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Research Paper

Frequency Optimization of Ultrasonic Welding System with Gradient Descent Method

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Abstract: Ultrasonic welding, with its entry into the friction welding group, is preferred in many sectors as a joining method in today's industry. In this way, the materials to be welded are joined without the need for filler material. Since there is no filling material during welding, toxic gases and wastes do not come out, so it has a more environmentally friendly structure than other sources. In addition to producing maximum power at the resonance operating frequency, disturbing noise also occurs. Optimum welding form occurs during resonance operation. Therefore, frequency shift occurs according to the size and mechanical properties of the welded materials. The resonant frequency must be captured during welding to prevent this shift. In this study, a new methodology has been developed to determine the resonance frequency of ultrasonic welding machines to increase the system's efficiency. This variable resonance frequency value, which needs to be re-determined when the load changes, is determined online with the gradient descent algorithm during the welding process. Simulation studies were carried out in Matlab/Simulink environment. Two different resonance frequencies with a maximum random variation of 5% and 20% were used. As a result, 5% changing resonance frequency within 150 ms and 20% varying resonance frequency within 250 ms were obtained with the Gradient Descent algorithm.

Keywords: Ultrasonic welding, Frequency optimization, Gradient descent algorithm.

1. Introduction

Ultrasonic welding machines are widely used in various fields today, as they are the fastest and the lowest cost solution used to join plastic and non-ferrous metals. Ultrasonic welding is the closest welding method to be used in tape production, giving more immediate results than other types of welding. It is effective in seam and spot welding since there is no need for any external filling material between the materials to be welded. The outer surface weld damage level is low because heat is generated between the materials instead of the outer surface experienced in other welding processes [1]. It has a healthy and environmentally friendly use since there is no spark toxic fume emission during the welding process [2]. Besides the advantages of ultrasonic welding, there are also some limitations. The thickness of the materials to be welded dramatically affects the quality of the welding process. Thickness of the materials causes less vibration, i.e. vibration, at the welding interface. Therefore, welding quality decreases when joining thick parts [3]. Another factor affecting the weld's quality is the material's physical properties. Material hardness can cause ultrasonic damping as well as affect the vibrations reaching the weld interface [4]. Since it is a welding method based on the propagation of mechanical vibrations with the material, a noisy welding process occurs at the resonance frequency [1].

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The ultrasonic welding method is used in an extensive area in the industry. It is preferred in aviation, electronics, automotive, and medical sectors. Ultrasonic welding is preferred because of the long process of chemical bonding and the increase in weight in connection methods, such as screwing in the aviation industry, where thin and light materials are used. In the production of electronic elements, this method is used to combine layers on top of each other [5]. Since it has a cleaner process in terms of hygiene, it is also frequently used in the production of medical tools and equipment. Since it is suitable for mass production during the pandemic, it has been especially preferred for mask production [6]. Many studies have been done on the optimization of ultrasonic welding. In these studies, optimization of welding parameters such as welding time, welding pressure, and welding density were carried out for the combination of the different algorithms. These studies mostly used genetic algorithm optimization and similar optimization techniques [7-11]. Various ultrasonic generator designs have also been made for ultrasonic welding machines to increase efficiency. These studies have met the need for high-frequency electrical welding required by the ultrasonic welding system. In this way, it is aimed to increase efficiency [12]. The researchers designed more efficient ultrasonic welding machines by modelling ultrasonic welding machines [13]. In addition, studies have been carried out for ultrasonic frequency optimization [14]. When the studies are examined, it is seen that optimization studies have been carried out in many different aspects for ultrasonic welding machines.

Numerous applications have been carried out for resonance frequency tracking in ultrasonic welding. In most proposed frequency tracking methods, frequency tracking is performed according to the voltage applied to the piezoelectric material and the phase difference of the current flowing through it [15-20]. PLL (phase-locked loop) was used as the tracking method in most applications. The PLL method operates at limited speeds in resonance frequency tracking monitoring [21]. Zhang suggested a new resonance tracking method for the piezoelectric ultrasonic transducer, the binary search algorithm that automatically tracks the transducer resonance frequency [22]. In the literature, structures that avoid fs value instead of following fr have been proposed, but very complex circuits have emerged. Operating at the point where the maximum power is produced reduces the lifetime of the ultrasonic welding working at fr instead of the natural resonance frequency fs [23-26].

