**June 5, 2004  
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Basics of Ultrasonic Cleaning Technology, 2004

# 1. What is ultrasonic cleaning?

　Photo 1 Photo 2

A major reason for the stagnation of ultrasonic cleaning technology over the past 20 years is a misunderstanding of the basic understanding of what ultrasonic cleaning is. Ultrasonic cleaning systems have made rapid progress in accordance with advances in peripheral technologies and user demand. Ultrasonic cleaning systems have rapidly progressed in accordance with advances in peripheral technologies and user demand, such as conveyor technology, instrumentation technology, and sheet metal welding technology. However, the basic content of ultrasonic cleaning technology has not changed significantly, with a few exceptions. Even if the appearance and transport technology change, ultrasonic cleaning technology will not be able to meet the demands of the times unless there is a fundamental innovation in ultrasonic cleaning technology.　In order to fully utilize the innovative ultrasonic cleaning technology that responds to the new era, it is first necessary to have a deep understanding of what ultrasonic cleaning is, why it removes contamination, and why it does not, and to dispel misconceptions about its principles. Ultrasonic cleaning is a cleaning method that emits powerful ultrasonic waves into a liquid and uses the impact force generated when cavities are created and extinguished. If cavities are not generated, it cannot be called ultrasonic cleaning. In other words, ultrasonic cleaning is a technology that uses cavities generated by ultrasonic waves for cleaning. Therefore, the basic requirement for understanding and effectively using ultrasonic cleaning is to correctly understand cavities and the phenomena of cavity generation and annihilation (cavitations). A liquid is irradiated with powerful sound waves of 20 KHz or higher, i.e., ultrasonic waves. When a certain level of sound pressure change occurs in the liquid, so-called cavities are generated. Cavities are composed of many vacuum nuclei (microcavities), and their overall size varies depending on the frequency and the magnitude of the sound pressure change, but at the practical level, the size ranges from about 100 microns to a few dozen millimeters. The shape also varies, and can be roughly divided into a gas nebula type [Photo 1] and a globular nebula type [Photo 2]. In order to distinguish cavities from cavities generated by sound pressure changes other than ultrasound, I call them cavities (microvacuum nuclei). Cavities (microvacuum nuclei) are repeatedly generated and annihilated as follows at 25 KHz.

During the initial (1/200,000th of a second) sound pressure decompression process, numerous microvacuum nuclei in the form of atomized microvacuum are generated in the cavity generating region. The microvacuum nuclei continue to coalesce and grow until they reach their maximum at three to four hundred thousandths of a second, and become a mass of a dozen or more microvacuum nuclei that are attached to each other like clusters of grapes that have grown up. This process is a high-speed ejection of liquid from the cavity region, and if the cavity has an outer diameter of 6 mm, the maximum liquid movement outside the cavity is about 200 m/sec, or a shock wave. This is called a positive shock wave. The size of the shock wave is determined by the size (shape) of the cavity and the speed of liquid movement. The liquid (space) confined between the microvacuum nuclei is subjected to high pressure.　This process is responsible for one part of the cleaning power of ultrasonic cleaning. However, if the pressure wave is merely in one direction, dirt may be trapped in some cases. The next step in ultrasonic cleaning is the decompression process.

## (1) [Generation process] Positive shock wave

## (2) [Extinction process] Negative shock wave

During the depressurization process, the growing microvacuum nuclei shrink without changing their position from the cavity center. After approximately 200,000/6 seconds, the microvacuum nuclei are annihilated. To be precise, the annihilation time is faster than the time from the generation to the growth maximum. In contrast to the generation process, a high-speed movement of liquid toward the center of the cavity occurs. Observations have measured a speed of about 220 m/sec. The liquid between the microvacuum nuclei is depressurized, expanded, and then subjected to the shock wave and turbulent concentration of the liquid at high velocity and high pressure during a period of 200,000ths of a second or two. In this process, the shock wave directed toward the center of the cavity is called a negative shock wave. This is the source of the cleaning power and a characteristic of ultrasonic cleaning.

