



# Development of an industrial ultrasonic cleaning tank based on harmonic response analysis

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## ARTICLE INFO

### Keywords:

Acoustic pressure  
ANSYS  
Cavitation  
Harmonic response analysis  
Simulation  
Ultrasonic cleaning

## ABSTRACT

A small industrial ultrasonic cleaning tank, which is one of the best-selling models, had cleaning problems. Customers sometimes complained that the tank did not completely clean all objects, or that some objects got damaged, so a solution to the problem was urgently needed. The tank has a volume of 18 L, frequency of 28 kHz, eight horn style PZT4 transducers, and a total electric power of 400 W. The cleaning occurs from the cavitation effect which corresponds to an increase in the acoustic pressure. A computer simulation is presented using a harmonic response analysis (HRA) in ANSYS to resolve and improve the efficacy of the tank. From the simulation, we found that the acoustic pressure within the tank was uneven. The distribution of acoustic pressure had a characteristic pattern depending on the placement of the transducers. When the temperature was increased, the acoustic pressure was decreased leading to a cleaning efficacy drop as well. All simulation results were correlated to the foil corrosion test and power concentration experiment. The HRA was used to redesign the tank for higher cleaning efficacy. The simulation results indicated that more suitable placement of the transducers lead to a more intensified acoustic pressure, and a better distribution throughout the tank. This research not only resolved the cleaning problems that occurred in the 28 kHz tank, but was also demonstrated that it can be applied to a 40 kHz tank as well. Results from this research were accepted and approved by the manufacturer, and were used by them to develop smarter industrial ultrasonic tanks with higher cleaning efficacy for commercial sale.

## 1. Introduction

Ultrasonic cleaning is transferring ultrasonic waves at a frequency between 20 and 400 kHz in an appropriate cleaning solution to create large quantities of tiny bubbles called the cavitation effect. The rapid collapse and implode of these bubbles generates great heat and pressure energy that cleans off any impurities from the object placed within. Ultrasonic cleaning started to play an important role in the manufacturing industry since the 1950s [1]. It is popularly used in the manufacturing industry of electronics, food, medical instruments, clothing and textiles, petroleum, etc. The ultrasonic frequency has effects upon the object intended for cleaning. Higher frequencies produce smaller bubbles with less acoustic pressure, and lower frequencies produce larger bubbles with higher acoustic pressure that can cause more damage to objects. Cleaning efficiency also depends on the type of solvent, temperature, sonication time, and power of transducers used in the cleaning process as well [2–4]. The efficacy of ultrasonic cleaning can be assessed from visual inspection, gravimetric analysis,

calorimetry, cavitation, power and removal of deliberating soiling.

From research review related to ultrasonic cleaning, we learned that most focus their research on improving the cleaning process e.g. as in Baoji et al. [5] which reported that the repositioning of aluminum foils and temperature solution change directly affect the corrosion due to the change of cavitation. Vetrimurugan et al. [6,7] verified the effects of ultrasonic frequency, sonication time, solvent and power towards cleaning capacity of hard disk drive components. They found that a suitable circumstance of ultrasonic frequency, sonication time and cleaning solvent shall give highest cleaning efficacy. Verhaagen et al. [8] also proposed a technique for using ultrasonic cleaning for 3D printed objects from actual experience which can be applied for cleaning general objects efficiently. Yusof et al. [9] studied physical and chemical effects of acoustic cavitation to apply in the medical field. From their report, it may be confirmed that not only can ultrasonic be used in cleaning medical apparatus but can also be developed to deactivate different germs (pathogens) as well. Loranger et al. [10] studied and compared cavitation that occurred in experiments, both in

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<https://doi.org/10.1016/j.ultras.2018.07.013>

Received 7 January 2018; Received in revised form 4 July 2018; Accepted 23 July 2018

Available online 25 July 2018

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## Nomenclature

$[C_f]$	acoustic damping matrix (N s/Pa)
$[R]^T$	acoustic fluid boundary matrix ( $\text{m}^3$ )
$\bar{\rho}_0$	acoustic fluid mass density constant ( $\text{kg}/\text{m}^3$ )
$[M_f]$	acoustic fluid mass matrix ( $\text{N s}^2/\text{Pa}$ )
$[K_f]$	acoustic fluid stiffness matrix (N/Pa)
$\{F_f\}$	acoustic load vector (N)
$p$	acoustic pressure (Pa)
$\omega$	angular frequency (rad/s)
$\rho$	density of liquid ( $\text{kg}/\text{m}^3$ )
$\mu$	liquid viscosity (Pa s)
$\{F\}$	load vector (N)

$\{\ddot{u}\}$	nodal acceleration vector ( $\text{m}/\text{s}^2$ )
$\{\dot{u}\}$	nodal velocity vector ( $\text{m}/\text{s}$ )
$\{u\}$	nodal displacement vector (m)
$\{\ddot{u}_f\}$	nodal acceleration vector of fluid ( $\text{m}/\text{s}^2$ )
$\{p\}$	nodal displacement vector of acoustic pressure (Pa)
$\{\dot{p}\}$	nodal velocity vector of acoustic pressure (Pa/s)
$\{\ddot{p}\}$	nodal acceleration vector of acoustic pressure ( $\text{Pa}/\text{s}^2$ )
$[C]$	structural damping matrix (N s/m)
$[K]$	structural stiffness matrix (N/m)
$[M]$	structural mass matrix (kg)
$t$	time (s)
$c$	velocity of sound in medium ( $\text{m}/\text{s}$ )

