example of a sequential coupled-field analysis where the thermal and mechanical fields are treated separately [5]. The simulation consists of a transient thermal analysis with a set of boundary conditions that approximate a laser pulse as a volumetric heat generation; the nodal results from the thermal analysis are subsequently read and applied as a load in a structural analysis where the out-of-plane displacements are recorded at various points.

The thermal properties of the epidermis, dermis and subcutaneous fat are: thermal conductivity of $2.4\text{x}10^{-4}$ $\text{Wmm}^{-1}\text{ K}^{-1}$, $4.5\text{x}10^{-4}$ $\text{Wmm}^{-1}\text{K}^{-1}$ and $1.9\text{ x}10^{-4}$ $\text{Wmm}^{-1}\text{K}^{-1}$, density of $1.2\text{x}10^{-3}$ g mm^{-3}, $1.2\text{x}10^{-3}$ g mm^{-3}, 1.0^{-3} g mm^{-3}, and specific heat of 3.590 $\text{Jg}^{-1}\text{K}^{-1}$, 3.300 $\text{Jg}^{-1}\text{K}^{-1}$ and 2.500 $\text{Jg}^{-1}\text{K}^{-1}$, respectively. The mechanical properties are Poisson's ratio of 0.48 for all skin layers, Young's modulus of $1.34\text{x}10^5$ Pa for the epidermis,8.8 $\text{x}10^4$ Pa, $8.0\text{x}10^4$ Pa, 7.5 $\text{x}10^4$ Pa, for the dermis in the three models (a, b and c respectively) and $3.4\text{x}10^4$ Pa for the subcutaneous fat [7], and thermal expansion coefficient of $3.0\text{x}10^{-4}$ K^{-1} for the epidermis and dermis, and $9.2\text{x}10^{-4}$ K^{-1} for the subcutaneous fat. The model extends to 20mm in length and the thickness of the epidermis is 0.08 mm in all models, the dermis is 1mm in models a, b and c and 1.5 mm in d, and the subcutaneous fat layer is 10 mm in all models.

The laser source used in the simulations is a 2 mJ laser with a rise time of 10 ns and 0.5 mm beam radius. Temporal and spatial resolution is critical for the convergence of these results choosing an adequate integration time step is important for the accuracy of the solution. Too large time steps results in the high frequency components not being accurately resolved, where too small time steps result in a waste of calculation time. In the simulations the integration time is 20 points for the highest frequency of interest, this has been shown to give an accurate solution. This can be expressed as:

$$\Delta t = \frac{1}{20 f_{\max}} \qquad [2]$$

where $f_{\max}$ is the highest frequency of interest, which is 10 MHz in this study. Element length is also critical importance, to accurately spatially resolve the propagating waves. This recommendation can be expressed as

$$l_c = \frac{\lambda_{\min}}{20} \qquad [3]$$

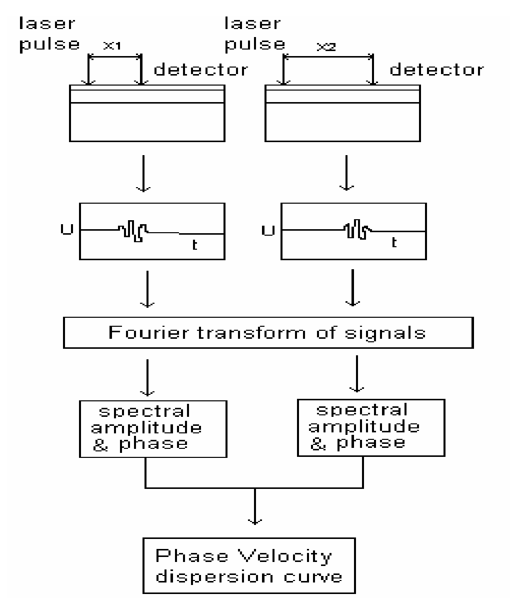


Figure 2 Schematic showing steps involved in determining dispersion curve.

A more detailed description of the FE model can be viewed is previous publication [8].

Rayleigh waves are SAW in which the longitudinal and shear displacements are coupled together and travel at the same velocity. To determine the dispersion relation the SAWs (out-of-plane displacement histories) are measured at two distances from the source on x_1 and x_2 on the model surface. The phase spectra $\phi_1(f)$ and $\phi_2(f)$ is calculated by applying a Fourier transform to the measured waveforms. The phase velocity c depending on frequency f (dispersion curve) is then determined by inserting $\phi_1(f)$ and $\phi_2(f)$ into the following equation:

$$c(f) = \frac{(x_2 - x_1)\omega}{\phi_2(f) - \phi_1(f)} \qquad [4]$$

where ω denotes the angular frequency.

