Simulation of Ultrasonic Cleaning and Experimental Study of the Liquid Level Adjusting Method

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Abstract

In this paper the three-dimensional models of ultrasonic cleaning were established in COMSOL Multiphysics and corresponding cleaning effect under different frequencies and liquid levels were simulated. Then the frequencies suitable for remanufactured components were studied and the cleaning effect under different liquid levels were tested by experiment. The experimental results were processed by Matlab and contrasted with simulation results. It shows that the disadvantages caused by the standing wave can be eliminated by adjusting the liquid level.

Keywords:
Ultrasonic Cleaning; Sound Field Simulation; Liquid Level Adjusting Method

1 INTRODUCTION

As one of the main methods of physical cleaning, Ultrasonic Cleaning is more and more popular in industry owing to the advantages of rapid, satisfactory cleaning and low cost [1-6]. Ultrasonic Cleaning is also free from restrictions to sophisticated shapes and surfaces and easy to realize automation. Any positions that cleaning liquid can reach, there will be the cavitation effect, and there will be the cleaning effect [7]. However, due to lack of theoretical researches and experimental evidences on the cleaning effect, most companies only rely on traditional experience to design cleaning equipments. Thus the low technological content of products and low degree of standardization are resulted from the absence of unified and objective evaluation methods.

At present, some numerical methods such as Computer Flow Dynamic Method, Finite Element Method and Finite-Difference Time-Domain Method are applied to the analysis on ultrasonic field. The two methods, Two-phase Fluid Model Simulation based on Computer Flow Dynamic Method and Two-step Calculation Method based on Finite Element Analysis Method, demand researchers to solve too many linear equations to get obvious sound field distribution. Here we applied COMSOL Multiphysics software to solve partial differential equations based on equivalent integral weak form and quickly get accurate results [8].
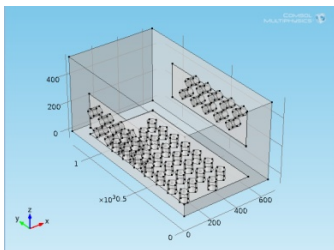

Figure 1: The model of the cleaning vessel.

Currently, almost all parameters are kept the same in practical ultrasonic cleaning process. But the cleaning result is not always satisfactory, because some positions on the surface of workpieces can't get cleaned thoroughly. To solve this problem, the liquid level adjusting method was put forward [9]. To measure the cleaning

effect, foil erosion assessments were carried out in this paper, but it is only suitable for qualitative measurements. To solve this problem, we provided a new idea for the quantitative assessment of cleaning effect by post-processing the experimental results.

2 SIMULATION OF ULTRASONIC SOUND FIELD

2.1 Model Definition

The BK-4800B ultrasonic cleaning machine was used in this study. Its dimensions were 1200 mm × 650 mm × 545 mm (depth).

Three vibrating plates made of stainless-steel are implanted. The three-dimensional model in COMSOL is shown in Figure 1. When the power is supplied, the electric energy will be transferred into ultrasonic mechanical energy by ultrasonic transducers [10]. The ultrasonic waves are transmitted in the cleaning vessel, and the vibrating plate, cleaning liquid and ultrasonic are motivated to generate multi-physical coupling effects.

To simulate the interior sound field of the cleaning vessel in two-dimensional condition, internal vibrators are arranged equidistantly. This paper takes ABCDEFGH eight cross-sections successively, and definitions of the eight cross-sections are shown in Figure 2.

Ultrasonic transducers attached to the interior of the vibrating plates use PZT-5H as the fundamental material. The vibrating plates are set to linear elastic body. In sound-solid coupling model, assume using reference pressure to water, temperature is set to 293.15 K. Select attenuation type of linear elastic as the fluid. Total absorption coefficient α for the sound waves in water is $5.684×10^{-7}$ (Np/cm).
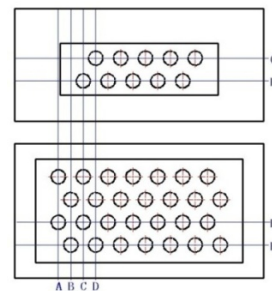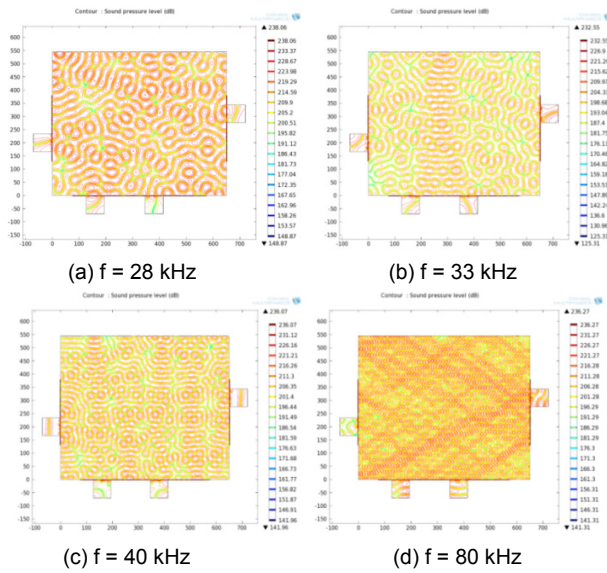

Figure 2: The A~H cross-sections.