ultrasonic bath and large-scale of sonoreactor. Their research results can be applied to enhance large-scale cleaning efficacy on industrial levels. Computer simulation is widely used to simulate ultrasonic cleaning to study, verify and seek conditions for the best cleaning process because it is cost-saving, consumes lesser time and gives quite credible results. Bretz et al. [11] used computational fluid dynamics (CFD) in 2D to simulate the position which cavitation occurs in liquid and compare the corrosion position on aluminum foil in accurately in actual experiment. Osterman et al. [12] used CFD to simulate the occurrence of near-wall bubble collapsed in an ultrasonic field. This helped them understand the basics of cavitation occurrence in ultrasonic cleaner even well. Acoustic pressure can be used to analyze the cavitation occurrence. Li et al. [13] simulated acoustic pressure in a 3D ultrasonic tank to study the frequency and level of solution in an ultrasonic tank towards the ability of cavitation occurrence using the COMSOL program. Tiong et al. [14] simulated acoustic pressure occurrence to enhance the performance of dental endosonic file. Niazi et al. [15] used CFD to simulate acoustic cavitation in sonoreactor to apply the results in improving the quality of crude oil in the petrochemical industry. Recently, harmonic response analysis (HRA) in ANSYS was primarily used to simulate acoustic pressure in an ultrasonic tank [16]. It predicted the accurate position where cavitation should occur. All mentioned researches assure the benefits of ultrasonic cleaning and indicate that computer simulation is an important tool for developing smart ultrasonic cleaning tank for the highest efficacy.

This research aims to solve an actual problem of a major ultrasonic tank manufacturer in Thailand who would like to improve their products. This manufacturer designs, develops and manufactures ultrasonic tank as requested by their customers in the industries. This tank has volume of 18 L and frequency of 28 kHz. It is the manufacturer's most popular tank due to its small size, lightweight and easily handled, suitable for cleaning 1–10 cm objects. In the past, the manufacturer received complaints from customers who used this tank to clean their products. Sometimes the tank did not clean thoroughly and sometimes it damaged their products. Therefore, this article reports the successful attempt of manufacturer to find the cause and solution to the problem, along to research methodology of developing the tank model for higher efficacy by using a computer simulation with the HRA in ANSYS program. The challenge of this research is that, normally HRA is used for solid materials [17–19]. Yet in this research, though the tank structure is solid, the solution is liquid and transducers are piezoelectric material. Since it is multiphysics simulation, the experiment is difficult, different and more complex than the other researches mentioned above. No existing research had used HRA to simulate acoustic pressure in the ultrasonic tank under actual conditions to resolve the mentioned problems, nor designed the experiment to confirm obtained simulation results. Thus, the methodology of this research is novel, fast, convenient and cost-saving. The authors are positive that this shall benefit engineers, researchers along to manufacturers who would like to develop and design ultrasonic tanks with better performance.

## 2. Theoretical background

### 2.1. Cavitation effect

When ultrasonic waves move into water, negative acoustic pressure occurs, creating lots of bubbles. When ultrasonic waves still pass through these bubbles, oscillation shall occur from the influence of positive pressure before growing to maximum negative acoustic pressure. Afterwards it will collapse and implode, called the cavitation effect [11–16]. The temperature of the bubble's pressure while it collapses is another important factor that affects the cleaning process. When the bubble grows to its maximum size, the area surrounding the bubble's temperature will rise to over 5500 °C with a pressure of over 70 MPa. The collapse shall rapidly occur in microsecond. The heat will not escape the bubble in time, and thus regarded that the bubble collapses adiabatically, resulting in the cleaning process [20,21].

### 2.2. Finite element equations

Acoustic pressure directly affects cavitation intensity [11–16]. The higher the acoustic pressure, the greater the cavitation intensity. In this research, once electric currents are applied to the PZT4 transducers, they will vibrate at a frequency of 28 kHz. The transducers' vibration will shake the tank's wall made of stainless steel and resulting in acoustic waves into the water and eventually cavitation. Therefore, it may be said that the ultrasonic tank consists of 3 domains: transducers, wall and water. The finite element equation of each equation differs from one another.

As for the transducers domain, the vibration of piezoelectric material causes coupling between the structure and electric properties. When voltage is applied to piezoelectric, it will vibrate causing displacement vector  $\{u\}$  to occur as in Eq. (1) [22].

$$\begin{pmatrix} M_{uu} & 0_{uv} \\ 0_{vu} & 0 \end{pmatrix} \begin{Bmatrix} \ddot{u} \\ \ddot{v} \end{Bmatrix} + \begin{pmatrix} C_{uu} & 0_{uv} \\ 0_{vu} & -C_{vv} \end{pmatrix} \begin{Bmatrix} \dot{u} \\ \dot{v} \end{Bmatrix} + \begin{pmatrix} K_{uu} & K_{uv} \\ K_{vu} & -K_{vv} \end{pmatrix} \begin{Bmatrix} u \\ v \end{Bmatrix} = \begin{Bmatrix} F \\ Q \end{Bmatrix} \quad (1)$$

where  $K_{uu}$ ,  $K_{vv}$ ,  $K_{uv}$  ( $K_{vu}$ ) 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 matrix.  $\{u\}$  is displacement vector and  $\{v\}$  is an applied voltage vector.

In wall domain,  $\{u\}$  from Eq. (1) will be passed to the wall causing vibration. When the wall vibrates, ultrasonic waves shall occur and passed to water domain. The finite element equation in wall domain can be written as in Eq. (2) [23].

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F\} \quad (2)$$

In water domain, when acoustic waves moves into the water domain, acoustic pressure may be found from solving the second order partial differential equation as in Eq. (3). Once considered that the propagation of sound waves through medium is linear, shear stress is negligible, density and compressibility of liquid medium are constant,

and pressure is time harmonic with  $p = p_0 \exp(i\omega t)$  [24]:

$$\nabla \left( \frac{1}{\rho} \nabla p \right) - \frac{\omega^2}{\rho c^2} p = 0 \quad (3)$$

HRA in ANSYS is employed to determine the steady-state response of a linear structure to load that varies harmonically with time. The idea is to calculate the structural response at several frequencies and obtain the nodal displacement vector versus frequency. The HRA in ANSYS gives a calculation equation based on the finite element method. To calculate acoustic pressure, the domain of water in Eq. (3) is changed from normal fluid domain to acoustic domain from Galerkin procedure principles [25] by multiplying Eq. (3) with testing function ( $w$ ) and integrating throughout the volume resulting in Eq. (4) used to calculate the acoustic pressure  $\{p\}$

$$[M_f]\{\ddot{p}\} + [C_f]\{\dot{p}\} + [K_f]\{p\} + \bar{p}_0 [R]^T \{\ddot{u}_{f,e}\} = \{F_f\} \quad (4)$$

Once all material properties and boundary conditions are set, ANSYS will calculate the acoustic pressure  $\{p\}$  of each position in the tank using Eqs. (1)–(4) and then will report  $\{p\}$  in the form of numerical results before displaying the calculated results into graphical color for easy analysis.

