



INCREASING THE EFFICIENCY OF ULTRASONIC DISPERSION SYSTEM WITH USE OF CONTROL LOOP TO AUTOMATIC FREQUENCY ADJUSTING

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Submitted: April 2, 2011

Accepted: May 23, 2011

Published: June 1, 2011

Abstract- A novel ultrasonic dispersion system for the dispersing of particles which are mixed in liquid has been proposed in this paper. The frequency of produced ultrasonic wave varies from 30 kHz to 60 kHz with 100 Hz steps. It means that the operating frequency band of designed system is 30 kHz. The maximum and optimum energy of ultrasonic wave can be transfer inside the liquid container with the high efficiency in majority of operating time by the use of some facilities which are implemented in our novel system, so it causes one of the superiority of manufactured system in compare with the other similar systems which are available in

markets. Ultrasonic transducers which are used in this system as the generator of ultrasonic wave is the type of air coupled ceramic ultrasonic piezoelectric with the nominal maximum power 50 watt. By the considering of frequency diagram of applied piezoelectric, it can be find out that the piezoelectrics produce the maximum amplitude of ultrasonic wave on their resonance frequency, so this system is designed to work on resonance frequency of piezoelectric, continuously. This is done by the use of control system which is consisted of two major parts, sensing part and controlling part. A Hall Effect current sensor is used as the sensing part and the controlling program is implemented on AVR microcontrollers. In addition, the control algorithm of program is presented in this paper. The manufactured ultrasonic dispersion system has been consisted of 9 piezoelectrics so that it can produce 450 watt ultrasonic energy, totally.

Index terms: Ultrasonic dispersion, frequency adjusting, Transducer, high power ultrasonic, nano-particles.

I. INTRODUCTION

Dispersion and deagglomeration by ultrasonication are a result of ultrasonic cavitation. When sonicating liquids at high intensities, the sound waves that propagate into the liquid media result in alternating high-pressure (compression) and low pressure (rarefaction) cycles, with rates depending on the frequency. During the low pressure cycle, high-intensity ultrasonic waves create small vacuum bubbles or voids in the liquid. When the bubbles attain a volume at which they can no longer absorb energy, they collapse violently during high pressure cycle. This phenomenon is termed cavitation. During the implosion very high temperatures (approx. 5,000K) and pressures (approx. 2,000atm) are reached locally. The implosion of the cavitation bubble also results in liquid jets of up to 280m/s velocity [1].

The cavitation forces induced during transient collapse of cavitating bubbles are of great importance and are known to cause many chemical and physical effects like lysis of solvent molecules resulting in formation of free radicals, augmentation of chemical reaction rates, mechanical effects like erosion of solid surfaces or pitting, dispersion of agglomerated powders in solution and particle breakage [3]. During the cavitation, how much the bubble sizes will grove

inside the liquid depends on the amplitude and the frequency of the signal applied to the ultrasonic transducer. The cleaning power can be increased until the unwanted effect, so called “cavitation erosion” occurs. The cleaning efficiency decreases if the applied power is increased further [2].

The whole structure of our proposed ultrasonic dispersion system has been shown on Figure 1 as a block diagram such that all of the blocks are explained in the next subsections accurately.

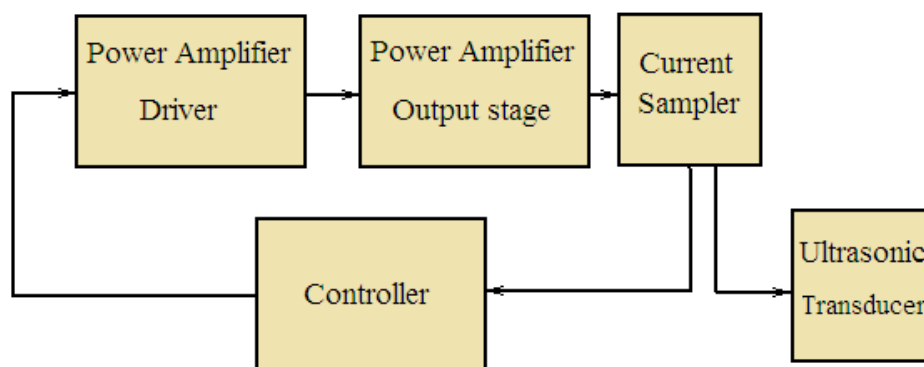


Figure 1. Block diagram of ultrasonic dispersion system

The dispersing power of a liquid tank depends on how strong the bubbles collapse. Existence of any gases inside the solution reduces the pressure of that region, which finally prevents the strong collapsing of the bubbles. Pulsing is most commonly done by means of a pulsing circuit provided integrally in the body of high quality ultrasonic generators. Therefore, microprocessor based generator implementations are widely preferred for the designers [4]. In this study, such an ultrasonic generator system, which has a novel software algorithm and a power-driver circuit, has been designed, implemented, and tested [2].