In this study, an innovative approach is proposed to determine the optimum operating frequency of the ultrasonic welding machine, which affects the system efficiency. It must be determined continuously according to the load characteristic. This frequency optimization process was made with the Gradient Descent Method. For this purpose, the behavior of the ultrasonic welding machine during operation is modeled with MATLAB and the efficiency of this optimization method was evaluated.

2. Material and Methodology

2.1. Ultrasonic Welding System

The ultrasonic welding machine consists of an ultrasonic generator, piezoelectric transducer, booster and horn. When driving piezoelectric transducers, the resonance frequency range should be preferred to obtain maximum power at the output [27]. In addition, the operating frequency is sensitive to load and environmental effects [28]. Since piezo materials have high electrical quality, a decrease in vibration amplitude may occur in small frequency shifts. Therefore, the operating frequency must be monitored in real time to keep the output power of ultrasonic welding systems at the maximum point. The tracking for the continuity of maximum power generation is also called resonance frequency tracking (RFT). Since standard ultrasonic welding is a process that takes less than one second, the detection and adjustment of the resonance frequency must be made in a short time [29].

The structure of the Piezoelectric transducer equivalent circuit is shown in Figure 1. The electrical capacitance and resistance of the piezoelectric ceramic plate transducer are R_p and C_0 respectively. Piezoelectric in resonance state is a mechanically vibrating block which represents the mechanical response of the transducer. L_1 is proportional to mass, R_1 is proportional to dissipation and C_1 is inversely proportional to stiffness.

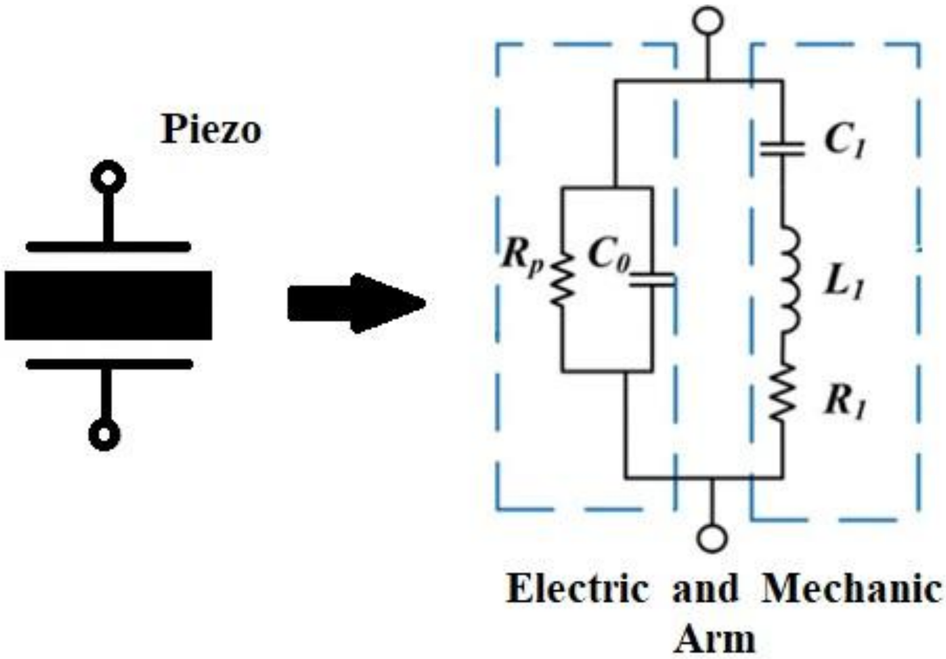

Figure 1. Piezoelectric transducer equivalent circuit

Equation 1 is used for the mechanical resonance frequency of the piezo material.

$$f_s = \frac{1}{2\pi\sqrt{L_1 C_1}} \tag{1}$$

An ultrasonic generator converts 50/60 Hz mains frequency to 20-40 kHz with AC/DC and DC/AC converters. This way, it produces variable high-frequency electrical energy for energizing a transducer that an ultrasonic welding system needs. The converter transforms the high-frequency electrical signals into mechanical vibration and transmits it to the booster. It is the part that converts electrical energy into mechanical energy. It increases the mechanical vibration power received from the booster transducer and transmits it to the horn. This part raises the mechanical vibration. The horn applies the mechanical vibration from the booster to the material to be welded under a certain pressure [30].

2.2. Gradient Descent Algorithm

The gradient descent algorithm is a first-order iterative optimization algorithm used to find the local minimum of a function [31]. This algorithm starts searching for the local minimum value from a random point. Then, as it gets closer to the minimum, it reduces its steps and it reaches its minimum value. This situation can be seen in Figure 2. Although the gradient descent method is ineffective in finding the global minimum if it is different from the local minimum, it is more effective in finding the local minimum value than other methods in terms of parameters such as speed and processing time. Therefore, in this study, the gradient descent method aims to find the local minimum.

