Fascination **Cavitation.**

The Wonderful World
of Ultrasonic Cleaning.

Elma Schmidbauer GmbH
David Holly

FOREWORD

Passion for highest purity. Since 1948.

From pioneer to innovation leader.
My grandfather Hans Schmidbauer was a tinkerer and always had a large portion of curiosity in his blood. He was never satisfied with the status quo. So it came as it had to come. As a trained watchmaker, he noticed that the process of cleaning watches and their smallest parts was too time-consuming.

And so it made sense for him to build a product. That was the birth of his own company, the „Präzisionsfabrik für Elektrische Maschinen", Elma. His first product, the **Elma Super Elite**, paved the way for the young company's success. The name Elma became a household word among watchmakers, and today there is probably hardly a watchmaker who does not know Elma.

The success story of Elma started in Singen (Hohentwiel) and developed continuously over the years. In the early 1960s, the first successful steps were taken in the field of **ultrasonic technology**, which over the years has become one of our core competences.

In 1973, there was the first handover within the family to my father Manfred H. Schmidbauer, who continued to shape the company, established ultrasound as a cleaning technology in other industries as well, and drove the international expansion to more than 80 countries today. Since 2021, I have been able to stand on the bridge and lead the company into the digital future.

As you read our ultrasonic magazine, I hope you enjoy your journey of discovery into **The Wonderful World of Ultrasonic Cleaning**.

Let us inspire you.

Sincerely
Yours, Mirja Schmidbauer

PROLOGUE

The Wonderful World of Ultrasonic Cleaning.

Fascination Cavitation.
Whether cleaning glasses at the optician around the corner, cleaning during the manufacturing process of medical instruments, or at a billion-dollar high-tech company in the semiconductor industry with the toughest requirements for purity: **Ultrasonic cleaning** is a highly relevant professional cleaning process.

It is remarkable that only few people know how ultrasonic cleaning actually works. Admittedly, it is not exactly an easy process to understand, often somewhat mystified due to its complexity. The following knowledge base is therefore intended to give you a simplified introduction to the world of ultrasonic cleaning and to give an overview of the most important interrelationships. There is no claim to completeness here; cavitation is still being researched, so it is still not fully understood in all areas.

Let us now dive together under the surface of the ultrasonic tank and enter the fascinating world of cavitation.

Elma Schmidbauer GmbH
David Holly
June 2023

PROLOGUE

Fascination Cavitation.

CAVITATION

Expert knowledge for your application.

CHAPTER 1

The Four Basic Parameters of Cleaning.

The cleaning[1] circle according to Dr Sinner.
Let's imagine that we spent a nice barbecue with friends or family. The next morning, the unpleasant task awaits – cleaning the grill grate. It can be an advantage to know the basic parameters of cleaning. These are summarized in the so-called **Sinner's circle**[2]:

Let's start with the first parameter: the **media**. For our grill grate, water with a dash of detergent is certainly more effective than simply tap water. If the water is then also as hot as possible, we have also already considered the **temperature** parameter. It is generally known that soaking the burnt-in grate for a few hours can help, and this is represented here by the **time** (or duration) parameter. Last but not least: the mechanical effect, in short **mechanics**. Well, what works better, a paint brush or a wire brush?

All four parameters together form a kind of conservation variable, a **cleaning effect**. Unfortunately, it is seldom the case that you simply compensate for a reduction in one parameter by increasing another. The individual parameters depend on each other and often show a kind of threshold behavior or a generally non-linear character.

In our example, even after a long soak and the use of hot water with detergent, scrubbing is certainly the most strenuous task. What if we could simply place the grill in a cleaning tank with a liquid that would do the mechanical part for us? Inside the tank, many small „micro-brushes" do the cleaning, removing the burnt and greasy residue everywhere on the grate.

Hard to imagine.
But that's exactly what **ultrasonic cleaning** can do!

