Ultrasonic Cleaning System with Self-tuning Oscillator

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***Abstract*—** This paper presents the "Ultrasonic Cleaning System with self-tuning Oscillator", which controls the of output frequency of ultrasonic generator to supply sandwich transducers unit in an ultrasonic cleaner. The mechanical resonance frequency of the oscillating system depends on many parameters and varies during the process. To obtain high efficiency cleaning frequency should be continuously monitored and tuned to that of the resonant frequency. This paper also gives details about sandwich type ultrasonic transducers made of PZT-4 crystals and ultrasonic cleaning tank construction.

Keywords—Resonance; Ultrasonic transducer; cavitation; frequency;

I. INTRODUCTION

Ultrasonic cleaning is a process in which the ultrasonic waves in the range 20kHz to 80 kHz is used in an appropriate aqueous cleaning solvent to clean items. Ultrasonic cleaners are used for precision cleaning of many types of objects such as car fuel injectors, musical instruments, lenses, optical parts, watches, surgical instruments, dental implants, jewellery, industrial parts and electronic parts. In ultrasonic cleaning, the transducers emit high pressure ultrasonic waves into aqueous medium which creates cavitation bubbles. These bubbles produce high forces on contaminants which are adhering on substrates such as metals, ceramics, glass, plastics and rubber. These have the capacity to penetrate blind holes, cracks. The intention is to thoroughly remove all traces of contamination tightly adhering on solid surfaces.

The high pressure ultrasonic waves used in the proposed work will create a strong agitation on the unwanted adhering substances on the solid surfaces. The high pressure waves have the capability to gain access to the blind holes. The performance tests for the proposed method was conducted based on aluminium foil test using the foil paper. The foil paper was highly contaminated with blind holes. The accuracy of the cleaning method proposed was found to be 89% accurate. Thus the proposed work can be considered to be one among the many other methods used in the field of ultrasonic cleaning.

II. ULTRASONIC CLEANING SYSTEM

The ultrasonic cleaning system generally includes

A. Ultrasonic generator
B. Ultrasonic Transducers
C. Cleaning tank

Piezoelectric transducers are bonded to the cleaning tank and driven by a suitable generator which generates ultrasonic waves which pass through the liquid and reach the cleaning element immersed in the tank. This creates high frequency and alternating areas of high and low pressure in the liquid. The area of low pressure forms millions of vacuum bubbles. When the pressure increases all the bubbles implode, releasing enormous energy simultaneously. This process is called as cavitation. These implosions work can be compared to multiple tiny cleaning brushes. The process spreads in all the directions and causes detachment of particles which adhered to the surface of cleaning object. An ultrasonic cleaning system is depicted in the Figure 1

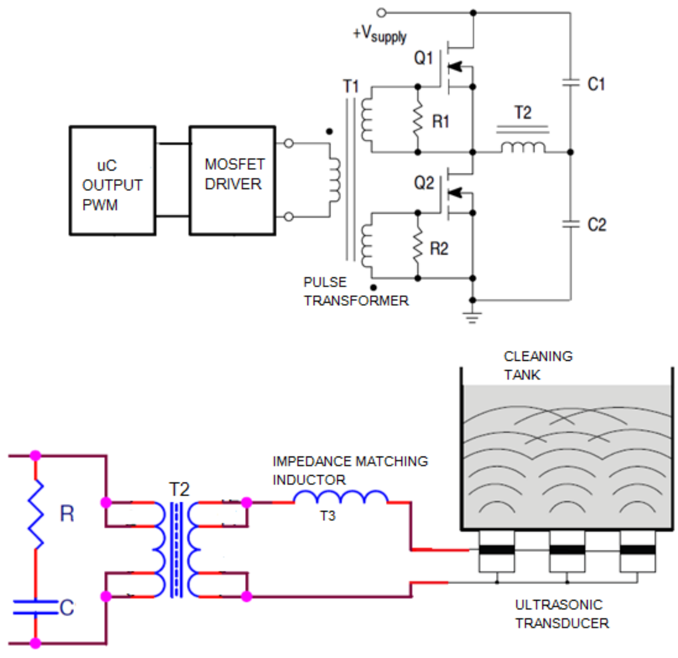

Fig 1: Ultrasonic cleaning system

A. Ultrasonic generator

The output frequency of ultrasonic generator must be equal to the mechanical resonance frequency of the transducers. It must be done by tuning with high precision. This mechanical resonant frequency depends on many parameters such as piezoelectric material, temperature, time, volume of liquid and the surface of the elements to be cleaned. In case of mismatch between mechanical resonant frequency of transducer and the generator, the frequency feedback control system of the generator must change the output frequency and tuning the inverter to the mechanical resonance frequency of transducers. Generator circuit is depicted in the Figure 2.