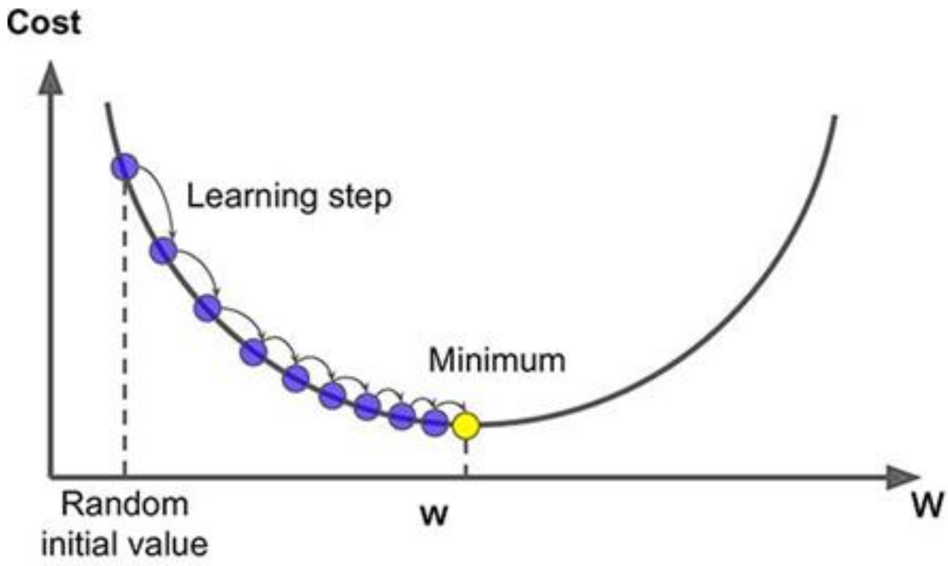

Figure 2. Finding the Local Minimum of Gradient Descent Algorithm [32]

2.2. Simulating Ultrasonic Welding System

The ultrasonic welding system is modelled with MATLAB. The model was created according to the matching circuit of the ultrasonic welding system, which is given in Figure 3.

