Improved Design of Ultrasonic Cleaning Tank Using Harmonic Response Analysis in ANSYS

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Abstract. Ultrasonic cleaning tank is a machine that many factories widely used to clean objects. At one factory, a problem occurred in the cleaning process, resulting in the factory not being able to clean objects, but cracks also appeared on some objects. It was anticipated that these were caused by uneven acoustics pressure distribution which resulted in unsuitable cavitation. This directly affected cleaning performance within the tank. In order to improve the tank's efficacy, in this research, we used Harmonic Response Analysis in ANSYS 17.2 to simulate the occurrence of acoustic pressure in the tank to find a suitable type and placing position of the transducer for the tank. We found that transducers made from PZT4 gives greater acoustic pressure than those made from PZT8. Changing the transducer type does not affect the acoustic pressure pattern. PZT4 is therefore the most suitable type of transducer for this tank. Simulation results also suggested that placing the transducer under and beside the tank will result in intense acoustic pressure that is evenly dispersed throughout the tank. Results from this simulation were then passed to the manufacturing factory, and were later accepted that it could truly enhance the tank's efficacy. Information regarding the issue was also used in the development of improved design of ultrasonic cleaning tank to have greater performance levels.

1. Introduction

The ultrasonic (u/s) cleaning tank is a machine used to clean valuable objects that are fragile yet contaminated or dirty to be more cleaned such as lens, jewelry, dental instruments and electronic devices etc. Acoustic pressure occurs from the vigorous vibration of the piezoelectric transducer. Once it has received electric currents, it will send ultrasonic waves into the medium following the transducer's built frequency which is between 20-20,000 kHz [1-2]. Liquid medium will then change pressure phase or lessen following the pulse of the harmonic wave. The rare fraction phase occurs during low or sub-zero pressure while the compression phase occurs during high or positive pressure. When the liquid medium is in the low-pressure phase, many tiny cavitation bubbles occur. When the liquid medium in any area is in the high-pressure state, the bubbles that occur will shrink and absorb energy. The bubbles continuously change according to cycle until they cannot absorb any more energy and will then collapse during the high-pressure phase. When bubbles collapse, they release an intense energy called the liquid jet, with a temperature of 5,500 ^{o}C, pressure of 68 MPa and a speed of approximately 280 m/s [3] that collides with contaminant particles on or nearby an object therefore cleaning the object's surface.

Our research is a collaboration between a u/s tank manufacturer and our research group. The u/s tanks used in the actual cleaning process had a problem of after cleaning, most of objects were cleaned but some objects still had particle contamination, and some were cracked. As for the unclean objects, it required recleaning process until it is clean while the damaged objects must be destroyed. The factory that used these u/s tanks had budget losses from the cleaning process approximately 100 million THB per year, therefore; this problem must be resolved urgently.

From a review, we found that the main cause of this problem leading to the losses is bad acoustics pressure distribution because an abrupt change in acoustic pressure distribution results in the cavitation effect. The main factors that affect acoustics pressure distribution are power, ultrasonic frequency, temperature of solution, sonication time, position of cleaning object and type of transducer. Cavitation intensity increases with increasing power generated into the medium [4]. The cleaning performance depends on the magnitude of acoustic pressure. It is good performance at the location of large acoustic pressure and poor at the location of small acoustic pressure. High frequency is proper for cleaning small objects, but low frequency is in opposite [5]. When the solution's temperature is increased, the cleaning performance decreases. It was found that the suitable temperature of solution for cleaning is in the range of 20 – 40 °C, while the best cleaning temperature is below 20 °C [6, 7]. Since sonication time, a time for cleaning objects using ultrasonic, is increased, corrosion due to cavitation is also increased [8]. The performance of transducers made from PZT4 and PZT8 were investigated by finite element method and experiment [9]. It was reported that PZT4 is better than PZT8. However, this work investigated only the performance of transducer. The u/s tank model and other environmental conditions did not include. Recently, to find ways for improving the performance of ultrasonic cleaning in a simple tank, we simulated the acoustic pressure distribution using the Harmonic Response Analysis in ANSYS based on actual conditions from the factory [10]. The results of simulation were confirmed by the experiment of foil corrosion test. We found that increasing the power applied to the transducer was unaffected the acoustic pressure pattern. Also, increasing ultrasonic frequency gave more uniform acoustic pressure distribution. The position that provided the highest cleaning efficiency was at the middle of the tank.