(a) f = 28 kHz

(b) f = 33 kHz

(c) f = 40 kHz

(d) f = 80 kHz

Figure 3: The photographs of cleaning effect at different frequencies in C cross-section.

2.2 Characteristic Frequency Analysis

Normally ultrasonic frequencies for cleaning are located between 25kHz and 130 kHz. 28 kHz, 33 kHz, 40 kHz, 80 kHz, 100 kHz and 120 kHz are commonly used. This paper calculates sound field distribution on C cross-section when the vessel is set to be full of water and corresponding frequencies are 28 kHz, 33 kHz, 40 kHz and 80 kHz. The frequency domain analysis is selected in acsl module. In sound-solid coupling module, the transducer is replaced by point source. Transducer power is set to 100 W/m. The simulation results of C cross-section are shown in Figure 3.

(a) f = 27857 Hz

(b) f = 27920 Hz

(c) f = 27996 Hz

(d) f = 28075 Hz
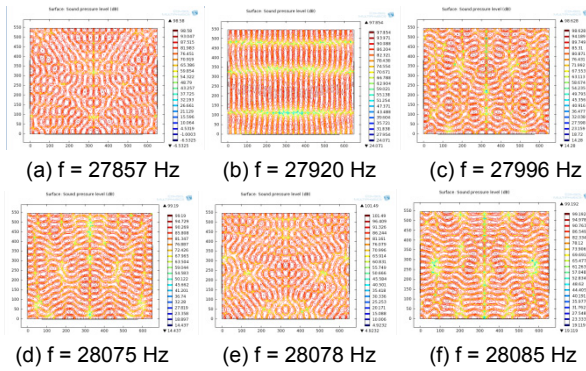
(e) f = 28078 Hz

(f) f = 28085 Hz

Figure 4: Characteristic frequency analysis of C cross-section.

As can be seen through the simulation, the higher the frequency is, the denser the contours distribute. It means that if the cleaning intensity is higher, the parts will get higher degree of cleaning. It can also be seen in Figure 3 that if the frequency is lower, the size of the vesicular outline produced by contour will be larger. The higher the value of the contour edges is, the higher the relative pressure of the cavitation bubble collapse will be. Thus, high frequency can be used for cleaning precision parts. Relatively low frequency can be used for cleaning non-precision, heavy dirt parts.
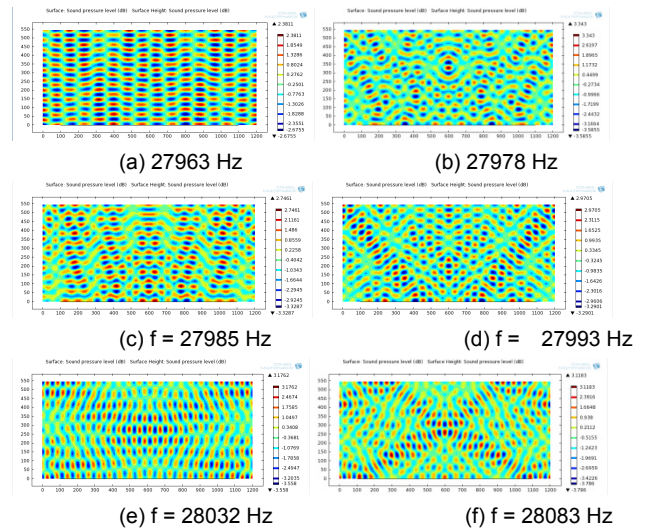

(a) 27963 Hz

(b) 27978 Hz

(c) f = 27985 Hz

(d) f = 27993 Hz

(e) f = 28032 Hz

(f) f = 28083 Hz

Figure 5: Characteristic frequency analysis of E cross-section.

2.3 The Effects of Characteristic Frequency on the Acoustic Field Distribution

This paper takes 28 kHz as the target frequency and analyzes the characteristic frequency of the cleaning vessel. During the simulation, the number of frequencies to be solved is taken as 6.

For C cross-section, the simulation results of characteristic frequency analysis are shown in Figure 4.