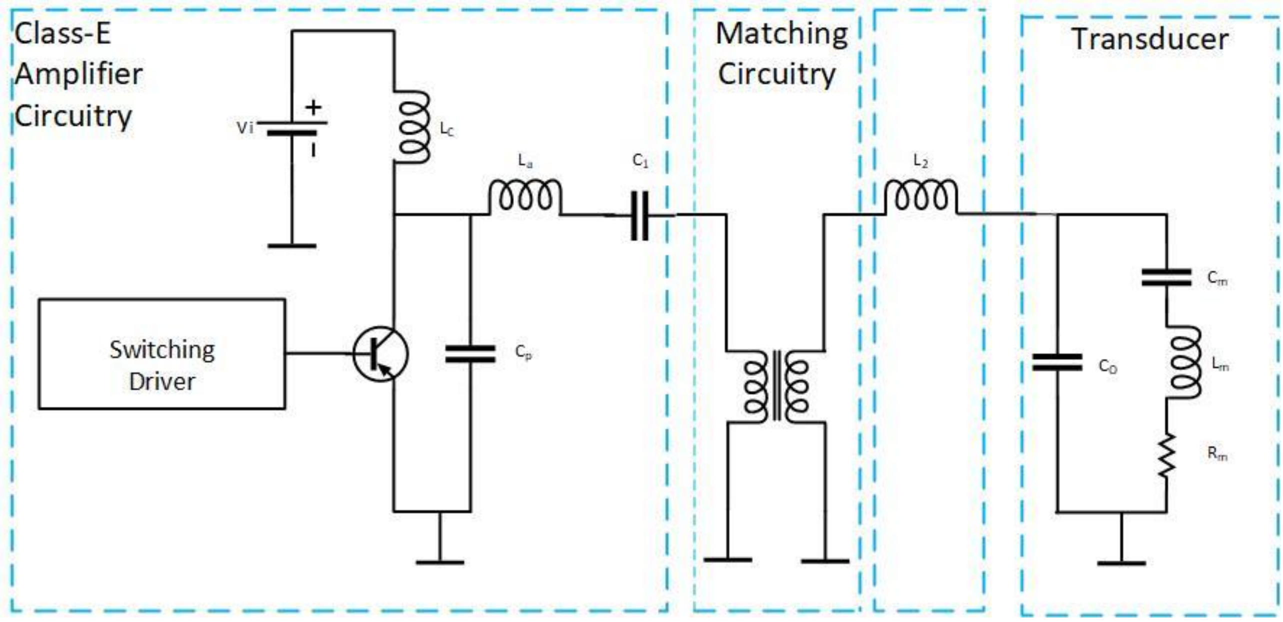

Figure 3. Matching Circuit of Ultrasonic Welding System

The developed Simulink model given in Figure 4 simulates the ultrasonic welding system. The real-time ultrasonic welding system works continuously and is loaded randomly during each process. In this model, an ultrasonic welding system operating at 500 ms intervals is modelled, and the transducer load changes randomly at 500 ms intervals.

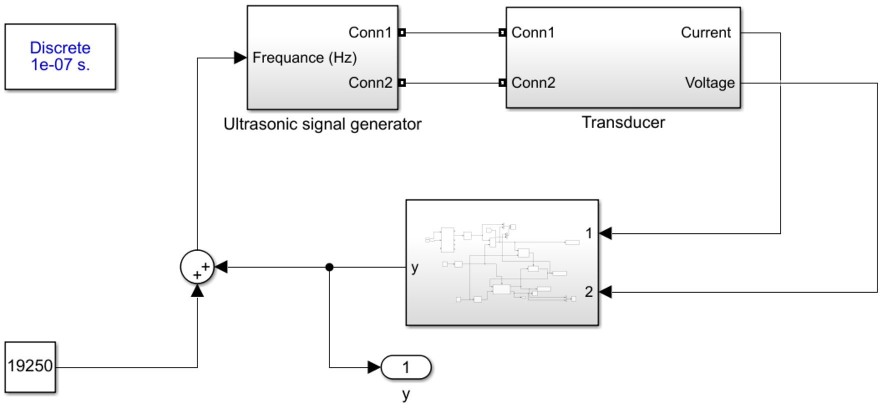

Figure 4. Matlab/Simulink Model of Ultrasonic Welding System

The transducer's R, L, C, and Cd values were measured in the laboratory environment to create the transducer model. These values are given in Table 1. The transducer can be seen in Figure 5.

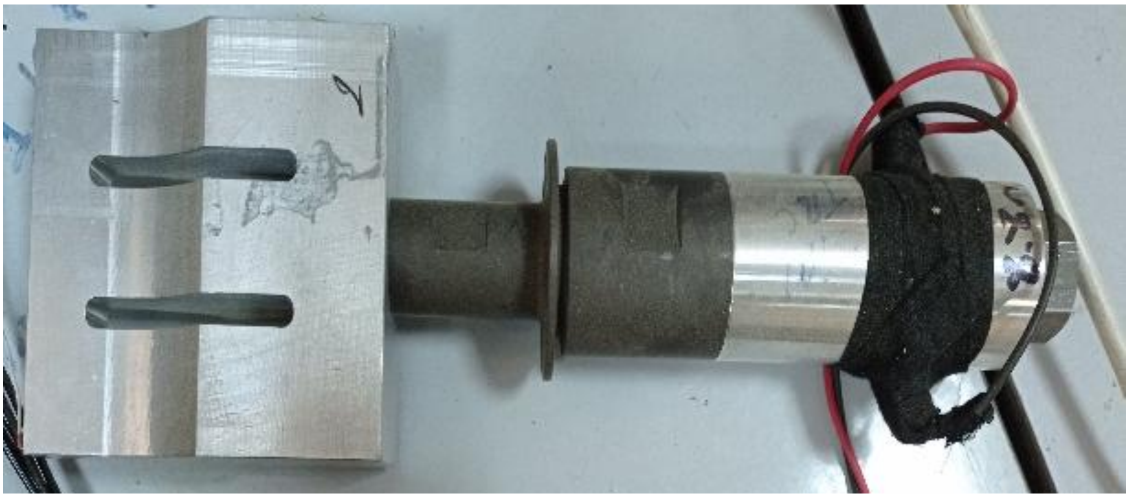

Figure 5. Transducer

Table 1. Data of the Transducer

R(Ω)	C (nF)	L(mH)	Cd (nF)	Random Load (pF)
22.89	1.173	55.7	17.97	Min: 0 Max:63

The converter model's random load block simulates the converter's variable load. The converter receives a random value with a minimum of zero for non-operating times and a maximum of 63 nF for operating time. The transducer model in Figure 6 was created with these values.