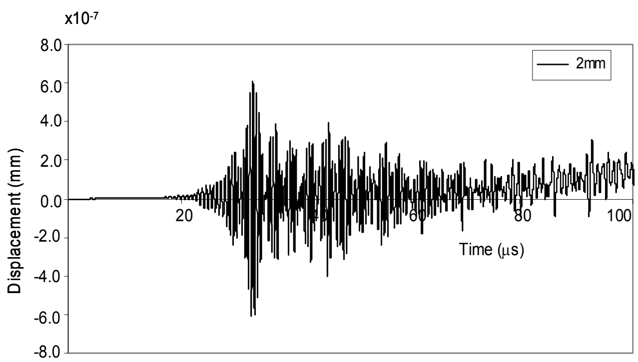


Figure 3. Out of plane displacement history measure 2mm from centre of laser source in model b

A schematic of the measurement and calculation procedure is shown in Figures 2 [6]. The shape of the dispersion curve depends on all the layers, the elastic parameters, density and layer thickness. The shape of the curves could provide a qualitative method of monitoring skin thickness and elastic properties and by the use of some form of inverse algorithm this can be made quantitative.

For the measured data, spatial and temporal aliasing effects have to be avoided. Aliasing is an effect caused by sampling a continuous signal with a digital sampling rate. If the signal contains frequencies about half the sampling rate or Nyquist frequency the frequency content above the Nyquist frequency is spurious. As the highest frequency of interest in this study is 10 MHz a sampling rate of $5.0\text{x}10^{-8}$ is used.

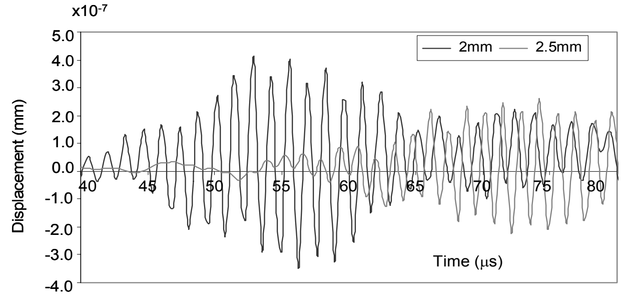


Figure 4. Out of plane displacement history measure 2mm and 2.5mm from centre of laser source in model b.

Results and Discussion

Figures 3 shows the out-of-plane displacement history measured 2mm from the centre of the laser source and Figure 4 shows the out-of plane displacement histories measure at various source receiver distances on the material surface (2 mm and 2.5 mm). These signals show a difference in phase and amplitude at different distances which is due to dispersion. Each impulse is an additive superposition of waves of varying frequencies with the deformation of the impulse containing the properties of the materials under test including the elastic properties, density and layer thickness.

Figure 5 shows the waveforms measured on two models with varying dermis layer thicknesses. There is a difference in phase and amplitude of these waves and it can be seen that there is a delay in the arrival time in the wave with a thicker dermis layer when compared to the model with 1mm dermis thickness. From this waveform it is clear that the generated surface layers are sensitive to variations in layer properties and can be used to characterise skin layers.