As can be seen in the C cross-section, at different characteristic frequencies, the photographs of sound field are different.
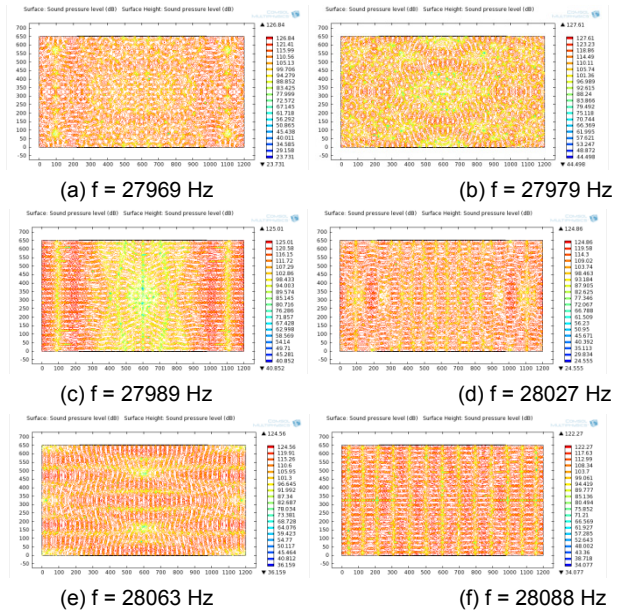

(a) f = 27969 Hz

(b) f = 27979 Hz

(c) f = 27989 Hz

(d) f = 28027 Hz

(e) f = 28063 Hz

(f) f = 28088 Hz

Figure 6: Characteristic frequency analysis of G cross-section.

However, in C cross-section there is an obvious central symmetry along the direction x=325.

For E cross-section, the simulation results of characteristic frequency analysis are shown in Figure 5.

For G cross-section, the simulation results of characteristic frequency analysis are shown in Figure 6.

According to the characteristic frequency analysis and combination of the sound field distribution in G cross-sections, it can be derived that: At different frequencies, the sound field is symmetric along y=600. According to the analysis of E cross-sections, due to the coupling effect of the underside of the vibration plate and the side of the vibration plate, the sound field is centrosymmetric along the direction z=255 instead of z direction.

2.4 Simulation of Ultrasonic Sound field with Different Liquid Levels

To study the relationship between the cleaning effect and the liquid level, D cross-section was taken as an example. The variations of sound field distribution in X-Z direction under different liquid levels are simulated. From the vessel being full of water, the height of the liquid level being 545 mm, we had the simulations every after lowering the height of the liquid level by λ/4 (λ equals 53.6 mm when the temperature is set to 293.15 K, the frequency of the ultrasonic wave is set to 28 kHz) until the height of the liquid level reached (545-3λ) mm. The typical simulation results of the D cross-section are shown in Figure 7.

From the simulation results, the following conclusions can be referred: The distribution of ultrasonic waves is inhomogeneous in the cleaning vessel. There exists standing wave in the sound field. The ultrasonic intensities are higher in the positions where the ultrasonic waves overlap and lower in the positions where the waves are offset by each other. So adjusting the height of the liquid level can change the sound field distribution and the position of the standing wave.

3 THE LIQUID LEVEL ADJUSTING EXPERIMENT IN ULTRA-SONIC CLEANING

(a) h = 545 mm   (b) h = (545-λ/4) mm

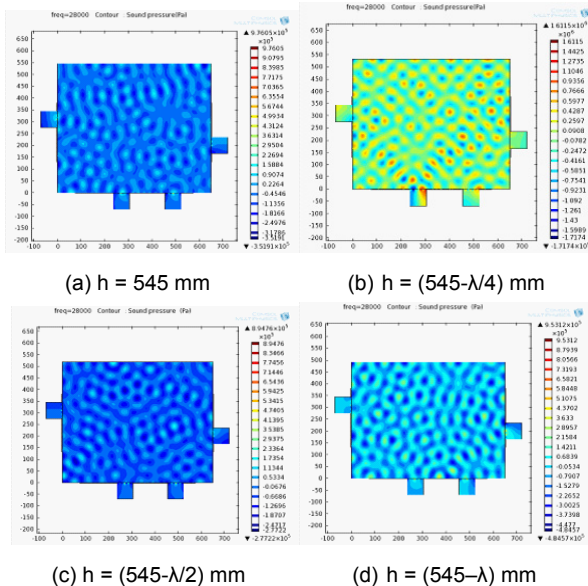(c) h = (545-λ/2) mm   (d) h = (545–λ) mm

Figure 7: The sound field distribution of D cross-section under different liquid levels.
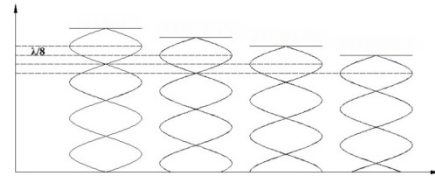

Figure 8: Cleaning result of D cross-section.

Figure 9: Schematic diagram of liquid level adjusting.

Figure 10: The cleaning result of D cross-section by liquid level adjusting method.

