MODELING AND PROCESS CONTROL
OF ULTRASONIC WELDING OF PLASTICS

DISSERTATION

Presented in Partial Fulfillment of Requirement for
the Degree Doctor of Philosophy in the Graduate
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By

Fugui He, B.S., M.S.

*   *   *   *   *

The Ohio State University
1992

Dissertation Committee:     Approved by
Avraham Benatar             Avraham Benatar
Chon-Liang Tsai              Adviser
Ming J Liou                  Department of Welding Engineering
To

My mother-in-law

Yude
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VITA

1968..........................B.S., Sichuan University, China

1968-1979.....................Engineer, Changjing Engineering Co.,
                          Loushou, Sichuan, China

1982..........................M.S., Dept. of Engineering Mechanics,
                          Chongqing University, China

1982-1985.....................Lecturer, Dept. of Engineering
                          Mechanics, Chongqing University, China

1989..........................M.S., Dept. of Welding Engineering,
                          The Ohio State University,
                          Columbus, Ohio

1989-present..................Research Associate, Plastics Joining
                          Group, Dept. of Welding Engineering,
                          The Ohio State University,
                          Columbus, Ohio

Major Field: Welding Engineering

Minor Field: Engineer Mechanics, Non-Destructive Evaluation
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Chapter I

Introduction

1.1 Plastics and Plastics Joining

The research, production, and applications of polymers and their composites are in one of the fastest growth fields among all materials in the last several decades. Because of their advantages, such as high ratio of strength to specific gravity, low friction, good corrosion resistance, and insulation properties, we find the use of polymers in almost every kind of industry as well as daily life. The latest example is demonstrated by the body panel of GM's new car SATURN which is made of thermoplastics composites instead of conventional metals. The need for the use of plastics and composites is continuously growing. For instance, in today's aircraft industry more than 40% of the weight of both civil and military aircraft consists of plastics or composites [1].

Like all processes in the manufacturing industry, in which the final products are assembled with small components using certain means, joining techniques for polymers and polymer composites play a
very important role in the plastic and composite manufacturing industries. Because of their special properties, the joining techniques for plastics and composites are different from those for the metals. For example, traditional arc welding technique can no longer be used for plastics because the conventional plastics do not conduct electricity.

Based on their properties the joining techniques for polymers and their composites fall into three categories [2].

1. Mechanical fastening
2. Adhesive bonding
3. Welding

The first category of the techniques, in fact, is simply the techniques used to join metals which is transferred to plastics. The rivets, screws, spring clips, and other means used to join metals are employed to join plastics. Mechanical fastening is simple and easy to perform. But the material damages caused by the machining and the stress concentration and fatigue problems in the joining areas under load-bearing applications seriously limit the technique for the construction of important plastic and composite structures. Reference [3] contains more detailed discussions and useful recommendations on mechanical joining.

Adhesive bonding is an old joining method; various cements have been used to join metals, wood, and ceramics for a long time. The
The difference for plastic adhesive bonding is that new adhesive systems were developed for plastics. To deal with different plastics and different circumstances, the adhesives are classified into two groups: two-component systems and single component system [4]. For single component systems the chemical reaction between the material and the adherents or the solutions of the adherents provide a firm bonding. On the other hand, for two component systems the components are mixed prior to use, and the chemical reaction between the two materials cures the adhesive and bonds the adherends. Epoxy is a typical example of two component system that is in major use today. Adhesive joining is particularly important for thermosets because they can not be molten. The disadvantages of adhesive bonding techniques are long curing process and crucial surface preparation of adherents.

Welding is a fast and economical joining method. Since welding processes involve heating and melting, they are only applicable to thermoplastics. Based on the heating methods, the processes can be further classified as follows [2]:

1. Thermal
   - Hot gas welding, extrusion welding, hot-tool welding, and infrared welding.

2. Mechanical
   - Spin welding, vibration welding, and ultrasonic welding.
3. Electromagnetic

Resistance welding, induction welding, dielectric welding, and microwave welding.

All welding techniques obey the same basic principles except that different ways of heating are applied. Although the process of welding usually takes a short period of time, it involves several sophisticated mechanisms. First, the welds are heated and molten by one or several ways of heating. Then, the molten polymer wets the surface and flows under pressure. Diffusion occurs simultaneously in the interface. Finally, as the joint area cools down, the molten material solidifies and a joint is formed.

The techniques of welding offer plenty of choices for thermoplastic and thermoplastic composites joining. Some of those techniques have advantages in one aspect but disadvantages in other aspects. The decision of utilization of the techniques depend upon the materials being joined, the service conditions of the joint, the quantity of products, the cost, etc.

Among the welding methods for the joining of thermoplastics, ultrasonic welding is most widely used based on the considerations of convenience, automation, quality assurance and rate of production. Since the 60's the development of highly efficient piezoelectric materials and the improvement in ultrasonic power supplies have made the trend more evident. Today, ultrasonic welding can be found in
applications from toy making to the automobile industry, from medical products to textile manufacturing.

1.2 Description of Ultrasonic Welding

Ultrasonic welding is performed on a specially designed machine. Figure 1.1 shows the core portion of the machine, which includes a power supply and a converter-booster-horn stack assembly. The converter that is made of piezoelectric discs converts electric signals from the power supply to mechanical vibration (usually 15KHz to 40KHz). A mechanical booster, which is attached to the converter, changes the vibration amplitude. Connected to the booster is a horn that further adjusts the amplitude and guides the vibration to the thermoplastic parts which are to be welded. The machine also offers fixtureing to hold the parts, and applies pressure to keep the horn and the parts in contact during the welding [5].

When the thermoplastic part vibrates, the polymer molecules are mechanically exited. Since the thermoplastic behaves as a viscoelastic material, heat is generated inside the part due to intermolecular friction. Heat is generated faster at interfaces due to greater deformed surface asperities, thereby melting the interface and fusion bonding the parts.
Figure 1.1: Ultrasonic welding machine and a welding sample.
To improve the welding process, man-made asperities or energy directors are molded on one of the parts. The energy director is a triangular or rectangular shape protrusion which is molded on the surface of one of the parts (see Figure 1.2). The function of the energy director is to reduce the initial contact area to localize the energy into a small region.

Ultrasonic welding is often divided into near-field and far-field welding. In near field welding the distance between the bottom surface of the horn and the joint interface is less than a quarter of inch. In far-field welding the distance mentioned above is more than a quarter of one inch. It should be noted that this is an arbitrarily chosen definition. A more rigorous examination of near and far field welding shows that wave propagation in the viscoelastic polymer must be considered [6].

In this project we will concentrate on near-field welding of thermoplastics with energy directors.

1.3 Mechanisms in Ultrasonic Welding Process

Although the ultrasonic welding process usually lasts only several seconds, some complicated physical mechanisms are involved. These are mechanical vibration, viscoelastic heat generation and heat transfer, squeeze flow of molten polymer, intermolecular diffusion and cooling.
Figure 1.2: A welding sample with a triangular energy director.
A simple description of these sub-processes and models for each are described below.

A thermoplastic can be represented as a viscoelastic solid using a Voigt-Kelvin model [7] which, consists of a spring and a damper connected in parallel (see Figure 1.3).

Considering viscosity, the modulus of the Voigt-Kelvin material is denoted by a complex modulus, $E^\ast$.

$$E' = E' + iE''$$

(1.1)

where $E'$ is the storage modulus and it is related to the material's ability to store elastic energy and $E''$ is the loss modulus which measures the material's ability to dissipate energy. If a viscoelastic material is subjected to a sinusoidal deformation, just as is the case in ultrasonic welding, the average energy dissipated per unit volume per unit time can be calculated from strain energy as [8]:

$$\dot{Q}_{avg} = \frac{\omega \varepsilon_0^2 E''}{2}$$

(1.2)

where $\omega$ is the circular frequency and $\varepsilon_0$ is the strain amplitude. It is seen that the energy dissipated (heat generated) is proportional to the frequency, the loss modules and the square of the strain amplitude. This relation was verified experimentally by Aliosio et al [9], Tolunay et al [10] and by Benatar [11].
Figure 1.3: Voigt-Kelvin model of a viscoelastic solid.
As the vibration inside the parts continues, the energy director becomes hotter and hotter since the heat generated is larger than conduction and convection heat loss. General heat transfer equations can be used to solve the problem and obtain the temperature rise rate and the temperature distributions in the energy director and in the parts. For the materials with isotropic and linear behaviors the 3-D heat conduction equation is,

$$ k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \dot{q} = \rho c \frac{\partial T}{\partial t} $$  \hspace{1cm} (1.3)

where $k$ is the thermal conductivity, $T$ the temperature, $\dot{q}$ the internal heat generation, $\rho$ and $c$ the density and the specific heat, and $t$ is time.

Once the temperature in the energy director exceeds the melting temperature, the thermoplastic material starts to flow. Because of the applied pressure, the flow of the molten polymer can be described as squeeze flow between two plates.

In modeling the squeeze flow, a power law liquid model is assumed, $\tau = \eta \gamma^n$, where $\tau$ is shear stress, $\gamma$ shear strain rate, and $\eta$ and $n$ the material parameters. Then, the relation between the force, the height of the gap, the length and the width of the fluid, and the properties of the fluid are given by the following equation [12].
\[
\frac{h_0}{h(t)} = \left(1 + \frac{t}{r}\right)^{2n+3}
\]

\[
r = \frac{4n+2}{2n+3} \left[ \frac{(2b_0)^{2n+3} \cdot w \cdot m}{(2h_0 b_0)^{n+1} \cdot F \cdot (n+2)} \right]^n
\]  

(1.4)

where \(2h(t)\) and \(2h_0\) are the gaps between the two plates at time \(t\) and at the initial time respectively. \(2w\) and \(2b_0\) are the length and width of the fluid respectively. \(F\) is the static force applied to the plates (see Figure 1.4). Equation 1.4 shows that when the thickness of the liquid layer between the plates, say \(h(t)\), is very small, further reduction of the layer thickness results in larger mechanical resistance. Or from the viewpoint of mechanics it is said that the liquid interface becomes more rigid. In practice, this situation happens in the final stages of ultrasonic welding.

Once the energy director is molten, the polymer flows and transfers heat to the cooler surfaces to melt more polymer. At the same time the polymer-to-polymer contact in the interface initiates a polymer diffusion process called autohesion. In autohesion the motion of a long chain polymer molecule is represented by a reptation model [13,14]. The model describes the motion of a polymer chain as similar to the motion of a snake moving in a tube. Except for the head and tail, the motion of other portions of the snake's body are restrained in the tube. The mean square path of the one-dimensional walk of the polymer chain within the tube is related to time through Einstein's relation
Figure 1.4: Squeeze flow between two plates.
\[ < \ell^2 > \approx 2D_c t \] (1.5)

where \( D_c \) is the reptation diffusion coefficient.

Unlike small molecules, the diffusion of the long polymer chains may move segments to the other side of the interface with the remainder staying on the original side of the interface. The average interpenetration distance of the chains across the interface, \( x \), is related to \( < \ell^2 > \) by the following equation. [15]

\[ x^2 \sim \langle \ell^2 \rangle^{0.5} \] (1.6)

Other important relations can be obtained as well through both experiments and theoretical arguments. The interpenetration distance and time have the relation.

\[ x \sim t^{0.25} \] (1.7)

The fracture stress of the joint is inversely proportional to the quarter power of the molecular mass

\[ \sigma \sim M^{-0.25} \] (1.8)

Many experiments that verify the above relations [16,17,18] have been performed.
After the ultrasonic vibration is stopped, the ultrasonic welding process enters the final step of cooling and resolidification. During this step the molten polymer solidifies and gains its final shape. For semicrystalline polymers the cooling rate in this step determines final microstructure, and therefore, the mechanical properties of the joint. The crystallization process for many polymers can be described by the Avrami kinetic equation [19,20]

\[ V_s = 1 - e^{-kt^n} \]  (1.9)

where \( V_s \) is the spherulite volume fraction, \( k \) is a rate parameter, and \( n \) is a parameter related to geometry and mode of growth of spherulites. Once \( V_s \) is obtained, the final overall crystallinity \( \phi \) is determined by

\[ \phi = \phi_s \cdot V_s \]  (1.10)

where \( \phi_s \) is the crystallinity within the spherulite.

1.4 Modeling of Ultrasonic Welding Process

Although all the sub-process' models of ultrasonic welding have been studied individually, it is very rare to see research work that deals with the modeling of the entire process. Benatar [11] made the
first attempt at an overall system modeling of ultrasonic welding. Because Benatar used a mechanical lumped parameter model to represent the whole welding system, I will refer to it as mechanical modeling.

In the lumped parameter model [21] the system, which includes booster, horn, thermoplastic welds, fixture and base, is divided into many elements. Then, all elements are connected by springs and dampers according to the material properties. For example, a spring and a damper in parallel are used to represent the thermoplastic parts as Voigt-Kelvin solid models. Since the base and fixture are made of metal, only springs are used to model them. Figure 1.5 is the general scheme of the mechanical multi-mass lumped parameter model. Letting velocity and force be the state variables of the system, it is possible to write the state equations for all elements (see Appendix A). Once the state equations are written for every element, a system of ordinary differential equations for the model is obtained. All the state equations for the ultrasonic welding system shown in Figure 1.5 are listed in Appendix A. Many methods are available to solve the system of ordinary differential equations.

After the displacement distribution in the energy director is known, the distribution of strain can be calculated. Using Equations 1.3 and 1.4 the heat generated and the temperature at every point are found. Based on the known melting temperature of the material, the molten region can be determined. With the flow model described by Equation 1.5 the liquid-solid boundary is found. At this moment the
Figure 1.5: Ultrasonic welding system and corresponding lumped parameter model. (taken from Reference [6])
geometry, the material properties, and the mechanical properties of
the system are changed to reflect their dependence on geometry and
temperature. Repeating the above calculations with the updated
parameters gives the new state. The ultrasonic welding process is
modeled with this iterative process.

1.5 Literature Review

In 1880 Pierre Curie and Jacques Curie [22] announced their
discovery of the electrical-mechanical conversion in crystals. Then,
many low power electrical ultrasonic generator appeared. In 1940 the
piezoelectric materials were discovered which in turn resulted in
high power ultrasonic devices becoming available. Ten years later,
Mason made his first ultrasonic horn driven by a high power generator
[23]. Ultrasonic welding was accidentally discovered in 1950 when an
investigator found that a weld was produced when the electrode of the
spot welder was ultrasonically excited, even though no current was
passing through it [24].

Ultrasonic welding appeared in thermoplastic assembly lines in
the beginning of 1960's because of the massive use of plastics. T.J.
Scarpa [25] reported early studies of the application of ultrasonic
vibration for plastic joining.

B. Ya. Chernyak et al [26] investigated the heat generation in
the ultrasonic welding of plastics. Samples were 3 mm thick
polyethylene plates. They found that the zone of maximum temperatures did not coincide with the interface of the materials being welded. They assumed that the hysteresis loss is the source of heat in the welding. On the above assumption they further calculated the displacement distribution and temperature distribution in the sample. The relation obtained from the theoretical calculation were in good agreement with the experimental results.

Tolunay et al [10] experimentally studied heating and bonding mechanisms in ultrasonic welding of thermoplastics. The samples without energy directors were molded from polystyrene. They measured the temperature changes in the interface and inside the samples (near the interface). After analyzing the experimental data, the following conclusions were made: 1. The rapid heating that occurred at the interface is probably due to the highly stressed surface asperities. 2. The internal temperature rises are significant over a longer period of time and are caused by viscous dissipation associated with local strain oscillations.

Menges and Potente [27] studied the weldability of thermoplastics. In their study Plexiglas, polystyrene, and polycarbonate samples with V shape energy directors were used. They measured the distributions of the vibration amplitude and the temperature in the energy director and found that the heating is mainly due to internal friction and not to interface friction. They also found that the maximum vibration amplitude corresponded with the maximum energy generation. Based on their observations and
calculations, an index, which is a function of material properties, geometry, vibration frequency, and weld pressure, was suggested.

Land et al [28] recorded the ultrasonic welding process of polycarbonate, ABS, and nylon with a high speed camera. From the analysis of the movie they observed that the development of the process is not continuous but occurs in stages. The gap between the upper part and the lower part decreases for a short time, then it remains constant for a while, and finally decreases again. A. Benatar used a high speed video to videotape the ultrasonic welding of PEEK APC-2 composites at a rate of 1000 frames per seconds. He measured the variation of the gap between the composites and reached the same conclusion namely that ultrasonic welding occurs in steps [20].

Aloisio et al [9] developed a viscoelastic model to predict the initial temperature rise rate within the rectangular energy directors during ultrasonic welding. Their investigation was conducted on polycarbonate, ABS, and nylon. The theoretical results of the temperature rise rate, even using elastic simplifications, were in good agreement with the experimental data.

A. Benatar [11] studied the ultrasonic welding of advanced thermoplastic composites. He used a five part model which included mechanics and vibration of parts, viscoelastic heating, heat transfer, flow and wetting, and intermolecular diffusion. The model predicted a large dynamic impedance change during the welding process. Most significantly, the model and the experimental
measurements indicated that the dynamic impedance of the composites' interface rises very quickly when the melting fronts of the energy director meet. Therefore, the bond quality could be monitored indirectly by monitoring the magnitude of dynamic impedance of the parts.