This article is an extension of the research in references [9-10]. We will simulate the acoustic pressure pattern in the u/s tank by using PZT4 and PZT8 as transducers based on actual operating conditions of the factory to compare the cleaning performance. Moreover, we will determine the optimal placement of transducer providing the highest cleaning performance by using Harmonic Response Analysis in ANSYS 17.2. The simulation results may be used to improve the cleaning process and to develop a prototype of u/s tank with higher efficiency for the manufacturer in near future.

2. Theoretical Background

The cleaning process results from the cavitation effect. It occurs when the solution's pressure changes phase abruptly. However, at present no mathematical equation may directly express the cavitation. Therefore, researchers rely on the wave equation of acoustic pressure in form of Helmholtz equation (1) to explain cavitation's behaviour, since it can illustrate the cavitation bubble occurrence well.

$$\nabla \cdot -\frac{1}{\rho}\left(\nabla p_t\right) - \frac{\omega^2 p}{c^2 \rho} = 0 \tag{1}$$

where acoustic pressure $p = p_0 exp(i\omega t)$. ω represents the frequency of wave. The constants c and ρ are the speed of wave and density of water, respectively.

The temperature and pressure of the bubble collapse are also important factors that affect the cleaning process. When the bubble expands to its maximum size, the area surrounding the bubble's temperature will rise to over 5,500 ^{o}C. Because the pressure is greater than 68 MPa [3], the collapse will occur quickly in the micro-seconds unit. The heat will not be able to escape from the bubble in time. This deems that the bubble collapses adiabatically and results in the cleaning process. The equation used to explain the relationship of collapse, temperature and bubble radius can be expressed by the well-known Reyleigh-Plesset equation as [11]:

$$P_{\text{collapse}} = \left(P_0 + \frac{2\sigma}{R_0}\right)\left(\frac{R_0}{R}\right)^{3\gamma} - \frac{2\sigma}{R} - \frac{4\mu}{R}\left(\frac{dR}{dt}\right) \tag{2}$$

where P_0 is the acoustic pressure in solution. P_{collapse} is the pressure inside the bubble. σ is the solution surface tension. R_0 is the starting radius of the bubble and R is the radius of the bubble while collapsing. γ is the ratio of gas specific heats. μ is the dynamic viscosity. Equation (2) implies that the cavitation bubble radius relates to acoustic pressure. This shows that the increase of acoustic pressure is the increased intensity of the cleaning process.
As for the ANSYS program, we used the Harmonic Response Analysis which is calculated the acoustic pressure based on the finite element method (FEM). The program calculates acoustic pressure in the solution where the cavitation effect occurs and reports as graphic colours. In calculating the acoustic pressure, the finite element formulation is obtained by a testing wave using the Galerkin procedure. The wave equation (1) is multiplied by the testing function (w) and integrated over the volume of the domain with some manipulation to yield [12]:

$$\begin{aligned}&\iiint_{\Omega_F} \frac{1}{\rho_0 c^2} w \frac{\partial^2 p}{\partial t^2} dv + \iiint_{\Omega_F} \nabla w \cdot \left(\frac{4\mu}{3\rho_0^2 c^2} \nabla \frac{\partial \rho}{\partial t}\right) \mathrm{dv} + \iiint_{\Omega_F} \nabla w \cdot \left(\frac{1}{\rho_0} \nabla p\right) \mathrm{dv} \\ &- \oiint_{\Gamma_F} w\left(\frac{1}{\rho_0} + \frac{4\mu}{3\rho_0^2 c^2} \frac{\partial}{\partial t}\right) \hat{n} \cdot \nabla p ds + \oiint_{\Gamma_F} w \frac{4\mu}{3\rho_0^2} \hat{n} \cdot \nabla Q ds \\ &= \iiint_{\Omega_F} w \frac{1}{\rho_0} \frac{\partial Q}{\partial t} dv + \iiint_{\Omega_F} \nabla w \cdot \left(\frac{4\mu}{3\rho_0^2} \nabla Q\right) \mathrm{dv}\end{aligned} \tag{3}$$

where dv is volume differential of acoustic domain Ω_F, ds is surface differential of acoustic domain boundary Γ_F and $\hat{n}$ is outward normal unit vector to the boundary Γ_F. From equation (3), the water with fluid domain is now adapted to acoustic domain which can be calculated the acoustic pressure by ANSYS. Readers who are interested in more details of derivation and meaning expression of equation (3) can be found in references [12].

3. Methodology

3.1. Ultrasonic cleaning tank

The u/s cleaning tank we used to draw a model is donated from the factory, the model which industrial factories widely purchase the most. The size is 244 mm (wide) × 340 mm (long) × 220 mm (depth). It may contain 18 litres of water. Beneath the tank are 8 PZT4 piezoelectric transducers. The overall power is 400 watts, with a frequency of 28 kHz as shown in figure 1.

Figure 1. Actual u/s cleaning tank.

3.2. Simulation model

To determine a suitable type of transducer for u/s tank, we draw a CAD model as shown in figure 2. This model is similar to the actual u/s tank but using PZT8 as transducer instead of PZT4. To investigate the change after repositioning the transducers and to find the best position for placing transducer. We created a CAD model for improved design of u/s tank by relocating 4 transducers from below to the side. We anticipated that this method will give better distributed acoustics pressure. The model with repositioned transducer is shown in figure 3. All models consist of 4 domains; water (solution), the plate (at the bottom of the ultrasonic tank), foil sheet (located at the middle position of the tank which has the highest cleaning efficiency) and the transducer. The transducers consist of back mass, piezoelectric, front mass and glue.

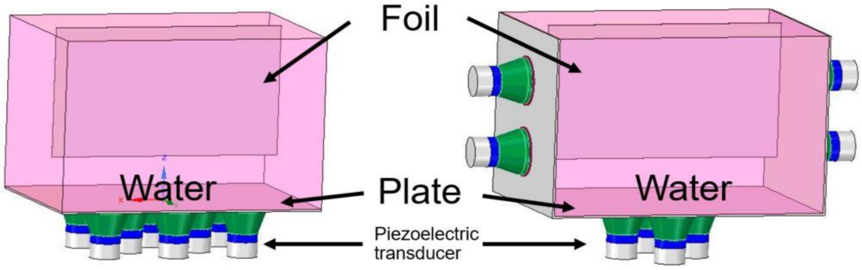

Figure 2. CAD model of actual u/s tank**.**

Figure 3. CAD model for improved design of u/s tank.

3.3. Mesh model

By simulation using the FEM method, we transferred the CAD models to a mesh model in order to divide large models into elements. The connected points between elements are called nodes. The more number of nodes, the higher accuracy of simulation. Our research simulated pressure occurrence from high frequency waves. Thus, we needed to create a highly detailed mesh. The mesh in each model must have at least 6-12 elements in 1 wave length to ensure that the pattern from our simulation is realistic [10, 12]. The mesh model for the actual and improved design of u/s tanks are shown in figure 4 and 5. We used hexahedral mesh, a mesh that gives more nodes than others but gives more accurate solution than other mesh types. Both models consist of approximately 240,000 elements and 706,000 nodes. They provided high accurate results in a limit of computer performance and computational time usage.