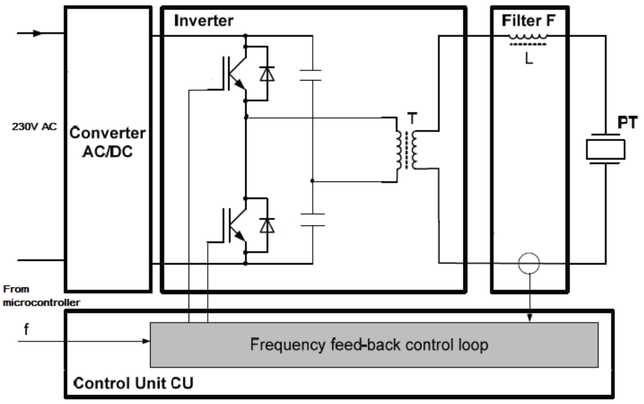

Fig 2: Block diagram of Ultrasonic Generator

Block diagram shown in Figure 2, consists of:

a) AC to DC converter
b) Half-bridge inverter
c) Control unit with frequency generator
d) Isolation transformer and filter
e) Current sensor of vibrations

The line voltage AC 230V with 50 hz frequency is rectified using a bridge rectifier to get DC voltage. This DC voltage is being converted to AC with frequency of ultrasonic range using half bridge MOSFET inverter. The output of inverter is fed to the piezoelectric transducer through isolation transformer and appropriate impedance matching filter.

To ensure maximum effectiveness of the piezoelectric transducers, the generator frequency must be equal to mechanical resonance frequency of transducer. This frequency is not constant and varies based on many condition.
To drive the ultrasonic transducer with its mechanical resonance frequency, a feedback system is used, which measures the phase difference between the phase of transducer current with the voltage. At resonance phase difference should be zero.

The Microcontroller PIC16F1509 is used to generate the waveform using inbuilt numerically controlled oscillator. The numerically controlled oscillator continuously tracks the phase and adjusts the frequency accordingly.

Figure:3 shows the algorithm in microcontroller to generate and auto tune the frequency to mechanical resonance frequency of the transducer.