1.6 Objectives

Although ultrasonic welding has been favored in many applications and some research has been conducted in this field, process optimization and control are still not possible. The determination of the process parameters, up to now, basically comes from experience. To improve the understanding and to further develop the ultrasonic welding techniques, the present study will focus on the following objectives:

1. Establish an electromechanical analogy model to reflect the most important characteristics of the system during the welding process.

2. Design and build an ultrasonic welding system being composed of a data acquisition portion, a welding machine and a computer to perform the experiments.

3. Based on the understanding of the process obtained from the electromechanical model, test new control schemes, open loop control and closed loop control, for the ultrasonic welding process.
4. Investigate the effects of hold pressure on the strength of welded joints.
Chapter II

Electromechanical Analogy Model of Ultrasonic Welding

2.1 Electromechanical Analogy

During investigation of the apparatus which transfers electrical energy into acoustical or mechanical energy, it was found that the electrical quantities and relevant mechanical quantities obey exactly the same differential equations. Therefore, from a mathematical viewpoint there is no difference between an electrical system and mechanical system when the analysis is performed.

Figure 2.1 shows a mechanical and two electrical systems. The mechanical system has a mass that is supported by a spring and a damper. The differential equation of motion of the system can be written as

\[ M \frac{dv}{dt} + b v + k \int v \, dt = F \]  \hspace{1cm} (2.1)

where \( M \) is the mass, \( v \) the velocity of the mass, \( F \) the force, \( t \) the time, \( b \) and \( k \) the spring constant and damper coefficient.
Figure 2.1: The analogy between an electrical system and a mechanical system.
respectively. For an electrical system (see Figure 2.1.a) in which an inductor, a resistor, and a capacitor are connected in series with a voltage source, the differential equation is:

$$L \frac{di}{dt} + Ri + \frac{1}{C} \int i dt = E$$

(2.2)

where $L$ is inductance, $i$ the current, $E$ the voltage, $R$ and $C$ the resistance and the capacitance respectively. Comparing Equation 2.1 and 2.2, the first analog system [29] (table 2.1) between the mechanical and electrical systems is obtained.

However, it is not a unique system because it is possible to change the association given above. When the electrical circuit in Figure 2.1(c) is considered, the second analogy system is obtained. The circuit consists of the same electrical elements as the first one except that all elements are connected in parallel. The differential equation for this circuit is:

$$C \frac{dE}{dt} + \frac{E}{R} + \frac{1}{L} \int E dt = i$$

(2.3)

Comparing equation 2.1 and 2.3, the second analog system [30] between the electrical and mechanical quantities is obtained and shown in table 2.2.
Table 2.1

The First Analog System—Analogy Between the Electrical and the Mechanical Systems

| Force (F) | ...... | Voltage (E) |
| Velocity (v) | ...... | Current (i) |
| Mass (M) | ...... | Inductor (L) |
| Damper (b) | ...... | Resistor (R) |
| Spring (k) | ...... | Capacitor (1/C) |
Table 2.2

The Second Analog System—Analogy Between the Electrical and the Mechanical Systems

<table>
<thead>
<tr>
<th>Force (F)</th>
<th>......</th>
<th>Current (i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (v)</td>
<td>......</td>
<td>Voltage (E)</td>
</tr>
<tr>
<td>Mass (M)</td>
<td>......</td>
<td>Capacitor (C)</td>
</tr>
<tr>
<td>Damper (b)</td>
<td>......</td>
<td>Resistor (1/R)</td>
</tr>
<tr>
<td>Spring (k)</td>
<td>......</td>
<td>Inductor (1/L)</td>
</tr>
</tbody>
</table>
The advantage of the application of the electromechanical analogy is not in obtaining the equivalent electrical quantities for a mechanical system but in reduction of the difficult differential equations of mechanical system to the symbolic solutions employed in electric network theory and the ability to apply the results of electric network theory to mechanical systems. This advantage finds its significant importance in system modeling for ultrasonic welding.

2.2 Analogy Circuit of Ultrasonic Welding System

The ultrasonic welding system is a complicated system including both electrical and mechanical portions. As discussed in Section 1.1, the converter in an ultrasonic machine is the coupling device between the electrical portion and the mechanical portion. The converter receives an input, motional voltage, from an ultrasonic power supply and produces a velocity on the bottom surface of the converter. For an X-cut piezoelectric disc (several discs makeup a converter) the output velocity is proportional to the voltage applied to its two surfaces [31]. It implies that when the electromechanical analogy is used to model the ultrasonic process, the second analogy system is appropriate because the voltage and velocity are described with the same derivative equation in the system.

From the point of view of network theory, the converter-booster-horn combination of an ultrasonic welding system is nothing but a
filter. In the equivalent filter circuit (see Figure 2.2), $C_c$ is the equivalent capacitor for the converter. $L_g$ is an inductor which changes the phase of the motional voltage $V_g$. $R_i$ is the coil resistance associated with $L_g$ which is about several ohms and is neglected. $C_m$ and $L_m$ are equivalent capacitor and inductor for booster horn assembly. The values of $C_c$, $L_g$, $C_m$, and $L_m$ for ACME 900M power supply were measured by Branson Ultrasonic Corporation [32]:

\[
\begin{align*}
L_g &= 3.85 \text{ mH} \\
C_c &= 16.5 \text{ pF} \\
L_m &= 0.01266 \text{ mH} \\
C_m &= 5.0 \mu \text{ F}
\end{align*}
\]

The filter lets the fundamental component of the motional voltage which comes from the power supply pass through and blocks all other harmonics. The output voltage from the power supply is a square wave with a 930 V amplitude. Figure 2.3 shows the MATHCAD approximation for the square wave (see Appendix B). Figure 2.4 shows the predicted voltage input to the converter (between points 1 and 2 in Figure 2.2), showing the filter behavior.

Under the converter-booster-horn is the top part of the welding sample. In the experiments, American Welding Society (AWS) samples suggested by the AWS G1 committee in 1990 were used. (see Figure 2.5) The sample consists of two parts. The bottom part is a T shape
Figure 2.2: Equivalent circuit of an ultrasonic system.
Figure 2.3: Motional voltage: a square wave.
Figure 2.4: Filtered motional voltage: an 20 KHz sinusoidal wave.
Figure 2.5: AWS sample.
structure and is 2" long and 0.5" high. The width of the upper surface is 0.1". The top part of the sample is also T shaped, but the height is only 0.25" to be suited for the near-field welding. An equilateral triangle energy director is molded on the lower surface of the top part. After welding the samples form an I beam. Tensile test is to be performed on the finished structure to evaluate the strength of the joint.

To simplify the problem, we assume that all deformations happen within the energy director, since the average cross sectional area of the energy director is much smaller than other portion of the top part. In addition, the mass of the energy director is only 0.5% of the whole top part. Thus, the top part of the sample is represented by a mass and the energy director is represented by a spring and a damper in parallel (see Figure 2.1). Because the sample is under the horn, using the second electromechanical analogy, the mechanical system representing the top part is converted into a complex load on the electrical circuit which includes a resistor, a capacitor, and an inductor in parallel (see Figure 2.1). The whole system model for the ultrasonic welding system is shown in Figure 2.2.

From the process control viewpoint there are two advantages of the above electromechanical analogy model for the ultrasonic welding system. First, the whole sophisticated system, which includes power supply, converter, booster, horn, and welding parts, becomes a unique electrical system in the analogy model. All electrical network theories can be easily used on the system and it is no longer needed
to consider all individual sub processes and their couplings. Second, since the top part (including the energy director) of the welding sample is converted into the load of the analogy circuit, the measured values of current, voltage or their combination power can reflected the changes of mechanical property of the interface.

2.3 Signal Processing

To verify the model the current and the voltage signals were collected from the power supply through a high speed data acquisition system HSDAS-12 (see Chapter III). The maximum sampling rate can be 200,000 samples/second for both current and voltage measurements. For a signal with a frequency of 20,000 Hz, 10 data points can be acquired per period. With these 10 data points, the current and voltage signals can be processed by means of Discrete Fourier Transform (DFT) [34, 35] to obtain their amplitude at 20 KHz, the phase angle between them, and the impedance of the analogy circuit.

According to the Sampling Theorem, to be able to recover the periodic signal \( f(t) \), it is necessary to sample \( f(t) \) at a rate greater than its highest frequency, i.e., the following relation must be valid

\[
N \geq 2k + 1
\]  
(2.4)
where \( N \) is the number of samples per fundamental period and \( k \) the highest harmonic in the Fourier series for \( f(t) \). Now if the sample set is \( N \), the DFT (Discrete Fourier Transform), \( \hat{F}_m \) is given by

\[
\hat{F}_m = \sum_{n=0}^{N-1} f_n e^{-i(2\pi mn/N)} \quad m = 0, 1, ..., N-1
\]  

(2.5)

The frequency \( \omega \) is related to \( m \) as follows:

\[
\omega = \frac{2\pi m}{NT}
\]  

(2.6)

where \( T \) is the sampling period. In our case, since 10 data points are collected for each signal in a period (\( N = 10 \)), the largest possible value of \( k \) is 4 according to Equation 2.10. Therefore, the highest harmonic frequency which can be obtained from the 10 data points is 80,000 Hz corresponding to the fundamental frequency, 20,000 Hz.

A program (see Appendix C) based on the above analysis was developed to calculate the amplitudes of the current and the voltage, the phase angle, and the impedance of the circuit from discrete current and voltage data. In the program, these discrete data from the data acquisition system are taken as the real parts of the time domain data set \( f(t) \). The imaginary parts of the set are zero. Then, the Discrete Fourier Transformation are performed according to Equation 2.15. The calculated result of the program agrees with test results using a signal generator for sinusoidal signals. The
calculated results is also in agreement with measurements done using the A920 Branson power supply.

2.4 Measurement of Current and Voltage Signals in Three Cases

In the experiments the current (at point 1 in Figure 2.2) and voltage signals (between point 1 and 2 in Figure 2.2) were measured for three cases. The cases are the air load, the beginning of the welding, and the end of the welding. The welding sample is ABS AWS sample.

Case 1: Air load

If the bottom surface of the horn only makes contact to air and the ultrasonic vibration is on, it is the case of air load. Since for air \( b << 1 \), \( k << 1 \), and \( M << 1 \), then referring to the analogy relations in table 2.2:

\[ 1/R \ldots b, \quad 1/L \ldots k, \quad C \ldots M \]

the load of the circuit becomes very large. In other words, \( R_t \) is very large (assumed to be 300K ohms), \( L_t \) is also very large (assumed to be 3 Henry) and \( C_t \) is very small (assumed to be 80 pF).

\[ R_t = 300K \text{ Ohms}, \quad L_t = 3.0 \text{ Henry}, \quad C_t = 80 \text{ pF} \]
Then, the current in the circuit can be calculated (see Appendix F). If the resistor and inductor take higher values and capacitor takes very smaller value, the calculated current does not change. This is, in fact, the case of the open circuit. Figure 2.6 shows the results of the calculations for open circuit and experimental measurements. The signals are for one cycle and include 3rd, 5th and higher harmonics. The calculation is close to the experimental measurements.

Case 2: Beginning of the welding

In the beginning of the welding, the energy director starts to melt. The measurements of the voltage, current, phase angle between the current and the voltage, and the impedance just after the transient time are shown in Figure 2.7 and 2.8. The RMS current is 0.6 ampere, the RMS voltage 500 volts, the phase angle -10 degrees, and the impedance 800 ohms.

Case 3: End of welding process

At the end of the process, the energy director is totally molten. A thin layer of the molten polymer spreads across the interface. From the theory of squeeze flow between two plates described in Section 1.2, any further movement of the plates will meet huge resistance. Figure 2.9 shows the relation between force and the ratio of the initial to the final gap (in this case it is assumed that \( n = 0.6 \), \( m = 0.58 \text{ psi} \cdot \text{second}^{0.6} \)).
Figure 2.6: Theoretical and experimental results of the current signals for air load.
Figure 2.7: Measured RMS current and RMS voltage during the first 0.1 seconds of the welding.
Figure 2.8: The impedance and the phase angle for the voltage and the current during the first 0.1 seconds of the welding.
Figure 2.9: Force vs. ratio of gaps in squeeze flow.
The initial gap is 0.015"", which equals the height of the energy director of AWS samples. The initial length of the energy director is 0.03"" and the width of the plate is 2"". Figure 2.9 shows that for constant flow time decreasing the gap (further flow of energy director) requires substantial increase in force. Therefore, in the final stage the mechanical impedance quickly rises. From table 2.2 since damping coefficient becomes very large, the resistance decreases. This is equivalent to an electrical short circuit. Because the current becomes very high (amplitude of 1.7 amperes), and a peak in power will appear. This peak power is important for process control because it means that intimate contact at the interface occurred and the process should be stopped.

2.5 Transfer Function of the Analogy Circuit

To investigate the dynamic change of mechanical impedance of the interface, the transfer function for the analogy circuit should be obtained. The analog circuit in Figure 2.2 can be simplified by using an equivalent capacitor for the parallel capacitors Cm and Cl and an equivalent inductor for Lm and Ll as shown in Figure 2.10. In the simplified circuit \( R = R_L, \ C = C_m + C_l, \ L = (L_m \ast L_l)/(L_m + L_l) \). Since the voltage and current signals in the experiment were measured before the converter between the points 1 and 2 (see Figure 2.2), the
Figure 2.10: Simplified analogy circuit.
inductor $L_g$ and $R_i$ are included in the power supply [32]. There are only three loops in the simplified circuit. Using Kirchhoff's voltage law, the differential equations for these three loops are written as the following

$$e = \frac{1}{C_c} \int i_1 \, dt + R(i_1 - i_2) \quad (2.7)$$

$$R(i_2 - i_1) + \frac{1}{C} \int (i_2 - i_3) \, dt = 0 \quad (2.8)$$

$$\frac{1}{C} \int (i_3 - i_2) \, dt + L \frac{di_3}{dt} = 0 \quad (2.9)$$

where $e$, $i_1$, $i_2$, and $i_3$ are motional voltage and currents in loop 1, 2, and 3. $C_c$ is the equivalent capacitor for the converter. After performing Laplace transformation on the above equations, the following system of algebraic equations are obtained

$$\frac{1}{C_c S} + R(I_1 - I_2) = E \quad (2.10)$$

$$R(I_2 - I_1) + \frac{1}{C} \left( \frac{I_2}{S} - \frac{I_3}{S} \right) = 0 \quad (2.11)$$

$$\frac{1}{C} \left( \frac{I_3}{S} - \frac{I_2}{S} \right) + LSI_3 = 0 \quad (2.12)$$
where \( E \) is the Laplace transform of motional voltage, and \( I_1, I_2 \)
and \( I_3 \) are the Laplace transforms of current with respective to loops
1, 2, and 3. Simplifying and eliminating \( I_2 \) and \( I_3 \) in the above
system of the equations results in the following transfer function
between the motional voltage and the current in loop 1:

\[
\frac{I_1}{E} = \frac{LRC^2 C_c S^3 + LCC_c S^2 + RCC_c S}{LRC^2 S^2 + (LCC_c R + LC)S + RC}
\]

(2.13)

The transfer function (Equation 2.13) shows that the system is a
second order system since the denominator of the transfer function is
a second order polynomial. Equation 2.13 also shows that because the
coefficient \( LCC_c R + LC \) is always positive, the two poles of the
system are in the left plane and the system is stable.
Chapter III
Experimental Setup

3.1 Ultrasonic Welding System

The welding system shown in Figure 3.1 includes three parts, an ultrasonic welder, a personal computer, and a data acquisition system. The photograph in Plate I shows the whole system.

The welding machine contains a pneumatic carriage, converter-booster-horn assembly (see Plate II), welds fixture, and power supply. The welding process is performed with the machine. Various sensors are installed in appropriate positions on the machine to collect welding parameters during the process.

The data acquisition system is a bridge between the welding machine and the control computer. Analog signals acquired by sensors go to the data acquisition system and are digitized. Then, the digital data are sent to the computer for further processing. The control commands in digital form from the computer are converted into analog signals through the data acquisition system. The actuators
Figure 3.1: An ultrasonic welding system.
Plate I: Photograph of the ultrasonic welding system.
Plate II: Photograph of the converter-booster-horn assembly.
(P691 pressure regulator and the data acquisition system), receive these analog signals and change the welding parameters.

An IBM compatible computer is used in the system. The computer processes the data, performs calculations, compares the system's actual output to the reference, and determines the optimum control parameters. The time reference for the whole control process is obtained directly from the computer CPU clock.

3.2 Branson A920 Welding Machine

The ultrasonic welding machine used in the project is a Branson A920 which operates at 20 KHz. The maximum power output of the machine is 2,000 watts. There are several important features [5] on the new model ultrasonic welding machine. The power supply of the machine is an all solid state design with no electromechanical relays in the starting circuit. The adjustable amplitude of the horn vibration is the most significant new feature of the machine. During the welding process the amplitude of horn vibration can be adjusted from 100% to 0% on the real time base. The amplitude control is protected against line and load changes. The line voltage can deviate $\pm 15\%$ from nominal with no more than a $\pm 2\%$ deviation in amplitude. Another important feature of the power supply of the machine is its instrumentation. A true wattmeter is built in the unit for consistent reading of real power output. Finally, the power supply of the
welding machine use a low level signal for "Auto Seek" to maintain a constant frequency.