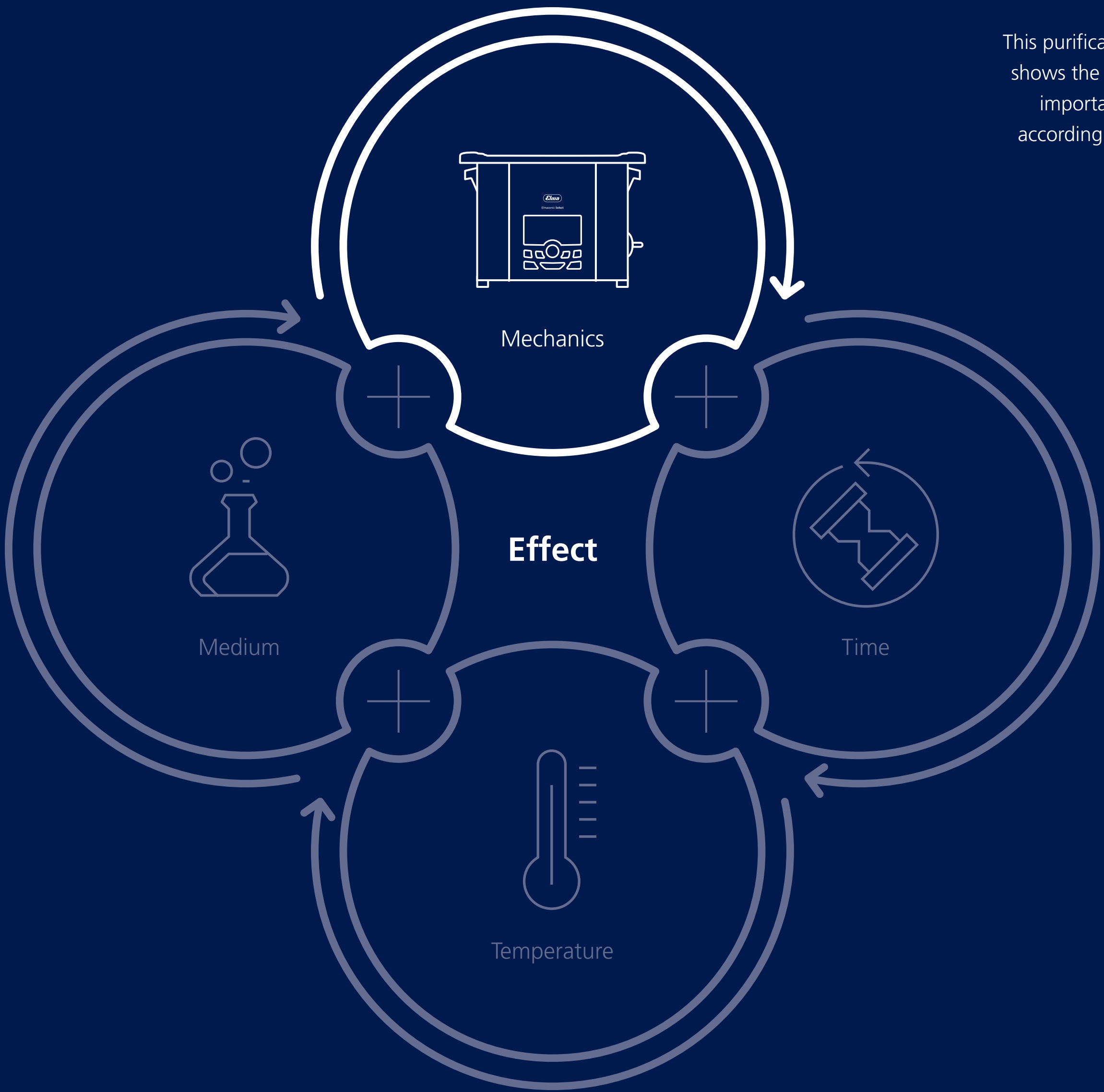
Of course, in reality it is not „micro brushes", but a particularly fascinating effect: **cavitation**.

[1] Also known as „purification circle".

[2] Named after the surfactant chemist Herbert Sinner (1900 in Chemnitz, † 1988 in Hilden).*

BASICS

This purification circle shows the four most important factors according to Sinner.



CHAPTER2

Ultrasound and Cavitation.