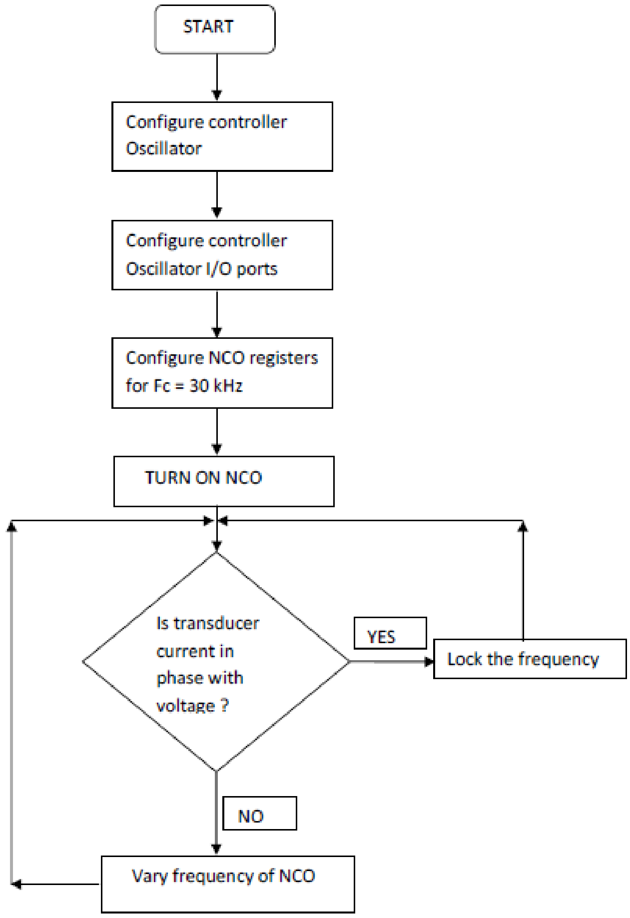

Fig 3: Control Algorithm

The filter inductor is calculated based on the below formula

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

C1 is effective capacitance of ultrasonic transducer
L1 is the external inductor added in series circuit.
fs is the resonance frequency

B. ULTRASONIC TRANSDUCER DESIGN

Ultrasonic cleaning is a high intensity ultrasound application which requires half wavelength transducers. Ultrasonic cleaning applications requires a resonant frequencies in the range of 18 kHz and 45 kHz. The sound velocity in the PZT4 ceramic is approximately 3200m=s .
By using the equation $V = f\lambda$.
where V is velocity, f is resonant frequency and λ is the wavelength.
The half wavelength length of PZT4 transducer would be ranging from 9 cm to 3.5 cm. The output power level required to excite such big mass transducer require a large surface area. Manufacturing of such single block of PZT4 ceramic is difficult. Also such ceramic blocks are not efficient, because the big transducer body will dissipate vibrational energy which varies inversely to the mechanical quality factor Qm. The mechanical quality factor is generally less in ceramics compared to that of metals. The stress amplitude in a half wavelength transducer will have maxima at the centre and end

portions acts as inert masses only. Hence the end portions can be replaced by suitable metal parts. This increases the mechanical quality factor of transducers and are relatively economical. Since the power requirement for ultrasonic cleaning is high, the tensile strength of the piezo ceramic is not sufficient to take the load of high mechanical stress. All the above limitations of the ceramic material is made good by adding two metal pieces at both the ends and pre-stressing (Torque at around
25M Pa) them in axial direction using bolts . The combination of steel-PZT-aluminium is favourable.

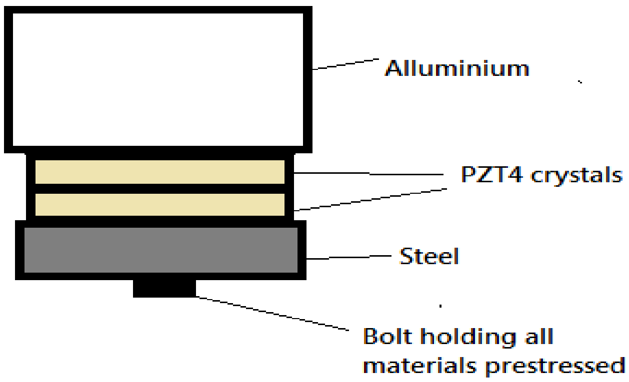

Fig 4: Ultrasonic transducer

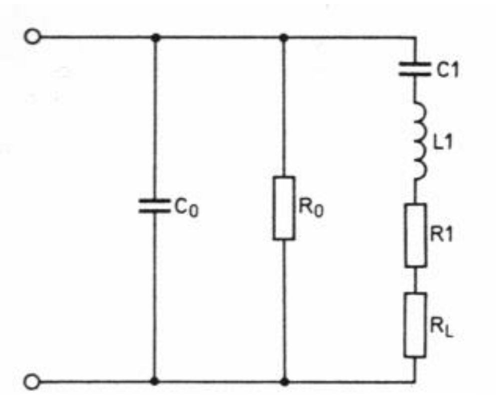

Fig-5 Electrical model of a PZT transducer

C. Cleaning tank Construction

Ultrasonic energy is usually measured in Watts/gallon. Many factors have to be considered in determining the appropriate amount of ultrasonic power for a specific application. The design includes finding the appropriate ultrasonic power density, the number of transducers to use and their position in the cleaning tank for getting maximum cavitation and cleaning efficiency. As tank size is increased, less the energy absorbed in the tank walls. It is due to the fact that as the tank size increases, the ratio of area of wall surface area to tank volume decreases. So the power, Watts per gallon required decreases as the tank size increases. In larger cleaning tank, ultra-sonic energy travels through the liquid for more distance without impeding and ultrasonic wave is reflected by large surfaces of sides and bottom of the tank. In smaller tanks as shown in the Figure 6, the ratio of surface area of the item being cleaned and the volume of the tank is more and also in smaller tanks the reflection from sides walls is frequent and more which causes dissipation of energy due to destructive interference. Due to this, higher Watt density is required in smaller tank.

