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Frequency Dependence of a Piezo-Resistive Method for Pressure Measurements of Laser-Induced Shock Waves in Solids

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Abstract: A shock wave is a mechanical high-pressure pulse that travels inside a medium with a full width at half-maximum of a few nanoseconds that may be induced with a high-power laser pulse. A piezo-resistive measurement method to determine the shock wave pressure has been widely employed even though there is inner inaccuracy in the calibration process. We are interested in developing a precise theoretical model of laser material processing for applications in material sciences that includes the frequency dependence of the electronic post processing. We show an approach to determine the correction factor to frequency response at a high frequency of a piezo-resistive experimental setup and the results of the pressure measurements obtained in this experimental setup. The theoretical and experimental work demonstrates the feasibility of piezo-resistive methods to measure a laser-induced shock wave pressure in the nanosecond range. The correction factor of the frequency dependence calibration allows the technique to be applied in different shock wave experiments.

Keywords: shock wave; strain gauge; laser pulse; signal conditioner; laser shock processing (LSP); laser shock wave (LSW)



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1. Introduction

A laser shock wave (LSW) is a mechanical pressure wave in a gigapascal (GPa) range with a full width at half-maximum (FWHM) in the order of nanoseconds (ns), induced by a high-power-density laser pulse [1–4]. An LSW propagates through a medium at a velocity greater than the sound speed (Mach > 1). The medium might be a solid, a liquid, or a gas. Some physical variables, including pressure, temperature, and particle velocity, to list a few, change discontinuously as the LSW propagates [5]. While the LSW propagates in a solid medium, some material characteristics improve through the relaxation of the compressive residual stresses [6].

Measurements of the LSW pressure inside a solid under controlled conditions are essential to regulate the optimal processing conditions (no ringing, for example) that result in the highest continuous pressure shock event. These material treatment applications include applied material science for high-performance metals, as in the aerospace, automotive, health, and defense industries, among others [7,8].

Several successful techniques have been proposed to measure the pressure induced by the LSW in solids. They include some piezoelectric methods [4,9], techniques that incorporate optical fibers [10,11], and piezo-resistive methods [12,13]. Such techniques developed in the previous decades presented some technological limitations. Piezoelectric methods have a nonlinearity response that needs to be considered. Fiber optic methods have a limited sensitivity and pressure range, restricting low-pressure measurements. Among the techniques mentioned, the piezo-resistive method has demonstrated, with

excellent results, its outstanding features including a wide detection range, linearity, and temporal response in the nanosecond range [14].

In piezo-resistive methods, the signal processing system has two stages: a Wheatstone bridge (WB) and an instrumentation amplifier (IA). A WB is used to provide a sensor linearization if the sensor requires it and impedance coupling to the second stage. Additionally, the WB can be calibrated as a null method and is coupled to the IA. In the second stage, an IA is used to set the gain and reduce the common-mode signals. This gain is frequency-dependent [15], and it decreases with increasing frequency. In previous work [16], we observe that this relation of the gain with respect to the frequency produces an error in the LSW pressure measurement accuracy.

In this work, we propose an approach to determine a correction factor of the measurement system frequency response at a high frequency of a piezo-resistive experimental setup. In addition, we present the results of the shock wave pressure measurements obtained in this experimental setup when applying the correction factor. According to this mathematical model, we may adjust the critical parameters required for the LSW optimized operation, including the minimization of energy use. Our experimental results demonstrate that we may use a piezo-resistive method to measure a laser-induced shock wave pressure in the nanosecond range.

The Principle of the Shock Wave Induction

Figure 1 presents the concept of induction of the LSW generation in solids. A lens, covered with an antireflection coating, focuses a high-power laser beam on a small surface sample area of 0.3 cm^2 . Most of the laser beam's energy is absorbed in the sample, subject to its specific optical material properties, as absorption and reflectivity at the laser wavelength.

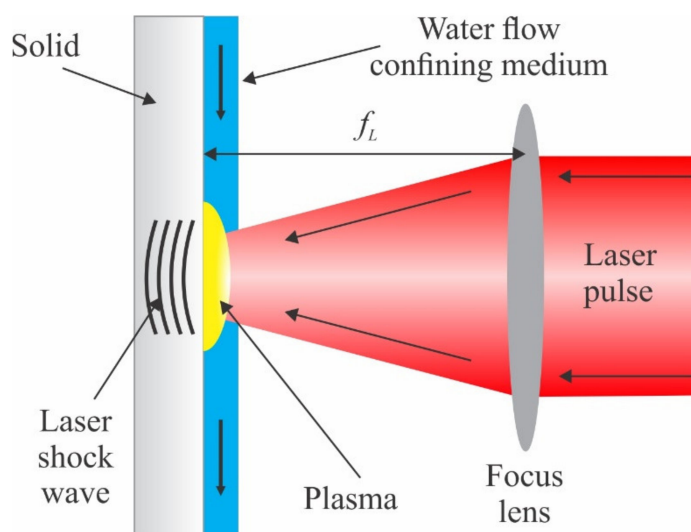


Figure 1. The physical principle of the laser shock wave induction. A high-power-density laser beam focused on the surface of a solid sample generates plasma. A high amplitude pressure wave with the magnitude of several GPa and a full width at half-maximum of a few nanoseconds is induced in the sample. It propagates from the sample's front surface to the backside while the plasma transfers its energy to the sample in an adiabatic process.

A thin layer of the sample surface is sublimated due to a rapid and large increase in the surface layer's temperature to about 10,000 K [17]. As described by Z. Zhang et al. [18], this process is separated into three stages: stage I, the absorption of laser pulse; stage II, the formation and expansion of laser-induced plasma; and stage III, the plastic deformation on the target surface due to the laser shock loading. We will focus on stages I and II, since stage III is beyond our study's scope.