3.3 Horn, Fixture, and Sample Holders

The horn is a very important part of the welding machine. The horn changes the vibration amplitude and transmits mechanical vibration to the welds. The horn should be designed to satisfy the needs of different parts. Horns usually are made of titanium or aluminum because of the low acoustic impedance's of these two materials.

The basic requirement of the horn design is to obtain optimum vibration amplitude in the joint interface at a specific resonant frequency. For near field welding this means that the maximum vibration amplitude happens on the bottom surface of the horn because the joint interface is very close to the horn. Like the booster which is a one half wave length resonator, the horn usually is of a half wave length too.

If the lateral dimension of the horn is much smaller than the wave length, usually less than a quarter of a wave length is assumed, one dimensional compression wave model can be used in the horn design. Among the three common types of horn designs are stepped, exponential, and catenoidal. The stepped horn design gives the largest amplitude increase. In the case of a stepped horn (see Figure
3.2) the length of the small cross section side can be calculated from the equation of motion and boundary conditions as [33]

\[
L_2 = \frac{1}{k_2} \tan^{-1} \left( -\frac{Z_1 \tan(k_1 L_1)}{Z_2} \right)
\]  

(3.1)

where \( L_1, L_2, k_1, k_2 \), and \( z_1, z_2 \) are lengths, wave number and acoustic impedance for the upper side and the lower side of the horn. The amplification coefficient can be obtained as well with the same method:

\[
\frac{v_2}{v_1} = \frac{Z_2 \sin(k_2 L_2)}{Z_1 \sin(k_1 L_1)}
\]  

(3.2)

where \( v_1, v_2 \) are vibration velocities of top side and bottom side. A computer program, which calculates the length and amplification coefficient and plots stress and displacement distributions along the step horn, is listed in appendix D.

In this project, a horn was designed for the AWS sample (see Figure 3.3, and Plate III). The horn is made from aluminum. The upper side of the horn is a 2" diameter cylinder and the cross section of the lower side is nearly rectangular. The two sides are connected with a fan shape of transition plane. The nodal point is at the point of intersection of cylinder and the transition plane. The cross section
Figure 3.2: A step horn.

S1: cross-sectional area of side 1
S2: cross-sectional area of side 2
V1: partical velocity of side 1
V2: partical velocity of side 2
Figure 3.3: Illustration of the horn used in the project.
Plate III: Photograph of the horn used for AWS samples.
of the lower side has been further decreased near the tip to fit the AWS sample. The amplification coefficient for the horn is about 1.2.

The fixture in the ultrasonic welding process performs two functions. First, it offers a rigid support to the welding parts which results in the largest amplitude drop to occur at the interface. Hence, more heat can be generated due to the viscoelastic heating. Secondly, it restrains the welding parts for proper alignment. A fixture was made for the welding of the AWS samples. The base of the fixture is an 1" (2.54 cm) thick aluminum plate. On the plate there are four adequately designed aluminum blocks which are adjustable and offer restrain to the samples. (see Plate IV)

In the research project the tensile test for the welded AWS samples were performed on an INSTRON test machine (model PS-5M). A pair of specially designed holders was made to hold AWS welded samples (see Plate V). For all tensile test the cross head speed is 0.05"/second.

3.4 Measurements of the Parameters

To realize process control, the welding parameters have to be measured. Those parameters are welding pressure, collapse of energy director, current, and voltage of the power supply. To measure these parameters sensors are properly installed in adequate positions (see Figure 3.4). All measured signals from these sensors were calibrated.
Plate IV: Photograph of the fixture for AWS welding samples.
Plate V: Photograph of the holders and AWS I beam sample.
Figure 3.4: Locations of displacement sensor and pressure sensor on the welding machine.
The signals, then, were sent to the data acquisition system. The following sections describe these sensors and their calibrations.

3.4.1 Static Force

The static force applied to the parts is measured through a solid state pressure sensor, MICRO SWITCH, 240PC. The sensor is embedded in a sealed chamber which is connected to the air cylinder of the actuator (see Figure 3.4). When the air pressure changes from 0 to 100 psi, the static force varies from 0 to 775 lb.

Since the ultrasonic welding process only lasts several seconds and the mechanical pressure regulator can not respond quickly enough in such a short period of time, an electro-pneumatic regulator P-691 is used to adjust the air pressure input. The air flow chart is shown in Figure 3.5. Plate VI is the photograph of P-691 regulator. An electronic switch in the regulator adjusts the air input according to the received control voltage and the actual pressure value detected by a pressure sensor. The P-691 was carefully calibrated. The control voltage on the regulator is 1-5V which adjusts the pressure from 0-100 psi linearly. The calibration curve in Figure 3.6 shows a good linear relationship between the control voltage and the pressure.

The response time of P-691 depends on the volume of storage tank of compressed air, the diameter of the pipe line and the volume of
Figure 3.5: Air flow chart of pressure control system.
Plate VI: Photograph of P-691 pressure regulator.
Figure 3.6: Calibration curve of P-691 pressure regulator.
the working cylinder of the machine. Figure 3.7 and 3.8 show the response of P-691 pressure regulator. In the experiments the down speed is 4.0"/second (the highest down speed). When the static force increases from 220 lb. to 300 lb., the lag time is 0.021 seconds and the rise (90%) time is 0.083 seconds. When the static force is decreased from 292 lb. to 252 lb., the lag time is 0.062 seconds and the rise time (90%) is 0.081 seconds.

3.4.2 Displacement

An optical encoder (see Figure 3.4) which is mounted on the Branson A920 detects the displacement of the carriage which houses the converter-booster-horn assembly. The encoder, Model LT of Dynamics Research Corporation, is used with a Quadrature Encoder card (Model 5312) which is installed in the computer [43]. The reading of the displacement is determined by the Encoder through a high level computer language program (BASIC, FORTRAN, PASCAL, or C). The travel length of the encoder is 4" and the resolution of the reading is 0.0001" [43].

3.4.3 Electrical Power

Figure 3.9 shows a switch circuit which was used to control
Figure 3.7: Response of P-691 when static force increases from 220 lb. to 300 lb. The command to increase the force was given at time 0 seconds.
Figure 3.8: Response of P-691 when static force decreases from 292 lb. to 252 lb. The command to decrease the force was given at time 0 second.
Figure 3.9: Switch circuit for sonic and solenoid on and off.
sonic and solenoid on or off. The control voltage is from I/O port of
the data acquisition system. When the voltage is high, the switch is
"on", when the voltage is low, the switch is "off".

Electrical power is a very important welding parameter. There are
three methods in this project to measure it. The first method
introduced in Section 2.4 uses DFT technique to process current and
voltage data to obtain their amplitude, phase angle, and power. The
second method directly collect the power data from a wattmeter built
in the power supply [5].

In third method, the current is measured with a current sensor
and the voltage is measured with a voltage divider. Both voltage and
current are measured just before the converter (see Figure 3.10).
When a 50 ohms resistor is connected in parallel with the current
sensor, the relation between current $i$ (ampere) and the voltage $v$
(volts) output from the resistor is:

$$i = 2 \cdot v$$

(3.3)

For the voltage divider the input voltage $V_{1}$ (motional voltage) is
related to the voltage signal $V_{2}$ (Figure 3.10) in the following
formula. The ratio between $V_{1}$ and $V_{2}$ is 1440 which is determined by
the values of the resistors composed of the divider:

$$v_{1} = 1440 \; v_{2}$$

(3.4)
Figure 3.10: The voltage divider and the current sensor.
Since the resonant frequency of the welding machine is 20,000±500 Hz, both current and voltage signals are filtered separately by two three-cascade Chebyshev low pass filters (see Figure 3.11). The two filters are the same with a cutoff frequency of 25KHz and an amplification coefficient of 1.842 to avoid additional phase shift between current and voltage. To measure power the filtered current and voltage signals are sent to an analog multiplier MPY634, (Burr Brown). The output of MPY634 is connected with a true rms-to-dc converter AD536 (Analog Devices) (see Figure 3.12). The output dc voltage of the AD536 is proportional to the power.

3.5 Data Acquisition System

The data acquisition system connects the welding machine and the computer. It collects welding parameter data; digitizes them and sends them to the computer. It transfers process commands from computer to actuators in the welding machine.

The data acquisition system used in the project is HSDAS-12, (Analogic Corporation) (see Figure 3.13). The highest sampling rate of the system is 400,000 samples per second when configured to accept one single ended channel. The data acquisition board contains a multimode, 12-bit, analog-to-digital converter (ADC) with 16 input channels, 2 12-bit digital-to-analog converters (DAC) with 32k
Figure 3.11: Chebyshev filter.
Figure 3.12: Power measurement with MPY634 multiplier and AD536 RMS-DC converter.
Figure 3.13: Illustration of input and output of HSDAS-12.
sample DAC input buffer memory, and a multi-configuration 16-bit parallel digital I/O (DIO) port. In the project, three of the eight differential A/D channels are used to collect data on pressure, current, and voltage. The computer sends control signals through two D/A channels to control the pressure and the amplitude of vibration. The signals to switch the solenoids and to activate the ultrasonic vibration are generated from I/O ports.

The advantages of HSDAS-12, besides its high speed and multichannel A/D and D/A conversions, are that all data transfers to and from the HSDAS-12 may be program-driven or via DMA (Direct Memory Access) and all functions are contained in a single, full length, PC/AT bus compatible board and are fully software programmable [36].

Another advantage of the HSDAS-12 is its interactive setup system, "Menus", designed for use in programming. The Menus program communicates with an application program through an *.cfg file which is written by Menus and read by the application or driver. Therefore, any change of board setup can be carried out during the process by calling the *.cfg file.
Chapter IV

Process Control Scheme

4.1 Present Process Control for Ultrasonic Welding

There are several characteristics for the ultrasonic welding process. First, the process is very fast, usually several seconds. Second, there are dramatic changes in the mechanical properties of the interface. The thermodynamic phase of the thermoplastic changes from solid to liquid and to solid again in the process. Third, there are uncertainties in the process which are caused by unpredictable changes of the system properties and by disturbances.

During the design of the process control for an ultrasonic welding system, the above system characteristics have to be considered. Therefore, the system response should be known and the response should be much faster than the whole welding process. In addition, a model should be established to describe the process as precisely as possible so that the transfer function of the plant will reflect the most important factors which affect the process. Finally,
a control method should be chosen which can deal with the uncertainties and disturbances in the process.

Until now, most ultrasonic welding machines have employed open loop control. The latest machines usually run under three modes: the time mode, the energy mode and the displacement mode, i.e., these three parameters are taken as the control parameters. Operators set the threshold values of weld time, energy, or displacement before welding. The threshold values are determined from experience. As soon as the threshold values are reached during the welding, the process is stopped automatically. However, it is not clear how those parameters are related to the mechanical properties of the interface which determine the strength of the joint.

4.2 Open Loop Control for Ultrasonic Welding

Benatar and Gutowski [37] showed that at the final stage, in which the molten fronts on the interface meet, the mechanical impedance rises quickly and it is associated with the quick increase in the power level. The experimental results shows the same results (see Figure 4.1). In Figure 4.1 a small peak power appears in the beginning of the welding because of the overshoot during the transient period. After the transient period a relative high power peak is observed which is caused by the increasing mechanical impedance of the interface in the final stage of the welding. Because it is
Figure 4.1: Single peak of power appearing in the ultrasonic welding for the samples with an energy director.
difficult to measure the mechanical impedance of the interface during the welding process, an alternate parameter needs to be measured. The power level, which is easy to measure, can be used as an indicator of the final stage of the welding process.

Based on the above result, switch open loop control can be used to monitor the process (see Figure 4.2). As soon as the actual power level $P_a$ reaches the threshold value $P_d$ corresponding to the power peak, a signal is generated to turn the sonic off. Although the control is still open loop, good quality joints can be expected because the control variable (power level) appropriately reflects changes in the geometrical and mechanical properties of the interface. In the actual control process other conditions, such as minimum welding time, minimum input energy may be added to increase the assurance of the quality.

4.3 Closed Loop Control for Ultrasonic Welding

In the real world there are always disturbances for any control process. In ultrasonic welding the disturbance may be caused by a defective energy director, the dimensional tolerances in the components and/or the material properties. Those disturbances may trigger local collapse of the energy director. In some cases the local collapse is large enough to cause a significant power surge. Figure 4.3 shows a welding process with a multi-peaks power curve.
Figure 4.2: Diagram of switch open loop control for ultrasonic welding process.
Figure 4.3: Multi-power peaks appearing in the ultrasonic welding for samples with an energy director.
For an open loop control process in which the quick rise of power level is considered as the indication of the end of the process, a wrong alarm signal may produce early termination of the process or cause an overload state. To compensate for disturbances in the welding process closed loop control should be used.

To design a closed loop control system three problems should be solved first. They are the transfer function of the system, the system response, and the controller being used in the control.

4.3.1 Relation between Power and Vibration Amplitude

In ultrasonic welding, power level from power supply is of primary importance not only because it causes the melting of the polymer but also power curve may indicate the mechanical impedance of interfaces. Naturally, the output power is chosen as the output of the ultrasonic welding control system. There are several ways to control the electrical power output in the process. For example, the power supply changes its motional voltage or impedance. However it will largely complicate the circuit design. The newest model of power supply, A920 ACME from BRANSON offers an easy way to adjust the electrical power during the process, i.e., adjusting vibration amplitude of the horn.

Noting that the ultrasonic welding machine converts electrical energy to mechanical energy, and mechanical energy is proportional to
the square of the amplitude of the mechanical vibration, the electrical power can be written as

\[ P = \frac{1}{k} A^2 \quad (4.1) \]

where \( k \) is a positive coefficient, \( A \) the relative mechanical vibration amplitude of the horn. The value of \( k \) depends on the efficiency of the converter, the booster-horn assembly, the welding parts, and other welding parameters, for example, welding pressure. However, for a specific converter-booster-horn assembly and a certain welding environment \( k \) should not vary too much.

Experiments were performed to prove the above relationship. In the experiments the power signal is collected from the output of a watt meter on the control board of Branson A920 power supply [5]. Instead of measuring vibration amplitude, the control voltage of vibration amplitude were pick up from A920 Branson power supply. Both power level data and vibration amplitude control voltage data were collected by the HSDAS-12 data acquisition board. The parts in the experiments were the AWS I beam samples.

Experimental results agree with the linear relation between the square of the vibration amplitude and the output power. Figure 4.4 shows one of the results for a polyester I beam sample under a pressure of 35 psi. For different materials and different welding pressures the slopes of the curves may be different. However, the proportional relation between electrical power and mechanical
Figure 4.4: Linear relation between the power and the square of the vibration amplitude.
vibration amplitude holds. During actual welding the slop varies because of the changing properties of the welding interface. Using a high speed data acquisition system, the instant slop can be determined from the measured power and the vibration amplitude control voltage. The calculated slop can be used for the control purpose. In fact, Equation 4.1 is the transfer function, the mathematical model, of the process, if the square of the mechanical vibration amplitude of the horn is chosen as the input and the electrical power is chosen as the output of the plant.

4.3.2 Mechanical Response of Converter-Booster-Horn Assembly

As was discussed early, the process is very fast. If the transition time is too long, compared to the process, we may not be able to control it. In the project the system responses for several typical cases have been measured. In the experiments, motional voltage and mechanical vibration amplitude of the horn were collected by the data acquisition system. The motional voltage is measured from the voltage divider described in Section 3.3.2. The horn vibration amplitude is detected by a Fotonic Sensor. To obtain this measurement a hole was drilled through the center of the sample. The Fotonic sensor is set in the hole. The distance between the sensor and the bottom surface is about 0.04" which is in the front side of the calibration curve [46]. The data was collected 620 times per second.
Every time, 10 points were measured for both the voltage and the horn vibration amplitude in one cycle. After the data was analyzed with a DFT program, (see Appendix C) the peak values of the signals were determined.

Figure 4.5 and 4.6 show the transition period of motional voltage and mechanical vibration amplitude of the horn for the air load condition. The input was a step function of motional voltage of about 300 volts (RMS value). With a 1:1.5 booster, the lag time of the relative vibration amplitude response is 3.2 milliseconds and the rise time is about 10 milliseconds.

Figure 4.7 and 4.8 show the transition period of motional voltage and mechanical vibration amplitude for a polyester AWS I beam sample in the beginning of welding. The weld pressure was 40 psi and the relative vibration amplitude was 55%. The input is a step function of 900 volts (RMS value) motional voltage. The rise time (90%) for relative vibration amplitude is 0.016 seconds, which is longer than air load condition because of the load under the horn.

Figure 4.9 and 4.10 are the experimental results of the system response for another input condition. In this experiment the input is a step function of vibration amplitude control voltage which varied from -5v to -3v during the welding for polyester I beam AWS sample. Accordingly, the relative vibration amplitude should vary from 50% to 70%. The rise time (90%) for the relative vibration amplitude is about 0.018 seconds (see Figure 4.10).
Figure 4.5: Response of the motional voltage for air load condition.
Figure 4.6: Response of the vibration amplitude of the horn for air load condition.
Figure 4.7: Response of the motional voltage for an I beam AWS sample in the beginning of welding.
Figure 4.8: Response of the vibration amplitude for an I beam AWS sample in the beginning of welding.
Figure 4.9: Response of the motional voltage for a change of vibration amplitude from 50% to 70% of maximum amplitude.
Figure 4.10: Response of the vibration amplitude for a 20% change (from 50%–70%).
All the experimental results show that the rise time of the relative vibration amplitude is less than 20 milliseconds for a step change of motional voltage or vibration amplitude control voltage. The control program can analyze the data and generate a control command every 2.5 milliseconds. Compared with the response of the relative vibration amplitude the control speed is adequate.