### 3. Methodology

In this section, we will explain simulation and experiment methods in detail. The results will be analyzed to find causes of the tank's problems and to find development methods and improvements, so the tank has better cleaning efficacy.

#### 3.1. An industrial ultrasonic tank

The ultrasonic tank used in this research is an actual one used in the industry. It is 245 mm × 340 mm × 225 mm (W × L × D) in size, has a volume of 18 L. Under the tank are 8 horn PZT4 transducers that generate ultrasonic waves at a frequency of 28 kHz. The generator's power can be adjusted from 0 to 400 W. The tank's wall is made of stainless steel. Fig. 1 shows the actual industrial ultrasonic tank and Fig. 2 shows a diagram and dimension.

#### 3.2. Fluid and mesh model

We used the ultrasonic tank in Fig. 1 as a prototype and its dimension in Fig. 2 to create a simplified CAD model as in Fig. 3(a). It consists of water as the solution, and transducers beneath the tank as PZT4 piezoelectric material, and the wall as stainless steel. The wall is also the tank's structure containing the water. Generator supplies electricity to the transducers which make the adjacent wall vibrate at a frequency of 28 kHz. The occurred ultrasonic waves will be passed to the water causing the cavitation and cleaning. The wavelength of the ultrasonic will determine the element amount of the mesh model, thus giving accurate simulation results. As for the hexahedron, there should be at least 6 elements per wavelength [25]. Therefore, for this tank we created the mesh model all in hexahedron elements. There is a total of 0.64 million nodes and 0.20 million elements. Fig. 3(b) shows the mesh model which is proper for simulation. From mesh analysis we found that this mesh model gives accurate results in short computational time.

#### 3.3. Harmonic response setting

We used the HRA in ANSYS version 17.0, which has been upgraded with an additional acoustic package called Acoustics ACTxR170 [25]. It is used to specifically study the results of the response of objects from sound. We set aluminum alloy and stainless steel to be solid domains as normal. For the transducers and water, we changed from solid and fluid domains to piezoelectric [22] and acoustic domains [25], respectively.

This action gives more accurate results than normal HRA without upgrading [25]. The PZT4 transducer properties and specifications were set following Tables 1 and 2, respectively. The water's properties were set according to Table 3. All information was given by the manufacturer. Other values were set as the default setting. Once all values are completely set, ANSYS will display the acoustic pressure results in all positions throughout the tank.

#### 3.4. Experiment

To confirm the validation of simulation results, we divided the experiment into 2 parts; foil corrosion (erosion) test and power concentration measurement. In the foil corrosion test, 18 L of water is used as the solution in the tank as seen in Fig. 4(a). The rectangular aluminum foil with a size of 20 cm × 29 cm and 0.038 mm thick will be tensely fixed using a metal structure. The foil sheet is submerged into the water at the level required in the experiment. We used power 400 W with 3 min of sonication time, at a temperature of 45 °C. Results from the corrosion test were analyzed to determine characteristic pattern of acoustic pressure distribution and aluminum mass loss.

For power concentration measurement, we used an NGL measurer model UPC3000 (Ultrasonic Process Controller) with resolution of measured power concentration of ± 0.1% W/liter and temperature of ± 0.2 °C. We measured the points at center, 17.5 cm above the bottom of tank as shown in Fig. 4(b) for temperature of 35, 45, 55 and 65 °C. Results of the experiment will be explained along with the simulation results in the next section. All experiments were repeated 5 times. Since this tank did not have a cooling system, the experiments regarding temperature could not be carried out at lower than room temperature. During the experiment, the water temperature was not constant, but always slightly changing and ranging between ± 1 °C in all experiments.

### 4. Results and discussion

#### 4.1. Validation and cause of unclean object

In order to verify the validation of simulated acoustic pressure, Fig. 5 shows characteristic patterns of acoustic pressure distribution compared to results from foil corrosion test when water temperature was 45 °C. Since results were symmetry, we showed compared half from both symmetrical results. It was clear that both results were consistent to one another. The area marked at the foil sheets did not tear but a lot of tiny corroded holes were distributed here. Therefore, acoustic pressure distribution using HRA in ANSYS can predict the position of corrosion and cavitation. These results were in agreement with the reports in references [5,15,16] and confirmed that acoustic pressure distribution has a characteristic pattern, which depends on the position of



Fig. 1. The actual industrial ultrasonic tank.