Stage I begins after the laser pulse is focused on the solid surface. Electrons instantaneously absorb the photons' energy on the Fermi surface. This instant energy absorption thermalizes the electrons through high temperatures in the picosecond range. Thus, vibration on the lattice begins to transmit their energy through phonons' emissions. This energy exchange tends to thermal equilibrium after decades of picoseconds and is described by the two-temperature model of the thermal conservation of energy expressed in terms of the electron temperature diffusion:

$$C_e \frac{\partial T_e}{\partial t} = \nabla \cdot (\kappa_e \nabla T_e) - \Gamma_{ei}(T_e - T_i) - \left(\frac{\partial E_e}{\partial V} + p_e \right) \frac{\partial V}{\partial t} + R_{Abs} - R_{Emis} + S, \quad (1)$$

$$C_i \frac{\partial T_i}{\partial t} = \nabla \cdot (\kappa_i \nabla T_i) - \Gamma_{ei}(T_e - T_i) - \left(\frac{\partial E_i}{\partial V} + p_i \right) \frac{\partial V}{\partial t} - q \frac{\partial V}{\partial t}, \quad (2)$$

where the subscript e and i correspond to electrons and ions, respectively; $C_{e,i}$ are the heat capacities per unit volume; $T_{e,i}$ are the temperature; $E_{e,i}$ are specific internal energies; $\Gamma_{ei} = C_e Z^2 \ln \Lambda_{ei} (A^2 V T_e^{3/2})$ is the electron-phonon coupling constant, which describes the energy exchange rate between electrons and ions where Z is the charge index, A is the relative atomic mass, and Λ_{ei} is the Coulomb term for electron-ion collisions; $p_{e,i}$ are the energy density; q is the Von-Neumann artificial viscosity; and V is the specific volume. Therefore, $\kappa_{e,i}$ are the thermal conductivities, which are described by

$$\kappa_{e,i} = 20 \left(\frac{2}{\pi} \right)^{3/2} \frac{(k_B T_{e,i})^{5/2} k_B \tau_{e,i}}{m_e^{1/2} e^4 Z \ln \Lambda_{ei,ii}}, \quad (3)$$

where k_B is the Boltzmann constant, m_e is the electron mass, e is the electron charge, and Λ_{ii} is the Coulomb term for ion-ion collisions, and $\tau_i = 1$ and $\tau_e = 0.43Z/(3.44 + Z + 0.26 \ln Z)$. R_{Abs} and R_{Emis} are radiation absorption and emission terms, which are given by

$$R_{Abs} = c \sum_g^{N_F} \left(\sigma_g^{PA} E_{R,g} \right), \quad (4)$$

$$R_{Emis} = \frac{8\pi (k_B T_e)^4}{c^2 h^3} \sum_g^{N_F} \left(\sigma_g^{PE} \int_{x_g}^{x_{g+1}} \frac{x^3}{e^x + 1} dx \right), \quad (5)$$

where g is the frequency group index, N_F is the number of frequency groups, c is the speed of light, $E_{R,g}$ is the radiation energy density for group g , σ_g^{PA} and σ_g^{PE} are Planck mean opacities for emission and absorption, respectively, and $x = \hbar\omega/k_B T_e$ where h is Planck's constant, and ω is the angular frequency. Finally, S is the laser source in Equation (1), described by

$$S = \alpha(1 - R)I(t) \left(\frac{w_0}{w} \right)^2 e^{-2r^2/w^2} e^{-\alpha z}, \quad (6)$$

where $\alpha = 1/\delta$ is the absorption coefficient of the sample, which is determined by the skin-depth $\delta = 1/\sqrt{\pi\mu f\sigma_0}$ of the electromagnetic wave penetrating into the solid, where μ is the magnetic permeability, f is the frequency of the wave, and σ_0 is the electrical conductivity; R is the reflectivity of the sample surface; $I(t)$ is the laser intensity as a function of time; w_0 is the radius at the beam waist; w is the radius of the beam spot the size on the metal surface; and z is the depth measured perpendicular to the surface of the target. Equation (6) relates the intensity of the laser and the solid sample's optomechanical properties for the laser heating.

In stage II, even if the laser pulse's fluence is near tens of J/cm², it is not sufficiently high to ionize all material. The ionization observed at the end of the stage I is due to collisions between fast electrons, multiphoton processes, and an ionization field near the laser focus area. This ionization is not symmetrical due to the collisions' incident, and reflected angles are not equal under an electromagnetic field. This asymmetry leads to the

rupture of the ionization field. However, in every collision between fast electrons and ions, there is energy gain in the form of the probability of the number of ionizations:

$$\left(\frac{dE_e}{dt}\right)_{gain} = \left(\frac{8k_B}{\pi}\right)^{1/2} \frac{ne^2I}{m^{3/2}\epsilon_0 c \omega^2} \sigma T_e^{1/2}, \quad (7)$$

where σ is the collision cross-section, n is the number density, and ϵ_0 is the vacuum permeability. If this energy gained from collisions is greater than the sum of the mean ionization energy or other energy dissipation components, an avalanche process induces a plasma breakdown. The plasma breakdown is described with a macroscopic two-fluid Vlasov model assuming the Maxwell-Boltzmann conditions to obtain the velocity moment, density, and pressure.