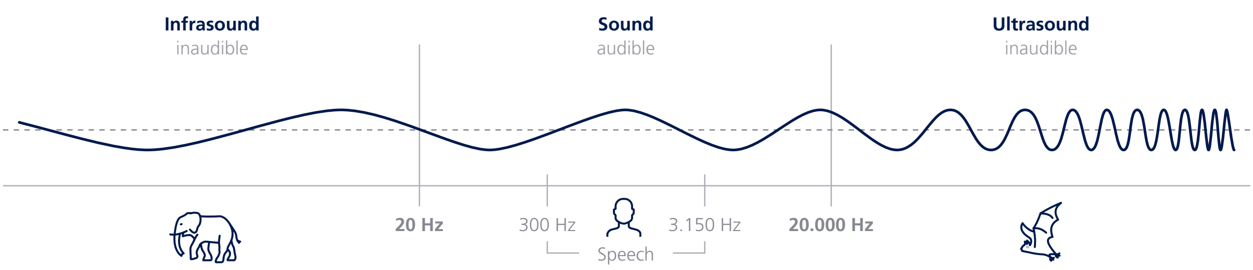
What is ultrasound anyway?

First, it is necessary to clarify a subtle but important difference: Strictly speaking, the term **ultrasonic cleaning** is not entirely correct. Actually, it is not the ultrasound that produces the cleaning effect, but rather the phenomenon known as cavitation. Nevertheless, **ultrasound** and **cavitation** are closely related, as will be explained below.

But let’s start from the beginning.

Without the propagation of sound waves, we could neither hear music nor speech. Loudspeakers or even the human vocal cords emit sound in the form of pressure waves in the air. The eardrum in the ear picks up these waves, commonly referred to as **sound waves**, and conveys them to the inner ear, where signals are generated from these waves and transmitted to the brain. The deeper the sound we perceive, the longer the waves. However, another physical quantity is usually used to describe sound waves - the so-called **frequency**. This is measured in **Hertz (Hz)**, where one Hertz corresponds to one oscillation per second. Wavelength and frequency are interrelated: a higher frequency results in shorter sound waves, while a lower frequency corresponds to longer sound waves.

All sound waves that are so low in frequency that humans can no longer hear them, i.e. below 20 oscillations per second – **20 Hz** – are termed **infrasound**. On the other hand, **ultrasound** refers to sound waves that vibrate at a frequency of more than **20,000 Hz (20 kHz)**, which is beyond human hearing on the upper range.

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The process of ultrasonic cleaning.

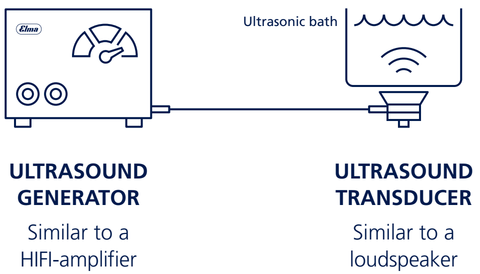
For ultrasonic cleaning, a device known as an ultrasonic transducer is affixed to the bottom, and sometimes to the sides, of an ultrasonic tank. These ultrasonic transducers can be thought of as similar to loudspeakers. An electrical generator produces an electrical oscillation signal and the ultrasonic transducer converts this signal into a sound vibration.

This means that the ultrasonic transducer moves the surface to which it is attached back and forth (up and down in our example) at the frequency of the ultrasonic signal. The sound waves propagate in the water with a sound velocity of about 1400 m/s. Typically, these sound waves are referred to as longitudinal waves, meaning they propagate in the direction of their excitation.

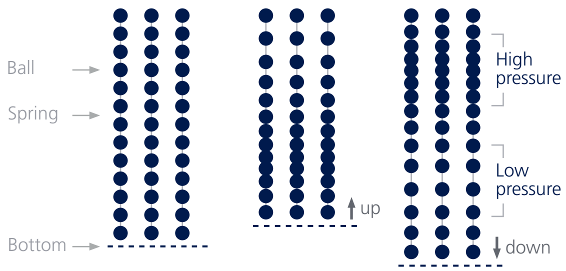
You can visualize the water in the cleaning tank as a chain of interconnected balls held together by mechanical springs. When we move the lowest balls – those at the bottom of the ultrasonic tank – up and down, they, in turn, push the next ones up and down, and so on. Each ball transfers energy to the next one. However, because each ball must first compress the mechanical spring in front of it before moving the next one, there is a certain delay. Consequently, regions are formed where the balls are tightly pressed together (high pressure) and other areas where the balls are pulled farther apart (low pressure).