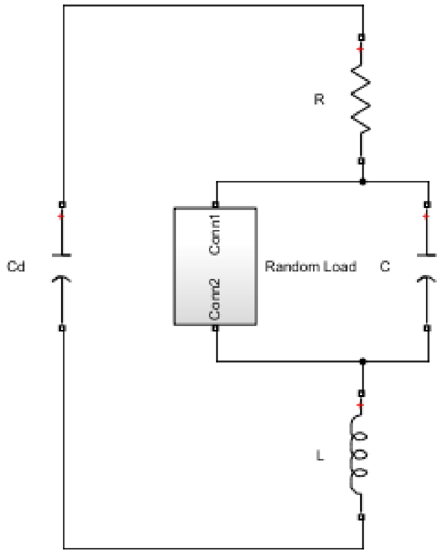

Figure 6. Model of Transducer

The impedance-phase graph in Figure 7 is obtained when the transducer model is unloaded. Looking at this graph, resonance, anti-resonance, and operating point values are seen. It is also noticed that the point where the phase is maximum is the operating point, and it is in the middle of the resonance and anti-resonance points on the impedance graph. The operating point constantly changes as the transducer is continuously loaded with a random load at runtime. In this model, the frequency value at maximum phase difference is found to find the continually changing operating point.

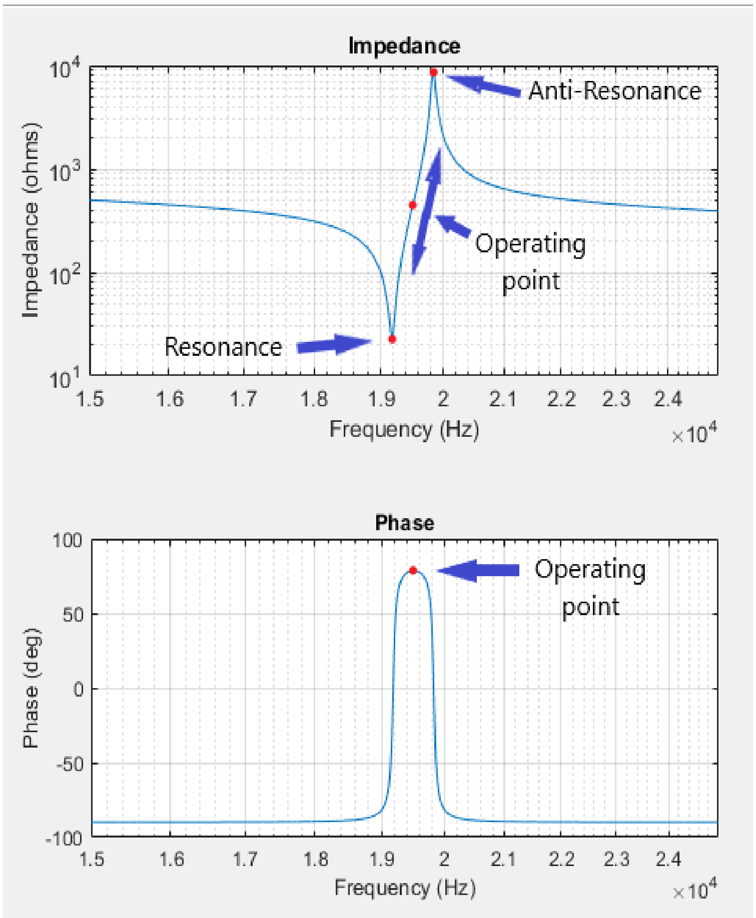

Figure 7. Impedance-Phase Graph of Transducer

3. Simulation Results

The flow chart of the simulation environment is given in Figure 8. According to this scheme, the random load continually changes, and the optimizer block tries to reach the most realistic result. As in the flow chart of the designed system, the scanning steps are initially 250 units. The frequency sweep direction is also defined as logical 1 at the beginning, increasing in the forward direction. The frequency value is reduced if the scanning direction is -1 in the algorithm. A value such as 19250 Hz, close to 20 kHz, the catalog value of the piezoelectric material, was chosen as the starting value of the simulation. Frequency scanning is close to the catalog resonance value of the material. The piezo transducer is activated when a random load is connected to the system. The system's phase value is read, the step size is increased in the scanning direction, and the phase is reread. If there is a phase difference at the desired optimum value, the frequency is scanned in the half-step backward direction by changing the direction. If the desired step range is reached, the system is paused at the set frequency. If the expected phase difference value is significant, scanning continues in the size and direction of the initial step value.