$$\frac{\partial f_\sigma}{\partial t} + \frac{\partial f_\sigma}{\partial \vec{x}} \cdot \frac{d\vec{x}}{dt} + \frac{\partial f_\sigma}{\partial \vec{v}} \cdot \frac{d\vec{v}}{dt} = \sum_\alpha C_{\sigma\alpha}(f_\sigma), \quad (8)$$

where the distribution function is denoted by $f(x, v, t)$ to characterize the instantaneous configuration of a large number of particles, such as the density of particles at each point in the phase spatial. If a one-dimensional (1D) approach is used, the conservation of mass equation with Lagrangian coordinates can be written as

$$\frac{\partial V}{\partial t} = V \frac{\partial u}{\partial r} = \frac{\partial u}{\partial m_0}, \quad (9)$$

where $V = 1/\rho$ is the specific volume, u is the velocity fluid, and m_0 is the Lagrangian mass variable. This mass density can be obtained by Equation (8) if the results are adapted to the number density of electrons and ions. If we assumed an isotropic system, the scalar pressure P_σ is obtained by multiplying Equation (8) with velocity and integrating it over the velocity space, taking into account the temporal evolution of the mean fluid velocity for each species (σ and α) under Lorentz force in the electromagnetic field $\vec{E}$ and $\vec{B}$:

$$n_\sigma m_\sigma \frac{\partial \vec{u}_\sigma}{\partial t} + n_\sigma m_\sigma \left(\vec{u}_\sigma \cdot \nabla \right) \vec{u}_\sigma = n_\sigma q_\sigma \left(\vec{E} + \vec{u}_\sigma \times \vec{B} \right) - \nabla P_\sigma - \vec{R}_{\sigma\alpha}, \quad (10)$$

where m_σ is the mass of the particle, q_σ is the particle charge, and $R_{\sigma\alpha}$ is the net frictional drag force due to collisions of species σ with species α . Furthermore, the momentum conservation equation is

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho} \frac{\partial}{\partial r} (P + q) = -\frac{\partial}{\partial m_0} (P + q) + \dot{u}_{TN}, \quad (11)$$

$P = P_e + P_i + P_r$ is the total fluid pressure due to electrons, ions, and radiations; q is the von Neumann artificial viscosity; and u_{TN} is the velocity change momentum exchange from the slowing down of fast particles. If the Vlasov equation of Equation (8) is multiplied with a factor of $m_\sigma v^2/2$ and integrated over the N-dimensional velocity space, a so-called Vlasov second moment is defined as

$$\frac{N}{2} \frac{\partial P_\sigma}{\partial t} + \frac{N}{2} \vec{u}_\sigma \cdot \nabla P_\sigma + \frac{2+N}{2} P_\sigma \nabla \cdot \vec{u}_\sigma = -\nabla \cdot \vec{Q}_\sigma + \vec{R}_{\sigma\alpha} \cdot \vec{u}_\sigma - \left(\frac{\partial W}{\partial t} \right)_{E\sigma\alpha}, \quad (12)$$

Equations (1), (2), (6), (10), and (12) describe the laser-matter interaction involved in the induction of LSW. The other steps in obtaining the equations that explain all procedures of laser-matter-plasma interaction are described in [18].

As a remark, the amount of the laser power needed to heat a thin surface layer of the sample to the point of sublimation depends on the full width at half-maximum (FWHM) of the laser pulse, the irradiated spot area, and the relative area of the irradiation with

respect to the sample linear dimension [19]. The large amount of the energy absorbed in the thin surface layer transforms the state of matter into plasma. Consequently, the plasma transfers its energy to the solid in an adiabatic process. This process induces a mechanical, high-amplitude pressure wave of several GPa inside the sample with an FWHM of a few nanoseconds. The pressure wave travels through the material from the front surface called the impact zone, to the back surface. We determined that the FWHM of the LSW is about 50 ns in our experiment. This parameter was determined at a frequency of 20 MHz. We consider that the LSW initiates a fast change in pressure (~ 25 ns), and it achieves peak pressure at a time of about one-half of this interval (13 ns).

A dielectric layer, referred to as a confining medium, is used to confine the plasma, delay its expansion, and increase the LSW pressure. The confining medium may be chosen as air, water, or glass, to name a few [20]. In many cases, water is preferred due to practical industrial considerations. It is coupled perfectly to the geometry. It is replaced easily after a pulse, has a low cost, and produces acceptable confinement. Two arrangements of confining plasma with water are possible: immersion and flow. In the immersion confinement, the confining medium surrounds the sample, assuring a single medium between the sample and the incident laser pulse. However, the immersion type generates a collapsing bubble that induces a secondary shock wave in the sample. That problem is overcome using water that absorbs a fraction of the laser pulse energy. Thus, the flow type, or so-called water jet, does not have this disadvantage. The water layer is only a few millimeters thick. Therefore, the water flow is considered laminar, avoiding the creation of the cavitation bubble.

2. Materials and Methods

The experimental procedure to obtain LSW pressure within solids using the piezo-resistive detection method and correction factor consists of two parts: First, we measured the pressure of the LSW. Then, we found the frequency response of the second stage to determine the correction factor and the attenuation of the gain. We used two plate samples to induce an LSW and perform the requisite pressure measurements; one was a 5 mm aluminum 6061-T6, and the other was a 1.3 mm aluminum 6063-T5. The mechanical properties for both samples are shown in Table 1. In this study, we chose aluminum blocks without absorbent coating [21–23] since they are used in many applications where lightweight metals are required (for example, in the aerospace industry). However, any other material, titanium or iron, may be used in the future, applying our proposed method.

Table 1. Aluminum alloy mechanical properties.

Aluminum Alloy	Tensile Strength	Elastic Limit	Elongation	Young's Modulus	Fatigue Strength	Thermal Shock
	MPa	MPa	%	GPa	MPa	Resistance
6061-T6	290	241	10	69	96	14
6063-T5	160	97	11	68	70	8

2.1. Experimental Setup

Figure 2 shows the experimental setup's typical schematic layout to induce an LSW in a solid sample. The power source is a Q-switched (Quantel Brilliant B Nd:YAG laser) with a wavelength of 1064 nm and a spot diameter of about 10 mm. It is operated in a single pulse mode, for the duration of 6 ns, with an energy density equal to 0.77 J cm^{-2} . These settings of the laser power source are typical for laser shock processing (LSP). A high-reflectivity, dielectric-coated planar mirror *DM* turns the beam direction for compact layout and decreases back-reflection into the laser cavity [24]. A biconvex lens *L* covered with an antireflection coating, a focal length of $f_L = 1 \text{ m}$, and a transmission of about 96% is used to focus the laser beam onto a spot diameter of about 1.2 mm on the sample surface. The local fluence on the laser spot is 68.08 J cm^{-2} . A fast silicon photodiode (Thorlabs DET10A) is

connected to trigger the oscilloscope. This photodiode has a spectral responsivity interval of 200–1100 nm and a 1 ns rise time. A water flow (in blue) confines the medium.