As can be seen on Figure 1, ultrasonic transducer is one of the important parts of the system that it can produce an ultrasonic wave by vibration. The transducer which is used in our novel system is a kind of piezoelectric transducer which is coupled with air directly. Since the impedance mismatching of the mentioned transducer with air and the attenuation effect of air on ultrasonic wave, it is needed to use high voltage to excitation of transducers.

Additionally, one another important problem that the similar systems have been encountered is the transferring of ultrasonic energy inside the tank. Finding any way to overcome the mentioned problem in which the majority of energy convey inside the tank, is the challenge between all researchers whom are working on this matter.

The method of transducer mounting on the surface of tank, and impedance matching of transducer with tank, is one of the solutions that it should be considered. The other solution which cause the superiority of our system in comparison with other systems, is adjusting of system to work on resonance frequency of piezoelectric during the working of system, entirely.

Liquid tank must be made of stainless steel and it must be as thin as possible. Ultrasonic transducers are located on the bottom of the tank by using special glue. The number of transducers to be placed and the distance between them depend on the size of the tank. There are also so called “immersible transducers” on the market. They are located inside the dispersing liquid by using a water resistant metal box, in which transducers are mounted.

In this paper, we present the brief introduction to ultrasonic transducers and their frequency characteristic. This is then followed by a presentation of power amplifier part of system and its fundamental parts. Control part of the system is presented at the next section and ultimately the experimental results of manufactured system have been demonstrated. Conclusion is presented in the last section.

II. TRANSDUCERS

There are two fundamental transducer designs used for power ultrasonic applications today, magnetostrictive and piezoelectric. Piezoelectric transducers utilize the piezoelectric property of a material to convert electrical energy directly into mechanical energy. Magnetostrictive transducers utilize the magnetostrictive property of a material to convert the energy in a magnetic field into mechanical energy. The magnetic field is provided by a coil of wire which is wrapped around the magnetostrictive material. Both types of transducers have advantages and disadvantages. The piezoelectric transducers have been used in this system [11,13].

The frequency characteristic of ultrasonic transducer on the resonance frequency region can be described using the Butterworth-Van Dyke (BVD) model. The mechanical parts (R_s , L_s , C_s) and the electrical parts (the clamping capacitor C_0) of the transducer are shown on Figure 2 [6].

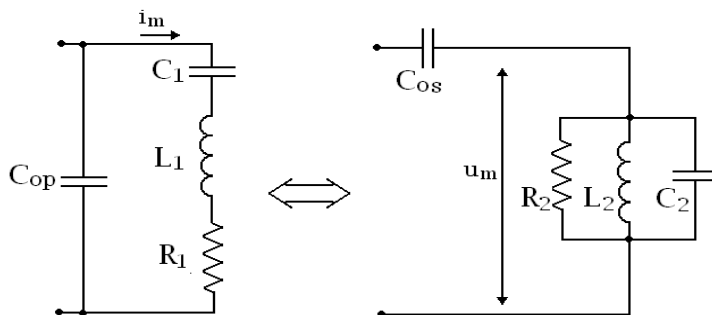


Figure 2. Butterworth-van dyke transducer model

Two of the most widely used lumped-parameters piezoelectric converter impedance models (mutually equivalent) has been demonstrated on Figure 2 which are valid for isolated couple of series and parallel resonances (of a non-loaded). The mentioned parameters on Figure 2 presents the simplest models applicable for relatively high mechanical quality factor piezoelectric converters, where thermal dissipative elements in piezoceramics could be neglected. Figure 3 demonstrates the more general model (again mutually equivalent), in which real piezoelectric (non-loaded) converters with dissipative dielectric losses and internal resistive electrode-elements (R_{op} (=) Leakage AC and DC resistance, $R_{os1} \gg R_{os2}$ (=) Dielectric resistive loss of piezoceramics) in piezoceramics has been presented. For high quality piezoceramics R_{op} , is in the range of 10 MW - 50 MW, and R_{os1} , R_{os2} are in the range between 50 W and 100 W, measured at 1 kHz, low signal. In most of the cases of high quality piezoceramics R_{op} can be neglected as too high resistance, and R_{os1} , R_{os2} , as too low values, but we should also know that dielectric and resistive losses are becoming several times higher when converter is driven high power, in series or parallel resonance, comparing them to low signal measurements [8,12].