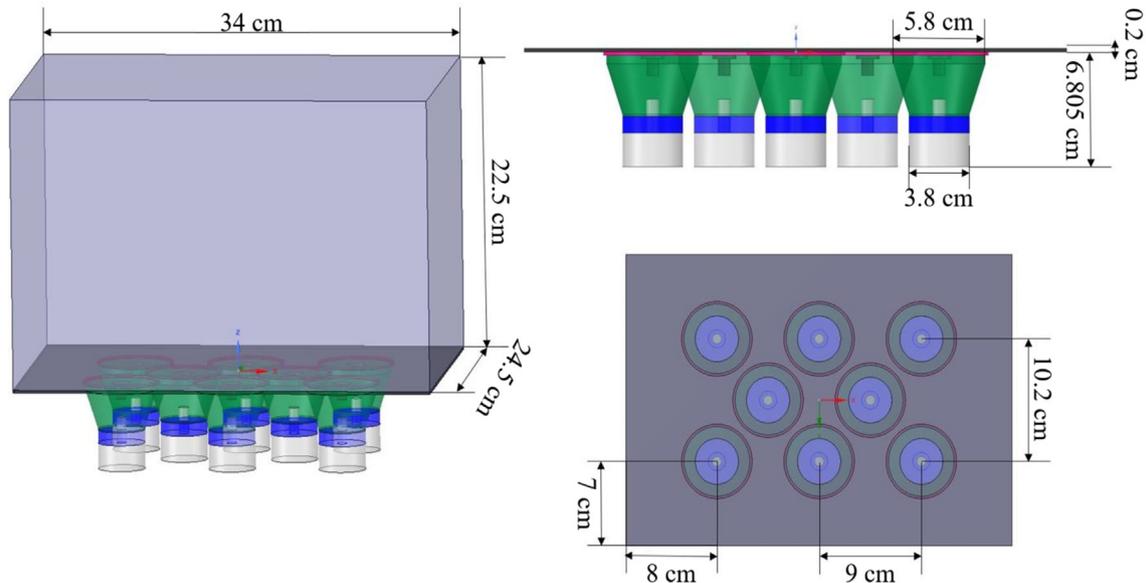


Fig. 2. A diagram and dimension of industrial ultrasonic tank.

measurement. Unclean objects may have been placed in low acoustic pressure areas, making cavitation intensity not ample for cleaning contaminations. Damaged objects may have been placed in high acoustic pressure areas, making cavitation intensity too great. Therefore, efficient ultrasonic cleaning should occur when objects were placed at an area with suitable acoustic pressure.

To investigate cleaning efficacy and effect of temperature on maximum negative acoustic pressure, we weighed the foil from Fig. 5 in a digital scale with resolution of 4 decimal digits. Weighing results showed mass loss in percentage, which were compared along with maximum negative pressure results that occurred within the tank as shown in Fig. 6. Maximum negative acoustic pressure was compared because acoustic pressure would expand the bubble to its collapsing point. From weighing 5 repeated times per point, the error bar did not exceed  $\pm 1\%$  of the mass loss, therefore; mass loss results were well consistent with the maximum negative acoustic pressure. The higher the temperature, the lower the mass loss and maximum negative acoustic pressure. These results aligned with those reported in the study of relation between temperature and maximum negative pressure of crude oil reported by Niazi et al. [15]. Fig. 6 also implies that when the temperature is increased the cleaning efficacy will decrease. These results were approved to confirm the customers that the water's temperature within the tank should be lower than 45 °C to achieve the higher cleaning efficacy.

We compared measured results of power concentration 17.5 cm

above the bottom at the center of the tank with the maximum negative acoustic pressure at the same position. Comparison results are shown in Fig. 7. Also, the results were well consistent to one another. We also compared both results for other positions. The comparison results also showed a similar trend. When the temperature was higher, the power concentration decreased thus giving low cleaning efficacy. All simulation results in this research were consistent to the foil corrosion test and power concentration measurement, ensuring us that our simulation results are quite credible.

#### 4.2. Scheme to develop a novel ultrasonic tank

To resolve the problem that objects are not cleaned thoroughly or damaged and to improve cleaning efficacy, we proposed novel models of ultrasonic tank by changing the placement of the transducer as in Fig. 8, (a) model A is the present tank, (b) model B has 2 transducers per side, on both sides and 4 underneath, (c) model C is similar to model B but the transducers underneath are aligned in a row, (d) model D has 1 transducer per side on both sides and 6 underneath the tank. We simulated the acoustic pressure in the tank using 28 kHz PZT4 as transducers with water temperature of 35 °C and power of 400 Watts, Fig. 9 shows the acoustic pressure in the same area as in Fig. 5(a). We found that when we changed placement of the transducer, characteristic pattern of acoustic pressure distribution changed, in models B, C and D, acoustic pressures were distributed throughout the tank even more. The

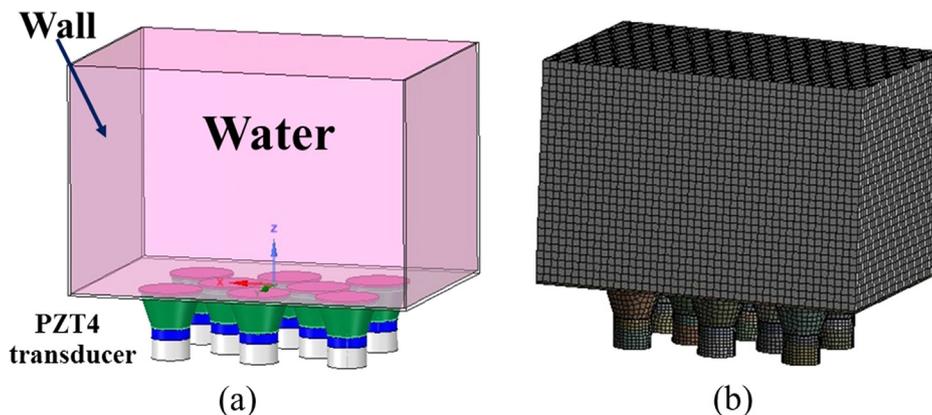


Fig. 3. The simplified CAD: (a) fluid model and (b) mesh model.