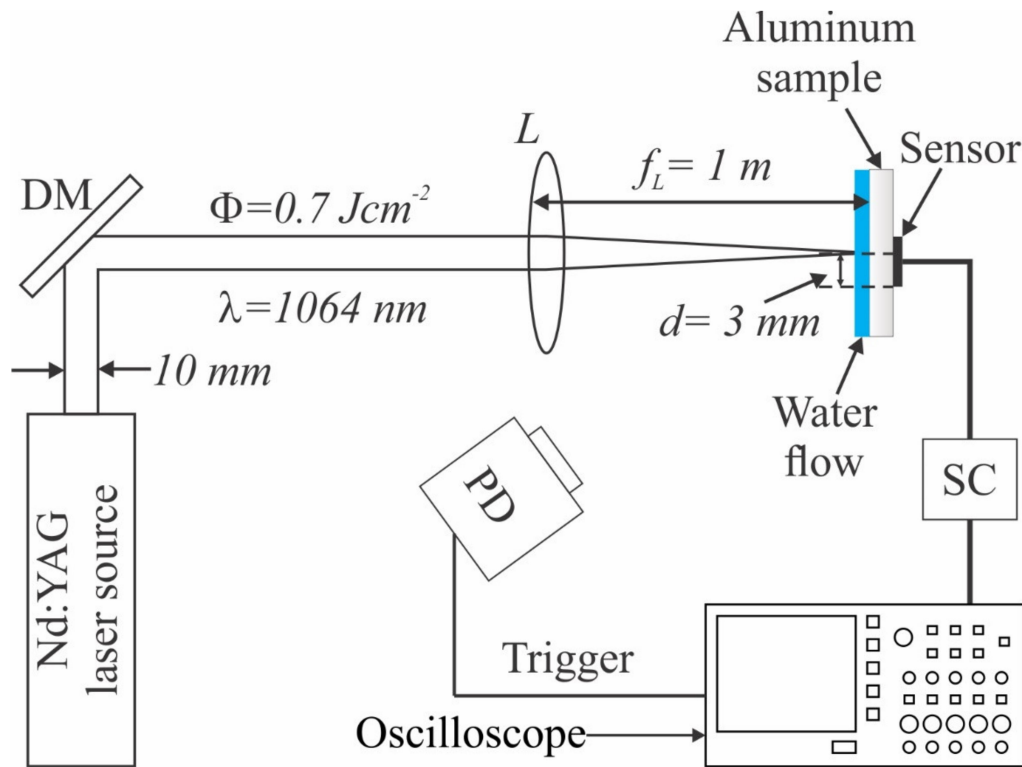


Figure 2. Experimental setup to induce a shock wave in a solid (aluminum, in our case). A single pulse from the Nd:YAG high power laser with $\lambda = 1064$ nm, an energy density of 0.77 J cm^{-2} , 6 ns pulse duration, and a spot diameter of 10 mm is focused on the sample surface with a bi-convex lens L covered with an antireflection coating to decrease a spot diameter to about 1.2 mm. A manganin piezo-resistive sensor is attached to the backside of the sample. The output signal from the sensor is connected to a signal conditioning system SC (WB, IA and a high-pass filter).

We measured the pressure induced by the shock wave through embedding a manganin piezo-resistive sensor (VISHAY LM-SS-125CH-048) in the back of the sample probe at a distance $d = 3$ mm below the laser spot, as shown in Figure 3. This distance corresponds to the length between the center and the boundary of the sensor active region. The sensor is attached by a thin film of bond M-Bond 200 (cyanoacrylate) for pressure gauges. This film is smaller ($< 2 \mu\text{m}$) than the wavelength of the shock wave ($320 \mu\text{m}$ for Al [25]), and its effects on the shockwave propagation may be negligible. Further, this alloy of the sensor has a quasi-linear response for wide pressure ranges, as shown by Duan Z. et al. [26]. Its output signal is connected to a quarter Wheatstone bridge transducer. Then, the signal is conditioned by an IA with a gain $G = 670$. The output signal is filtered with a first-order passive high-pass filter, with a cut-on frequency of 300 kHz to reduce the $1/f$ noise. The detector output signal is exhibited in an oscilloscope (Tektronix TDS 7054) that measures data with a 500 MHz bandwidth, time-gated at 2 GS/s and within a time window of 1 μs . Data is recorded for further processing on a PC.

We used a quarter Wheatstone bridge as a conditioning piezo-resistive sensor. The resistance of the sensing element (in our experiment, manganin) is denoted by $R_{\text{Gauge}} = R_{x\text{NOM}} + \Delta R_{\text{Gauge}}$, where $R_{x\text{NOM}} = 48 \Omega$ is the nominal resistance with no disturbance and $\Delta R_{\text{Gauge}} = 0.1 \times 10^6 \times P \times S_s \times R_{x\text{NOM}}$ is the resistance change due to a shock wave transit (the steady-state of the sensor is $\Delta R_{\text{Gauge}} \neq 0$), where P is the shock wave pressure in [Bar] ($1 \text{ Bar} = 100 \times 10^3 \text{ Pa}$) and S_s is sensor sensitivity in $[\Omega \Omega^{-1} (\text{kPa})^{-1}]$. Subsequently, an instrumentation amplifier (IA) is connected to the WB terminals to reduce the two inputs'

common-mode signals. The output voltage V_{out} of the IA is related to the pressure P in terms of sensitivity S_s and gain $G(f)$ of the measurement system:

$$P(G(f), V_{out}) = 0.1 \times 10^6 [G(f) S_s R_{xNOM}]^{-1} \left[\left(\frac{R_3(R_2\alpha + \beta)}{R_1\alpha - \beta} \right) - R_{xNOM} \right], \quad (13)$$

where $\alpha = GV_S$ and $\beta = V_{out}(R_1 + R_2)$. The gain of the measurement system decreases with frequency. Thus, an attenuation factor $G(f)$ is included for the gain explicitly in the mathematical model. Its frequency response is experimentally measured in the following subsections. Appendix A shows the electronic details of the experiment and the mathematical manipulation to obtain Equation (13).