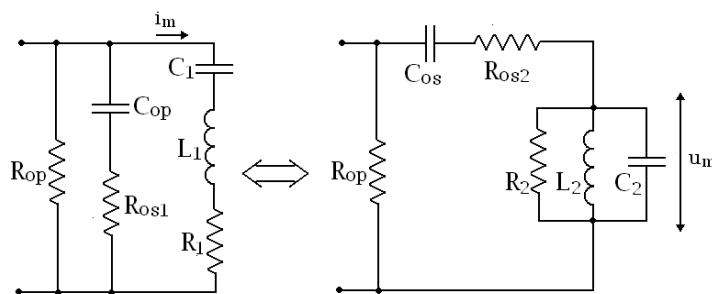


Figure 3. Complete electrical model of transducer

The losses described by R_1 , can be split:

$$R_1 = R_0 + R_{xm} \quad (1)$$

Where R_0 describes the dielectric losses in piezoceramic material and R_{xm} the acoustic emission into medium. Assuming R_{xm} is the largest part, the power supplied to R_1 can be considered as the transducer acoustic efficiency measure [7]. The derived ultrasonic transducer input impedance is given by:

$$z_s = \frac{(R_1 + j\omega L_1 + \frac{1}{j\omega C_1}) \cdot \frac{1}{j\omega C_{op}}}{R_1 + j\omega L_1 + \frac{1}{j\omega C_1} + \frac{1}{j\omega C_{op}}} \quad (2)$$

From Eq.2 the resonance frequency of transducer can be achieved by [7]:

$$\omega_n = \frac{1}{\sqrt{L_1 C_1}} \quad (3)$$

and the parallel resonance [7]:

$$\omega_1 = \frac{1}{\sqrt{L_1 \frac{C_1 C_{op}}{C_1 + C_{op}}}} \quad (4)$$

The Impedance property of piezoelectric and its circuit model has been demonstrated on Figure 4. These models are the summarized models of real models. It is our favorite that piezoelectric works on the series resonance of frequency, because in this case the impedance value of piezoelectric is minimum and maximum current can be flow through the piezoelectric. When the maximum current flows through the piezoelectric, the maximum power can be produce by the piezoelectric.

The parameters of our used ultrasonic transducer have been presented in Table 1. It should be mentioned that these parameters can be changed by connecting the piezoelectric on the surface of the liquid tank and the new impedance according to the level of liquid of tank and the rigidity of stainless steel can be achieved.

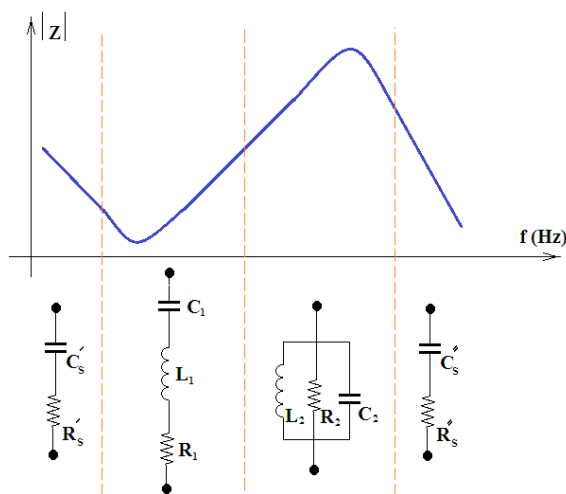


Figure 4. Impedance property of piezoelectric transducer according to various frequencies

Table 1: Essential parameters of used ultrasonic transducer in this system

A	Type	f_o (kHz)	C_{op} (pF)	$R_1(\Omega)$	K_r	Q_m
	ANN-50030	46	5800	15	0.55	500

a. Impedance matching

The method of sticking of piezoelectrics on the steel wall of liquid tank is very important. There are some interfaces to deliver the high power ultrasonic wave to inside the liquid tank. One of the significant interfaces is the contacting surface of piezoelectric to steel tank. Each of the layers has the own acoustic impedance and if the impedance matching is not concerned it causes the loose of big amount of ultrasonic energy which can be passed through the tank. There are some equations that they have a valuable role in finding the suitable material as the coupling material for impedance matching.

$$I_R = I_T \exp\left(-\int_L f(x, y)dI\right) . \quad (5)$$

Where I_R = the receiver intensity, I_T = the transmitter intensity, L = path length in the object field and $f(x, y)$ = the attenuation function by the object field [14].