## (3) [Cavity migration] Cleaning and diffusion

Contaminants on the solid surface (contaminants to be cleaned) are pushed by the shock wave (positive shock wave) from the center of the cavity and then pulled by the negative shock wave (negative shock wave) in the cavity generation process as described above, which is repeated more than 20,000 times per second. The cavity is then captured by the negative shock wave, which is repeated more than 20,000 times per second, and moves at high speed with the cavity through a complex compression and expansion process in the space between the micro vacuum nuclei.　The distance traveled by the cavity is up to the lower limit of the threshold (threshold) of the sound pressure change of cavity generation. Thus, a spherical nebula-type cavity (with low ultrasonic attenuation) has a wavelength of about 1/8λ (wavelength). For gas nebula cavities, the moving distance of the cavity is small and negligible.　The moving speed reaches 50m/sec to 150m/sec. This is the principle of ultrasonic cleaning and the difference from the cleaning principle of cavities generated by other than ultrasonic waves.

## (4) [The biggest misconception in ultrasonic cleaning].

The biggest misconception in ultrasonic cleaning technology is the illusion that the visible bubbles that are generated when ultrasonic waves are applied to a liquid are cavities (groups of microvacuum nuclei) created by the ultrasonic waves described above.　Most cleaning solvents other than water contain large amounts of air. In the majority of alcohols, chlorinated solvents, hydrocarbon solvents, and other solvents that can be and are used for cleaning, the oxygen dissolved content is 20 mg/ℓ or more. When the solvents are irradiated with powerful ultrasonic waves, the pressure change causes the dissolved air to deflate and form bubbles, which burst at the surface of the rising liquid! It does not disappear or shrink in the liquid. This is called ultrasonic gas aeration. The air that has escaped from the liquid is re-dissolved from the liquid surface, and the bubble generation phenomenon by ultrasonic waves, ultrasonic bubbling (or ultrasonic gas aeration), persists. The good news is that the tiny bubbles of air that are generated at this time originate from the vibrating surface of the ultrasound and serve to effectively absorb and block the ultrasound waves. It does not generate the cavities that would otherwise be generated by ultrasound. Without countermeasures for these bubbles, it is absurd to compete with ultrasonic oscillators in terms of frequency and oscillation method.



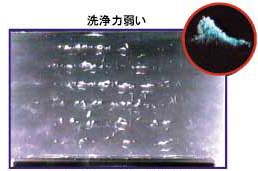
**In non-water ultrasonic cleaners without measures to reduce dissolved air, more than 99% of the ultrasonic energy disappears at the surface of the vibrating surface! (Author's measurement)**

The reason this has not been a problem in non-water cleaning is that the cleaning agent itself had a certain degree of cleaning power, and thus has been overlooked, but these are not rough times. Cavities generated by ultrasonic waves are high-speed phenomena that are created and extinguished more than 20,000 times per second, and are not visible to the human eye as bubbles. It is not a phenomenon that is visible to the human eye as bubbles, etc.

**When visible bubbles are observed during ultrasonic oscillation, the ultrasonic tank should be considered to have disappeared, as most of the ultrasonic energy is not used.**

## [Photo 3

## 2. Importance of Cavitation Control



The author calls the early ultrasonic cleaners, in which ultrasonic cleaning is considered possible if the object to be cleaned is placed above the ultrasonic transducer, the first generation of ultrasonic cleaners. Then, in response to the importance of cavities in ultrasonic cleaning, ultrasonic cleaners that attempt to control cavities in the ultrasonic cleaning tank are called second-generation ultrasonic cleaners. In this section, we will briefly discuss cavity control in second-generation ultrasonic cleaners. This is the basis of all ultrasonic cleaning system design, and I am convinced that no new era of ultrasonic cleaning design can be achieved without understanding and practicing this concept.

