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Simulation study and guidelines to generate Laser-induced Surface Acoustic Waves for human skin feature detection

Tingting Li [a], Xing Fu [a], Kun Chen [a,*], Dante J. Dorantes-Gonzalez [b], Yanning Li [a], Sen Wu [a], Xiaotang Hu [a]

[a] State Key Laboratory of Precision Measuring Technology and Instruments, Tianjin University, No. 92, Weijin Road, Tianjin 300072, PR China
[b] Department of Mechanical Engineering, MEF University, Ayazağa Cad. 4, Maslak, Sarıyer, 34396 Istanbul, Turkey

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ABSTRACT

Despite the seriously increasing number of people contracting skin cancer every year, limited attention has been given to the investigation of human skin tissues. To this regard, Laser-induced Surface Acoustic Wave (LSAW) technology, with its accurate, non-invasive and rapid testing characteristics, has recently shown promising results in biological and biomedical tissues. In order to improve the measurement accuracy and efficiency of detecting important features in highly opaque and soft surfaces such as human skin, this paper identifies the most important parameters of a pulse laser source, as well as provides practical guidelines to recommended proper ranges to generate Surface Acoustic Waves (SAWs) for characterization purposes. Considering that melanoma is a serious type of skin cancer, we conducted a finite element simulation-based research on the generation and propagation of surface waves in human skin containing a melanoma-like feature, determine best pulse laser parameter ranges of variation, simulation mesh size and time step, working bandwidth, and minimal size of detectable melanoma.

1. Introduction

According to figures of the American Cancer Society, skin cancer accounts for about half of all cancer diseases in the United States. Melanoma, the most serious type of skin diseases, accounts for more than 9900 of the more than 13,000 skin cancer deaths each year [1]. Therefore, early diagnosis of human skin diseases becomes more and more significant.

Laser-induced Surface Acoustic Wave (LSAW) technique is a non-destructive detection approach that usually uses nanosecond laser pulses to excite Surface Acoustic Waves (SAWs) [2]. This technique has been promisingly used in recent years due to its high accuracy and non-contact testing potential of layered and thin film materials [3–5]. Since some characteristics of the SAW propagation, such as the phase velocity, are directly related to the properties of the tested material, surface wave changes happened during the propagation process can be used to characterize the tissue properties, which may be a useful testing tool in biological and biomedical applications [6–8].

However, the interaction effects between laser and matter is a complex process. When a pulse laser beam impinges on to the skin, part of the energy is scattered, and a significant part is converted into heat. With this conversion process, elastic waves are mainly caused by local thermal expansion during the temperature rise, and then, spread in the skin surface. So far, little research has been done on providing practical recommendations to best generate strong LSAW for detection. This procedure has been guided mainly by the experience of researchers [8–10], rather than by a series of systematic recommendations that could help in the acquisition of a proper pulse laser, which costs usually in the order of one to several tens of thousands of Euros.

This paper intends to identify those key parameters and provide first guidelines to choose the ranges of variation where strong LSAWs can be generated. Provided that strong, but not causing biological damage LSAW are generated, they can be potentially detected in human skin, and specifically, in the detection of such skin features as melanoma. Moreover, the investigation also provides insights on how these parameters can be used within a Finite Element Method (FEM) model to simulate the generation of proper surface waves, determine what ranges of variation work better, and what the minimal human skin melanoma-like features are able to be detected with this technique under given model conditions.

* Corresponding author.
E-mail address: chenkun@tju.edu.cn (K. Chen).

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2. Main parameters that have influence in the generation of LSAWs in human skin

Human skin has a complex multilayer structure, usually divided into three lamellar structures: The epidermis (0.07–0.12 mm), the dermis (0.3–4 mm) and the subcutaneous fat (usually larger than 4 mm) [11,12]. At this current research stage, a simplification of the simulation model is made, considering the normal skin model to be free of race, gender or age effect, as well as of scars, moles, pores, glands, capillaries, etc., so the skin model is assumed to be isotropic and homogenous in each layer within the small scale skin sample. Only skin parameters such as density, specific heat, thermal conductivity, stiffness, Poisson's ratio and thermal expansion coefficient are taken into account in the model of each corresponding skin layer. The thermal and mechanical properties of the skin layers that used in the simulations are listed in Table 1 [8,9]. Based on a review of existing investigations on this topic, the main parameters that have shown influence in the generation of LSAWs in skin can be listed as follows: Wavelength, pulse energy, laser beam radius, rise time, absorption and scattering coefficients [8–10].

2.1. Wavelength and pulse energy

The pulse laser wavelengths that have been used for SAW excitation experiments so far are usually 532 nm and 1.06 μm [6,13]. The maximum permissible exposure (MPE) is the maximum permissible level of electromagnetic radiation that a person can be exposed to without dangerous biological changes. MPE is usually expressed as the pulse laser radiant exposure in J/cm^2 [8]. It is related to the electromagnetic wavelength, to the pulse energy and the irradiated area. It has been found from FEM simulations that big pulse energy helps to get larger SAW amplitudes, but has little effect in generating high SAW frequency components. Considering MPE and high SAWs quality for detection purposes, i.e. sufficiently large amplitudes and wide range of high frequency components, the irradiance intensity should be in a range, which would not cause damage to skin but help getting strong SAWs [6,14], is recommended to be between 0.1 and 10 mJ/mm^2.