3.1 Experimental Scheme

The foil erosion assessment is based on the erosion effect of the ultrasonic cavitation on the aluminum foil. The 20~30 mm thick aluminum foil was supported by a stainless steel stent and positioned within the cleaning vessel. After being eroded by the ultrasonic for 40 seconds, the aluminum foil was taken out. The ultrasonic intensity can be qualitatively tested by measuring the area lost in the cleaning process. The photograph of the erosion patterns produced by the cleaning vessel is shown in Figure 8.

From Figure 8, standing wave exists in the ultrasonic cleaning process and it causes the inhomogeneous cleaning effect in the cleaning vessel. This phenomenon affects the cleaning result severely. The liquid level adjusting method is adopted to change the positions of the standing wave, and the schematic diagram of the liquid level adjusting method is shown in Figure 9. By changing the cleaning parameters in the cleaning process, we can realize the homogeneous cleaning effect to the workpieces. The following sections are detailed experiment process.

Firstly, when the cleaning vessel was full of water (the height of the liquid level was 545 mm), the aluminum foil was put on the D cross-section and we switched on the cleaning machine. 10 seconds later, the cleaning machine was switched off and we got the aluminum foil numbered D1.

Secondly, the aluminum foil was kept in the same position and the drain valve was opened, the drain valve was closed when the height of the liquid level reached 538.3 mm, switched on the cleaning machine. 10 seconds later, we got the aluminum foil D2.

Thirdly, the process above was repeated and got the aluminum foil numbered D3 (the height of the liquid level was 531.6 mm) and aluminum foil numbered D4 (the height of the liquid level was 524.9 mm).

	1	2	3	4	5
D4-1	1	3	45	43	8
D4-2	0	4	55	36	5

Table 1: Grayscale percentages of D4-1 and D4-2 (%).

The next step we scanned the aluminum foil and cut the image under the height of liquid level 524.9 mm and got image numbered D4-1, which is shown in Figure 10. Last, one piece of aluminum foil was put in the vessel and corroded by the normal cleaning method for 40 seconds. Using the same processing method above, we got image D4-2, which is shown in Figure 8.

3.2 The Analysis of Experimental Results

In this section we adopted the statistical method to measure the sound field distribution of D4-1 and D4-2. After the experiment, we processed the image grayness by Matlab. The principle of the grayscale percentage is that the grayscale is divided into 255 color values. Taking 1~50, 51~100, 100~150, 150~200, 200~255 as 5 grayscale groups. The points falling in each grayscale group were counted respectively. The percentages are given in Table 1. The curves of the percentages are shown in Figure 11.

From Figure 11 we can see, when the workpieces are cleaned without adjusting the liquid level, the percentage of the points falling in the color threshold 100~150 is much higher than the other points. The distribution of sound field is inhomogeneous. By adjusting the liquid level, the percentage of the points falling in the color threshold 100~150 is lower than before but the percentage of the points falling in the color threshold 150~200 is higher. This means that the sound field distribution is improved by the liquid level adjusting method, the ultrasonic energy is redistributed and the cleaning blind zones are eliminated.

4 SUMMARY

- In the process of the sound field simulation, COMSOL Multiphysics can overcome the contradiction between accuracy and the amount of computation. Through modeling and simulation computation, ultrasonic frequency and power of the vibrators can be determined for different cleaning objects. Under higher frequencies, the contours are denser. That means, with higher cleaning intensity, the higher cleanliness the parts will get. If the frequencies are lower, there will be the larger the size of the vesicular outline produced by contour, and there will be higher values of the contour edges, also there will be higher relative intensity caused by the cavitation bubble collapse. So high frequency can be used for cleaning precision parts. Relatively low frequency can be used for cleaning non-precision, heavy pollution parts.

- Because of the reflection and overlapping of the ultrasonic waves in the cleaning vessel, standing wave exists in the cleaning process.

- The standing wave has an influence on the sound field distribution and leads to the inhomogeneous cleaning effect. The positions where the ultrasonic intensities are higher, the cleaning effect is better; the positions where the ultrasonic intensities are lower, the cleaning effect is not satisfactory.

- The sound field distribution in the cleaning process is much homogeneous by adjusting the liquid level. The liquid level adjusting method can weaken the influence of the standing wave and eliminate the cleaning blind zones and finally reach the requirement of thorough cleaning.
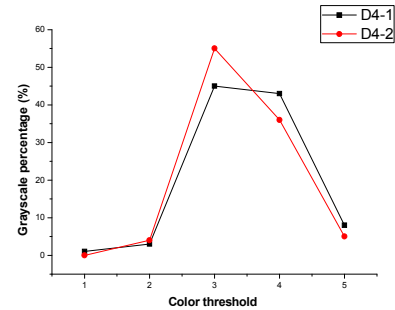

Figure 11: The grayscale percentage curves.

5 ACKNOWLEDGMENTS

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