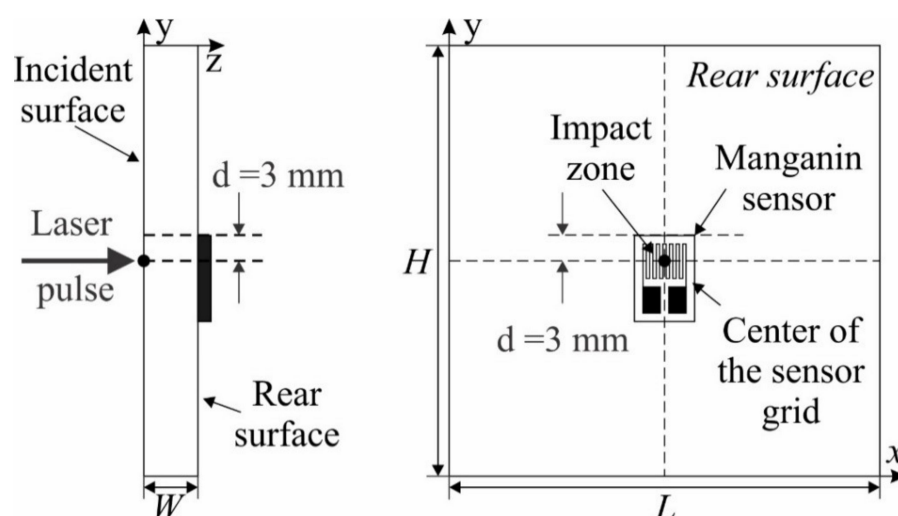


Figure 3. The manganin piezo-resistive sensor is embedded in the back of the solid sample. It is placed 3 mm below the impact zone, between the center and the active region boundary, at the middle of the sample.

2.2. Frequency Dependence Correction

The experimental setup to determine the correction factor $G(f)$ of the frequency dependence is exhibited in Figure 4. This correction factor is used to accurately determine the pressure signal in Equation (13). A sweep generator (Rode & Schwarz SWM05, 10–18,000 MHz) produces a sinusoidal signal that increases its frequency in a time window of 30 seconds, with an amplitude of 448 mV peak-to-peak. This sweep generator is used as the signal source to obtain a Bode diagram of the measurement system. The initial and the final window frequency of the signal source are 10 MHz and 30 MHz (20 MHz bandwidth), respectively. The output signal of the measurement system is recorded with a spectrum analyzer (HP8593A), with a 9–26.5 GHz bandwidth, a span bandwidth of 20 MHz, and the center frequency at 30 MHz. A Tektronix TDS 2024B oscilloscope is connected with a temporal base to observe the sweep signal. A Faraday cage with a cut-off frequency of 60 GHz is set all around the measurement system to minimize external noise and electrical interference. A cooling system has been implemented to reduce the thermal (Johnson) noise. The electrical characteristics of the measurement system are listed in Table 2.

Table 2. Electrical characteristics of the measurement system.

IA Voltage Source	WB Voltage Source	Output Impedance	Current Consumption
[Vdc]	[Vdc]	[Ω]	[mA]
±4	10	50	205

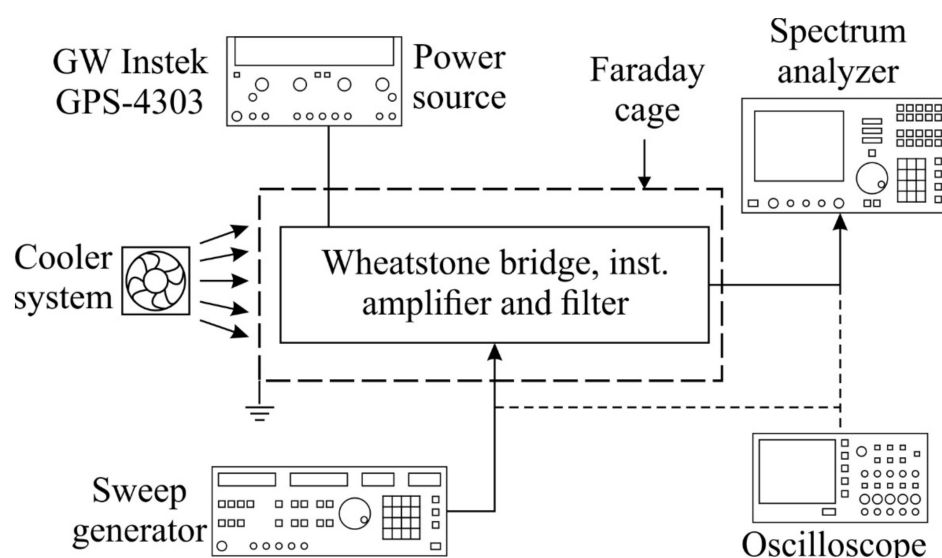


Figure 4. Functional pictographic diagram of the experimental setup to measure the system frequency response. A sweep generator produces a variable frequency sinusoidal signal probe to use as the input signal. A spectrum analyzer is connected to the output of the measurement system to find the frequency response curve, including its associated gain attenuation function.