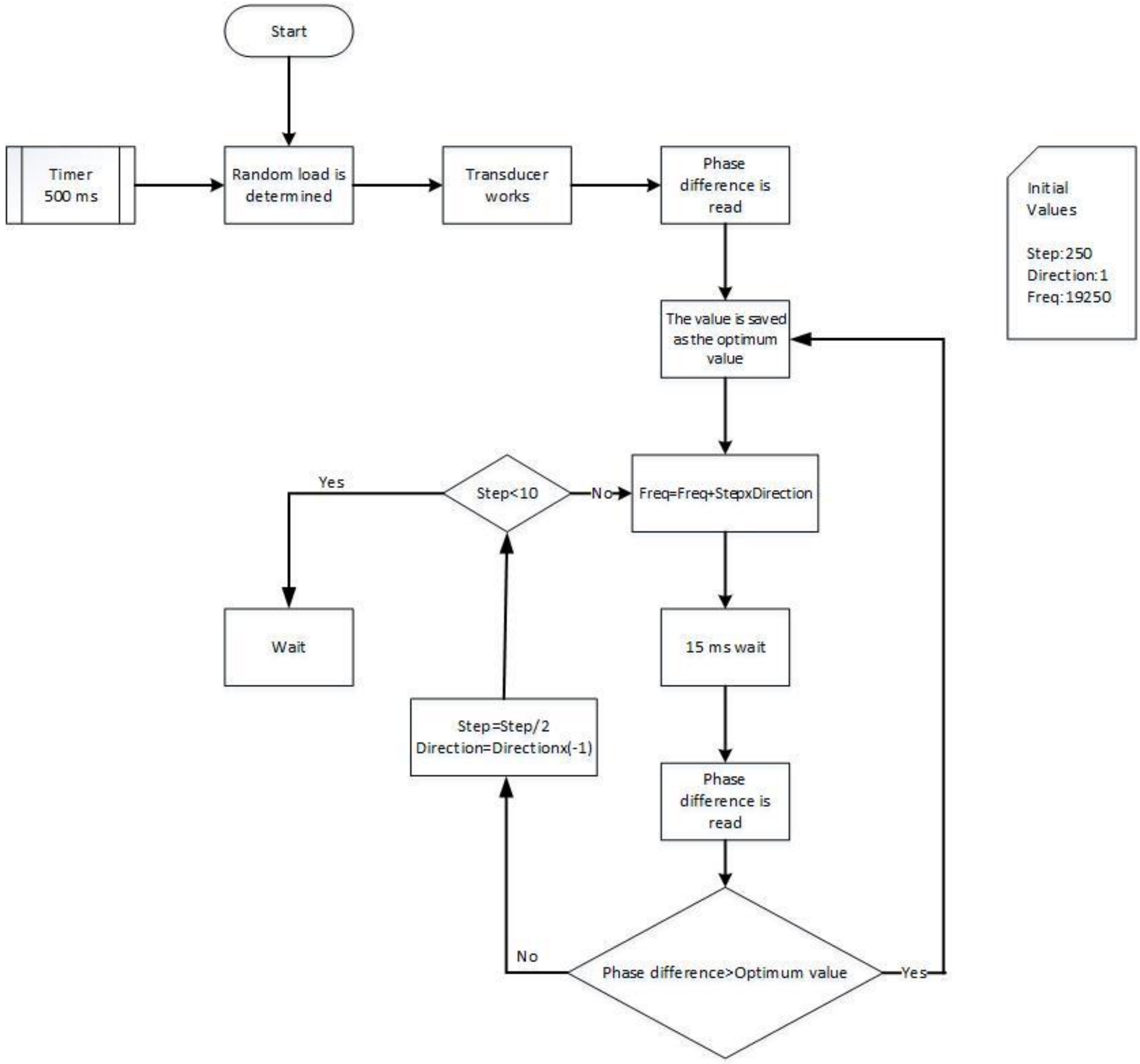

Figure 8. Flowchart of The Simulation Environment

The simulation results are given in Figure 9. According to this graph, the real value has been reached at 120 ms. The trial value is the output value of the Gradient Descent Optimization Method. This value is the value obtained through trial and error.