**Table 1**  
Material properties.

Material	Type	Value
Aluminum alloy	Density	2770 kg/m <sup>3</sup>
	Young's modulus	7.1 × 10 <sup>10</sup> Pa
	Poisson's ratio	0.33
	Bulk modulus	6.961 × 10 <sup>10</sup> Pa
	Shear modulus	2.669 × 10 <sup>10</sup> Pa
Stainless steel	Density	7750 kg/m <sup>3</sup>
	Young's modulus	1.93 × 10 <sup>11</sup> Pa
	Poisson's ratio	0.31
	Bulk modulus	1.693 × 10 <sup>10</sup> Pa
	Shear modulus	7.366 × 10 <sup>10</sup> Pa
Piezoelectric PZT4	Density	7500 kg/m <sup>3</sup>
	Permittivity constant ( $\epsilon_0$ )	8.854 × 10 <sup>-12</sup> F/m
	Stiffness matrix [ $c^e$ ] (× 10 <sup>10</sup> )	$c_{11} = c_{22} = 13.9, c_{21} = 7.78,$ $c_{31} = c_{32} = 7.43, c_{44} = 3.06,$ $c_{55} = c_{66} = 2.56$ Pa
	Stress matrix [ $e$ ]	$e_{31} = -5.2, e_{33} = 15.1,$ $e_{15} = 12.7$ C/m <sup>2</sup>
	Relative permittivity [ $\epsilon_r$ ]	$\epsilon_{r11} = \epsilon_{r22} = 1475, \epsilon_{r33} = 1300$
Piezoelectric PZT8	Density	7600 kg/m <sup>3</sup>
	Permittivity constant ( $\epsilon_0$ )	8.854 × 10 <sup>-12</sup> F/m
	Stiffness matrix [ $c^e$ ] (× 10 <sup>10</sup> )	$c_{11} = c_{22} = 14.7, c_{21} = 8.11,$ $c_{31} = c_{32} = 8.10, c_{44} = 3.29,$ $c_{55} = c_{66} = 3.13$ Pa
	Stress matrix [ $e$ ]	$e_{31} = -3.9, e_{33} = 13.9,$ $e_{15} = 10.3$ C/m <sup>2</sup>
	Relative permittivity [ $\epsilon_r$ ]	$\epsilon_{r11} = \epsilon_{r22} = 1,290, \epsilon_{r33} = 1000$

**Table 2**  
PZT4 transducer specifications.

Type	BJC-2850T-45SS PZT4	BJC-4060T-48SS PZT4
Frequency	28 kHz ± 1 kHz	40 kHz ± 1 kHz
Power	50 w	60 w
Radiating surface	45 mm	48 mm
Length	82 mm	56 mm

**Table 3**  
Water properties.

Temperature (°C)	Density (kg/m <sup>3</sup> )	Acoustic velocity (m/s)	Dynamic viscosity (kg/m s)
27	996.45	1499.2	0.8592
35	993.60	1518.4	0.7191
45	990.15	1533.5	0.5958
55	985.36	1546.5	0.4903
65	980.35	1553.5	0.4221

change of acoustic pressure distribution results from changes of transducers' placements. This alters the positions both constructive and destructive interferences. Especially in model C, acoustic pressure not only was distributed throughout the tank but also had a higher value wider than all other models. This is suitable for developing a novel ultrasonic tank that has a higher efficacy and resolves the problem of objects not being cleaned well enough.

For even more confidence, we simulated by changing the transducer's frequency to 40 kHz, using information from Table 2. given by the transducers' manufacturer in China, who is a supplier of the manufacturer. Simulation results of the acoustic pressure are shown as in Fig. 10. Acoustic pressure distribution for all transducer placements of models A-D differ from the 28 kHz tank. The 40 kHz tank distributed throughout the tank more. This result agrees with the contents reported



(a)



(b)

**Fig. 4.** The experiments: (a) foil corrosion test and (b) power concentration measurement.

by Li et al. [13] that simulated the frequency change towards sound field in a larger ultrasonic tank. From Fig. 10, the legend scale was adjusted to identify the contrast of characteristic pattern of acoustic pressure distribution. We also found that models C and D have higher acoustic pressure than model A. Once added to the results from 28 kHz tank, we concluded that placing transducer as in model C with 2 transducers on both sides and 4 aligned in a row underneath, is the optimal model for developing into the new ultrasonic tank for both 28 kHz and 40 kHz with high cleaning efficacy. This can resolve the problem of an object not being properly cleaned. Results from this research were sent to the manufacturer, which were approved and applied to knowledge to develop smart ultrasonic tank for commercial sale.

Because PZT4 and PZT8 are favorite materials used as transducers of the ultrasonic tank, we therefore simulated the acoustic pressure of the proposed novel 28 kHz ultrasonic tanks for models A–D using PZT8 as transducers with the material properties in Table 1. The results reveal in Fig. 11. The acoustic pressure distributions were similar to those depicted in Fig. 9 using PZT4 transducers but using PZT4 gave the higher acoustic pressure than PZT8. Since high acoustic pressure gave the greater energy of cavitation and better cleaning performance, the PZT4 transducer was a proper material for developing novel ultrasonic tanks. This supports the work of DeAngelis and Schulze [26] who investigated the performance of PZT4 versus PZT8 piezoelectric materials in ultrasonic transducers.

Simulation for this research considered that the cleaning occurs in an empty tank with water as the solution. In real industry, an object shall be placed inside a tank, and surfactant solutions will be added into the water to decrease surface tension, and increase temperature to effectively clean oil contaminants from the object. If simulations were carried out with those circumstances, the research results will be even more beneficial and practical. Other than this, there are many types of contamination and sizes from 0.3 μm and above. The contamination