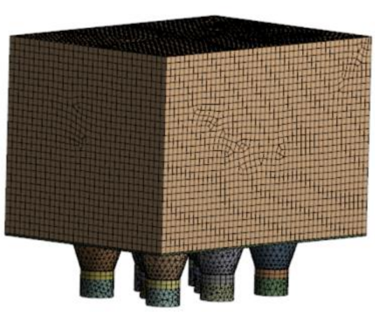

Figure 4. Mesh model of actual u/s tank.

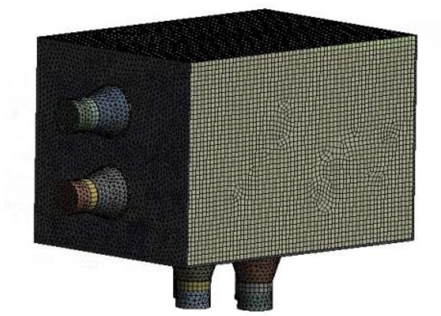

Figure 5. Mesh model of modified u/s tank.

3.4. Harmonic response analysis

Harmonic Response Analysis is a package in ANSYS 17.2 used to determine the steady-state response of a linear structure to loads that vary sinusoidally with time [12]. It was integrated with an additional package of piezoelectric and MEMS [13] to increase the capability for simulating the solution in piezoelectric domain. This integration was ensured that gives the higher accurate solution. Therefore; it was employed to determine the acoustic pressure and intensity of the u/s tank in this research. The important values required for simulation are: material properties of water at 45 ^oC, PZT4 and PZT8, which are shown in Table 1. Other values we used the default setting of the program.

The calculation is separated into 3 domains: in PZT domain, plate domain and water domains. In PZT domain, piezoelectric is coupling between structural and electric fields that occurs in the piezoelectric materials. Applying a voltage to transducer (PZT) creates a displacement, and vibration. The equation governs finite element method in PZT domain is [13]

$$\begin{pmatrix} K_{UU} & K_{UV} \\ K_{UV} & -K_{VV} \end{pmatrix} \begin{Bmatrix} U \\ V \end{Bmatrix} + \begin{pmatrix} C_{UU} & 0 \\ 0 & -C_{VV} \end{pmatrix} \begin{Bmatrix} \dot{U} \\ \dot{V} \end{Bmatrix} + \begin{pmatrix} M_{UU} & 0 \\ 0 & 0 \end{pmatrix} \begin{Bmatrix} \ddot{U} \\ \ddot{V} \end{Bmatrix} = \begin{Bmatrix} F \\ Q \end{Bmatrix} \tag{4}$$

where K_{UU}, K_{VV}, K_{UV} are structural stiffness, dielectric permittivity and piezoelectric coupling element matrices, respectively. C_{UU}, C_{VV} are structural damping and dielectric dissipation, respectively. M_{UU} is mass. U is displacement vector and V is an applied voltage.

After completing the calculation of node displacements and vibration in PZT domain using equation (4), the results will transfer to the plate domain and then to the water domain where the acoustic pressure is numerically calculated using equation (3). Finally, the computer will display the acoustics pressure distribution results into different colors according to the acoustics pressure value in considered area.

