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

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A B S T R A C T

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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Nomenclature

$[C_f]$	acoustic damping matrix (N s/Pa)
$[R]^T$	acoustic fluid boundary matrix (m^3)
$\bar{\rho}_0$	acoustic fluid mass density constant (kg/m^3)
$[M_f]$	acoustic fluid mass matrix ($N\,s^2/Pa$)
$[K_f]$	acoustic fluid stiffness matrix (N/Pa)
$\{F_f\}$	acoustic load vector (N)
p	acoustic pressure (Pa)
ω	angular frequency (rad/s)
ρ	density of liquid (kg/m^3)
μ	liquid viscosity (Pa s)
$\{F\}$	load vector (N)
$\{\ddot{u}\}$	nodal acceleration vector (m/s^2)
$\{\dot{u}\}$	nodal velocity vector (m/s)
$\{u\}$	nodal displacement vector (m)
$\{\ddot{u}_f\}$	nodal acceleration vector of fluid (m/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 (Pa/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 (m/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].

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

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].

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

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,