## Photo 4] Second-generation ultrasonic cleaning system Example of cavitation distribution

If the positive and negative impact forces of the cavities are too weak, the cleaning cannot be done; if they are too strong, they damage the object to be cleaned, resulting in defective products. Naturally, if the impact force of the cavity cannot be controlled, it is impossible to design ultrasonic cleaning.　Recently, ultrasonic cleaning objects have become more and more precise and delicate, and the range of cavity selection has become narrower. However, if you have a better understanding of cavities in ultrasonic cleaning, you will have a better understanding of how to control the impact force. In general, the impact force of a cavity is proportional to the pressure of the liquid and inversely proportional to the frequency, vapor pressure of the liquid, and amount of dissolved air.　The impact force of the cavity is proportional to the mass of the liquid that the cavity removes (attracts) in a unit of time, so once the principle is understood, it is clear what to control. Cavitation control in ultrasonic cleaning equipment is an important basic technology in ultrasonic cleaning design. It is impossible to introduce a new ultrasonic cleaning technology without controlling the cavitation.

## (3) Cavitation impact force control

Cavities in ultrasonic cleaning do not occur on a surface. They occur at points. There is a distance between cavities, and multiple cavities do not occur attached to each other. In general degreasing cleaning, however, the spaces between cavities cause defects in so-called precision cleaning. Therefore, efforts are made to increase cavity density in various ways. Or, efforts are made to increase the distance traveled by the cavities. We are making a lot of efforts to improve the ultrasonic waveform, oscillation efficiency, liquid injection efficiency, output per unit area, and the method of attaching the vibrating elements to reduce the amount of wasted liquid, etc.　The latest ideas for ultra-compact, high-speed, high-density ultrasonic cleaning are an extension of this concept.

## (2) Control of cavitation generation density

## (1) Control of cavitation generation position

In an ultrasonic cleaning tank (the same applies to ultrasonic spray), it is an extremely important basic technology to determine where and how cavitation is generated in a stable manner. The position and shape of the cavitation distribution are determined by the frequency, type of liquid, temperature, depth of liquid, placement of transducers, direction of liquid flow, temperature distribution, etc., as well as the type of material to be cleaned.　The basic distribution of cavitation can be horizontal, vertical, grid, even, or cylindrical, etc., depending on the purpose. The ultrasonic cleaning engineer and the user must clarify the purpose of each ultrasonic bath, and share the distribution of cavitation in each bath and the method of checking it. If the liquid depth is unstable or not theoretically supported, it can be assumed that the basics of cleaning design have not been established.

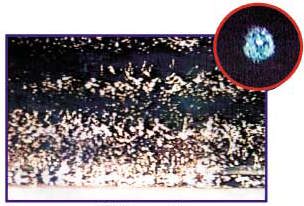
## 3. Third Generation Ultrasonic Cleaning Technology [Basic Idea]

Before seeking specific new technology for each application, I would like to talk about ultrasonic cleaning, which is the backbone of new technology. The principle is important, and the applications are unlimited, depending on the object. This is the basic technology that the author discovered and put to practical use for the first time in the world during the CFC era, and has been refining under the banner of "CFC free" (presented by the author at the 1993 Washington International Conference). （Without precise cavity control, this cleaning technology will not provide the required performance, and in some cases will lead to the destruction of the ultrasonic transducer and a significant reduction in cleaning power. However, without this technology, we believe that innovation in cleaning technology for the new era would not be possible.