4.3.3 PID Controller

Because of the proportional relation between electrical power level and the square of the amplitude of mechanical vibration discussed in section 4.3.1, the following equations are written for the square of vibration amplitude $A^2$ and the electrical power level $P$:

$$A_d^2 = k P_d$$  \hspace{1cm} (4.2)

$$A_a^2 = k P_a$$  \hspace{1cm} (4.3)

where subscript $a$ and $d$ represent actual and desired values respectively. From the above two equations we have

$$A_d^2 = A_a^2 + k (P_d - P_a)$$

$$= A_a^2 + k e$$  \hspace{1cm} (4.4)
where \( e \) is the difference between desired power level and the actual power level, the so called error function. Since the square of the desired vibration amplitude is proportional to the error, the controller is identified as a proportional feedback control. For ordinary control objective, proportional controller is effective. However, for the ultrasonic welding process, because of the dramatic changes of the system's characteristics, derivative control and integral control should be added to the proportional control to provide an acceptable degree of error reduction simultaneously with acceptable stability and damping. Thus, a PID controller (proportional plus integral plus derivative) finally is used in the ultrasonic welding process.

\[
A_d^2 = A_e^2 + k \left( e + \frac{1}{T_i} \int_0^t e \, dt + T_d \frac{d e}{d t} \right)
\]  

(4.5)

where \( T_i \) is called integral, or reset time, and \( T_d \) is called derivative time.

Figure 4.11 shows the control diagram. To close the loop, an actual power signal is picked up from the power supply and fed back to the comparator. The reference here is the desired power level. From the controller the desired value of the square of amplitude is obtained [38].

There is no theoretical formula yet to determine the values of the gains, i.e., proportional coefficient, integral time and
Figure 4.11: The diagram of the closed loop control for ultrasonic welding.
derivative time. In practice, the gains are determined experimentally, which is called system tuning [39,40,41]. One common tuning procedure (desired power level 300 watts) is as follows:

1. Set the integral time to be very large and the derivative time to zero (there is only proportional controller in the system). Change $k$ until a small amplitude oscillation response is obtained. The range of the values of $k$ can be estimated through the amplitude-power level relation experimentally described in Section 5.3.1. Figure 4.12 shows the power output for nylon AWS I beam samples when $k = 2$, $T_d = 100,000$, and $T_i = 0$. As $k$ decreases, the oscillation in power output decreases as well. Decrease $k$ until the system response reaches the desired value after 2-3 cycles. Figure 4.13 shows the case when $k = 0.8$, $T_i = 0$, and $T_d = 100,000$.

2. Add derivative controller. Increase value of derivative time from zero gradually until the system response reaches the desired value in one cycle and the overshoot become the smallest. Figure 4.14 shows the power output when $k = 0.8$, $T_d = 0.004$, and $T_d = 100,000$ for nylon AWS I beam sample.

3. Decrease integral time gradually until the satisfactory accuracy is obtained.

Figure 4.15 shows that a constant gain can control the power level to follow a three step change for a AWS I beam polyester sample. However, for a AWS sample with an energy director a constant gain can not fit the three power level stages. Figure 4.16 shows this
Figure 4.12: System tuning: large value of proportional coefficient

\[ k = 2, \quad T_i = 0, \quad T_d = 100,000 \]
desired power level: 300 W

\[ \text{power level (watts)} \]

\[ \begin{array}{c}
0 & 100 & 200 & 300 & 400 & 500 & 600 \\
0 & 0.1 & 0.2 & 0.3 & 0.4 & 0.5 \\
\end{array} \]

\[ k=0.8, \quad T_\text{i}=0, \quad T_\text{d}=100,000 \]

Fig. 4.13 System tuning: the adjustment of proportional coefficient
desired power level: 300 W

$k=0.8, \quad ti=0.004, \quad Td=100,000$

Figure 4.14: System tuning: the adjustment of derivative time.
Figure 4.15: Dynamic tracking for the step changes of power level for polyester AWS I beam samples.
Figure 4.16: Dynamic tracking for the step changes of power level for polyester AWS samples (constant gain).
situation. Changing the gain for each power level stage results in a greater improvement. (see figure 4.17)

4.4 Control Program

The welding process is controlled by the program OCCWP.C (see appendix E) for open loop control process. The program OCCWPID.C controls the closed loop control process (see appendix F). Both programs have the same basic structure, except for differences in the control portion. As shown in Figure 4.18, the main program consists of three stages. The first stage is for the input of the welding parameters. These parameters include trigger force, welding force, hold force, hold time, minimum and maximum welding time, minimum and maximum collapse, or minimum and maximum energy. Ultrasonic welding is activated in the second stage. In the second stage the computer collects data, calculates the needed values, evaluates the criteria, and sends control signals to their relevant devices. The last stage comes after the end of the process. There are five options being offered: plotting data, saving data, typing data, another trial or exiting the program. The structure of the program is shown in Figure 4.18.

The flow chart of the open loop control stages is shown in Figure 4.19. After the real force is equal to the trigger force, the ultrasonic vibration is switched on. In the open loop control, the
Figure 4.17: Dynamic tracking for the step changes of power level for polyester AWS sample (variable gain).
Figure 4.18: Structure of the control program.
Figure 4.19: Flow chart of the open loop control for ultrasonic welding.
process is limited either by the time window, the energy window, or the collapse window. The end of the process is decided at the moment the power level reaches a threshold value. If the threshold value has not been reached but the upper limit of the window has been reached, the process is stopped with a warning. In the closed loop control process (see Figure 4.20) the control voltage for the vibration amplitude is calculated and is used to adjust power level about 200 times per second. The total input energy is equal to the sum of the energy increase in each interval of the calculation. When the total input energy equals the threshold value, the process is stopped.
Figure 4.20: Flow chart of the closed loop control for ultrasonic welding.
Chapter V
Experimental Results and Discussion

5.1 Electrical Impedance Measurement in Welding Process

In Chapter II an electromechanical model was established to simulate ultrasonic welding process. From the model it can be seen that mechanical impedance and electrical impedance vary inversely. Because there is a dramatic change of mechanical property of interface, it is very difficult to find the values of the load in the analogy circuit as a function of time. Therefore, three typical cases, air load, beginning of the process, and the final stage of the process, are considered. However, by means of the high data sampling rate of HSDAS-12 a continuous observation of impedance variation is available. The procedure of the observation is almost like the measurement of system response. The motional voltage and current signals are collected (10 points per cycle for both voltage and current). The data is analyzed with DFT program in the computer to calculate the electrical impedance.
Figure 5.1 shows a typical result of the measurement of the electrical impedance variation in the welding process for a polycarbonate AWS sample. Two significant decreases of the impedance can be observed. The first one occurs in the beginning of welding and may be caused by a local collapse of the tip of the energy director. The second decrease is much more important than the first one for the understanding of the process and for the process control. In fact, the second decrease reveals the characteristics of the final stage of the welding process in which the dynamic mechanical impedance of the interface becomes very large.

The variation of the electrical power which changes inversely with the electrical impedance in the process is shown in the same figure. It can be seen that every minimum point of the electrical impedance corresponds to a maximum point of the electrical power. It is also seen that in the final stage when the electrical impedance reaches its minimum value, the electrical power attains its highest peak. Because the variation of the mechanical impedance of the interface changes inversely with the electrical impedance, the electrical power level can be used as a substitute for the mechanical impedance as a process parameter. The latter point is very useful because the electrical power level can be easily measured by a watt meter in the process.
Figure 5.1: Impedance and power variation during ultrasonic welding.
5.2 Open Loop Control Test

The open loop control experiment has been performed on polycarbonate (amorphous) and polyethylene (semicrystalline) samples. In the experiments a Branson 910 power supply was used. The maximum power output of the power supply is 1,000 watts. For both material a 1:1.5 booster was used. The welding conditions are:

<table>
<thead>
<tr>
<th>Material</th>
<th>Vibration Amplitude</th>
<th>Trigger Pressure</th>
<th>Welding Pressure</th>
<th>Hold Pressure</th>
<th>Hold Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene</td>
<td>90%</td>
<td>30 psi</td>
<td>30 psi</td>
<td>30 psi</td>
<td>1 second</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>80%</td>
<td>30 psi</td>
<td>30 psi</td>
<td>30 psi</td>
<td>1 second</td>
</tr>
</tbody>
</table>

The samples are AWS type with an energy director. For polycarbonate samples the threshold power level was changed from 200 watts to 400 watts. For polyethylene samples the threshold power level was changed from 300 watts to 600 watts. The experimental results are shown in Figure 5.2 and 5.3. For the two materials the
Figure 5.2: Effect of threshold power level on the joint strength in the open loop control (polyethylene).
Figure 5.3: Effect of threshold power level on the joint strength in the open loop control (polycarbonate).
strength of the joint is strongly related to the threshold power level. Higher threshold power level results in stronger joints.

From the process model described in Section 2 and the experimental observation in section 5.1, higher power level means higher mechanical impedance of the joint interface. From the squeeze flow model, higher mechanical impedance indicates that the molten polymer layer in the interface is thinner and spreads wider. In this condition better diffusion can be achieved. Therefore, the joints are stronger.

5.3 Closed Loop Control Test

The closed loop control tests have been performed for AWS samples on BRANSON A920 power supply in this project. In the control system, desired power level and actual power level are taken as reference and output respectively. The square of vibration amplitude of the horn is the control variable. The closed loop control uses a PID controller.

In the experiments the open loop control tests had been done before the closed loop control was carried out. The purpose of running the open loop control tests is to find the optimum welding conditions and determines the curve of power. Then, in the closed loop control tests the same welding conditions, trigger pressure, welding pressure, hold pressure etc., are used. The power level in
the closed loop control is controlled by changing the vibration amplitude of the horn. The power curves are manipulated as a two step function. In the beginning of the welding the power level rises to a relatively low level after a transition time. Then it keeps on at that level for a certain period of time. Finally, very quickly, a peak power appears as the energy director totally collapses and intimate contact of the interface is reached.

Figure 5.4 and 5.6 show the power curves obtained in open loop control for polycarbonate and for nylon. Figure 5.5 and 5.7 show the power curves in closed loop control. The gain, the derivative time and the integral time of the controller should be carefully adjusted according to the guidelines described in section 4.3.3. Because there are two power levels in the welding process, different gain, derivative time and integral time should be used with respective to the different power levels.

The experimental results of tensile test for the welded AWS samples are shown in Figure 5.8, 5.9 and 5.10. Compared to the open loop control, the closed loop control improves the quality consistency (smaller standard deviation for joint strength test) and increases joint strength for a semicrystalline polymer (nylon).

The above improvements may be due to the following reasons: First, the closed loop control process guarantees the presence of a peak in power at the final stage of welding. Because the peak in power indicates a high mechanical impedance of the interface, then, better intimate contact forms at the interface which helps to
Figure 5.4: Power curve in the open loop control for polycarbonate AWS sample.
Figure 5.5: Power curve in the closed loop control for polycarbonate AWS sample.
Figure 5.6: Power curve in the open loop control for nylon AWS sample.
Figure 5.7: Power curve in the closed loop control for nylon AWS sample.
Figure 5.8: Comparison of the joint quality between the open loop control and the closed loop control (polyester AWS sample).
Figure 5.9: Comparison of the joint quality between the open loop control and the closed loop control (polycarbonate AWS sample).
Figure 5.10: Comparison of the joint quality between the open loop control and the closed loop control (nylon AWS sample).
increase the joint strength. Second, because the closed loop control can manipulate the power curve to follow a pre-set two step function or any other function, the area under the power curve which equals the total input energy is more consistent. This may contribute to the consistency in the joint strength. For example, for nylon AWS samples, the average energy input in the experiment for open loop control and closed loop control are almost the same (open loop control: 280 Joules, closed loop control: 277 Joules). But the standard deviation of the input energy in closed loop control is much lower (222 Joules) than in open loop control (444 Joules). With improved closed loop control (better tracking of desired power) this standard deviation could be reduced further.

Figure 5.11, 5.12, and 5.13 show the comparison of the joint quality between different control processes and welding modes. The welding time in time mode is equal to the weld time of the closed loop control. The threshold values of energy and displacement in energy mode and in displacement mode are equal to the average values of the input energy and the displacement in time mode.

Comparing open loop control process and other conventional control modes (time mode, energy mode, and displacement mode), closed loop control results in the highest joint quality in both the highest joint strength and low standard deviation. This tendency appears to be very strong for semicrystalline materials like nylon.
Figure 5.11: Comparison of joint quality for different welding process and welding modes.
(polyester AWS samples)
1. closed-loop control  
2. open loop control  
3. time mode  
4. energy mode  
5. displacement mode

Figure 5.12: Comparison of joint quality for different welding processes and welding modes. (nylon AWS samples)
Figure 5.13: Comparison of joint quality for different welding process and welding modes.
(polycarbonate AWS samples)
5.4 Joint Strength and the Warping of Injection Molded AWS Samples

For the four kinds of materials used (polyester, ABS, polycarbonate, and nylon) the ultimate strength of weld joint is lower than the bulk material. In most cases the ultimate joint strength is about 50-60% of the ultimate strength of the bulk materials. Examining the failure area indicates that the warping of the samples (generated in the process of injection molding) results in the low weld strength. In many cases the crack initiates in the middle of the joint because of the warping. Figure 14 show the warping of the top parts and the bottom parts for the injection molded samples. Table 5.1 gives the measured values of the warping for the four materials. Comparing the height of the energy director 0.015" (see Figure 2.5), to the warpage shows that it is too large to be neglected.

Figure 15 shows the photograph of poorly welded area in the middle of an AWS sample where the energy director is not fully molten and the cracks initiate

5.5 The Effect of Hold Pressure on Joint Strength

Because the P-691 pressure regulator was installed in the ultrasonic welding system, the pressure can be adjusted during the process. The effect of hold pressure on the joint strength was
Figure 5.14: Warping of injection molded AWS samples.
Table 5.1: Warping (inches) of AWS Samples.

<table>
<thead>
<tr>
<th>Materials</th>
<th>d1</th>
<th>d2</th>
<th>d3</th>
<th>d4</th>
</tr>
</thead>
<tbody>
<tr>
<td>polyester</td>
<td>0.010</td>
<td>0.004</td>
<td>0.006</td>
<td>0.004</td>
</tr>
<tr>
<td>ABS</td>
<td>0.009</td>
<td>0.003</td>
<td>0.004</td>
<td>0.001</td>
</tr>
<tr>
<td>polycarbonate</td>
<td>0.010</td>
<td>0.001</td>
<td>0.007</td>
<td>0.001</td>
</tr>
<tr>
<td>nylon</td>
<td>0.010</td>
<td>0.003</td>
<td>0.006</td>
<td>0.003</td>
</tr>
</tbody>
</table>
Plate VII: Photograph of poorly welded area in the middle of an AWS sample.
investigated. In section 3.4.1 it is seen that the transient time of the change of the pressure is about 0.15 second when down speed is set for 4.0"/second (the highest down speed). To guarantee that the value of hold pressure is reached before the molten polymer solidifies, the command to change the pressure was sent to the regulator 0.2 seconds before the end of welding. To avoid overload in the beginning of welding the down speed in all experiments was set to 2.46"/seconds. Figure 15 and 16 show the changes of the pressures in the experiments for polyester. The chosen hold pressures are reached in the beginning of the hold time.

The samples used are injection molded AWS samples. A 1:1.5 booster was used for the welding. In the experiments the welding conditions (see table 5.2) which were obtained from the optimization process of the welding parameters for the four materials were:

<table>
<thead>
<tr>
<th>Material</th>
<th>Weld Time</th>
<th>Relative Amplitude</th>
<th>Weld Pressure</th>
<th>Hold Time</th>
<th>Hold Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester</td>
<td>1.0 seconds</td>
<td>60%</td>
<td>35 psi</td>
<td>1.0 seconds</td>
<td>20, 35, 45 psi</td>
</tr>
<tr>
<td>ABS</td>
<td>0.6 seconds</td>
<td>50%</td>
<td>30 psi</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 15: Hold pressure in the welding process (the hold pressure is higher than the welding pressure).
Figure 16: Hold pressure in the welding process (the hold pressure is lower than the welding pressure).
Table 5.2: Optimum Welding Conditions for Four Materials

(booster 1:1.5)

<table>
<thead>
<tr>
<th>material</th>
<th>vibration amplitude (%)</th>
<th>weld pressure (psi)</th>
<th>weld time (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>polyester</td>
<td>60</td>
<td>35</td>
<td>1.0</td>
</tr>
<tr>
<td>ABS</td>
<td>50</td>
<td>30</td>
<td>0.6</td>
</tr>
<tr>
<td>polycarbonate</td>
<td>60</td>
<td>30</td>
<td>0.7</td>
</tr>
<tr>
<td>nylon</td>
<td>70</td>
<td>30</td>
<td>1.2</td>
</tr>
</tbody>
</table>
hold time: 0.6 seconds
hold pressure: 20, 30, 40 psi

Polycarbonate
weld time: 0.7 seconds
relative amplitude: 60%
weld pressure: 30 psi
hold time: 0.7 seconds
hold pressure: 20, 30, 40 psi

Nylon
weld time: 1.2 seconds
relative amplitude: 70%
weld pressure: 30 psi
hold time: 1 second
hold pressure: 20, 30, 40 psi

Figure 5.17, 18, 19, and 20 show the effects of hold pressure on the welded joint strength for polyester, ABS, polycarbonate, and nylon respectively. For polyester the change of hold pressure does not effect the joint strength (Figure 17). For ABS and polycarbonate (Figure 18, 19) higher hold pressure reduces the average strength of the joints. It may be caused by the orientation of polymer chains. On the other hand, the lower hold pressure reduces slightly the average strength of the joints. One possible reason for the reduction may be the lower power level when the welding pressure is decreased. In addition, due to the warpage of the samples the low hold pressure
Figure 5.17: Effect of the hold pressure on the joint strength (polyester AWS sample).
Figure 5.18: Effect of the hold pressure on the joint strength (ABS AWS sample).
Figure 5.19: Effect of the hold pressure on the joint strength (polycarbonate AWS sample).
Figure 5.20: Effect of the hold pressure on the joint strength (nylon AWS sample).
may increase the size of the poorly welded area in the middle of the weld (see Plate VII). From the above experimental results, it seems that the optimum hold pressure is related to the material property.