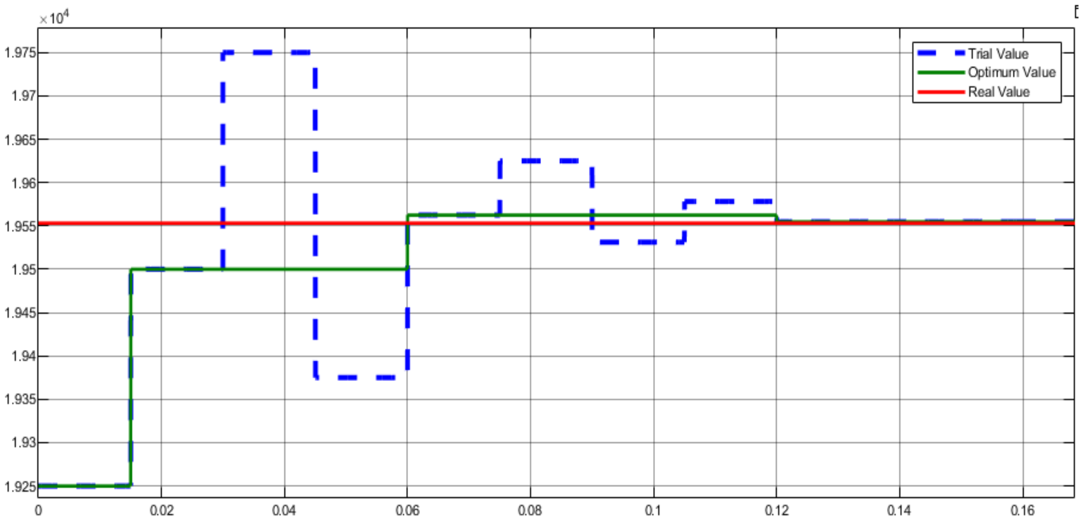

Figure 9. The Results of Optimizer Block

As can be seen in Figure 10, the simulation takes approximately 1700 ms. The first optimum frequency value was found at approximately 110 ms during this simulation. Then a random load was generated at 500 ms, and it was observed that the time taken to find the optimum frequency values for these load values was at most 150 ms.

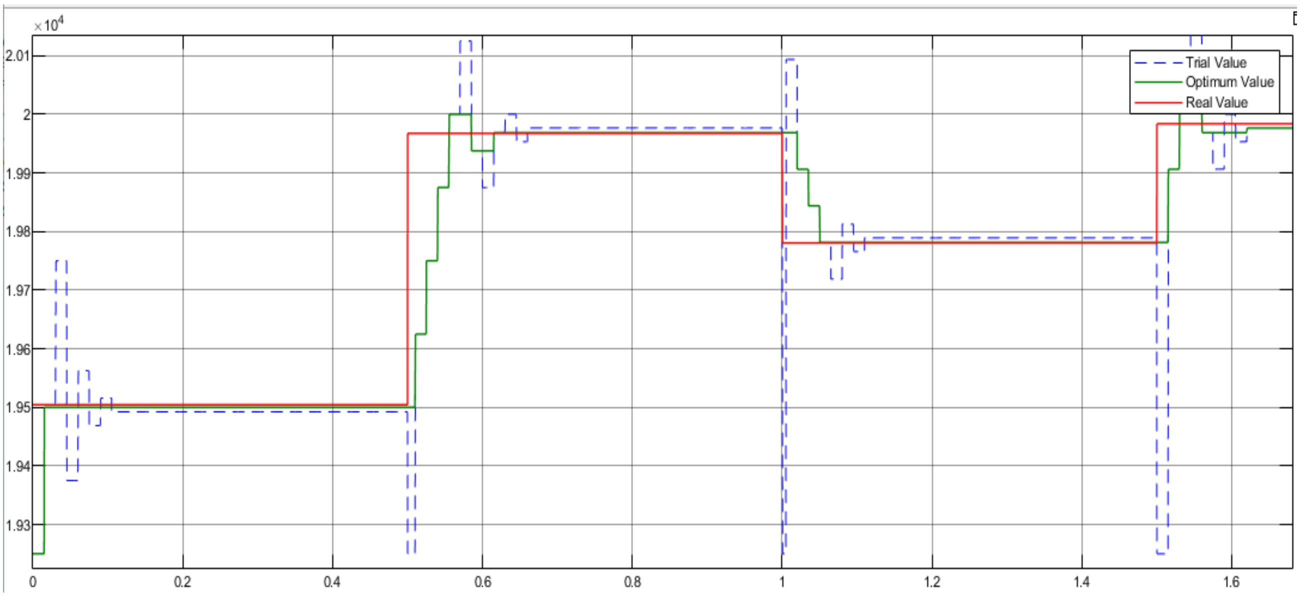

Figure 10. The Results of Optimizer Block

For ultrasonic welding system with a maximum resonance frequency of 20%, a maximum random load value of 512 pF was taken and simulated again. Here the model has a resonant frequency of 20 kHz at no load, while at maximum load it has a resonant frequency of 16 kHz. For this reason, the initial step value was determined as 1000 and the initial frequency value was determined as 18 kHz in the simulation. When this model is simulated with random load, the results are given in the graph in Figure 11. As can be seen from the graph, the optimum result was found at a maximum of 250 ms.