2.2. Pulse laser beam radius and rise time

The intensity distribution of a pulse laser along with its beam radius is usually well fitted by a Gaussian distribution. Rise time is the time where the pulse intensity increases from zero to the highest value. The curves in Fig. 1 describe these spatial and temporal characteristics. The skin model has been used to investigate the effects of pulse laser sources for different beam radius and rise time. It has been proved that when the beam radius is larger, the temperature of the specimen increases more rapidly, reaching a higher maximum, but leading to smaller SAW amplitudes. When the pulse laser rise time becomes larger, the temperature reaches a higher maximum [9]. Smaller pulse laser beam radius and shorter rise time can also produce high frequency waves confined closer to the surface [8]. Based on these investigations, the beam radius and rise time are suggested to be ≤1 mm and ≤20 ns, respectively.

Table 1
Thermal and mechanical properties of skin layers.

Thermal and mechanical properties	Epidermis	Dermis	Subcutaneous fat
Density (g mm^{-3})	1.2×10^{-3}	1.2×10^{-3}	1.0×10^{-3}
Specific heat (J g^{-1} K^{-1})	3.590	3.300	1.900
Thermal conductivity (W mm^{-1} K^{-1})	2.4×10^{-4}	4.5×10^{-4}	1.9×10^{-4}
Young's Modulus (Pa)	1.36×10^5	8.0×10^4	3.4×10^4
Poisson's Ratio	0.499	0.499	0.499
Thermal Expansion Coefficient (K^{-1})	3.0×10^{-4}	3.0×10^{-4}	9.2×10^{-4}

2.3. Absorption and scattering coefficients

The absorption and the scattering coefficients due to the effect of pulse laser in skin tissue also have an extremely significant role in the generation of LSAWs [10]. In order to explain the different effects that pulse lasers with different absorption and scattering coefficients have on skin, a FEM simulation experiment was conducted. As the pulse energy mainly contributes to the SAW amplitude, two pulse lasers A and B with the same beam radius, rise time and, distinctively, different absorption and scattering coefficients, with values shown in Table 2 respectively, were used. From this table, it can be seen that pulse laser A corresponds a case with high absorption, while B, a high scattering case.

In order to save calculation time, a two-layer skin model with 1.7 mm in length, 0.08 mm epidermis thickness and 0.3 mm dermis thickness was build. After a pulse laser A or B impinged on the skin respectively, the temperature distribution of the skin at the end of the pulse was obtained and plotted in Fig. 2. What can be seen is that the skin temperature increase in the high absorption case is 0.629 K, and for the high scattering case is 0.315 K. The temperature difference is double, but the heated zone of the skin in a highly absorbing case has a rather shallow penetration and a small affected area in comparison with the highly scattering case. At 10 μs in Fig. 3(a) and (c), surface waves were already generated and propagated. Displacement signals y1 and y2 picked both at a distance of 1.5 mm from the source, correspond to the effects of pulse laser A and B respectively. Obviously, signal y1 has higher frequency components than signal y2, which can also be proved by their amplitude spectra in Fig. 3(b) and (d). Therefore, we can conclude that the affected surface with shallow penetration, with low skin damage, led to a better quality of the generated SAWs, providing a wider bandwidth with a rich content of higher frequencies.

When light falls perpendicularly on a sample of turbid material with certain thickness, reflections happen on the surface, and absorption and scattering occurs inside the material. To this regard, the Kubelka–Munk theory is a model that utilizes the theoretical relations between the diffuse reflectance, transmittance, scattering and absorption to calculate the scattering and the absorption coefficients of skin. In the Kubelka–Munk theory, light scattering includes both forward and backward scattering. As Fig. 4 shows, $i(x)$ and $j(x)$ represent the forward flow and backward flow, respectively. When part of the backscattered light survives absorption and comes out to the surface, it makes up a diffuse reflection, R_d. Similarly, part of the forward scattering light escape from the specimen bottom to join a collimated transmission, becoming the total transmitted light T_t [15].

The relations of measuring the absorption coefficient A, and the scattering coefficient S, referring the diffuse reflectance R_d and the total transmission T_t of a tissue specimen with thickness x [cm] are expressed as [16–18]:

$$A = S(a-1), \quad S = \frac{1}{xb}\left(\frac{1-R_d(a+b)}{T_t}\right), \quad \text{where} \quad a = \frac{1+R_d^2-T_t^2}{2R_d} \quad \text{and} \quad b = \sqrt{a^2-1}$$

Kubelka has shown that the absorption A and the scattering S coefficients of the diffuse flux in a turbid material is twice the absorption μ_a and scattering μ_s coefficients of a collimated flux, i.e. $A = 2\mu_a$ and $B = 2\mu_s$ [16]. Other researchers have validated the scattering and absorption coefficients relations by inverse