5.6 Effect of Hold Pressure on the Joint Strength for Mechanically Machined AWS Samples

To minimize the effect of warpage, polycarbonate (LEXAN) AWS samples were machined from polycarbonate plate, 0.5" thick. During machining, the cutting speed was carefully chosen to avoid heating.

Then, the samples were welded under different hold pressure. The booster was 1:2. The weld conditions were:

- weld time: 1.0 seconds
- vibration amplitude: 50%
- weld pressure: 30 psi
- hold time: 1.0 seconds
- hold pressure: 25, 30, 40 psi

The command to change the hold pressure was sent to regulator 0.1 seconds before the end of welding. Figure 5.21 shows that the joint strength is related to the hold pressure; the higher the hold pressure, the lower the joint strength.
Figure 5.21: Effect of hold pressure on the joint strength for mechanically machined polycarbonate AWS samples.
Chapter VI

Conclusions and Recommendations

Ultrasonic welding of thermoplastics is a complicated process. The electromechanical analogy model used in this project aids in understanding the process. The theoretical calculations of the model for air load, and end of welding agree with the experimental results. The theoretical results of the model further support the conclusions obtained by the multi-mass lumped parameter model proposed by Benatar [11].

Open loop control tests with the power level as a control parameter show that the strength of the welding joint is strongly related to the power level. The higher the power level, the stronger the joint.

Closed loop control using a PID controller improves both in the joint strength and the quality consistency for both amorphous and semicrystalline polymers. Therefore, closed loop control will play an important role in the quality assurance of ultrasonically welded plastic parts.

The effect of hold pressure on the joint strength was observed. For polyester, the change of hold pressure does not affect the joint
strength. Experimental results on ABS and polycarbonate AWS samples show that the higher hold pressure reduces the average joint strength. On the other hand, lower hold pressure lightly reduces average strength of the joint. For nylon, lower hold pressure reduces the average strength probably because of the high viscosity of the molten polymer and the warpage of the injection molded AWS sample. For mechanically machined AWS polycarbonate AWS sample, experimental results show that lower hold pressure improves the joint strength.

The research also reveals the following aspects to which more attention should be paid in the future. First, other closed loop control methods should be studied. Because there are many disturbances and uncertainties in ultrasonic welding, simple PID controller is not effective enough to fulfill the control task. Especially, it is difficult to find a time function for the gains to fit every part of the process. A possible alternative control method is adaptive control. Adaptive control can deal with uncertainties appearing in the process and it has learning ability [44,45]. Figure 6.1 shows a block diagram of a proposed adaptive control of ultrasonic welding based on the present PID controller. In the diagram a new loop is added to the original control loop. Through this loop, process data are collected from the output of the process. Then, control parameters are estimated from the data. The estimation
Figure 6.1: Diagram of adaptive control for ultrasonic welding.
will be used to design new parameters for the PID controller, for example $q$, $T_i$, and $T_d$.

In this research, only the amplitude of the horn vibration is used as the control variable. In fact, other parameters, for example, the pressure, also play an important role in the power output. Besides the power level, displacement or the collapse of the energy director may be considered as an output of the ultrasonic welding control process. In this control mode the input energy during the process and the final dimensions can be controlled. Therefore, the joint quality may be improved by using a linear servo actuator to control the welding force or welding displacement.
Appendix A

State Equations of Ultrasonic Welding System
A. Benatar derived the state equations for the ultrasonic welding system shown in Figure 1.4 [47]. The procedure is: first, write elemental equations and corresponding junction equations; then, combine the elemental and junction equations to obtain state equations. The following are all the state equations of the ultrasonic welding system showing in Figure A.1:

\[
\frac{dV_{m2}}{dt} = \frac{1}{m_2 + m_1} (F_0 + m_1 \frac{dV_0}{dt} - f_{k2} - b_2 V_{m2} + b_2 V_{m7})
\]

\[
\frac{d f_{k2}}{dt} = k_2 (V_{m2} - V_{m7})
\]

\[
\frac{dV_{m3}}{dt} = \frac{1}{m_3} (f_{k3} + b_3 V_{m3} - b_n V_{m3} - f_{k3} - b_3 V_{m3} + b_3 V_{m4})
\]

\[
\frac{d f_{k3}}{dt} = k_3 (V_{m3} - V_{m4})
\]

\[
\frac{dV_{m4}}{dt} = \frac{1}{m_4} (f_{k3} + b_3 V_{m3} - b_3 V_{m4} - f_{k4})
\]

\[
\frac{d f_{k4}}{dt} = k_4 (V_{m4} - V_{m5})
\]
Figure A.1: Ultrasonic welding system and corresponding lumped parameter model. (copy of Figure A.1)
\[
\frac{dV_{m5}}{dt} = \frac{1}{m_5} (f_{k4} - f_{k5})
\]

\[
\frac{df_{k5}}{dt} = k_5 (V_{m5} - V_{m6})
\]

\[
\frac{dV_{m6}}{dt} = \frac{1}{m_6} (f_{k5} - f_{k6} - b_6 V_{m6})
\]

\[
\frac{df_{k6}}{dt} = k_6 V_{m6}
\]

For the energy director the state equations are:

\[
\frac{dV_{m1}}{dt} = \frac{1}{m_1} (f_{k2} + b_2 V_{m2} - b_2 V_{m7} - f_{k7} - b_7 V_{m7} + b_7 V_{m8})
\]

\[
\frac{df_{k7}}{dt} = k_7 (V_{m7} - V_{m8})
\]

\[
\frac{dV_{m_i}}{dt} = \frac{1}{m_i} (f_{k_{i-1}} + b_{i-1} V_{m_{i-1}} - b_{i-1} V_{m_i} - f_{ki} - b_i V_{m_i} + b_i V_{m_{i+1}})
\]

\[
\frac{df_{ki}}{dt} = k_i (V_{m_i} - V_{m_{i+1}})
\]

for \( i = 8, 9, \ldots, n-1 \)
\[
\frac{dV_{mn}}{dt} = \frac{1}{m_n} (f_{kn-1} + b_{n-1}V_{mn-1} - b_{n-1}V_{mn} - f_{kn} - b_n V_{mn} + b_n V_{m3})
\]

\[
\frac{df_{kn}}{dt} = k_n (V_{mn} - V_{m3})
\]
Appendix B

Calculations of Voltage and Current in Equivalent Circuit
Volatges and current in equivalent circuit (see Figure B.1) are calculated with MATHCAD program.

The motional voltage is a square wave which is a sum of the fundamental component (20 KHz) and higher odd harmonics, for example 60 KHz, 100 KHz..., etc. The RMS value of the voltage is 930 volts. The expression of the voltage $V_g(t)$ is:

$$V_g(t) = \frac{4}{\pi} \cdot 930 \cdot \sum_i \frac{\exp(i \cdot j \cdot \omega t)}{i}$$

where $\omega$ is circular frequency, $j$ unit of imaginary number, $t$ time, $i$ the odd order of harmonics.

The current in the circuit can be calculated from the voltage and the impedance. Following are the calculations of the impedance (see Figure 2.2):

$$Z_{L_8}(i) = j \cdot i \cdot \omega \cdot L_8$$

$$Z_{L_m}(i) = j \cdot i \cdot \omega \cdot L_m$$

$$Z_{L_1}(i) = j \cdot i \cdot \omega \cdot L_1$$

$$Z_{C_e}(i) = \frac{1}{j \cdot i \cdot \omega \cdot C_e}$$

$$Z_{C_m}(i) = \frac{1}{j \cdot i \cdot \omega \cdot C_m}$$

$$Z_{C_{t}}(i) = \frac{1}{j \cdot i \cdot \omega \cdot C_t}$$

$$Z_I(i) = Z_{L_8}(i) + R_g + Z_{C_m}(i)$$
Figure B.1: Equivalent circuit of an ultrasonic system.
(copy of Figure 2.2)
\[ Z_2(i) = \frac{(Z_{Lm}(i) + R_m) \cdot Z_{cm}(i)}{Z_{Lm}(i) + R_m + Z_{cm}(i)} \]

\[ Z_3(i) = \frac{Z_{Lt}(i) \cdot R_t \cdot Z_{Cl}(i)}{Z_{Lt}(i) \cdot R_m + Z_{Lt}(i) \cdot Z_{Cl}(i) + R_t \cdot Z_{Cl}(i)} \]

\[ Z_t(i) = Z_1(i) + \frac{Z_2(i) \cdot Z_3(i)}{Z_2(i) + Z_3(i)} \]

The current, therefore, can be calculated from the voltage and the impedance:

\[ I_g(t) = \frac{4}{\pi} \cdot 930 \cdot \sum_i \frac{\exp(i \cdot j \cdot \omega \cdot t)}{i \cdot Z_t(i)} \]

The voltage after the converter is equal to:

\[ V_{out}(t) = \frac{4}{\pi} \cdot 930 \cdot \sum_i \frac{\exp(i \cdot j \cdot \omega \cdot t) \cdot Z_2(i)}{i \cdot Z_t(i)} \]
Appendix C

DFT Program
About DFT Program

1. The DFT program performs Discrete Fourier Transformation to two sets of signals.

2. The program calculate the amplitudes and phase angles of the above two signals for their fundamentals and the harmonics.

3. The input data is in text mode.

4. The highest harmonics obtained depends on the size of set of the signal to be analyzed. According to the Sampling Theorem following relation exists:

   \[ N \geq 2K + 1 \]

   where \( N \) is the number of samples per fundamental period and \( K \) the highest harmonic in the Fourier series.
/ * DFT program */
/* The program receive 10 measured values for each of two periodic
 signals with 20 kHz frequency. The program do DFT for the two
 signals
 and calculate modes and phase angle between them. */

#include <math.h>
#include <stdlib.h>
#include <io.h>
#include <stdio.h>
#include <errno.h>
#include <graph.h>

FILE *stream;

main ()
{
  int i, j, k, n, m, number;
double fir[100], fl[100], fvr[100], fvi[100], zr[100], zi[100],
       mo[100], mov[100], moz[100], alf[100], alf[100], alfavl[100];
  float ft[100], fvt[100], tf, delta;
double a, pi, ai, av, tir, tii, tvr, tvi, atv, cwt, swt, phi, va;
  char fname[20];
  pi=3.1415926;

  printf("\n\n Enter the name of data file : ");
  scanf("%s", fname);
  printf("\n\n Enter the size of point set : ");
  scanf("%d", &n);
  printf("\n\n Enter the highest harmonics you want to analize : ");
  scanf("%d", &k);
  printf("\n\n enter phase angle (degree) : ");
  scanf("%f", &delta);
  printf("\n\n enter amplitudes of V and I : ");
  scanf("%lf %lf", &av, &ai);

  /* stream=fopen(fname,"r");

  for (i=0; i<n; i++)
  {
    fscanf ( stream, "%f", &tf);
    ft[i]=tf;
    fscanf ( stream, "%f", &tf);
    fti[i]=tf;

    */
for (i=0; i<n; i++)
    printf("n i = %f v=%f ", fti[i], ftv[i]);

fclose (stream);
*/

for (i=0; i<n; i++)
{
    
    fti[i]=ai*sin(2*pi*i/n)+ai*sin(4*pi*i/n)+av*cos(6*pi*i/n);
    ftv[i]=av*sin(2*pi*i/n+(10.0+delta)*pi/180);
}

for (i=0; i<k+1; i++)
{
    a = 2*pi*i/n;
    tir =0; tii=0; tvr=0; tvi=0;

    for ( j=0; j<n; j++)
        {
            fir[i]=tir+fti[j]*cos(a*j);
            fiii[i]=ti-ffi[j]*sin(a*j);
            tir=fir[i];
            tii=ffii[i];
            fvr[i]=tvr+ftv[j]*cos(a*j);
            fvi[i]=tv-ftv[j]*sin(a*j);
            tvr=fvr[i];
            tvi=fvi[i];
        }
    moi[i]=(sqrt(fir[i]*fir[i]+fii[i]*fii[i]))*2/n;
    if (fabs(fir[i]) < 1e-30 ) alfai[i]=90.0;
    else
        {
            atv=ffii[i]/fir[i];
            if (fabs(atv) < 1e-30 ) alfai[i]=0;
            else alfai[i]= atan(atv)*180.0/pi;
        }
    mov[i]=(sqrt(fvr[i]*fvr[i]+fvi[i]*fvi[i]))*2/n;
    if (fabs(fvr[i]) < 1e-30 ) alfav[i]=90.0;
    else
        {
            atv=fvi[i]/fvr[i];
            if (fabs(atv) < 1e-30 ) alfav[i]=0;
            else alfav[i]= atan(atv)*180.0/pi;
        }
    zr[i]=(fir[i]*fvr[i]+fii[i]*fvi[i])/(fir[i]*fir[i]+fii[i]*fii[i]);
zi[i] = (fi[i] * fvi[i] -
    fii[i] * fir[i]) / (fir[i] * fir[i] + fii[i] * fii[i]);
mo[i] = sqrt(zr[i] * zr[i] + zi[i] * zi[i]);

    if (fabs(zr[i]) < 1e-30)  alfaz[i] = 90.0;
    else
      at[i] = zi[i] / zr[i];
      if (fabs(at[i]) < 1e-30)  alfaz[i] = 0;
      else  alfaz[i] = atan(at[i]) * 180.0 / pi;
    }
  
  if (zi[i] > 0 && zr[i] < 0)  alfaz[i] = 180.0 + alfaz[i];
  if (zi[i] < 0 && zr[i] < 0)  alfaz[i] = 180.0 + alfaz[i];

  cwt = (ftv[2] + ftv[0]) / (2 * ftv[1]);
  swt = sqrt(1 - cwt * cwt);
  phi = atan(swt / (ftv[1] / ftv[0] - cwt));
  va = ftv[0] / sin(phi);

  for (i = 0; i < k1; i++)
  {
    printf("\n nir[\d]=%8.4f\ni[i]=%8.4f\nmoi[\d]=%8.4f\nalfai[\d]=%8.4f",
                        i, fir[i], i, fii[i], i, moi[i], i, alfai[i]);
    printf("\n fvi[\d]=%8.4f\n mov[\d]=%8.4f\n alfav[\d]=%8.4f",
                        i, fvi[i], i, mov[i], i, alfav[i]);
    printf("\n zr[i]=%8.4f\n moz[\d]=%8.4f\n alfaz[\d]=%8.4f",
                        i, zr[i], i, moz[i], i, alfaz[i]);
    printf("\n va=%8.4f " , va);
  }
}
Appendix D

Horn Design Program
About HD Program

1. The program HD is used to design a step horn.

2. The principle of the design is based on one dimensional compressive wave theory. It assumes that the lateral dimension of the horn should be at least less than a quarter of the wave length.