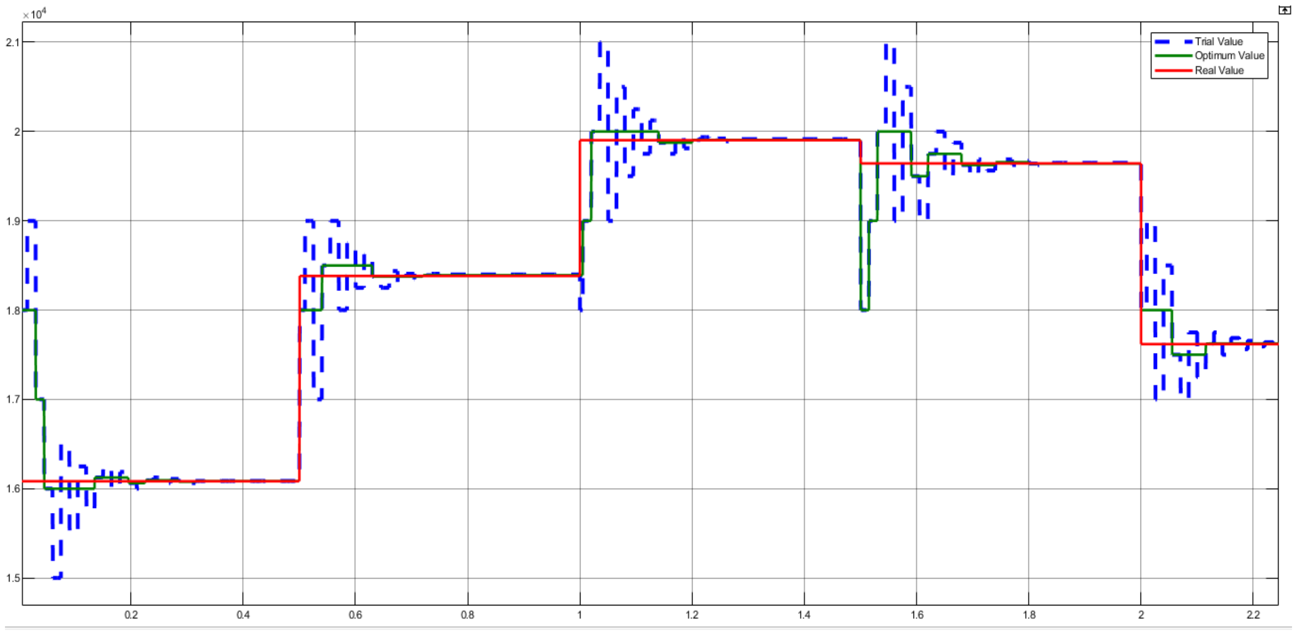

Figure 11. The Results of Optimizer Block

Takasaki et al. studied resonance frequency tracking control of ultrasonic transducers and found the phase shifting on resonance frequency. They obtained about 180 ms settling time for 0^0 phase shifting [33]. Du et al. presented a novel constant frequency ultrasonic amplitude control method based on various controllers. They found 230 and 92 ms for 24 μm target with PID and fuzzy controllers respectively [34].

4. Conclusion

In this study, a novel optimization algorithm for the determination of the operation frequency of ultrasonic welding machines was developed. This process is the most critical factor in efficiency that needs to be re-defined according to the load level. The gradient descent optimization method was used to determine this frequency, and Matlab/Simulink model was created to test the system's effectiveness. When the results of the literature review were compared, settling time values between 180 ms and 230 ms were found. In our study, in the case of a 5% difference in the resonance value, the result was produced within 150 ms, while in the case of 20% variability, the optimum result was reached within 250 ms. When the results are examined, it has been observed that the optimum point can be reached faster with the gradient descent method.

Authors' Contributions

AK developed the optimization algorithm. MT and MÖY modeled the ultrasonic system. FD and MT write the publication.
Four authors read and approved the final manuscript.

Conflict of Interests

The authors declare that they have no competing interests.

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