Table 1 Material properties required for setting in Harmonic Response Analysis

Domain	Type	Value
Water (45 ^oC)	Water density	990.15 kg/m^3
	Acoustic velocity	1,533.5m/s
	Dynamic viscosity	5.7977x10^{-4} kg/m·s
Piezoelectric (PZT4)	Density	7,500 kg/m^3
	Permittivity Constant (ε_0)	8.854e-12 F/m
	Stiffness (c^E)	C_{11} =1.39x10^{11}=C_{22}, C_{21}=7.78x10^{10}, C_{31}=7.43x10^{10}=C_{32}, C_{44}=3.06x10^{10}, C_{55}=2.56x10^{10}=C_{66} Pa
	Piezoelectric stress (e)	e_{31}= -5.2 c/m^2, e_{33}= 15.1 c/m^2, e_{15}=12.7
	Relative Permittivity($\frac{\varepsilon_T}{\varepsilon_0}$)	K_{11} = 1,475, K_{33} = 1,300
Piezoelectric (PZT8)	Density	7,600 kg/m^3
	Permittivity Constant (ε_0)	8.854e-12 F/m
	Stiffness (c^E)	C_{11} =1.47x10^{11}=C_{22}, C_{21}=8.11x10^{10}, C_{31}=8.10x10^{10}=C_{32}, C_{44}=3.29x10^{10}, C_{55}=3.13x10^{10}=C_{66} Pa
	Piezoelectric stress (e)	e_{31}= -3.9 c/m^2, e_{33}= 13.9 c/m^2, e_{15}=10.3 c/m^2
	Relative Permittivity($\frac{\varepsilon_T}{\varepsilon_0}$)	K_{11} = 1,290, K_{33} = 1,000

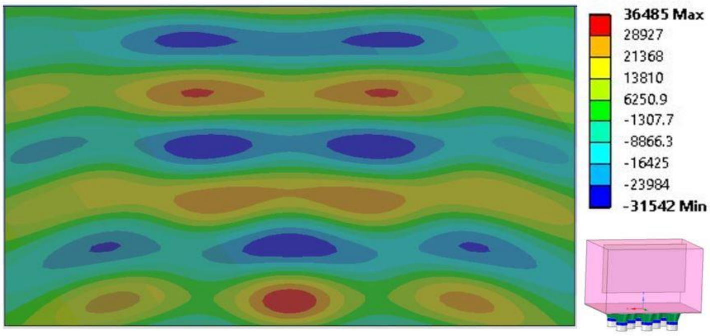

Figure 6. Acoustic pressure distribution of actual u/s tank using PZT4 as transducers [10].

4. Results and Discussion

As mentioned in the introduction that this research will study the results of using the PZT8 as the transducer and the results after repositioning the transducers to the side and its influences towards the acoustic pressure within the tank. We would therefore like to use the acoustic pressure from the simulation in our previous work [10] as reference. The results from reference [10] were confirmed the accuracy by comparing with foil corrosion test. Since our work in this article uses similar methodology, u/s tank model and operating conditions to the work in reference [10], this makes us confident that the methodology used, and simulation results obtained in this research are credible. The simulation results of the acoustic pressure in the middle plane of the tank when we used the PZT4 transducer as shown in figure 6. Once the transducer was changed to type PZT8, acoustic pressure distribution results as shown in figure 7.

From the comparison of figures 6 and 7, once the type of transducer is changed from PZT4 to PZT8, the acoustic pressure distribution pattern did not change. The acoustic pressure distribution in a middle plane, a plane that gave the highest cleaning performance, revealed that using PZT4 transducer has higher intensity of acoustic pressure than PZT8. High intensity of acoustic pressure gives the higher energy of cavitation and better cleaning performance. According to Table 1, we can see that the permittivity constant, stiffness, piezoelectric stress and relative permittivity of PZT8 are lesser than PZT4, therefore; resulting in less cavitation intensity. From the simulation results, we may say that the PZT4 is most suitable material for using as transducer for manufacturing the u/s cleaning tank.

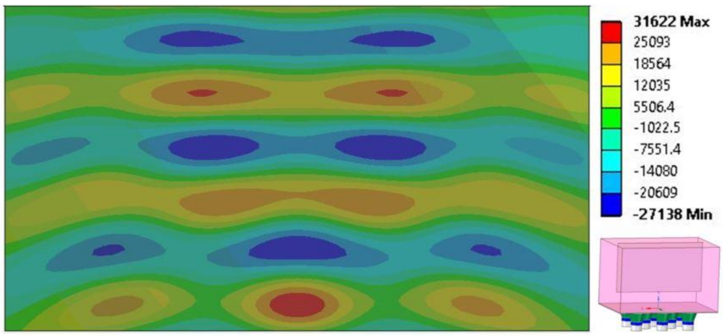

Figure 7. Acoustic pressure distribution of actual u/s tank using PZT8 as transducers.