3. Results and Discussions

3.1. Frequency Dependence Correction

The Bode diagram of the pressure measurement system is displayed in Figure 5a to determine the correction factor. The vertical axis corresponds to the gain of the measurement system with respect to the frequency. The usual response of the LSW in the experimental setup is expected in the frequency range of 10 MHz to 50 MHz. The gain decreases with frequency and may be approximately described as a cubic curve. Examining Figure 5a, we can read that it is about -27 dB at 20 MHz, corresponding to a correction factor $G(f) = 0.0006$. Dots represent a cubic polynomial fit, and a fourth-degree polynomial fit is shown with dashes, $G(f)_1$ and $G(f)_2$. Their corresponding functions, with frequency measured in MHz, are as follows:

$$G(f)_1 = -1.3f^3 + 7.5 \times 10^{-3}f^2 - 0.66f - 17, \quad (14)$$

$$G(f)_2 = -6.4 \times 10^{-6}f^4 + 0.76 \times 10^{-3}f^3 - 0.025f^2 - 0.12f - 20. \quad (15)$$

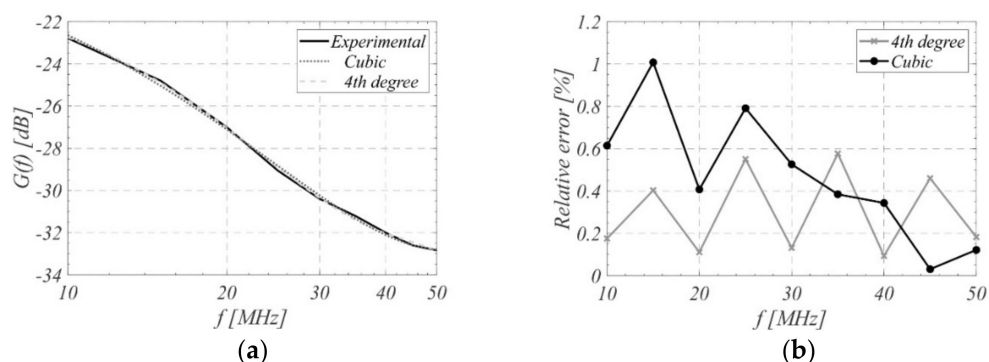


Figure 5. (a) Bode diagram of the frequency response of the pressure measurement system. Two polynomial fits were used to obtain a mathematical model for the frequency correction factor curve, a cubic and a quartic one. (b) The relative error of fourth- and third-degree polynomial fits. The fourth-order polynomial fit has a lower relative error than the cubic; however, the improvement is relatively small.

The relative error for each gain function is graphed in Figure 5b. We summarize, according to errors obtained in the polynomial fits, the fourth polynomial order fit is used in the mathematical model of the correction factor curve.

3.2. Shock Wave Pressure

We measured the parameters describing the behavior of the shock wave pressure in our experimental setup. The shock wave pressure was calculated using Equation (13) for two aluminum samples: 1.3-mm thick Al 6063-T5 and 5-mm thick Al 6061-T6. Figure 6 shows the shock wave pressure in both Al 6061-T6 5-mm thick slab (gray) and Al 6063-T5 1.3-mm thick slab (black) for a 1- μ s time interval after the irradiation pulse.

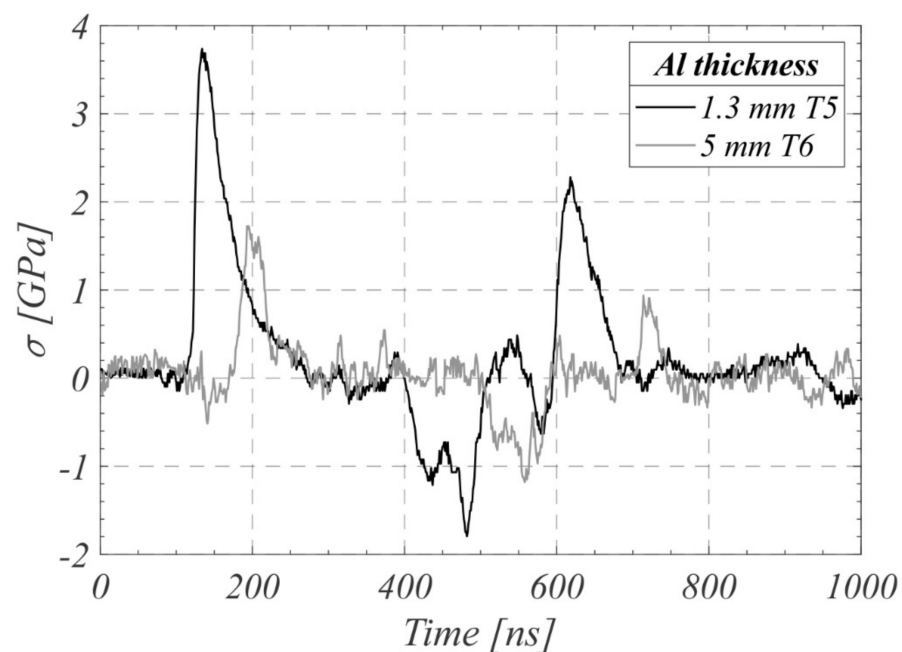


Figure 6. Shock wave pressure profile in both Al 6061-T6 5-mm thick (gray) and Al 6063-T5 1.3-mm thick (black) in a 1 μ s time interval. It shows the two first pressure peaks. The second pressure peak represents one cycle, corresponding to the shock wave's travel from a sample rear surface to the sample front side. Peak pressure for the 1.3-mm thick sample is 3.8 GPa, and the 5-mm thick sample is 1.68 GPa. Similar profile tendencies are observed between the highest consecutive peaks.

The shock wave pressure in Al 6063-T5 is 3.8 GPa, and for Al 6061-T6 it is 1.68 GPa. The pressure peak recorded for the Al 6063-T5 sample is about two-times higher than that of the four-times thicker Al 6061-T6 sample. A higher amount of energy is dissipated after the shock wave is transmitted into a thicker slab of material, producing a decreased peak amplitude. This is interpreted as the whole block reacting to the shock imposed by the thermal impulse. The pressure difference between samples is due to the shock wave traveling a longer distance on the 5-mm thick specimen than the 1.3-mm thick specimen. In this more extended route, the shock wave undergoes a rapid pressure amplitude decrement due to dissipation in the form of heat. Moreover, in the 5 mm sample, the thermal shock resistance (shown in Table 1) causes a more noticeable pressure difference. The pressure difference does not have a linear relationship with the material thickness due to nonlinear shock wave propagation inside the medium. This is also in agreement with the results reported by H. Hu et al. [27].