3. The program inputs are:
   - longitudinal wave velocity of ultrasound in the bulk material
   - shear wave velocity of ultrasound in the bulk material
   - density of the material
   - length of one side of the step horn

4. The program outputs are:
   - length of other side of the horn
   - amplification coefficient of the horn

5. The program plots distribution of displacement and stress inside the horn.
HD1
Horn Design 1 (step section)

draw the draft of horn

SCREEN 2
LOCATE 2, 30: PRINT " Horn Design 1"
LINE (100, 30)-(400, 30)
LINE (100, 30)-(100, 70)
LINE (100, 70)-(400, 70)
LINE (400, 70)-(400, 30)
LINE (400, 40)-(500, 40)
LINE (400, 60)-(500, 60)
LOCATE 7, 28: PRINT "top end"
LOCATE 7, 53: PRINT "tool end"
LINE (100, 70)-(100, 90)
LINE (100, 85)-(220, 85)
LINE (400, 70)-(400, 90)
LINE (400, 85)-(280, 85)
LINE (500, 60)-(500, 90)
LINE (400, 85)-(420, 85)
LINE (500, 85)-(480, 85)
LINE (500, 40)-(500, 60)
LOCATE 11, 32: PRINT "L1"
LOCATE 11, 56: PRINT "L2"
LOCATE 7, 10: PRINT "S1"
LOCATE 7, 65: PRINT "S2"

PRINT " "
PRINT " "
PRINT " "
PRINT " "
PRINT " "
PRINT " "

input data and calculate the parameters of horn

INPUT "the area of top end (in.in.)" S1="; S1
INPUT "the area of tool end (in.in.)" S2="; S2
INPUT "the length of tool end (in.)" L2="; L2
INPUT "longitudinal velocity (m/s)" Vl="; Vl
INPUT "transverse velocity (m/s)" Vt="; Vt
INPUT "density of the material (kg/m.m.m.)" D="; D
PRINT " "
MU = D * Vt ^ 2
LAMDA = D * (V1 ^ 2 - 2 * Vt ^ 2)

E = MU * (3 * LAMDA + 2 * MU) / (LAMDA + MU)
V = SQR(E / D)
PRINT "compressing wave velocity (m/s) ="; V

L1 is the length of top end of the horn (in.)
L1 = (V / (314.16 * 4 * 2.54)) * (3.1416 + ATN(-(S2 / S1) * TAN(314.16 * 2.54 * 4 * L2 / V)))

XD is the position of nodal section from top end surface (in.)
XD = V * 100 / (2.54 * 4 * 20000)

K is the amplitude magnification factor
K = (S1 / S2) * SIN(2 * 314.16 * 2 * 2.54 * L1 / V) / SIN(2 * 314.16 * 2 * 2.54 * L2 / V)
PRINT " "
PRINT "The design parameters are:"
PRINT "The length of top end section L1 ="; L1;
"(in.)"
PRINT "The distance of nodal section from S1 XD="; XD; "(in.)"
PRINT "The amplitude magnification factor K="; K;

END
LOCATE 2, 10: PRINT "Relative velocity and stress distributions in the horn"
LOCATE 8, 5: PRINT "1"
LOCATE 18, 5: PRINT "-1"
LOCATE 15, 35: PRINT "velocity"
LOCATE 9, 40: PRINT "stress"
' input parameters

L1 = 4.6597
L2 = .75
V = 194488
pi = 3.1416
k1 = 2 * pi * 20000 / V
k2 = k1
S1 = 2
S2 = .5
'
the formula of velocity and stress

DEF FNV1 (x)
FNV1 = COS(k1 * x)
END DEF

DEF FNV2 (x)
FNV2 = -(S1 / S2) * SIN(k1 * L1) * SIN(k2 * x) + COS(k1 * L1) * COS(k2 * x)
END DEF

DEF FNT1 (x)
FNT1 = SIN(k1 * x)
END DEF

DEF FNT2 (x)
FNT2 = (S1 / S2) * SIN(k1 * L1) * COS(k2 * x) + COS(k1 * L1) * SIN(k2 * x)
END DEF
'
draw the distribution curves

l = L1 + L2
dL = l / 520

N1 = INT(L1 / dL)
N2 = INT(L2 / dL)

LINE (N1 + 60, 40)-(N1 + 60, 170)
LINE (60, 165)-(30 + N1 / 2, 165)
LINE (N1 / 2 + 80, 165)-(N1 + 60, 165)
LINE (60 + N1, 165)-(40 + N1 + N2 / 2, 165)
LINE (40 + N1 + N2, 165)-(580, 165)
LOCATE 21, 35: PRINT "L1"
LOCATE 21, 68: PRINT "L2"

velocity distribution in the top end

I = 0
x0 = 60
y0 = FNV1(0)
IF y0 < 0 THEN
y0 = -y0 * 40 + 100
ELSEIF y0 >= 0 THEN
y0 = 100 - y0 * 40
END IF
FOR I = 1 TO N1
x1 = x0
y1 = y0
x2 = x1 + 1
x = I * dL
y = FNV1(x)
IF y < 0 THEN y2 = -y * 40 + 100
y2 = 100 - y * 40
LINE (x1, y1)-(x2, y2)
x0 = x2
y0 = y2
NEXT I

velocity distribution in tool end

J = 0
x0 = x0
y0 = FNV2(0)
IF y0 < 0 THEN
y0 = -y0 * 40 + 100
ELSEIF y0 >= 0 THEN
y0 = 100 - y0 * 40
END IF
FOR J = 1 TO N2
x1 = x0
y1 = y0
x2 = x0 + 1
x = J * dL
y = FNV2(x)
IF y < 0 THEN y2 = -y * 40 + 100
y2 = 100 - y * 40
LINE (x1, y1)-(x2, y2)
x0 = x2
\[ y_0 = y_2 \]

```
NEXT J

stress distribution in top end

II = 0
x0 = 60
y0 = FNT1(0)
IF y0 < 0 THEN
y0 = -y0 * 40 + 100
ELSEIF y0 >= 0 THEN
y0 = 100 - y0 * 40
END IF
FOR II = 1 TO N1
xi = x0
yi = y0
x2 = xi + 1
x = II * dL
y = FNT1(x)
IF y < 0 THEN
y2 = -y * 40 + 100
ELSEIF y >= 0 THEN
y2 = 100 - y * 40
END IF
LINE (xi, yi)-(x2, y2)
x0 = x2
y0 = y2
NEXT II

stress distribution in tool end

II = 0
x0 = x0
y0 = FNT2(0)
IF y0 < 0 THEN
y0 = -y0 * 40 + 100
ELSEIF y0 >= 0 THEN
y0 = 100 - y0 * 40
END IF
FOR II = 1 TO N2
xi = x0
yi = y0
x2 = xi + 1
x = II * dL
y = FNT2(x)
IF y < 0 THEN
y2 = -y * 40 + 100
ELSEIF y >= 0 THEN
```
\[ y_2 = 100 - y \times 40 \]
END IF
LINE (x_1, y_1)-(x_2, y_2)
x_0 = x_2
y_0 = y_2
NEXT I_2
END
Appendix E

Open Loop Control Program for Ultrasonic Welding: OCWP.C
About OCUMP.C Program

1. OCUMP.C program performs an open loop control for ultrasonic welding.

2. The structure of the program can be found in Fig.4.18 and Fig.4.19 of this dissertation.

3. The program is used on Branson A920 power supply which has vibration amplitude control function.

4. The program is associate with a data acquisition system SHDAS-12. Two A/D channels are for pressure and power level measurements. Two D/A channels are used to control weld pressure and vibration amplitude respectively. On/off switch of sonics and solenoid are controlled by I/O port of the data acquisition system.

5. A threshold value of power level can be set by users as a control parameter to end the welding process.

6. To avoid the over welding and the damage to the power supply, a maximum welding time limitation or a maximum energy limitation can be preset to deal with the low power level situation.
/* OCDWP.C open loop control program for ACME 920AM */
/* Power is taken as control parameter. When the threshold value of the
 power is reached within time window the process is terminated
 automatically*/
/* The power is measured from power meter pin4 J50 on the control board
*/
/* Vibration amplitude is controlled through J2 on the rear panel */
/* The control board is alfa type? units */
/* time window is set */

#include <share.h>
#include <fcntl.h>
#include <math.h>
#include <malloc.h>
#include <stdlib.h>
#include <stdio.h>
#include <graph.h>
#include <sys\types.h>
#include <sys\stat.h>
#include <process.h>
#include <errno.h>
#include <io.h>
#include <time.h>
#include <adas_defs.h>
#include <das.h>
#include <5312.h>

#define BCOLOR 4
#define RATE 186

/* there are no low contrast color selected */
static int color_map[16]={15,14,10,12,11,9,0,10,7,6,5,4,3,15,14,13};
extern int gtdata(unsigned short far *, int, double far *, double, int);

/* start the program */

main ()
{
  void plot_box(void);

  FILE *streamf;

  int ierr,i,i1,i2,j,ja,k,kk,ka,k1,k2;
  int base addr, bd_type, dac_dma_channel, adc_dma_channel,b_addr;
  int dma_timeout;
  int x0, y0, x1, y1;

  long c1,c2;
unsigned short *input_data, *input_force, *input_amplitude;
unsigned short *dac0data, *dac1data;

char s[10], fname[10];

clock_t start, finish, t0, t1, t2, t3, t4;

double *volts1, *volts2;

double eus_per_volt, dt, dt0, dt1, dt2, dt3, dt4, dt5, tj;

float real_pressure, trigger_pressure, hold_pressure, weld_pressure,
     weld_time_max, weld_time_min, hold_time, power_max, amplitude_level;

float ox, en, tn, forcep, tc, prn[9], pon[9];

float far *force, *energy, *power, *collapse;

struct dacspec dac0setup, dac1setup;

extern struct das_CFG das_cfg_table;

/* allocated buffers for input data and DAC channels */
input_data = (unsigned short*) calloc(18, sizeof(unsigned short));
input_force = (unsigned short*) calloc(1, sizeof(unsigned short));
input_amplitude = (unsigned short*) calloc(1, sizeof(unsigned short));
volts1 = (double *) calloc(9, sizeof(double));
volts2 = (double *) calloc(9, sizeof(double));

dac0data = (unsigned short *) calloc(1, sizeof(unsigned short));
dac1data = (unsigned short *) calloc(1, sizeof(unsigned short));

force = (float *) calloc(5000, sizeof(float));
energy = (float *) calloc(4000, sizeof(float));
power = (float *) calloc(4000, sizeof(float));
collapse = (float *) calloc(4000, sizeof(float));

/* set graphic mode */
_clearscreen (_GCLEARSCREEN);
_setvideomode (_FRESCOLOR); /**<640x350, 4 or 16 color */
_setbkcolor (_LIGHTBLUE);

while (!kbhit())
{
    _settextposition(7,14);
    printf(" Welcome! \n\n\n\n\n\n"");
    printf(" You are running OCEDIT.C 

program\n\n\n\n\n");
    printf(" For safety, please turn off switch 
!
\n\n\n\n");
    printf(" Then, hit any key to continue");
}
/* initiate the SHDAS12 board with "bdinit" */
base_addr = 0x300;  b_addr = 0x31a;
ad_c_dma_channel = 5;  dac_dma_channel = 6;

 ierr=bdinit(base_addr,&bd_type,adc_dma_channel,dac_dma_channel);
 init_encoder(AXIS_A,MCR,ICR,OCR,QR,b_addr);

 setdio(1,1);  /* close solenoid and sonics */
 *input_force = 819*(1.354+0.03646*30);  /* preset pressure 30psi*/
 dac0setup.data = (int *)input_force;
 dac0setup.data_buf_size = 1;
 dac0setup.dac_rate = 100;
 dac0setup.update_path = 0;
cfgdac (&dac0setup, &dac1setup);
 outdio(0);

 if (ierr<0)
  {printf("\n\a %d Data Acquisition Board Malfunction", ierr);
   exit(-1); }

kk=getch();  /* empty the console */

  _clearscreen (G_CLEARSCREEN);
  _setvideomode (_E_16COLOR);  /* 640x350 4 or 16 color */
  _setbgcolor (_LIGHTBLUE);

  while (!kbhit())
  {
    _settextcolor(color_map[1]);
    _settextposition (5,18);
    _outtext("SHDAS-20 BOARD HAS BEEN SUCCESSFULLY INSTALLED\n\n");
    _settextposition (10,18);
    printf(" The board type is : %d \n\n",bd_type);
    _settextposition (15,18);
    _outtext("Turn the switch on !\n");
    _settextposition (19,18);
    _outtext("Press any key to input welding parameters\n");
  }

/* input trigger force, weld time, and hold time */
kk = getch();  /* empty the console */
  _clearscreen (G_CLEARSCREEN);
  _setvideomode (_V_16COLOR);
  _setbgcolor (_LIGHTBLUE);

  while (kk != 'Y')
  {
    _clearscreen (G_CLEARSCREEN);
    _settextposition(1,1);
    printf("\n Please input following parameters:\n");
printf("\n\n\ninput weld pressure (<100psi) : ");
scanf("%f", &weld_pressure);
printf("\ninput trigger pressure (psi) : ");
scanf("%f", &trigger_pressure);
printf("\ninput hold pressure (<100psi) : ");
scanf("%f", &hold_pressure);
printf("\ninput amplitude level (0-100percent) : ");
scanf("%f", &amplitude_level);
printf("\ninput maximum power (Watts) : ");
scanf("%f", &power_max);
printf("\n\n\ninput minimum weld time (seconds) : ");
scanf("%f", &weld_time_min);
printf("\n\n\ninput maximum weld time (seconds) : ");
scanf("%f", &weld_time_max);
printf("\n\n\ninput hold time (seconds) : ");
scanf("%f", &hold_time);
printf("\n\n\nif the parameters are correct, hit [ y ] and wait");
printf("\n\n\nor press any other key to input correct values");
kk = getch();
}
kk = 0;

dma_timeout = 0; /* set time_out function */
stdio (dma_timeout);

do
{

/* open solenoid and set trigger force */
outdio(1);
*input_force = 819*(1.354+0.03646*trigger_pressure); /* p691 */
dac0setup.data = (int *) input_force;

cfgdac (&dac0setup, &dac1setup);

/* configure the A/D converter with ocw.cfg */
adinit ("ocwp.cfg");

/* check if the weld pressure is high enough to trigger sonic */
eus_per_volt = 1.0;
real_pressure = 0;
t0 = clock();
while ( real_pressure < trigger_pressure )
{
get dma(input data, 9);  
gt dat(input data, 1, volts1, 1, 1);  
real pressure = volts1[0]*20.58-10.0; /* (change 12.76) to 10.0 */  
Vout relation */

/* sensitivity of pressure sensor: 0.02volts/psi */

t1 = clock();  
dt0=(double)(t1-t0)/CLOCKS_PER_SEC;  
if ( dt0 > 10 ) /* terminate the process after 10 sec */  
{
    out dio(0);  
    printf(" The real force is smaller than weld  
force\n\n");  
    printf(" Adjust pressure and try again");  
    exit(0);  
}


/* set weld pressure and amplitude */
*input force = 819*(1.354+0.03646*weld_pressure); /* p691 */
dac0setup.data = (int *) input_force;  

*input amplitude = 409*(amplitude_level/10);  
dac1setup.data = (int *) input_amplitude;  
dac1setup.data_buf_size = 1;  
dac1setup.dac_rate =100;  
dac1setup.update_path = 0;  
cfgddac (&dac0setup, &dac1setup);

/* turn sonic on and start welding process */
out dio(3);  
t0=clock();  
j=0;

/* acquire data and start control process */
do  
{
    get dma(input data,18);  
gt dat(input data,1,volts1,eus_per_volt,9);  
gt dat(input data,2,volts2,eus_per_volt,9);  

t1=clock();  
dt1=(double)(t1-t0)/CLOCKS_PER_SEC;  

for (i=0; i<9; i++)
{ prn[i]=volts1[i]; pon[i]=volts2[i]; }

for (i1=0; i1<7 ; i1++) /* numerical filter */
{ for (i2=i1+1; i2<8 ; i2++)
  {
    if ( prn[i1] > prn[i2] )
      { cx=prn[i2]; prn[i2]=prn[i1]; prn[i1]=cx; }
    if ( pon[i1] > pon[i2] )
      { cx=pon[i2]; pon[i2]=pon[i1]; pon[i1]=cx; }
  }
}

force[j]=(prn[4]-0.96)*183.215;
power[j]=pon[4]*200;

if (j<1)
  {
    c1=read_cntr(Axis_A, b_addr);
collapse[j]=0;
    energy[j]=power[j]*0.0033; /* 1/RATE(300)=0.0033 */
  }
else
  {
    c2=read_cntr(Axis_A, b_addr);
collapse[j]=(c1-c2)*0.0001+collapse[j-1];
    ci=c2;
    energy[j]=energy[j-1]+power[j]*0.003333;
  }

if ( dt1 >= weld_time_max )
  {
    outdic(1); /* turn sonic off */
    *input_force = 819*(1.354+0.03646*hold_pressure);
dac0setup.data = (int *)input_force;
cfgdac (&dac0setup, &dac1setup);
jc=j;
    _clearscreen (_GCLEARSCREEN);
    while ( !kbhit() )
    {
      _settextposition (7,10);
      printf ("\n\nwarning: the process was terminated\n");
      printf ("\n\nweld time >= weld_time_max!\n");
      printf ("\n\npress any key to plot data\n");
    }kk=getch();
    break;
  }
j = j+1;

}
while (dt1<weld_time_min || (dt1>=weld_time_min && power[j-1]<power_max));
ja=j-1;

/* sonic off and hold time begin with ct1ihold.cfg */
outdio(1);
*input_force = 819*(1.354+0.03646*hold_pressure); /* set hold pressure */
dac0setup.data = (int *)input_force;
cfgdac (&dac0setup, &dac1setup);

start=clock(); j=0; k1=1;

do
{

gtdata(input_data,18);
gtdata(input_data,1,volts1,eus_per_volt,9);
for (i=0; i<9; i++) prn[i]=volts1[i];
for (i1=0; i1<7; i1++)
{
  for (i2=i1+1; i2<8; i2++)
  {
    if ( prn[i1] > prn[i2] )
    {
      cx=prn[i2]; prn[i2]=prn[i1]; prn[i1]=cx;
    }
  }
}
force[ja+k1]=(prn[4]-0.96)*183.215;
k1=k1++;
for (i=0; i<1800; i++) tc=3/5;
finish=clock();
dt4=(double)(finish-start)/CLOCKS_PER_SEC;
}
while ( dt4 < hold_time ); ka=k1-1;