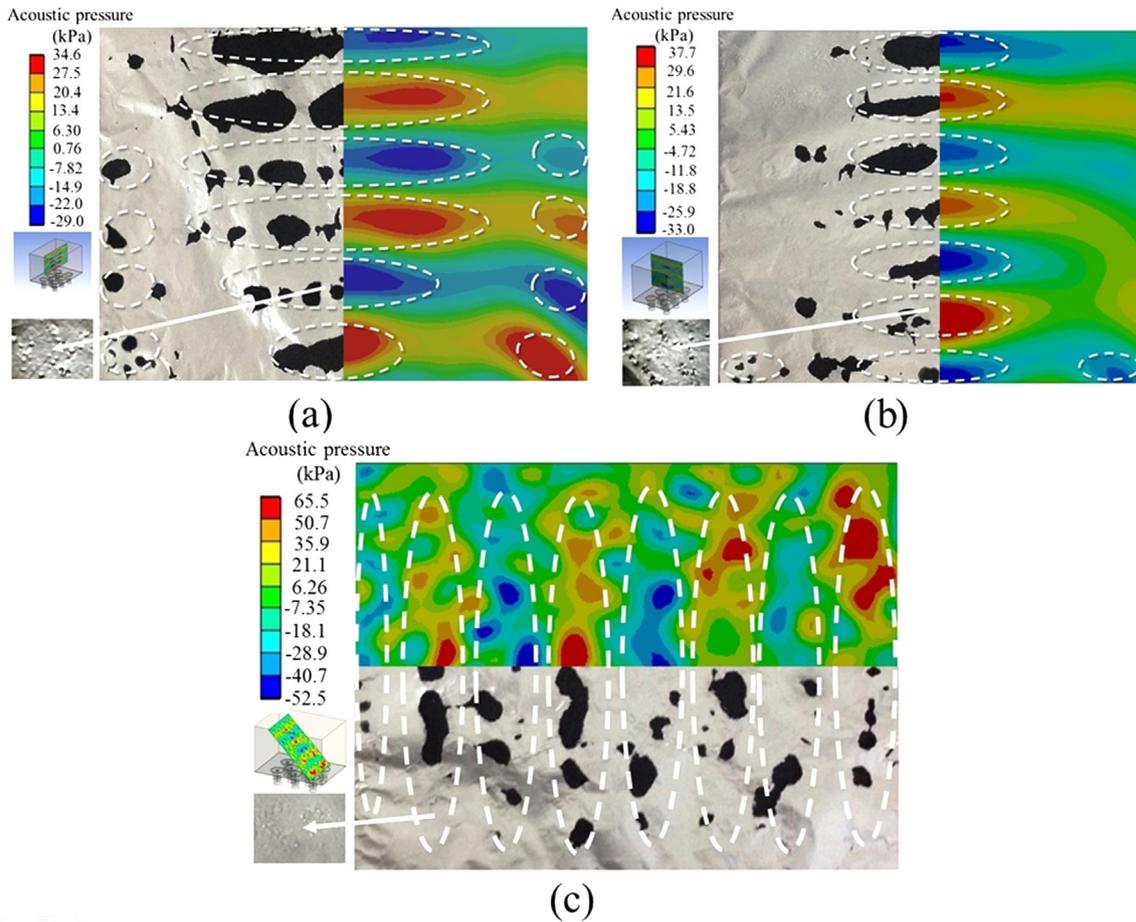


Fig. 5. Acoustic pressure distribution in some areas inside the tank compared to the results from foil corrosion test for water temperature of 45 °C.

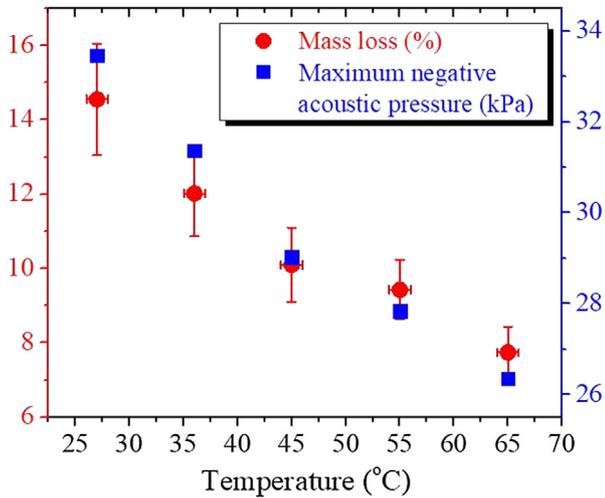


Fig. 6. Comparison between the maximum negative acoustic pressure and mass loss of foil sheet for water temperature of 45 °C.

particle size is affected by different frequencies. Efficient cleaning occurs when a tank consists of transducers with multi-frequency transducers within the tank as reported in the work of Manickham et al. [27], and the best conditions from simulation such as temperature, position of transducer, frequency and design of the tank as reported in this article. Therefore, it would be interesting to carry out the simulation as multi frequency, which will be even more beneficial and can be further developed for commercial purposes. At present, the

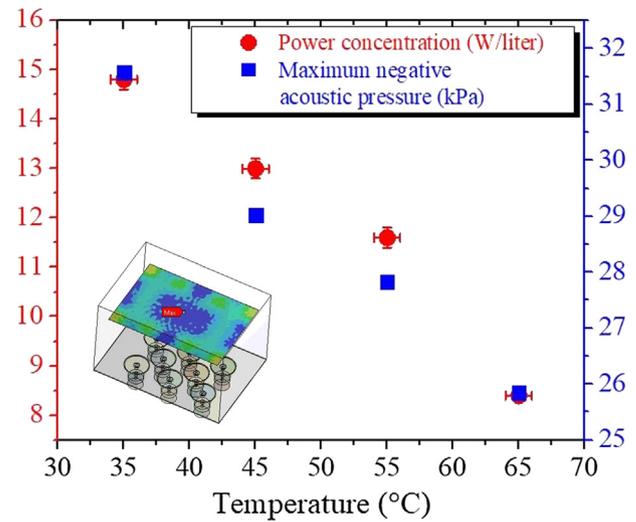


Fig. 7. Comparison between the maximum negative acoustic pressure and power concentration for water temperature of 45 °C.

manufacturer requires the simulation results and the best conditions for multi-frequency transducers.