Figure 6 presents a similar profile for the first and the second pressure peaks and an approximate mirror profile for the first compression peak. We refer to the positive peak as a pressure peak, and a negative peak is a compression peak. The difference between a pressure peak and a compression peak is their trajectories. We consider pressure as the wave traveling from the induction surface towards the sensor and compression as the wave

traveling from the sensor towards the induction surface. The time elapsed between the first pressure peak at 140 ns and the second pressure peak at 620 ns for Al 6063-T5 sample of 480 ns is significantly lower than the time difference for Al 6061-T6 of 520 ns (200 ns, 720 ns). We ascribe it to different slab thicknesses. The shock wave takes longer to reach the rear surface for the second time in Al 6061-T6 as compared to that in Al 6063-T5. The shock wave period is about 50 ns. In making this assessment, we consider the onset of the abrupt increase in pressure after a steady state.

We show the pressure signals displaced along the time scale to the onset of the first pressure pulse in Figure 7. The time delay between the beginning of the first pressure peak and the beginning of the first pressure valley for the 1.3-mm thick sample is 348 ns, and for the 5 mm sample, it is 365 ns. This is a time difference of 17 ns or 5% (negligible) between two samples. The time delay between the beginning of the first pressure valley and the beginning of the second top pressure peak is 136 ns for a 1.3-mm thick sample and 156 ns for a 5 mm sample. This is a time difference of 20 ns between two samples. Analyzing the beginning of the second pressure peak in samples, we can appreciate a different initial time. This difference in time is about 44 ns. These three time differences indicate a general increase in times between complete shock wave reflections cycles in the 5 mm sample to those in the 1.3 mm sample; that is, the shock wave propagation times increase between each reflection from the rear surface to the front surface. This difference in time arises because the aluminum slabs have different chemical compositions. The specimen Al 6061-T6 has an improved elasto-mechanical property and thermal shock resistance compared to those of aluminum 6063-T5, as shown in Table 1. This enhanced composition produces more shock wave dissipation, exhibited as a signal deceleration.

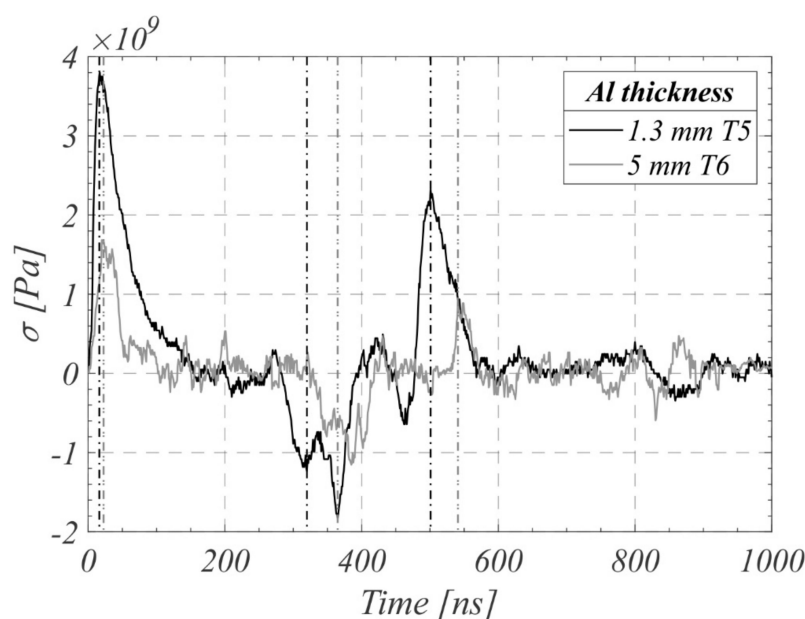


Figure 7. The peak pressure signals are displaced versus time from the beginning of the first pressure pulse. The difference in time between both samples, marked as vertical lines, at the beginning of the first pressure peak and origin of the first compression peak is 17 ns. At the beginning of the first compression peak and the beginning of the second pressure peak, the delay time is 20 ns. The difference between the beginning of the second pressure peak between both samples is 44 ns.

4. Conclusions

We demonstrate the signal-processing stages effects on the measurement quality, and its precision needs to be considered to measure the LSW pressure with a piezo-resistive method. We have shown that the manganin-based piezo-resistive method may be used to measure pressure in nanoseconds with fast response time, high sensitivity, linearity, and low cost.

We measured the pressure in two different aluminum alloy samples in thickness and composition, obtaining high-accuracy results. Energy dissipation and propagation of the shock wave exhibit a nonlinear relation to material thickness. Similarly, the time increase between complete reflection cycles in both samples has not indicated a linear relationship to the material thickness increases.

We presented and characterized a novel method to determine the frequency correction factor of the gain due to frequency dependence of a piezo-resistive measurement system for laser shock wave pressure measurements in nanoseconds, within 10 to 50 MHz, corresponding to a shock of 20 ns to 100 ns. We custom-designed the signal processing system to handle such rapid events, obtaining its correction factor curve.

We expanded the application of the piezo-resistive method to the laser-induced pressure measurement using a manganin sensor and a custom-designed signal processing system. This allows a systematic performance comparison for different frequencies, not only for the laser induced shock, but also for other shock wave phenomena.

Author Contributions: G.G.-T. and G.G.-R. conceived the ideas; R.G.-R. realized the prototype; R.G.-R. performed the measurements; all the authors analyzed the data; M.S. and G.G.-T. contributed to the principle verification, results, and discussion of the work; M.S. and R.G.-R. wrote the paper. All authors reviewed and commented on the manuscript; G.G.-T. provided supervision and guidance in this work. All authors have read and agreed to the published version of the manuscript.