/* raise stack and recover pressure 30psi */
outdio(0);
*input_force = 819*(1.354+0.03646*30); /* recover 30psi presurre */
dac0setup.data = (int *)input_force;
cfgdac (&dac0setup, &dac1setup);
/* the end of the welding and the data writing process */
/* display and save data */
while ( kk != 'r' )
{
  _clearscreen (_GCLEARSCREEN);
printf("\n The process is over and the data has been recorded\n");
printf("\n the sample rate is %6.1f \n", ja/dti1);
printf("\n total data points ja = %d\n\n",ja);
printf(" Please choose one of the following options\n\n");
printf(" ( 1 ) : plot data\n\n") ;
printf(" ( 2 ) : save data\n\n") ;
printf(" ( 3 ) : perform another trial\n\n") ;
printf(" ( 4 ) : type data ( or hit any key to stop)\n\n") ;
printf(" ( 5 ) : exit to DOS\n") ;

while(!kbhit());

printf("\n\n please hit [ enter ], after you choose ");
cscanf("%c", &choption);
kk = getch();

/* preparation of graphic mode and draw the outline box */

__clearscreen (__GCLEARSCREEN);

switch (choption)
{

case '1': /* plot data */

printf("\n Please choose data you want to plot\n\n");
printf("\n ( 1 ) : force vs time \n\n");
printf("\n ( 2 ) : collapse vs time curve\n\n");
printf("\n ( 3 ) : power vs time\n\n");
printf("\n ( 4 ) : energy vs time\n\n");
printf("\n ( 5 ) : previous options\n");

while(!kbhit());
printf("\n\n please hit [ enter ], after you choose ");
cscanf("%c", &chplot);
kk = getch();

__clearscreen (__GCLEARSCREEN);

switch (chplot)
{

case '1': /* force-time */

plot_box();
for(I=0; i<3; i++)
{ for (j=0; j<50; j++)
   { _moveto(70+j*10-1,130+i*75); _lineto(70+j*10,130+i*75); }
}
for(i=0; i<8; i++)
{ _moveto(70,355-75*i); _lineto(70+3,355-75*i); }
_settextposition(2,15); _outtext("Force(lb) vs. Time(s)\n");
_settextposition(4,5); _outtext("800\n");
/* plot force data  force max = 1500 lb , 300/800=0.375*/
for (i=0; i < ja+ka; i++) /* sensitivity=50psi/v, area=200/30 in.in */
{
  x0 = 70 + ceil(i*500.0/(ja+ka));
  y0 = 355 - ceil(force[i]*0.375);
  x1 = 70 + ceil((i+1)*500.0/(ja+ka));
  _moveto(x0,y0);
  _lineto(x1,y0);
}
_settextposition(30,20);
_outtext("press [ c ] to continue");
while ( !kbhit());
kk = getch();
break;

_case '2':  /* plot collapse-time curve */
plot box();
for(i=0; i<3; i++)
  { for (j=0; j<50; j++)
    { _moveto(70+j*10-1,130+i*75); _lineto(70+j*10,130+i*75); }
  }
for (i=0; i<5; i++)  /* markers and legend */
  { _moveto (70,355-75*i); _lineto (70+3, 355-75*i); }
_settextposition(2,15); _outtext("Collapse(in.) vs. Time(s)");
_settextposition(4,6);   _outtext("0.1");
_settextposition(9,4);   _outtext("0.075");
_settextposition(13,5);  _outtext("0.05");
_settextposition(18,4);  _outtext("0.025");
_settextposition(23,7);  _outtext("0");
_settextposition(25,20);
printf("weld time = %4.2f seconds",dt1);
/* plot collapse(inches) , D max=0.1, 300/0.1=3000 */
for (i=0; i<ja; i++)
  {
    x0 = 70+ceil(i*500.0/ja);
    y0 = 355 - collapse[i]*3000;
    x1 = 70+ceil((i+1)*500.0/ja);
    _moveto(x0,y0);  _lineto(x0+1, y0);
  }
_settextposition(30,20);
_outtext("press [ c ] to continue");
kk = getch();
break;

case '3': /* plot power-time curve, Pmax=2000 wats, 300/2000=0.15 */
plot_box();
for(i=0; i<3; i++)
{ for (j=0; j<50; j++)
    { _moveto(70+j*10-1,130+i*75); _lineto(70+j*10,130+i*75); }
}
for (i=1; i<4; i++)
{ _moveto(70,355-75*i); _lineto(70+3,355-75*i);
}
_settextposition(2,15); _outtext("Power(W) vs. Time(s)" );
_settextposition(4,4); _outtext("2000");
_settextposition(9,5); _outtext("1500");
_settextposition(14,5); _outtext("1000");
_settextposition(18,5); _outtext("500");
_settextposition(23,6); _outtext("0");
for ( i=0; i<ja; i++)
{ 
x0=70+ceil(i*500.0/ja);
x1=70+ceil((i+1)*500.0/ja);
y0=355-power[i]*0.15;
_moveto(x0,y0); _lineto(x0+1,y0);
}
_settextposition(25,20);
printf("weld time = %4.2f seconds",dt1);
_settextposition(30,20);
_outtext("press [c] to continue");
k = getch();
break;

case '4': /* energy-time curve */
plot_box();
for(i=0; i<3; i++)
{ for (j=0; j<50; j++)
    { _moveto(70+j*10-1,130+i*75); _lineto(70+j*10,130+i*75); }
}
for (i=0; i<5; i++)
{ moveto (70,355-75*i); lineto (70+3, 355-75*i); }
_settextposition(2,15); _outtext("Energy(J) vs. Time(S)");
_settextposition(4,4); _outtext("1000");
_settextposition(9,5); _outtext("750");
_settextposition(14,5); _outtext("500");
_settextposition(18,5); _outtext("250");
_settextposition(23,5); _outtext("0");
_settextposition(25,20);
printf("weld time = %4.2f seconds", dt1);
for (i=0; i<ja; i++)
{ 

x0 = 70+ceil(i*500.0/ja);
y0 = 355 -energy[i]*0.3; /* 300/1000 = 0.3 */
x1 = 70+ceil((i+1)*500.0/ja);
moveo(x0,y0); lineto(x1,y0);
}
settextposition(30,20);
outtext("press [ c ] to continue");
kk = getch();
break;

case '5': /* back to previous options */
break;
}

break;

case '2': /* save data */

while ( kk != 'y' )
{
  clearscreen(GCLEARSCREEN);
  printf("n\n\n\n You can save following data in a data
file: n\n\n" );
  printf("n\n\n\n force collapse power energy \n" );
  printf("n\n\n\n Enter file name you want to save as : ");
  scanf("%s", fname);
  kk = getch(); kk=0;
  printf("n\n\n press [ y ] to save data");
  kk = getch();
}
dt4 = dt1/ja; kk=0;
dt5 = hold time/ka;
streamf = fopen (fname,"w");
if ( streamf == NULL )
{
  printf("n\n\n The file did not open!");
  exit(0);
}
fprintf(streamf," N time force collapse power energy" );

for ( k=0; k<ja+1; k++)
  fprintf ( streamf, "\n%d %5.2f %8.2f %8.2f %8.2f %8.2f",
    k, dt4*k, force[k], collapse[k], power[k], energy[k]);
for ( k=1; k<ka+1; k++)
  fprintf ( streamf, "\n%d %5.2f
%8.2f", ja+k, dt4*ja+dt5*k, force[k+ja]);

fclose (streamf);
break;

case '3': /* start another welding */
_clearscreen (_GCLEARSCREEN);

printf("\n\n
please choose parameter input");
printf("\n\n
( 1 ) : use old parameters");
printf("\n\n
( 2 ) : input new parameters");

while (!kbhit());
printf("\n\n\n\nplease hit [ enter ], after you choose ");
cscanf("%c", &chinput);
kk = getch();

_clearscreen (_GCLEARSCREEN);

switch (chinput)
{
  case '1':  /* old parameters */
    _settextposition(20, 10);
    _outtext("press [ r ], then [ enter] to use old parameters");
    kk = getch();
    break;

  case '2':  /* new parameter */
    while ( kk != 'r' )
    {
      _clearscreen(_GCLEARSCREEN);
      printf("\n\n\n
input new parameters:");
      printf("\n\n\n
input weld pressure (<100psi) : ");
      scanf("%f", &weld_pressure);
      printf("\n\n\n
input trigger pressure (psi) : ");
      scanf("%f", &trigger_pressure);
      printf("\n\n\n
input hold pressure (<100psi) : ");
      scanf("%f", &hold_pressure);
      printf("\n\n\n
input amplitude level (0-100%) : ");
      scanf("%f", &amplitude_level);
      printf("\n\n\n
input maximum power (watts) : ");
      scanf("%f", &power_max);
      printf("\n\n\n
input minimum weld time (sec.) : ");
      scanf("%f", &weld_time_min);
      printf("\n\n\n
input maximum weld time (sec.) : ");
      scanf("%f", &weld_time_max);
      printf("\n\n\n
input hold time (sec.) : ");
      scanf("%f", &hold_time);
      printf("\n\n\n
If the parameters are correct, hit [r] then [enter]");
      printf("\n\n\n
or press any other key to input correct values");
      kk = getch();
    }
    break;

  default: printf("\a");
kk = getch();
break;
}
break;

case '4': /* type data */
    _clearscreen (_GCFORCESCREEN);
    dt4 = weld_time_max/ja;
    dt5 = hold_time/ka;
    printf("\n N time force collapse power energy\n");
    for ( k=0; k<ja+i; k++)
        { printf("\n%4d %6.2f %8.2f %8.2f %8.2f ",
               k, dt4*k, force[k], collapse[k], power[k], energy[k]);
            if ( kbhit() ) break;
        }
    for ( k=1; k<ka+1; k++)
        { printf("\n%4d %8.2f %8.2f", ja+k, dt4*ja+dt5*k, force[k+ja]);
            if ( kbhit() ) break;
        }
break;

case '5': /* exit to dos */
    _setvideomode(_DEFAULTMODE);
    _exit(0);
break;

default: printf("\a");
    kk = getch();
break;
}
}
k= getch();

while ( !kbhit() );
}

void plot_box(void)
{
    int i, j, k;
    int xul, xlong, yul, yhigh;
    xul=70; xlong=570; yul=55; yhigh=355;
    _setcolor(BCOLOR);
_rectangle (_GBORDER, xul, yul, xlong, yhigh);
_setcolor(color_map[1]);
_settextcolor(color_map[1]);
_rectangle (_GBORDER, xul-1, yul-1, xlong+1, yhigh+1);

for (i=0; i<10; i++) /* write time time axis legend */
    { _moveto (70+50*i, 355);
      _lineto (70+50*i,355-5);
    }
Appendix F

Closed Loop Control Program for Ultrasonic Welding: CCUPID.C
About CCWPID.C Program

1. CCWPID.C program performs a closed loop control for ultrasonic welding.

2. The structure of the program can be found in Fig.4.19 and Fig.4.20 of this dissertation.

3. The program is used on Branson A920 power supply which has a vibration amplitude control function.

4. The program is used with a data acquisition system SHDAS-12. Two A/D channels are for pressure and power level measurements. Two D/A channels are used to control weld pressure and vibration amplitude respectively. On/off switch of sonics and solenoid are controlled by I/O port of the data acquisition system.

5. Before the use of the program an optimum power curve should be obtained. The optimum power curve has only one power peak appearing in the final stage of the welding. This power curve will lead an acceptable joint strength.

6. According to the optimum power curve, a tracking curve is set which is a two step power level curve. The first power level is equal to the average power level of the optimum power curve before the appearing of the power peak. The second level equals the power peak.

7. A PID controller is used in the program. The following steps should be followed to tune the controller:
   (1) letting derivative time Td be zero and integral time Ti very large, adjust gain K until two or three oscillations is observed.
   (2) fixing K and Ti, increase derivative time Td until only one overshoot appears.
   (3) Fixing K and Td, decrease Ti until a satisfactory accuracy is obtained.

8. A linear variable gain can be set on your experience or experimental results.
// CCUWPID.C  proportional+integral+derivative Closed-loop Control
// for ultrasonic Welding  */
// * dynamic tracking for given power curve */
// * gain of the system can be adjusted in two steps */
// * peak power can be set */
// * input: amplitude of vibration output: power or impedance */
// * SHDAS-12 channel 1: pressure, channel 2: power (from A920) */

#include <share.h>
#include <fcntl.h>
#include <math.h>
#include <malloc.h>
#include <stdlib.h>
#include <stdio.h>
#include <graph.h>
#include <sys	ypes.h>
#include <sys	at.h>
#include <process.h>
#include <errno.h>
#include <io.h>
#include <time.h>
#include <adas_defs.h>
#include <das.h>
#include <5312.h>

#define BCOLOR 4
#define RATE 300
#define MAX_VAL 400

/* there are no low contrast color selected */
static int color_map[16]={15,14,10,12,11,9,0,10,7,6,5,4,3,15,14,13};

extern int gtdata(unsigned short far *, int, double far *, double, int);

/* start the program */

main ()
{  
  void plot_box(void);
  
  FILE *streamf;
  
  int ierr, dma_timeout, i, j, ja, k, ka, m, kk;
  int base_addr, bd_type, dac_dma_channel, adc_dma_channel, b_addr;
  int x0, y0, x1, y1;
  
  long c1, c2;
  
  unsigned short *input_data, *input_force, *input_amplitude;
  unsigned short *dac0data, *dac1data;
  
  char choice, choption, chplot, chinput, ch, s[10], fname[10];
  
  clock_t start, finish, t0, t1, t2, t3, t4;
  
  float hold_time, real_pressure, trigger_pressure, hold_pressure,
       dwell_pressure, weld_time_max, amplitude_level,
       ini_amplitude_level, d_power, p_power, tf;
  float energy_max, enrg, *amplitude, *energy;
  float ampdsq, kg, kgg, kv, kg1, ti, til, td, td1, el, eint, edot,
       tp;
  
  double eus_per_volt, dt, dt0, dt1, dt2, dt3, dt4, dt5, tj;
  
  struct dacspec dac0setup, dac1setup;
  
  extern struct das_CFG das_cfg_table;
  
  /* allocated buffers for input data and DAC channels */
  input_data = (unsigned short*) calloc(20, sizeof(unsigned short));
  input_force = (unsigned short*) calloc(1, sizeof(unsigned short));
  input_amplitude = (unsigned short*) calloc(1, sizeof(unsigned short));
  
  volts1 = (double*) calloc(10, sizeof(double));
  volts2 = (double*) calloc(10, sizeof(double));
  
  dac0data = (unsigned short*) calloc(1, sizeof(unsigned short));
  dac1data = (unsigned short*) calloc(1, sizeof(unsigned short));
  
  force = (double*) calloc(2000, sizeof(double));
  active_power = (double*) calloc(2000, sizeof(double));
  amplitude = (float*) calloc(2000, sizeof(float));
  energy = (float*) calloc(2000, sizeof(float));
  collapse = (double*) calloc(2000, sizeof(double));
  
  /* set graphic mode */
_clearscreen (_GCLEARSCREEN);
_setvideomode (_FRESCOLOR); /*640x350, 4 or 16 color */
_setbkcolor (_LIGHTBLUE);

while (!kbbhit())
{
    _settextposition(7,14);
    printf("Welcome! \n\n\n\n");
    printf("You are running CUWME.C program\n\n\n\n");
    printf("For safety, please turn off switch\n\n\n\n");
    printf("Then, hit any key to continue");
}