**This is called the third generation of cleaning technology, the Cavitation Enhancement System.**

## (1) Cavitation enhancement system

Ultrasonic cleaning equipment that controls the dissolved amount of air in the liquid according to the purpose, based on the premise of an ultrasonic tank that precisely controls cavitation, is called ultrasonic cleaning equipment with a cavitation enhancement system (third-generation ultrasonic cleaning equipment).　The ultrasonic cleaner with a cavitation enhancement system (third-generation ultrasonic cleaner) is called an ultrasonic cleaner with a cavitation enhancement system (third-generation ultrasonic cleaner). The ultrasonic cleaning technology of the future is inconceivable without controlling the dissolved oxygen content (hereinafter, for the sake of measurement technology, we will substitute dissolved oxygen). When the dissolved oxygen content is more than a few ppm, in other words, in the case of general water and water-based ultrasonic cleaning, **gas nebula cavities** are generated. In the case of **gas nebula cavities**, the speed of movement of the liquid at the time of cavity formation and annihilation is slow, and as a result, the impact force is extremely weak.　　In addition, the cavities themselves move only a short distance (within a few millimeters), resulting in severe cleaning irregularities. Although this is better than ultrasonic cleaning equipment that generates visible bubbles, it is not suitable for the ultrasonic cleaning equipment that will compete for precision in the future.　Therefore, the **spherical nebula cavity** should be used for future ultrasonic cleaning. Ultrasonic cleaning that uses these **spherical nebula cavities** stably and efficiently by controlling the amount of dissolved oxygen in the liquid is called the third-generation ultrasonic cleaning and cavitation enhancement system.



In ultrasonic cleaning in the range of 20 KHz to 10 MHz, it is an absolute prerequisite to control dissolved oxygen to a low level and to use spherical cavities in order to achieve efficient precision cleaning.　Spherical cavities absorb and discharge a large amount of liquid per unit time, and the cavities themselves move at a high speed. Therefore, the cleaning power is the highest under the same conditions, and the diffusion effect (dirt transport effect by cavities) is also the highest.　The air entering from the liquid surface, the gas contained in the liquid itself, and the air on the surface of the object to be cleaned should be removed from the ultrasonic cleaning area, and the air content of the liquid around the object to be cleaned and between the object and the vibrating plate should be kept stable at less than half the saturation level.　This is exactly the same if the ultrasonic irradiation utilizes a cavity, no matter what medium or what flow path it goes through.　How much oxygen (air) content is appropriate depends on the frequency of the ultrasound, the type and temperature of the liquid, and above all, the purpose of the cleaning. In order to use this technology stably and efficiently, it is not enough to simply degas the liquid, but it is necessary to strictly adhere to the aforementioned cavitation control. In Japan, many attempts have been made since the presentation of this technology by the author, and as a result, we have to consider that similar products cannot be made yet, because of the lack of technology to comply with the cavity control. The following is a list of the main fields of application of this spherical cavity technology.

## (2) Globular nebula-shaped cavity

## Photo 5] Cavitation distribution of the third generation

## 4. Third Generation Ultrasonic Cleaning Technology and Applications

## 1. Applications and Features in the Liquid Crystal Field 　(1) Larger ultrasonic vibration plates

The most significant feature of this field is the increasing size of ultrasonic transducers that are compatible with glass substrates. Since ultrasonic transducers are composed of a large number of piezoelectric elements connected in parallel, the increase in size naturally requires technological innovations in all aspects of attaching and inspecting the transducers. Simply bonding a large number of elements to a large plate is not enough. In response to the increasing size of glass substrates, we are now in the process of commercializing 7.5-generation products ranging from 3,600W to 7,200W, and combinations thereof. At the extreme end of the spectrum of ultrasonic cleaning equipment with cavity enhancement systems that use spherical cavities, we are also commercializing a number of cleaning equipment with ultrasonic reflection surface designs of only 75 mm.