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Appendix A

We used a quarter Wheatstone bridge (WB) for our experiment, as exhibited in Figure A1. This electronic, passive-component device is used as a conditioning piezo-resistive sensor. The resistance of the sensing element (in our experiment, manganin) is denoted R_{Gauge} . The voltage V_{CD} , called the differential voltage, measured between terminals C and D, is different from zero as the pressure wave travels through the sensor, generated upon a change in sensor resistance.

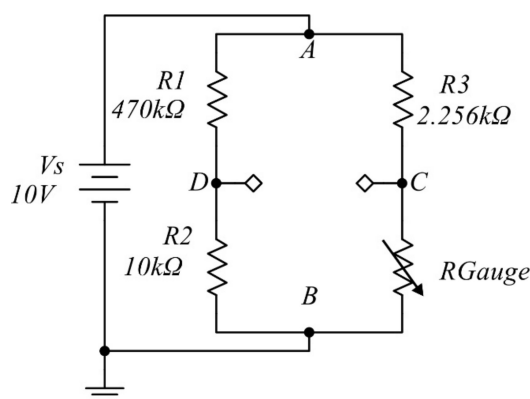


Figure A1. The Wheatstone bridge is an electronic, passive-component, null-detection sensor incorporated into the piezo-resistive sensors. The components R_1 , R_2 , R_3 are fixed-value resistors. The R_{Gauge} represents the manganin as the piezo-resistive gauge element. The incremental change in resistance of the piezo-resistive sensor due to the creation of the shock wave yields a differential voltage increase between points C and D.

The voltage V_{CD} of the bridge is obtained analytically using the Thevenin's theorem. The resistors R_1 , R_2 , and R_3 are selected in such a way to linearize the sensor responsivity. Linearity of the bridge is achieved by decreasing sensitivity with appropriated values of R_1/R_2 and R_3/R_{Gauge} [16]. The WB resistances are $R_1 = 470 \text{ k}\Omega$, $R_2 = 10 \text{ k}\Omega$, $R_3 = 2.256 \text{ k}\Omega$, and $R_{Gauge} = 48 \text{ }\Omega$ (null detection). These values yield a ratio of 47 for R_1/R_2 and R_3/R_{Gauge} relationships. The increase in voltage V_{CD} may be related to ΔR_{Gauge} resistance.

$$V_{CD} = V_S \left(\frac{R_1}{R_1 + R_2} - \frac{R_3}{R_3 + R_{Gauge}} \right), \quad (A1)$$

where V_S is WB voltage source and $R_{Gauge} = R_{xNOM} + \Delta R_{Gauge}$ is the resistance change. $R_{xNOM} = 48 \text{ }\Omega$ is the nominal resistance. If a shock wave disturbs the steady-state of the sensor ($\Delta R_{Gauge} \neq 0$), the resistance change ΔR_{Gauge} is defined as follows:

$$\Delta R_{Gauge} = 0.1 \times 10^6 \times P \times S_S \times R_{xNOM}, \quad (A2)$$

here, P is pressure in [Bar] ($1 \text{ Bar} = 100 \times 10^3 \text{ Pa}$) and S_S is sensor sensitivity in $[\Omega \Omega^{-1} (\text{kPa})^{-1}]$. Subsequently, an instrumentation amplifier (IA), shown in Figure A2, is connected to the WB terminals C and D. Further signal processing and conditioning results in noise reduction and signal magnification. The instrumentation amplifier reduces common-mode signals of the two inputs. It has a gain obtained by $G = 1 + (2R_6/R_{Gain})$. The output voltage V_{out} corresponds to the differential voltage of the Wheatstone bridge V_{CD} multiplied by gain G

$$V_{out} = \Delta V_{CD} \times G. \quad (A3)$$

Solving for pressure P , we substitute Equation (A1), and Equation (A2) into Equation (A3), then we obtain pressure P in terms of sensitivity S_S of the measurement system, output voltage V_{out} , and system gain G :

$$P(G(f), V_{out}) = 0.1 \times 10^6 [G(f) S_S R_{xNOM}]^{-1} \left[\left(\frac{R_3(R_2\alpha + \beta)}{R_1\alpha - \beta} \right) - R_{xNOM} \right], \quad (A4)$$

here $\alpha = GV_S$ and $\beta = V_{out}(R_1 + R_2) + R_2$. The total gain of the measurement system decreases with frequency. Thus, an attenuation factor $G(f)$ is included for the gain explicitly in the mathematical model.

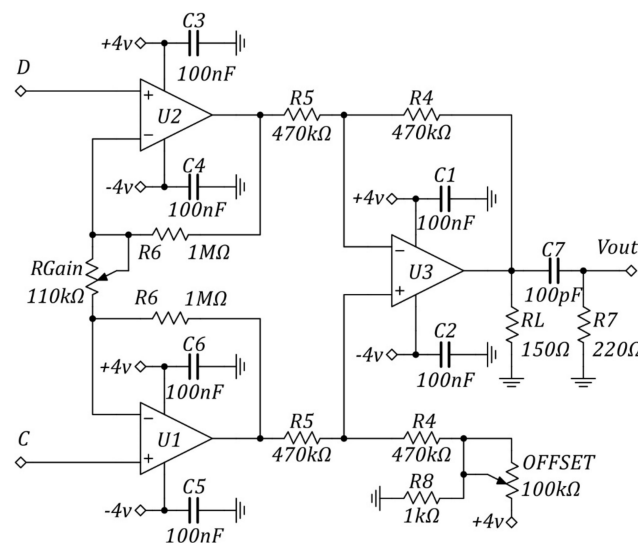


Figure A2. An instrumentation amplifier is used to subtract sensor signal, reject common mode voltage signals, and amplify the signal. A three-operational amplifier topology is implemented to obtain experimentally measured pressure data.

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