At room temperature, the acoustic impedances of water (liquid) and air (gas) are 1.5×10^6 kg/m²s and 430 kg/m²s respectively. The reflection coefficient, R at the interfaces can be calculated as below:

$$R_{(water/air)} = \left[\frac{Z_2 - Z_1}{Z_2 + Z_1} \right] = \left[\frac{430 - 1.5 \times 10^6}{430 + 1.5 \times 10^6} \right] = -0.9994 \times 100\% \\ = -99.94\% . \quad (6)$$

Where Z_1 = the liquid (water) acoustic impedance (kg/m²s) and Z_2 = the gas (air) acoustic impedance (kg/m²s) [14].

The negative sign indicates the reversal of the phase relative to the incident wave. By the consideration of equation 6, we find out that 99.94% of ultrasonic wave will be reflected at liquid/gas boundary and scattered within the liquid area due to the large different of acoustic impedance between the liquid and gas medium.

Since the mentioned reason, in practice, if an ultrasonic transducer is placed on the surface of a material, very little ultrasonic energy will actually enter the material. This is because of a very small air gaps will usually exist between the face of the transducer and the surface of the material. Air, being a very poor conductor of sound energy either will prevent effective coupling of the transducer to the material or will attenuate the strength of ultrasonic wave, so some sort of coupling material is normally used. Normally, a liquid type of coupling material (wet coupling) is used to allow easy application and conformity to the void between the transducer and the surface. It also should be a very good conductor of sound energy to allow maximum transfer to the structure [15]. Other characteristics of coupling materials are generally dependent on particular applications such as the more viscous coupling material would be used to effectively fill in the roughness, for the rough-surfaced material [16]. The proposed acoustic coupling as used in

configuration in Figure 5 is silicone sealant, which is a viscous material that changes state to become solid when it dries off. This type of coupling material, ensure the transmission of maximum energy of ultrasonic wave to inside the liquid tank.

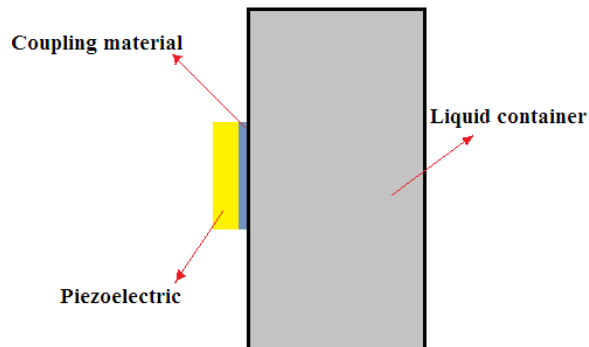


Figure 5. Method of connecting the piezoelectric on stainless steel liquid tank

b. Power amplifier part of system

By the consideration in type of ultrasonic transducer which has been used in our dispersion system and its needing to apply high voltage for producing of high amplitude ultrasonic wave, the power amplifier section is one of the important parts. There is a various types of amplification method to use as a power amplifier part [5]:

- (1) Linear power amplifiers by the use of bipolar junction transistors (2N3055, Mj2955,etc)
- (2) Power switching amplifiers by adding transformers for impedance matching and amplifying the voltages.

Since the first way needs a lot of elements and their resistivity above the increasing of heating is not good, so it is not affordable to choose the first choice as a power amplifier part. The second choice has been selected as a power amplifier of our system.

The block diagram of amplifier has been showed on Figure 6. As can be seen on Figure 6, one of the blocks is driver of power amplifier which its circuit has been demonstrated on Figure 7. The type of switching amplifier which is selected as the output stage of amplifier is the kind of

flyback amplifiers. The working methodology of this circuit is such that the current inside the inductor T_2 as the integral of applied pulse voltage is increased linearly when the MOSFET is switched on [10]. The energy has been saved in the inductive magnetic field. Reversal voltage with the opposite polarity has been yield when the MOSFET is switched off. The mentioned process causes the current exists continuously and the saved energy inside the inductor transmit to the ultrasonic transducer.