To check the acoustics pressure distribution results from repositioning 4 transducer heads to the side of the u/s tank so the cleaning process within the tank is evenly done as shown in figure 3 by using the PZT4 as the transducer**.** Simulation result of the acoustic pressure occurrence is shown in figure 8**.** Once compared to the simulation results of the original tank without repositioning in figure 6, it was found that, by changing the transducers**'** position, the acoustic pressure pattern at an overall figure had changed**.** Better acoustic pressure distributions to all areas in the tank were observed**.** Other than this, the highest and lowest acoustic pressure are also greatened, resulting in better and more intense cavitation. The better acoustic pressure distribution change is from relocating transducers to the side resulting in acoustic waves from 3 directions that give more constructive and destructive interference points than the original u/s tank which all 8 transducers were installed beneath the u/s tank resulting in acoustic wave from a single direction. All results mentioned above made us confident that by repositioning 4 transducers to the sides will also enhance the performance of cleaning as well. All results of this research were submitted to the tank manufacturer. At the present, they have already used the knowledge to build newer model with better cleaning performance than the original one. This simulation is done at 45 ^{o}C. Cleaning performances depend on the temperature as well, therefore; a further study of the temperature and its effects upon cleaning performances by using simulation is an interesting and challenging topic in the future. In addition, during research, we also found that the transducer has a short life expectancy. If we applied the Harmonic Response Analysis and the Fatigue Analysis in ANSYS to deal with the problem following the work in reference [14], the results could be solved the problem and extended a lifetime usage of the transducers.

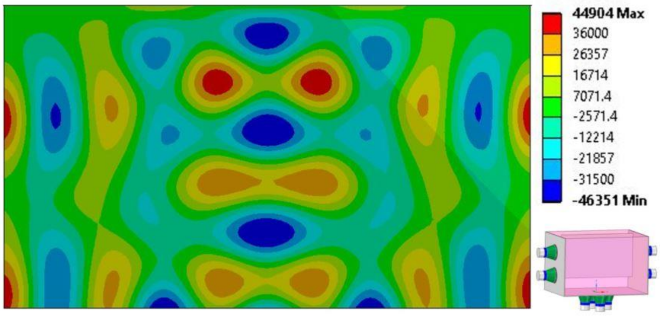

Figure 8. Acoustic pressure distribution of modify u/s tank.

5. Conclusion

This research simulated acoustic pressure distribution occurrence which directly affects the ultrasonic (u/s) tank's object cleaning efficacy. The ultrasonic cleaner tank has a frequency of 28 kHz with power of 400 watt. The tank in this research originated from the manufacturer where a problem occurred. The problem was after cleaning, most of objects were cleaned but some objects still had particle contamination, and some were cracked. This made a low efficiency in cleaning. To solve the problem, we used Harmonic Response Analysis in ANSYS to simulate the acoustic pressure to determine the optimal design of u/s tank with higher efficiency. First, we changed the piezoelectric transducer type from PZT4 which is a conventional material to PZT8. The simulation results showed that the acoustic pressure distribution pattern did not change but using PZT4 as transducer gave the higher intensity of acoustic pressure. To determine suitable positions for placing the transducers, we changed the installation position of the transducer of the tank to the side, it was found that the acoustic pressure distributed more evenly throughout the tank and thus intensified the acoustic pressure within the tank as well. Therefore, we concluded that using PZT4 as transducer and placing the transducers beneath and beside the tank contribute to better cleaning efficacy than the original u/s tank. The finding from this research was proposed to the tank manufacturer. It was used as novel information for developing an improved design of u/s tank with higher efficiency in near future.

6. References

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