Fig: 6 ultrasonic tank with bonded transducer

III. Cavitation test using aluminium foil

The common test for cavitation is aluminium foil test. In this test, a piece of aluminium will be placed in the ultrasonic cleaning tank. Foil to be immersed for one minute in the bath. After one minute the foil should be taken out and careful observation has to be made. A uniform indentation pattern or tiny holes should occur on the foil as shown in the Figure. If the ultrasonic tank, power and frequency are designed properly, there should be a uniform indentation pattern covering the entire area of the foil. If the indentation pattern is not consistent, not uniformly occurring then the cleaning will not be uniform all over the tank.

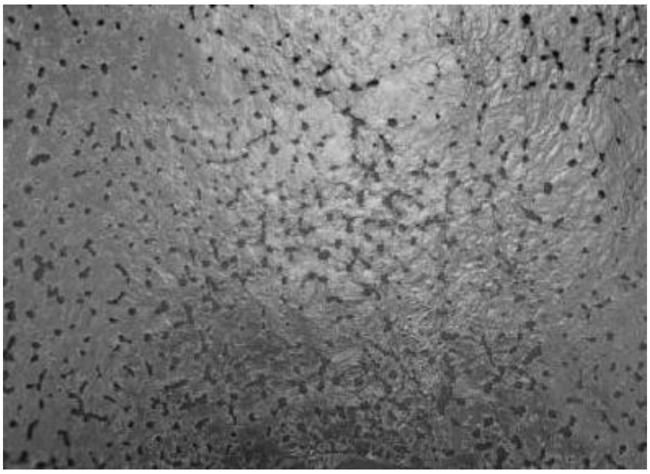

Fig 7: Aluminium foil after cavitation

IV. SIMULATION AND RESULTS

The microcontroller generated frequency output is shown by the MPLAB IDE simulator. The generated frequency is also measured in a frequency meter. As simulator, MPLAB Simulator is used which is built in the package of MPLAB X IDE.
Program can be tested without the hardware. Output waveforms is demonstrated in the Figure 8. Using the simulator analyser in the MPLAB X IDE tools, we can analyse the output waveforms of the PWM i.e., output of

complementary waveform generators. The Complementary waveforms can be seen from the MPLAB Simulator Analyser.

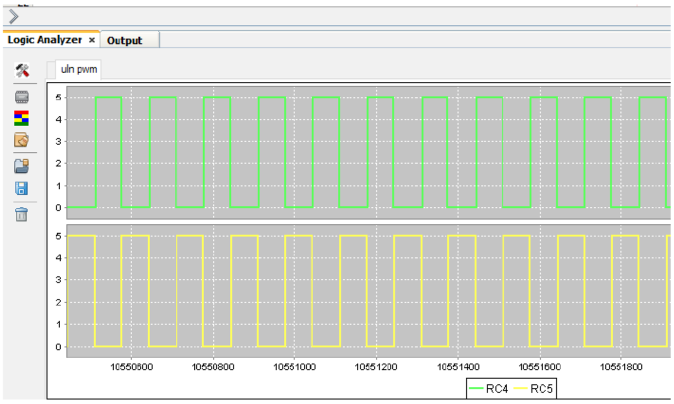

Fig 8: Complementary Waveforms driving MOSFET inverter

ACKNOWLEDGMENT

The satisfaction that accompanies the successful completion of any task would be incomplete without the mention of people who made it possible and whose constant guidance and encouragement crowned our efforts with success. We consider our privilege to express the voice of gratitude and respect to all those who guided us and inspired us in completion of this paper. We would like to thank our parents and our families for their constant moral support throughout the completion of this project.

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