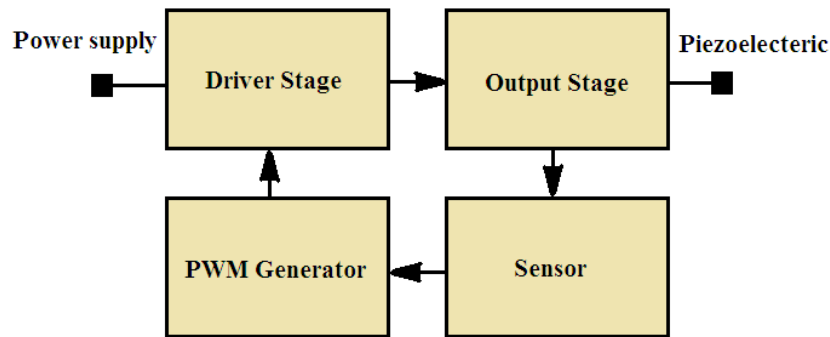


Figure 6. Block diagram of power amplifier

Since the current flowing capability of MOSFETs with low resistor on the path of flowing and heating wastage is better than the BJT transistors, high power MOSFETs are selected as the switch of flyback topology. The switching rate of MOSFETs makes them suitable for the use as a switching element that it is needed for ultrasonic application. High power MOSFET which is used in our system is IRFP450 with the maximum voltage 500 V (V_{DS}) and maximum current 14 A. The used current sensor on the path of current flowing is CSNE150-100 and it can measure amount of current which is passed through the ultrasonic transducer. The output of current sensor is current that it varies linearly by the alternation of transducer current.

Advantages of using transformer at the output stage are:

- (1) Eliminating of clamping affection of capacitor which is shown on Figure 2.
- (2) Impedance matching between transducer and output stage of power amplifier.
- (3) Ferrite affection on output stage.

Due to the requirement to have relatively low frequencies included in the pass band, a high magnetizing inductance is required. Together with high the step-up ratio of the transformer, this sets the requirement to use the ferrite core. Ferrite has a DC resistivity in the crystallites. We considered MnZn ferrites because of a higher permeability and higher induction levels. But the MnZn ferrites resistivity is lower - 0.1 to 1Ωm. It must be kept in mind that the higher permeability usually means the higher core losses. In our case it might cause the excessive core heating. Core influence on a coil is expressed by a complex permeability μ' (indicating the achievable inductance) and μ'' (indicating the core associated losses). We just indicate that EE65 material comb core has been chosen. The core parameters are summarized in Table 2.

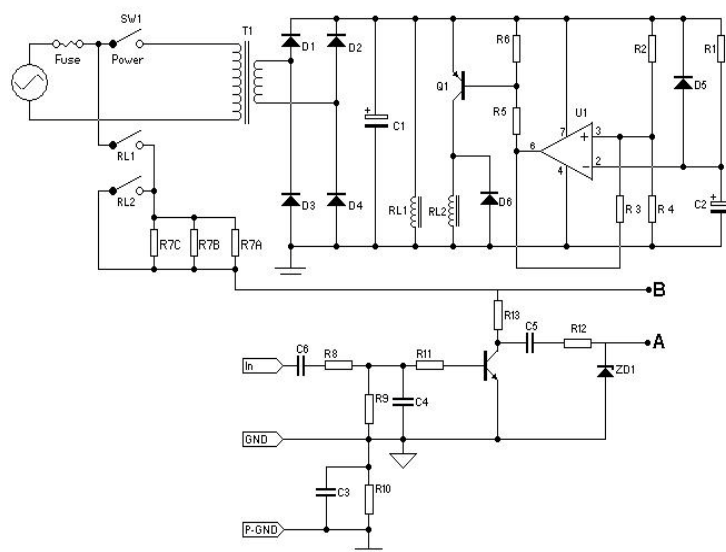


Figure 7. Circuit schematic of driver stage of power amplifier

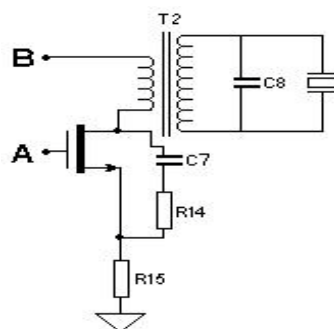


Figure 8. Circuit schematic of output stage of power amplifier

Table 2: Parameters of EE65 ferrite core

Type number	EE65/32/27-3C92
AL (nH)	6000±25%
μ_e	≈ 1310
Total air gap (μm)	≈ 0

For the designing of transformer and computing the winding ratio of each side of transformer, we use the following steps [9]:

$$\frac{Z_p}{Z_s} = \left(\frac{N_s}{N_p}\right)^2 \quad (7)$$

where Z_p and Z_s are impedance of primary winding and secondary winding respectively. N_p and N_s are the winding quantity of primary and secondary side of transformer. The ratio which has been chosen as the winding ratio of our designed transformer is 1:10. The DC level of power supply and the quantity of primary and secondary windings can be achieved by the use of following equation [9].