## (2) Review of ultrasound frequency

The effectiveness of ultrasound has long been questioned in this field. An extreme example is the MHz ultrasonic spray or shower, in which ultrasonic waves are applied to a spray for cleaning. It is true that I was the first person in Japan to put this technology to practical use 15 years ago and obtained a patent for it, but at the time I could not solve a certain problem, and I withdrew from the project myself. However, I was unable to solve a certain problem at that time, and I withdrew from the project myself.　The frequency of 1.5 MHz is linear, but because of its high frequency, it has a high defoaming capability, and a large amount of fine bubbles of less than 1 mm are generated from the surface of the vibrating plate, efficiently absorbing and blocking ultrasonic waves. At the same time, bubbles adhere to the vibrating plate surface, forming a reflective surface, resulting in an empty oscillation state, and leading to the destruction of the vibrating plate. To prevent this, a high-speed water flow (turbulent flow) is created on the diaphragm surface to remove the air bubbles that cause the empty oscillation. Although the diaphragm is protected, turbulence and the supply of a large amount of liquid generate more bubbles, effectively eliminating the MHz. Currently, in LCD glass substrate cleaning, the ultrasonic waves generated by the MHz diaphragm do not reach the glass substrate at all, and it appears that the glass substrate is merely being cleaned with an intense shower of pure water. Moreover, the effective range of the MHz spray cleaning is only less than 10 m, and the cleaning time per unit area of glass substrate is only a few seconds. The time the substrate is in the cleaning tank is longer, though. (These problems have been solved by the author, though.)　In the first place, MHz entered this field before the cavity enhancement system (third generation ultrasonic cleaning) was put into practical use in many fields, and due to the adverse effects of the misuse of low frequency gas nebula type cavities.　Now, I recommend simultaneous wide-area multiplexing up to 275 KHz with a basic frequency of 50 KHz and 80 KHz as the final frequency, on the premise of efficient use of spherical nebula cavities for ultrasonic cleaning of increasingly larger glass substrates and the like.　The impact force of the cavities can be controlled, and it is a mistake to try to solve the problem by suppressing the output power or raising the frequency to an extreme level (e.g., to MHz) to avoid damage.

This is a field where relatively strong cleaning is in high demand. However, there are two directions of development in this field as well. One is toward larger and more powerful systems, and the other is toward smaller, faster, and more precise systems.　Compared to other fields, inquiries for ultrasonic deburring have been greater, and ultrasonic cleaning and deburring of metals, plastics, ceramics, and composite materials in general has grown to be one of our mainstay products.　Here, we will discuss continuous vacuum [reduced pressure] ultrasonic cleaning deburring as a representative example of the remarkable growth in this field. This is a new form of ultrasonic cleaning. (Patent pending)

## 4. Automotive industry related fields

## 3. Computer-related fields and mobile communication devices

25 to 40 KHz is difficult to use because ultrasonic cavities often cause microscopic damage and contamination in the opposite direction. Therefore, the author has developed and utilized high acoustic pressure wide-area simultaneous multiple waves up to 535 KHz with 50 KHz and 80 KHz as basic frequencies. 1200 W to 7200 W with ultrasonic output density of 1 W./cm2 and 2 W/cm2 classes are used. In this field, as well as cleaning, minute burrs are also a cause of defects, so naturally, we also use them for deburring.

While ultrasonic etching is considered a new cavity application technology, 10 MHz ultrasonic waves have also been used successfully to flux clean 50 to 100 µm gaps (close contact areas) in high-density flip-flop chips. Ultrasonic deburring and simultaneous precision cleaning of a large number of packages is another new cavity-applied technology in this field.

## (2) Device manufacturing field, etc.

Although MHz seems to be at the height of its popularity, there are persistent dissatisfaction with its cleaning power: as mentioned above, MHz usually generates minute gas nebula-shaped cavities and countless air bubbles in pure water, making it difficult to clean larger wafers. Less than 10% of the ultrasonic energy reaches the liquid surface. Therefore, the amount of dissolved oxygen is controlled according to the size of the wafer, and only spherical cavities are generated to enhance cleaning power. In this case, the cavities move perpendicularly to the vibrating plate, so care must be taken.　However, the author recommends simultaneous multiple waves of 80 KHz to 535 KHz on the premise that damage is controlled. a new powerful, dense, high acoustic pressure ultrasonic wave that solves the problems of MHz has been created.

To reduce output is to reduce the number of cavities and lose cleaning effectiveness, and to evacuate to extreme high frequencies is to lose the impact force of individual cavities.　As substrates become larger, more delicate, and more precise, the cleaning power expected from the cleaning object must also be increased. However, the smaller the foreign matter, the greater the adhesive force per unit area. What is required here is a cavitation control technology that can generate a larger number of cavities with the necessary positive and negative impact force = cleaning power in a more uniform and stable manner, without causing damage.　Although it is not possible to go into too much detail here due to the number of pages, some ultrasonic cleaning designers are oblivious to the nature of glass in glass cleaning.　Glass for liquid crystal displays (LCDs) is passed through ultrasonic waves more than 99% of the time. Reflected waves cannot be formed by themselves. If this is the case, where should the glass be placed in relation to the vibrating plate in ultrasonic cleaning? (To be precise, this question is incorrect.)　Or, what position from the reflective surface can the glass be passed through for cleaning? The idea that ultrasonic cleaning is possible when the glass substrate passes over the diaphragm is exactly the idea of the first generation of ultrasonic cleaning.