### 5. Conclusion

We used harmonic response analysis (HRA) in ANSYS 17.0 to simulate acoustic pressure occurred in this tank by using water as solution along with problematic condition from the manufacturer. We

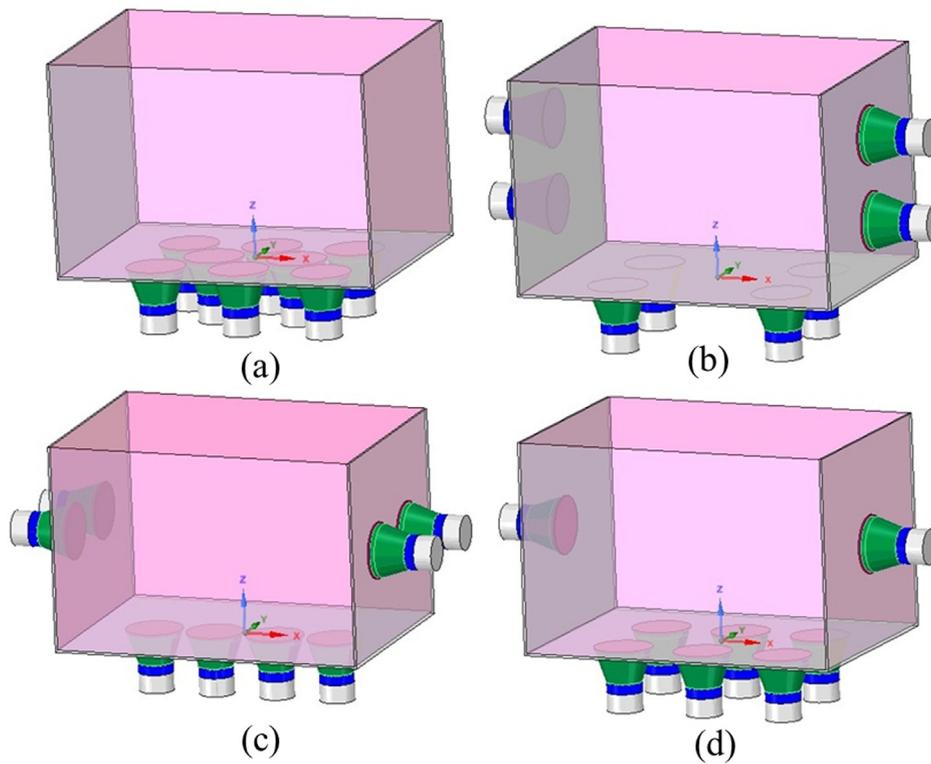


Fig. 8. Proposed novel models of ultrasonic tank: (a) model A, (b) model B, (c) model C, and (d) model D.

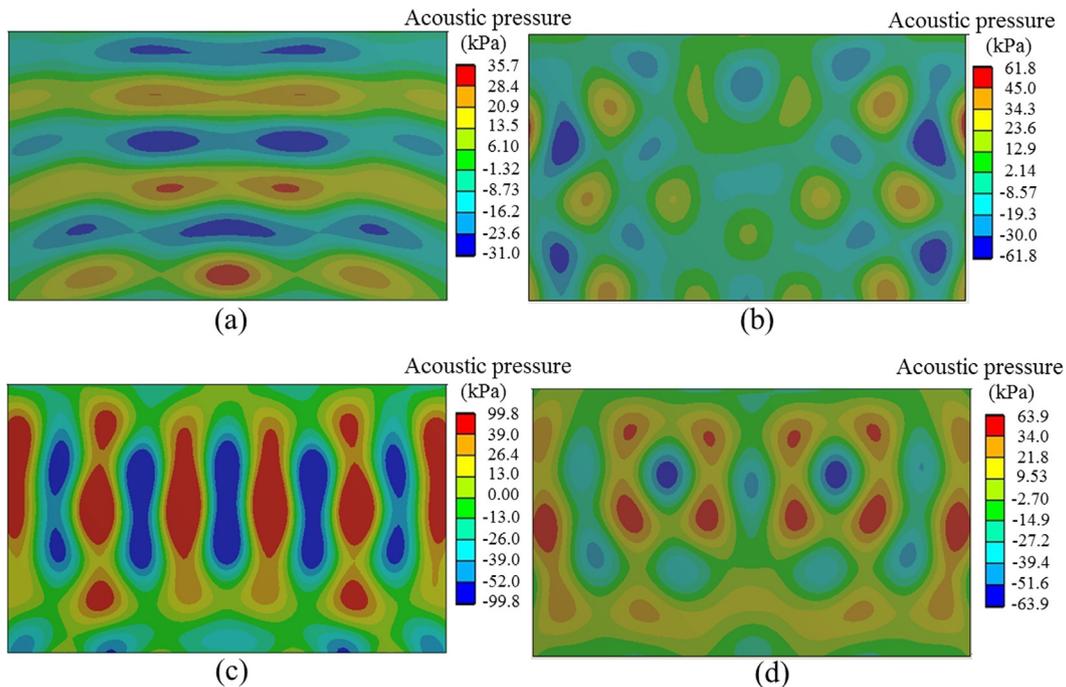


Fig. 9. Acoustic pressure distributions of the proposed novel 28 kHz ultrasonic tanks for: (a) model A, (b) model B, (c) model C, and (d) model D, using PZT4 as transducers.

proposed detailed methodology, which is new, cost-saving and gives accurate simulation results. Simulation results showed that acoustic pressure is well consistent to the foil corrosion test and power concentration measurement. From analyzing simulation results we found that acoustic pressure may explain occurred cavitation. The greater the acoustic pressure, the higher in cavitation. The increase of temperature lessens cleaning efficacy. The reason why objects were not thoroughly

cleaned or damaged is from uneven acoustic pressure in the tank and using water with temperatures that are too high in the cleaning process. Characteristic pattern of acoustic pressure distribution depends on the placement of the transducer. Unclean objects happened when they were cleaned at a position where the acoustic pressure was near 0 Pa. On the opposite hand, damaged objects were cleaned at a position where the acoustic pressure was too high and too low. For this tank, the PZT4 was