$$N = (V t)(B A_e) \quad (8)$$

where N is the quantity of winding, V shows the applied voltage on the windings, t is the total time of being on in each period of pulse signal; B is the maximum variation of flux density in core and A_s is the effective area of core. By the use of data which has been demonstrated on table 2, $N_s=35$ and $N_p=125$ then the computation of inductance of each winding is calculated by [9]:

$$L = N^2 AL(nH) \quad (9)$$

then L_p and L_s are equaled with 3.6 mH and 57.6 mH respectively.

III. CONTROL PART OF SYSTEM

The program of software algorithm which is written in C language is approximately too long such that the flowchart of program is shown on Figure 9. Here, the developed software algorithm to be run on the AVR microcontroller circuit has the following features:

- (1) Ability to set the operating frequency manually in the range of 30 kHz-60 kHz.
- (2) Dispersing-power control by PWM pulses.
- (3) Timing control for adjusting by the user.
- (4) Automatic power shut-down property when the temperature of power MOSFETs overflows the temperature limit.
- (5) Display controls to indicate temperature, operating modes, power adjustment, frequency adjustment, and operation time.
- (6) Recovering the resonant frequency of ultrasonic transducers due to possible deviations on their resonant frequencies resulted from changes on tank loadings. An analogue feedback has been proposed for this purpose in addition to the power unit.

In the main loop of program, the primary circumstances are set and the proper values allocated to the primary parameters, then interrupt operation for the retrieval of the previous case has been done or the new commands of user execute. Ultimately the mode of operation is selected. If user wants to change the operation mode of system, he can do it by the use of control interface board which is located on the system.

By the pushing of start button, microcontroller begins to generate the PWM pulses. Duty cycle of PWM pulses chooses with the specified power of system. The flowed current of piezoelectric is measured by the in line located current sensor. Output of current sensor is in the form of current and it is necessary that it converts to the voltage form to be applicable to the microcontroller. In the resonance frequency of piezoelectric, phase of applied voltage equals with the phase of flowed current and in this case current of system reaches the maximum value. Voltage which is measured by the sensor applies to the analogue comparator pin of microcontroller and it compares with the source voltage (the voltage in resonance frequency of piezoelectric).