## (1) Silicon wafer manufacturing field

Basically, the approach is the same as in the field of liquid crystals. We will focus on the application of ultrasonic cavities. We are fully aware of the importance of hardware, but we believe that what is lacking now, or what has been stagnant for the past 20 years, is the software aspect of ultrasonic cleaning technology.

## 2. Ultrasonic Cleaning in the Semiconductor Field

## (1) Continuous vacuum [reduced pressure] ultrasonic deburring cleaning

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The author has developed an ultrasonic washing system that washes a large quantity of clothes in a short time (about 2 minutes) without moving them while they are still packed in a basket or on hangers. In addition, the author has developed a short-time ultrasonic cleaning system for high-temperature, high-pressure filters with several thousand layers of metal mesh of a few microns, which was said to be impossible with ultrasonic waves. The principle is basically the same.

　It is well known that air in the liquid affects the performance of ultrasonic cleaning (whether or not the proper measures are taken is another matter!) ) Air bubbles, whether large or small, on the surface or inside the object to be cleaned can cause cleaning failures. Bubbles, whether large or small, can cause cleaning problems. Of course, if the gas does not move, the cleaning solution will not be fully immersed in it.

　Ten years ago, the author introduced a method of continuous cleaning by first placing the cleaned material in a vacuum to remove air from the interior and surface of the material, and then introducing a liquid from which dissolved gases have been removed. The disadvantage of this method was that the cleaned material would be released back into the air when it was transferred to the next tank, making continuous non-air contact ultrasonic cleaning impossible. Last year, in collaboration with a major Japanese valve body manufacturer, we developed and successfully commercialized a continuous vacuum [reduced pressure] ultrasonic deburring and cleaning system for valve bodies.

　　Several valve bodies are placed vertically in a cassette 700 mm long, and then flowed on a conveyor. Tact time is 70 seconds. The first tank is a vacuum treatment tank. The second tank is an ultrasonic deburring tank with two ultrasonic transducers of 25KHz to 535KHz and 3600W on both sides of the cleaning tank. 3600W is resonated by two units synchronously. The ultrasonic sound pressure is constantly monitored by the U-sonic ultrasonic cleaning power meter developed by our company, and an alarm is issued if the sound pressure is too high or too low. The controlled sound pressure is 20 to 25 V. The third tank is a rinse tank. The third tank is the rinse tank, and there are shutters between the tanks to prevent contact with air, including during transfer of the cleaned product. We call this submersible ultrasonic cleaner [SUB-MERGING]. The same method is basically used for cleaning not only valve bodies but also various engine blocks (including F1). Before the experiment, the cleaned items are moved up and down in the liquid, and all items with even the slightest air bubbles remaining or complicated shapes, which may cause such bubbles, are vacuum treated and then ultrasonically (3rd generation) cleaned.

## 6. New Era, Development of Ultrasonic Cleaning Technology

The author believes that we are now in the midst of new developments in ultrasonic cavitation application technology. Ultrasonic cleaning is becoming larger and smaller in size, and higher performance is being achieved based on more precise measurement and control. One area of development, deburring, will create a large market. In addition, ultrasonic etching, ultrasonic abrasive polishing, ultrasonic high-speed pulverization, ultrasonic organic synthesis, ultrasonic clothing cleaning, and ultrasonic applications for foodstuffs are just a few of the new applications that will develop in the next 10 years. We are convinced that the key to this development lies in the third generation of ultrasonic cleaning technology with cavity enhancement systems.

**This is the manuscript of the technical seminar in Shanghai, China in 2004**. (shibano added on February 1, 2013)