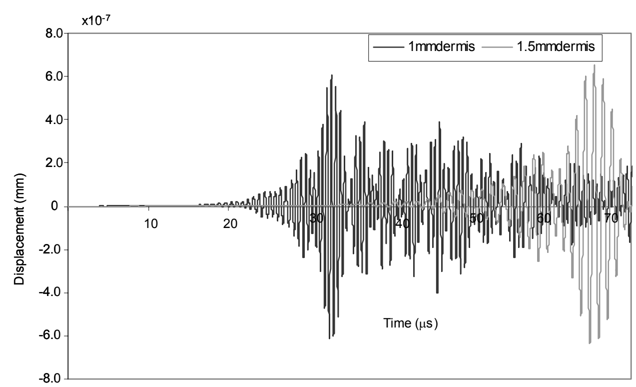
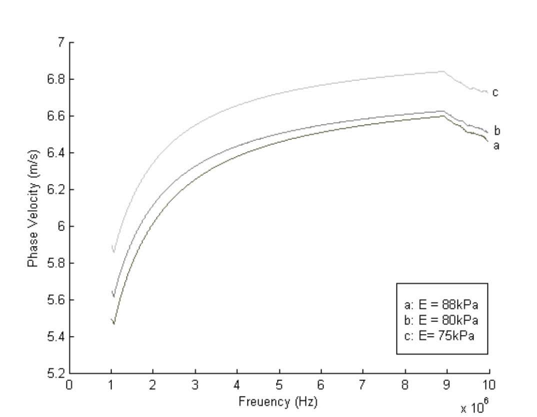
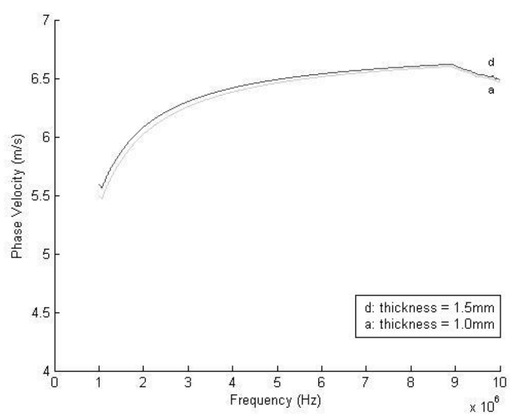


Figure5. Out of plane displacement histories measured at 2mm from centre of laser source in models with varying dermis thicknesses

Figure 6a and b shows the calculated dispersion curve from the different FE simulations. Figure 6(a) shows the calculated dispersion curves in three models with varying Young's Modulus of the dermis layer while figure 6(b) shows the calculated dispersion curves with varying dermis thicknesses. It can be seen that the calculated dispersion curves are sensitive to changes in the material and geometrical properties and material properties. It is the combination of all of the different layer properties that determines the character of the SAW and the resultant dispersion curve. Extrapolating the curve to zero frequency gives the velocity measurements for the substrate layers in the skin model and can be used to extract substrate layer properties. The higher frequency part of the curve represents the surface layers and can used to extract the surface layer properties and the curve of the slope cam be used to extract geometrical properties of the skin layers including thickness.



(a)



(b)

Figure 6. Phase Velocity dispersion curve measured on three layered skin models: (a) Variation in Young's Modulus of dermis; (b) Variation in dermis thickness.

Conclusion

The finite element simulation of laser generated SAW was performed in a multilayered skin model and the waveforms at different points on the material surface and measured. The measured SAW are processed from the time to the frequency domain by Fourier transformation to obtain the phase velocity dispersion cur0ve to explore the use of the laser ultrasonic surface acoustic wave technique to measure the characteristic of human skin non-destructively. The study shows that this technique is very sensitive to changes in layer properties and further research will be carried out to develop an inverse technique that will extract the elastic and geometric properties of each of the skin layers quantitively.

References

[1] C.B.Scruby, L.E.Drain, *Laser Ultrasonics: Techniques and Applications* (Adam Hilger, Bristol 1990).

[2] D.Schneider, Th.Witke, Th. Schwarz, B.Schöneich, B.Schultrich, Testing ultra-thin films by laser-acoustics Surface and Coatings Technology 126(2000) p136-141.

[3]D.Schneider,T.Schwartz, A Photoacoustic method for Characterising Thin Films, Surface and Coatings Technology, 91(1997) 136-146

[4] T.-T. Wu, Y.-C.Chen, Inverse determinations of thickness and elastic properties of a bonding layer using laser-generated surface waves, Ultrasonics, Vol. 37, (1999), p23-30.

[5] B.Xu, Z.Shen, X.Ni, J.Lu, Y.Wang, Finite element model of laser-generated surface acoustic waves in coating-substrate system J.Appl.Phys, Vol 95(4) (2004) p2109-2115.

[6] F.Peters,L.Petit, A broad band spectroscopy method for ultrasound wave velocity and attenuation measurement in dispersive media Ultrasonics Vol 41 (2003) p357-363.

[7] G.J.Gerling, G.W.Thomas, The Effect of Fingertip Microstructures on Tactile Edge Perception WHC First Joint Eurohaptics Conference and Symposium (2005) p.63-672

[8] A.L'Etang, Z.Y.Huang, FE Simulation of Laser Generated Surface acoustic wave propagation in skin, Ultrasonics, 2006.