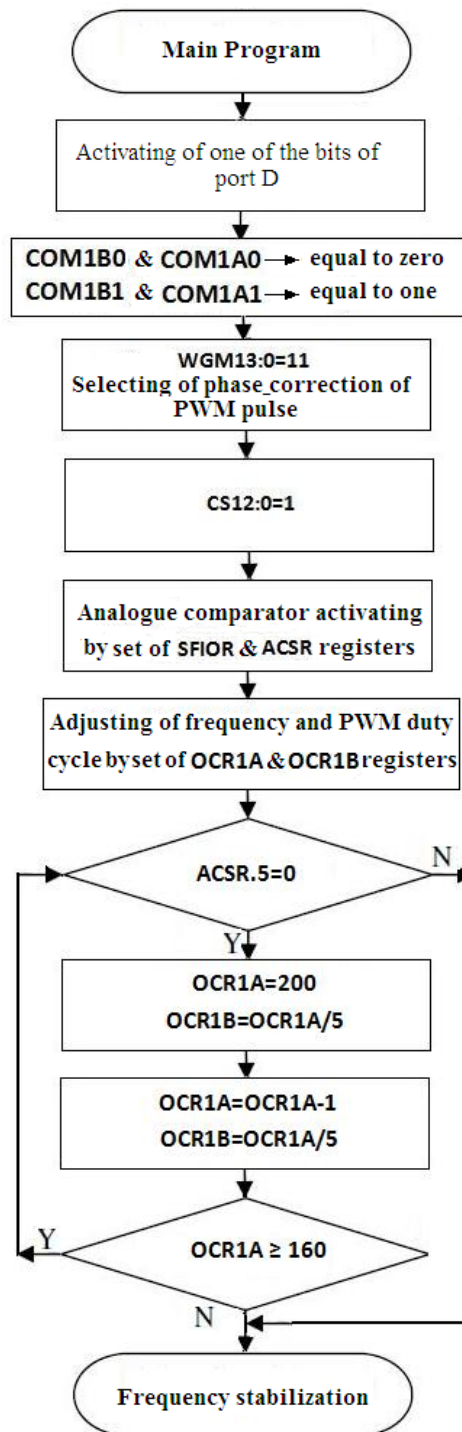


Figure 9. Flowchart of main program

Automatic frequency adjusting is done by the execution of following steps. As we know from the data sheet of piezoelectric, the resonance frequency of piezoelectric without load is 45 kHz so at first, frequency sweep is done from 42 kHz to 48 kHz with the 100 Hz steps. The mentioned sweeping is done until the detection of maximum current then frequency locks on the detected frequency. While the maximum current does not exist in the mentioned frequency band then frequency band of sweeping has been extended from 40 kHz to 50 kHz.

When the frequency of system locks on resonance frequency, time counter starts to work (it shows the working time of system which is determined by user). In addition, temperature control of system is such that detected voltage from temperature sensor which is connected to the container of liquid sends to the ADC pin of microcontroller in each 10 seconds and it compares with the critical temperature of system.

Time controlling method is such that the entire working time of system adjusts with the keypad by the user. While the system suddenly is switched off for any reason, the rest of time is saved in microcontroller and with the restarting, system asks the user if it continues the before settings or rest the system to initial settings.

IV. EXPERIMENTAL RESULTS

Ultrasonic dispersion system with frequency band from 30 kHz to 60 kHz and maximum power 500 W has been demonstrated in this paper and explanation of various structural parts of system discussed in previous subsections. Experimental result of this system is showed in this subsection. The generated PWM pulses by the microcontroller are shown on Figure 10. As can be seen in Figure 10, the duty cycle of generated PWM pulses are 20%. The signal form in the secondary side of transformer which is applied to the piezoelectric is demonstrated on Figure 11. The shown signal in Figure 11 is the attenuated signal with the 0.1 factor which is done on the real signal by the selecting of 0.1 attenuation mode on the probe of oscilloscope. It is clear from the Figure 11 that the real applied voltage signal to the piezoelectric is 1200 V.

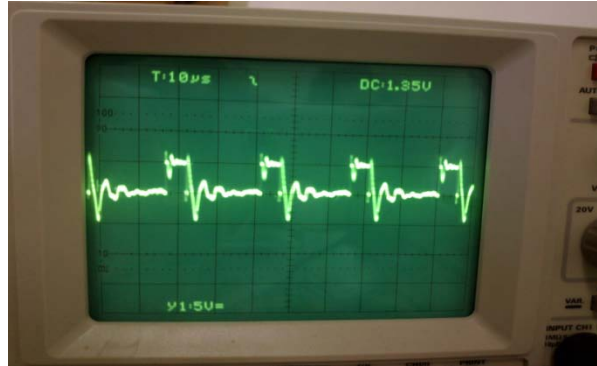


Figure 10. PWM pulses is generated with microcontroller

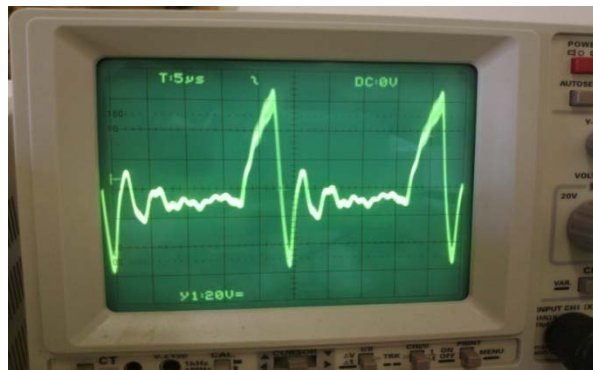


Figure 11. Output voltage signal to excite the piezoelectric

In the Figure 12 the manufactured system to excite the connected piezoelectric to the bottom of tank, has been shown. Various parts of system is cleared on the Figure 12 but in this case just one piezoelectric is excited. Additionally, the similar system has been used for the excitation of 9 piezoelectrics which are mounted on the stainless steel tank. The tank of the ultrasonic dispersion system has been demonstrated on Figure 13.