/* initiate the SHDASL2 board and encoder */
base_addr = 0x300; b_addr = 0x31a;
adc_dma_channel = 5; dac_dma_channel = 6;

init_encoder(AXIS_A,MCR,ICR,OCR,QR,b_addr);
ierr=bdinit(base_addr, &bd_type, adc_dma_channel, dac_dma_channel);

setdio(1,1); /* close solenoid and sound */
*input_force = 819*(1.354+0.03646*30); /* preset pressure 30psi*/
dac0setup.data = (int *)input_force;
dac0setup.data_buf_size = 1;
dac0setup.dac_rate = 100;
dac0setup.update_path = 0;
*input_amplitude = 4095*(50/100); /* preset amplitude 50% */
dac1setup.data = (int *)input_amplitude;
dac1setup.data_buf_size = 1;
dac1setup.dac_rate =100;
dac1setup.update_path = 0;
cfgdac (&dac0setup, &dac1setup);
outdio(0);

if (ierr<0)
    {printf("\n\a %d Data Acquisition Board Malfunction", ierr);
     exit(-1); }

kk=getch(); /* empty the console */

_clearscreen (_GCLEARSCREEN);
_setvideomode (_FRESCOLOR); /* 640x350 4 or 16 color */
_setbkcolor (_LIGHTBLUE);

while (!kbbhit())
{
    _settextcolor(color_map[1]);
    _settextposition (5,18);
/* input trigger force, weld time, and hold time */
kk = getch();  /* empty the console */
_clearscreen (_GCLEARSCREEN);
_setvideomode (_VRES16COLOR);
_setbkcolor (_LIGHTBLUE);

while (kk != 'y')
{
    _clearscreen (_GCLEARSCREEN);
    _settextposition(1,1);
    printf("n
parameters: ");
    printf("n
input weld pressure (<100psi) : ");
    scanf("%f", &weld_pressure);
    printf("n
input trigger pressure (<100psi) : ");
    scanf("%f", &trigger_pressure);
    printf("n
input hold pressure (<100psi) : ");
    scanf("%f", &hold_pressure);
    printf("n
input initial amplitude level (0-100percent) : ");
    scanf("%f", &ini_amplitude_level);
    printf("n
input maxium energy limit (Joules) : ");
    scanf("%f", &energy_max);
    printf("n
input maximum weld time ( <= 10 seconds) : ");
    scanf("%f", &weld_time_max);
    printf("n
input control power (watts) : ");
    scanf("%f", &power);
    printf("n
input peak power (watts) : ");
    scanf("%f", &p_power);
    printf("n
input power tolerance (watts) : ");
    scanf("%f", &d_power); */
    printf("n
input proportional gain kg : ");
    scanf("%f", &kg);
    printf("n
input gain coefficient kv : ");
    scanf("%f", &kv);
    printf("n
input integral time ti : ");
scanf("%f", &ti);
printf("\n
scanf("%f", &td);
printf("\n
scanf("%f", &ti1);
printf("\n
scanf("%f", &td1);
printf("\n
scanf("%f", &tp);
printf("\n
scanf("%f", &hold_time);
printf("\n\n
if the parameters are correct, hit [ y ] and wait"")
printf("\n\n
or press any other key to input correct
values");
    kk=getch();
}
    kk = 0;

dma_timeout = 0;    /* set time_out function */
stm0 (dma_timeout);

do
{
    /* open solenoidal and set weld_force and amplitude level */
    outdio(1);
    *input_force = 819*(1.354+0.03646*weld_pressure);    /* p691 */
    dac0setup.data = (int *) input_force;
    amplitude_level = ini_amplitude_level;
    *input_amplitude = 4095*(amplitude_level/100);
    dac1setup.data = (int *) input_amplitude;
    cfgdac (&dac0setup, &dac1setup);    /* A/D out put */
    adinit ("ccuwp.cfg");

    /* check if the weld pressure is high enough to trigger sonic */
    eus_per_volt = 1.0;
    real_pressure = 0;
    t0 = clock();
    while ( real_pressure < trigger_pressure )
    {
        getdma(input_data, 9);
        gtdat(input_data, 1, volts1, 1,1);
        real_pressure =volts1[0]*20.58-10.0;    /* (change 12.76) to 10.0P-Vout relation */
/* sensitivity of pressure sensor: 0.02volts/psi */

t1 = clock();
dt0=(double)(t1-t0)/CLOCKS_PER_SEC;
if ( dt0 > 10 ) /* terminate the process after 10 sec */
{
  outdio(0);
  printf("The real force is smaller than weld force\n\n");
  printf("Adjust pressure and try again");
  exit(0);
}

/* turn sonic on and start welding process */
outdio(3);

/* configure the A/D converter with ctl1new.cfg.
collect data and do calculations */

t0=clock();  j=0;  eus_per_volt=1;  enrg=0;  eint1=0;  e1=0;
c1=read_cntr(AXIS_A, b_addr);

/* acquire data and start control process */
do
{
  getdma(input_data,20);
gtdat(input_data,1,volts1,eus_per_volt,10);
gtdat(input_data,2,volts2,eus_per_volt,10);

  force[j]=(volts1[0]-0.96)*183.215;
  active_power[j]=volts2[0]*200;
  amplitude[j]=amplitude_level;

  energy[j]=enrg+active_power[j]/440.0;
  enrg=energy[j];

  c2=read_cntr(AXIS_A, b_addr);
collapse[j]=(c1-c2)*0.0001;
c1=c2;

  if ( j > 10 )
  {
    if ( dt1 < (weld_time_max-tp))
    {
      eint1 = eint1+(power-active_power[j])/440;
      edot = (power-active_power[j])-e1)*440;
      e1=power-active_power[j];
      kgg = kg-kv*dt1;
    }
  }
}
ampdsqu = amplitude[j-1]*amplitude[j-1]+kga*(power-active_power[j-1])
    +eint1/ti+td*edot;
}
else
{ eint1 = eint1+(p_power-active_power[j])/440;
  edot = ((p_power-active_power[j])-e1)*440;
  e1=p_power-active_power[j];

  ampdsqu = amplitude[j-1]*amplitude[j-1]+kg1*(p_power-active_power[j-1])
          +eint1/til+td1*edot;
}
if (ampdsqu >= 10000) ampdsqu=10000;
if (ampdsqu <=0 ) ampdsqu=1;
  amplitude[j] = sqrt(ampdsqu);

*input_amplitude = 4095*(amplitude[j]/100);
dac1setup.data = (int *) input_amplitude;
cfgdac (&dac0setup, &dac1setup);
}

if ( energy[j] >= energy_max )
{
  outdio(1); /* turn sonic off */
  *input_force = 819*(1.354+0.03646*hold_pressure);
  dac0setup.data = (int *)input_force;
  cfgdac (&dac0setup, &dac1setup);
  break;
}

j = j+1;
t1=clock();
dt1=(double)(t1-t0)/CLOCKS_PER_SEC;

}
while ( dt1 <= weld_time_max );
ja=j-1; power=power;

/* sonic off and hold time begins */
outdio(1);
*input_force = 819*(1.354+0.03646*hold_pressure); /* set hold
pressure */
dac0setup.data = (int *)input_force;
cfgdac (&dac0setup, &dac1setup);
start=clock();
do
{ finish = clock();
  dt2 = (double)(finish - start) / CLKS_PER_SEC;
}
while ( dt2 < hold_time );

/* raise stack and recover pressure 30psi and initial amplitude */
  outdio(0);
  *input_force = 819*(1.354+0.03646*30); /* recover 30psi presure */
  dac0setup.data = (int *)input_force;
  amplitude_level = ini_amplitude_level;
  cfgdac (&dac0setup, &dac1setup);

/* the end of the welding and the data writing process */

/* display and save data */
while ( kk != 'r' )
{

  _clearscreen (_GCLEARSCREEN);

  printf( "\n The process is over and the data has been recorded \n");
  printf("\n the sample rate is %6.1f \n", ja/dt1);
  printf("\n energy=%8.2fjoules time = %5.2f\n\n\n", energy[ja], dt1);
  printf(" Please choose one of the following options\n\n")
  printf(" ( 1 ) : plot data\n\n")
  printf(" ( 2 ) : save data\n\n")
  printf(" ( 3 ) : perform another trial\n\n")
  printf(" ( 4 ) : type data ( or hit any key to stop
")
  printf(" ( 5 ) : exit to DOS\n")

  while(!kbhit());
  printf("\n\n please hit [ enter ], after you choose ");
  scanf("%c", &choption);
  kk = getch();

/* preparation of graphic mode and draw the outline box */

  _clearscreen (_GCLEARSCREEN);

  switch (choption)
  {
  case '1': /* plot data */
printf("\n Please choose data you want to plot\n\n");
printf("\n ( 1 ) : force vs time \n\n");
printf("\n ( 2 ) : active power vs time curve\n\n");
printf("\n ( 3 ) : collapse vs time curve\n\n");
printf("\n ( 4 ) : amplitude vs time curve\n\n");
printf("\n ( 5 ) : energy vs time curve\n\n");
printf("\n ( 6 ) : previous options\n");

while(!kbhit());
printf(" \n\n please hit [ enter ], after you choose
");
cscanf("%c", &chplot);
k = getch();
clearscreen(_GCLEARSCREEN);
switch(chplot)
{
  case '1': /* force-time */
    plot_box();
    for(i=0; i<3; i++)
      { for (j=0; j<50; j++)
          { _moveto(70+j*10-1,130+i*75); _lineto(70+j*10,130+i*75); }
      }
    for(i=0; i<8; i++)
      { _moveto(70,355-75*i); _lineto(70+3,355-75*i);
      }
    _settextposition(2,15); _outtext("Force(lb) vs. Time(s)\n");
    _settextposition(4,5); _outtext("800\n");
    _settextposition(9,5); _outtext("600\n");
    _settextposition(13,5); _outtext("400\n");
    _settextposition(18,5); _outtext("200\n");
    _settextposition(23,5); _outtext("0\n");
    _settextposition(25,5); printf("weld time = %4.2f s hold time = %4.2f s ", dt1,dt2);

    /* plot force data  force max = 800 lb , 300/800=0.375*/
    for (i=0; i < ja; i++)   /* sensitivity=50psi/v, area=200/30 in.in */
      {
        x0 = 70 + ceil(i*500.0/ja);
        y0 = 355 - ceil(force[i]*0.375);
        x1 = 70 + ceil((i+1)*500.0/ja);
        _moveto(x0,y0);
        _lineto(x1,y0);
      }
    _settextposition(30,20);
    _outtext("press [ c ] to continue\n");
    while (!kbhit());
k = getch();
break;
case '2':  /* plot active power-time curve */
plot_box();
for (i=0; i<5; i++)  /* markers and legend */
{  _moveto (70,355-75*i);  _lineto (70+3, 355-75*i);
}
_settextposition(2,15);  _outtext("active power vs. Time(s) ");
_settextposition(4,6);  _outtext("2000");
_settextposition(9,4);  _outtext("1500");
_settextposition(13,5);  _outtext("1000");
_settextposition(18,4);  _outtext("500");
_settextposition(23,7);  _outtext("0");
_settextposition(25,20);
_printf("weld time = %4.2f seconds",dt1);
/* plot active power max=2000, 300/2000=0.15 */
for (i=0; i<ja; i++)
{  
x0 = 70+ceil(i*500.0/ja);
y0 = 355 - active_power[i]*0.15;
x1 = 70+ceil((i+1)*500.0/ja);
_moveto(x0,y0);  _lineto(x0+1, y0);
}
_settextposition(30,20);
_outtext("press [ c ] to continue");
_kk = getch();
break;

case '3':  /* plot collapse-time curve */
plot_box();
for (i=0; i<5; i++)  /* markers and legend */
{  _moveto (70,355-75*i);  _lineto (70+3, 355-75*i);
}
_settextposition(2,15);  _outtext("collapse(in) vs. Time(s) ");
_settextposition(4,6);  _outtext("0.05");
_settextposition(9,4);  _outtext("0.0375");
_settextposition(13,5);  _outtext("0.025");
_settextposition(18,4);  _outtext("0.0125");
_settextposition(23,7); _outtext("0");
_settextposition(25,20);
_printf("weld time = %4.2f seconds",dt1);
/* plot velocity (in./s) , collapse max=0.1, 300/0.05=6000 */
for (i=0; i<ja; i++)
{  
x0 = 70+ceil(i*500.0/ja);
y0 = 355 - collapse[i]*6000;
x1 = 70+ceil((i+1)*500.0/ja);
_moveto(x0,y0);  _lineto(x0+1, y0);
}
_settextposition(30,20);
_outtext("press [ c ] to continue");
kk = getch();
break;

case '4':    /* plot amplitude-time curve */
plot_box();
for (i=0; i<5; i++)    /* markers and legend */
{    _moveto (70,355-75*i);    _lineto (70+3, 355-75*i);
    _settextposition(2,15);    _outtext("amplitude(%) vs. Time(s)");
    _settextposition(4,6);    _outtext("100");
    _settextposition(9,4);    _outtext("75");
    _settextposition(13,5);    _outtext("50");
    _settextposition(18,4);    _outtext("25");
    _settextposition(23,7);    _outtext("0");
    _settextposition(25,20);
    printf("weld time = %4.2f seconds",dt1);
    /* plot velocity (in./s) , V max=100, 300/100=3 */
for (i=0; i<ja; i++)
{    x0 = 70+ceil(i*500.0/ja);
    y0 = 355 - amplitude[i]*3;
    x1 = 70+ceil((i+1)*500.0/ja);
    _moveto(x0,y0);    _lineto(x0+1, y0);
}
    _settextposition(30,20);
    _outtext("press [ c ] to continue");
    kk = getch();
break;

case '5':    /* energy-time curve */
plot_box();
for (i=0; i<3; i++)
{    for (j=0; j<50; j++)
{    _moveto(70+j*10-1,130+i*75);    _lineto(70+j*10,130+i*75);}
    }
for (i=0; i<5; i++)
{    _moveto (70,355-75*i);    _lineto (70+3, 355-75*i);    }
    _settextposition(2,15);    _outtext("Energy(J) vs. Time(S)");
    _settextposition(4,4);    _outtext("2000");
    _settextposition(9,5);    _outtext("1500");
    _settextposition(14,5);    _outtext("1000");
    _settextposition(18,5);    _outtext("500");
    _settextposition(23,5);    _outtext("0");
    _settextposition(25,20);
    printf("weld time = %4.2f seconds", dt1);
for (i=0; i<ja; i++)
{    x0 = 70+ceil(i*500.0/ja);
    y0 = 355 - energy[i]*0.15;    /* 300/2000 = 0.15 */
    x1 = 70+ceil((i+1)*500.0/ja);
moveto(x0,y0); lineto(x1,y0);
}
settextposition(30,20);
outtext("press [ c ] to continue");
kk = getch();
between;

case 'c': /* back to previous options */
between;
}

break;

case '2': /* save data */
while ( kk != 'y' )
{
  clearscreen(_GCLEARSCREEN);
  printf("\n\n\n\n\n You can save following data in a data
file:\n\n\n\n\n\n" );
  scanf("%s", fname);
  kk = getch();
  printf("\n\n press [ y ] to save data");
  kk = getch();
}

dt4 = weld time max/ja;
streamf = fopen (fname,"w");
if ( streamf == NULL )
  { printf("\n\n\n The file did not open! ");
    _exit(0);
  }
fprintf(streamf," N time force power amplitude
energy collapse");
  for ( k = 0; k < ja; k++ )
    fprintf( streamf, "\n%5d %7.4f %10.2f %6.2f %6.2f
%8.2f %8.4f",
k, k/440.0, force[k], active_power[k], amplitude[k], energy[k], collapse[k] );

fclose (streamf);
between;

case '3': /* start another welding */
_clearscreen (_GCLEARSCREEN);
printf("\n\n\nplease choose parameter input");
printf("\n\n( 1 ) : use old parameters");
printf("\n\n( 2 ) : input new parameters");

while (!kbbhit());
printf("\n\n\nplease hit [ enter ], after you choose ");
cscanf("%c", &chinput);
kk = getch();
_clearscreen (_GCLEARSCREEN);

switch (chinput)
{
    case '1':  /* old parameters */
        _settextposition(20, 10);
        outtext("press [ \r ], then [enter] to use old parameters");
        kk = getch();
break;

    case '2':  /* new parameter */
        while ( kk != 'r' )
        {
            _clearscreen(_GCLEARSCREEN);
            printf("\ninput new parameters:");
            printf("\ninput weld pressure (<100psi) : ");
            scanf("%f", &weld_pressure);
            printf("\ninput trigger pressure (<100psi) : ");
            scanf("%f", &trigger_pressure);
            printf("\ninput hold pressure (<100psi) : ");
            scanf("%f", &hold_pressure);
            printf("\ninput initial amplitude level (1-100%) : ");
            scanf("%f", &ini_amplitude_level);
            printf("\ninput maximum weld time ( <= 10 sec. ) : ");
            scanf("%f", &weld_time_max);
            printf("\ninput maximum energy limit (Joules) : ");
            scanf("%f", &energy_max);
            printf("\ninput control power (watts) : ");
            scanf("%f", &power);
            printf("\ninput peak power (watts) : ");
            scanf("%f", &p_power);
printf("\n
(watts) : " );
scanf("%f", &d_power); /*
printf("\n
scanf("%f", &kg);
printf("\n
scanf("%f", &kv);
printf("\n
" );
scanf("%f", &ti);
printf("\n
" );
scanf("%f", &td);
printf("\n
scanf("%f", &kg1);
printf("\n
" );
scanf("%f", &ti1);
printf("\n
" );
scanf("%f", &td1);
printf("\n
scanf("%f", &tp);
printf("\n
scanf("%f", &hold_time);
printf("\n\n
If the parameters are correct, hit [r] then
[enter]";
printf("\n\n
| or press any other key to input correct
values");
kk = getch();
}
break;

default: printf("\a");
kk = getch();
break;
}
break;

case '4': /* type data */
_clearscreen (_GCLEARSCREEN);
printf("\n
N time force power amplitude energy
collapse" );
for ( k=0; k<ja; k++)
{ printf ("\n%4d %6.4f %8.2f %8.2f %8.2f
%8.4f",
k,k/440.0,force[k],active_power[k],amplitude[k],energy[k],collapse[k]);
if ( kbhit() ) break;
}

break;

case'5': /* exit to dos */
  _setvideomode(_DEFAULT/MODE);
  _exit(0);
  break;

default: printf("\a");
  
  break;

}

kk = getch();

}

while ( !kbhit());

}

void plot_box(void)
{
  int i, j, k;
  int xul, xlong, yul, yhigh;
  xul=70; xlong=570; yul=55; yhigh=355;

  _setcolor(BCOLOR);
  _rectangle(_GBORDER, xul, yul, xlong, yhigh);
  _setcolor(color_map[1]);
  _settextcolor(color_map[1]);
  _rectangle(_GBORDER, xul-1, yul-1, xlong+1, yhigh+1);

  for (i=0; i<10; i++) /* write time time axis lengend */
  {
    _moveto (70+50*i, 355);
    _lineto (70+50*i,355-5);
  }
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