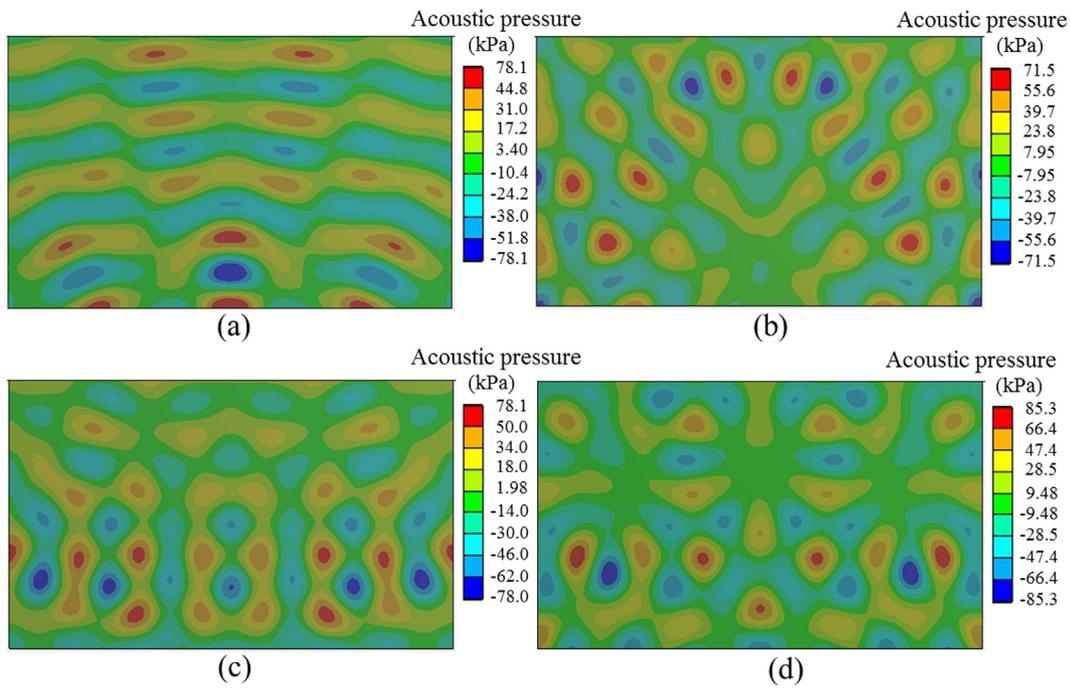


Fig. 10. Acoustic pressure distributions of the proposed novel 40 kHz ultrasonic tanks for: (a) model A, (b) model B, (c) model C, and (d) model D, using PZT4 as transducers.

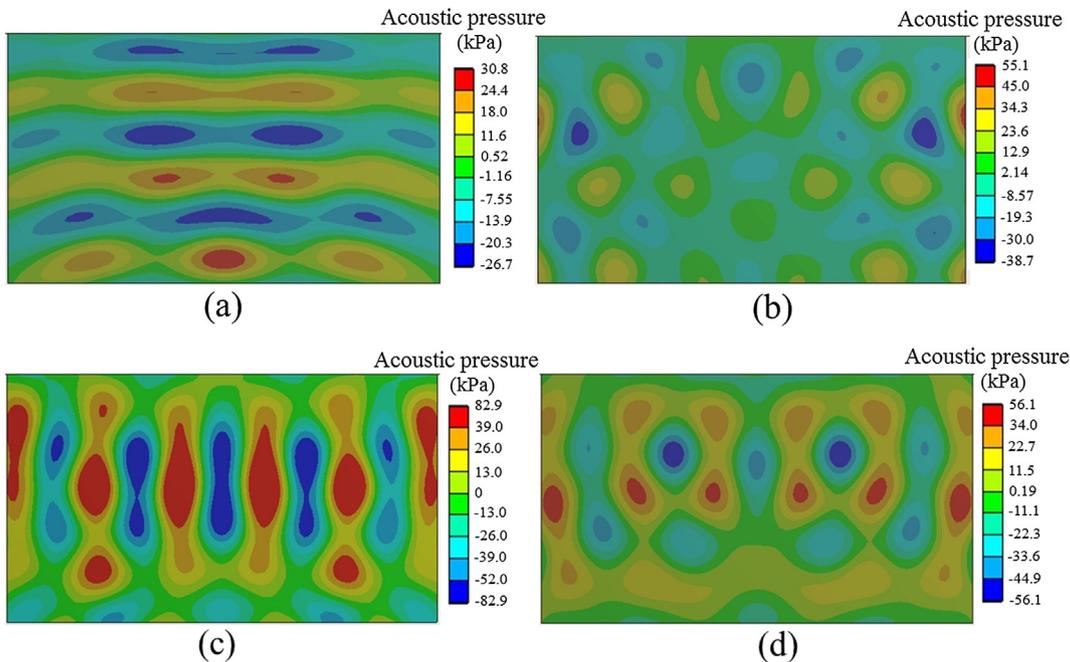


Fig. 11. Acoustic pressure distributions of the proposed novel 28 kHz ultrasonic tanks: (a) model A, (b) model B, (c) model C, and (d) model D, using PZT8 as transducers.

a proper material used as transducer since it gave higher acoustic pressure than the PZT8. We also proposed a scheme to develop the ultrasonic tank using simulation results of acoustic pressure by changing the placement of the transducer in 3 ways under the same conditions. We found that by placing the transducer at the side (2 per 1 side) and 4 underneath in a row, the acoustic pressure distribution is smoothly distributed throughout the entire tank, which is better than the original tank. This method increases the acoustic pressure level to be higher and improves cleaning efficacy as well. We have also simulated the acoustic pressure for the 40 kHz tank by repositioning the transducers. We found that the results aligned with the 28 kHz tank.

**Acknowledgements**

This research was supported by Seagate Technology (Thailand) Ltd., Pasuda Supplies and Services Co., Ltd., College of Advanced Manufacturing Innovation, and King Mongkut’s Institute of Technology Ladkrabang.

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