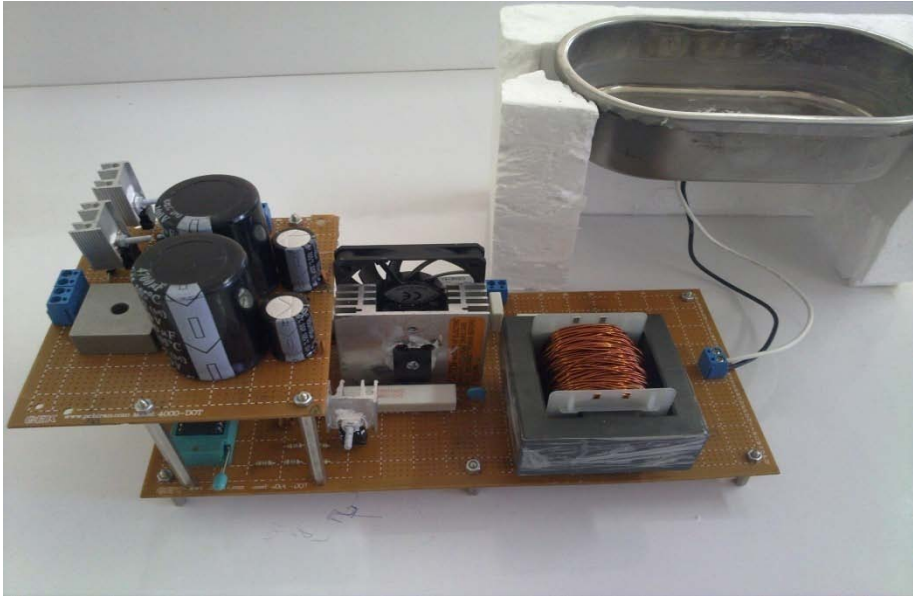


Figure 12. Experimental circuit to excite one piezoelectric

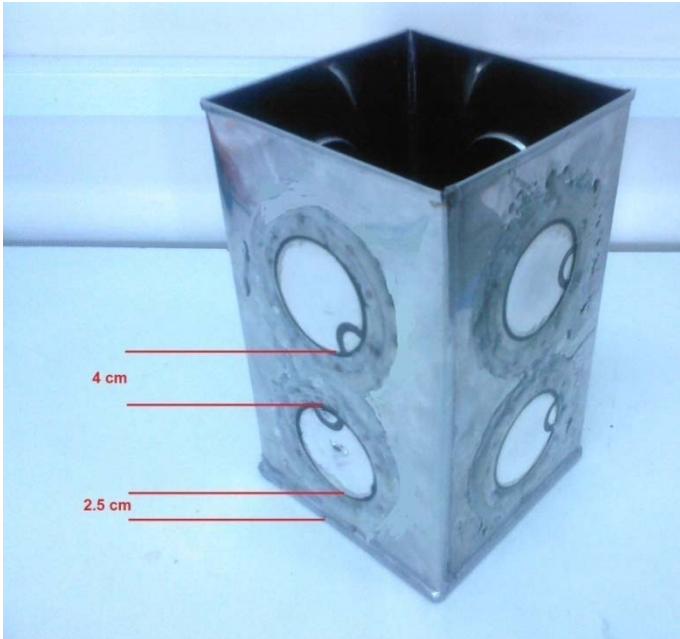


Figure 13. Manner of sticking of 9 piezoelectrics on the stainless steel tank

V CONCLUSION

In this paper a novel ultrasonic dispersion system with automatic frequency adjusting has been proposed that its frequency band is from 30 kHz to 60 kHz and maximum delivered power is 500 W. It consists of 9 piezoelectric ultrasonic transducers such that one of them sticks on the bottom of stainless steel tank and the rest of the piezoelectrics stick on the surrounding of tank. The flyback output stage of power amplifier has been used to excite the piezoelectrics and any ferrite core transformer is used to amplify the voltage and impedance matching of piezoelectric with the output stage. In addition, ATmega32 microcontroller is used as the controlling unit of system and PWM pulse generator.

This system has been used in the Catalyst laboratory and its performance in compare with the other ultrasonic dispersion system is good. The total time of nano powder producing by the use of this system is decreased considerably.

ACKNOWLEDGMENTS

The authors are indebted to Universiti Teknologi Malaysia for facilities and financial supports.

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