The degree to which the balls are compressed together and pulled apart depends on how much the base is moved up and down. This variation determines the so-called **sound pressure**, which can be thought of as the volume of the sound. In ultrasonic cleaning tanks, sound pressures of up to **200 kPa (200,000 pascals)** are typically generated.

These sound pressures are so strong that, at low pressure, they can pull the springs between the balls apart, causing them to break.



Technical operating principle of ultrasonic cleaning.



Simplified representation of sound wave propagation in a liquid medium.

Let’s remind ourselves that the ball chain is merely our visual model; we are, in fact, discussing water! Strong ultrasound is able to tear water apart – unbelievable, isn’t it?

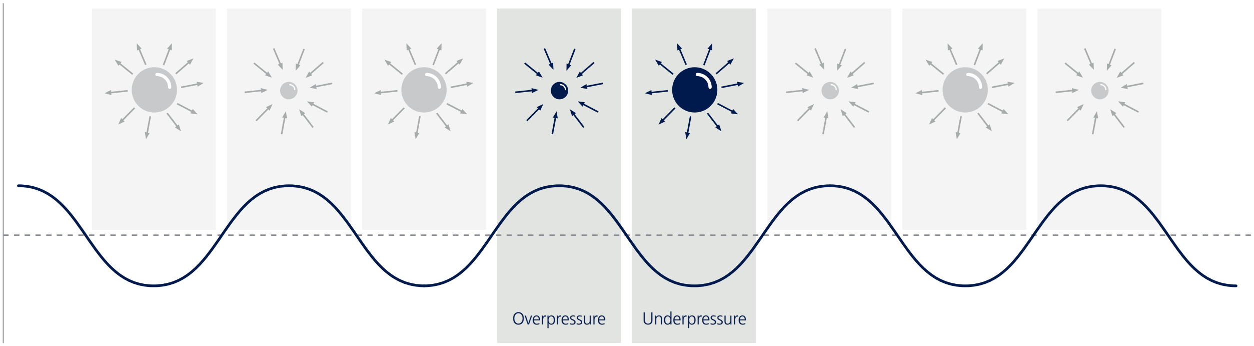
However, it’s worth noting that water typically doesn’t have a perfectly pure structure. There are usually imperfections caused by salts, dust, stabilized nanobubbles, or even small pockets of gas on surfaces. At these so-called nucleation locations, breakage is more likely to occur than in an absolutely pure water structure. With a little thought, one can easily come to the following conclusion: When the structure of water breaks down, there can actually be no more water in liquid form at the point of rupture.

What remains is, in fact, gaseous. Strictly speaking, it’s assumed to be a mixture of water vapor and air. A spherical boundary layer is thus formed between the accumulation of gas particles and the water, and this is nothing other than a **bubble**. The formation of bubbles caused by the rupture of water is called **cavitation**. The etymology of the word is also interesting here: Latin: *cavatio* = the hollow, English: *the cavity* = the hollow space. So, at this point, we now have an understanding what cavitation is.

But how does cavitation work?

The resulting bubbles continue to be exposed to the changing sound pressure around them. Specifically, the bubbles are compressed when the surrounding pressure is high and expanded when the pressure is low.

Bubbles in ultrasonic bath



Alternating sound pressure: overpressure compresses the bubble, underpressure expands it.

Influence of the sound pressure.

In the following, we will consider the behavior of a single bubble, but it should not be forgotten that the processes described below occur simultaneously at various locations in the ultrasonic tank. The ratio of the bubble's initial size (radius) to the ultrasonic frequency and sound pressure, along with other important influencing parameters, determines its further behavior and also its lifecycle.

At lower sound pressures, the bubble resonates with the changing sound pressure, constantly stretching and compressing. With slightly higher sound pressures, one can observe a certain momentum of the bubble. The radius of the cavitation bubble can then follow this course: The bubble initially grows slightly, about twice its original radius, before shrinking again immediately after the sound pressure reaches its minimum. Due to the surface tension of the bubble wall, there is a certain „springing" effect, resulting in a partial „re-springing". This behavior is demonstrated below for an ultrasonic period at 25 kHz and approximately 100 kPa sound pressure. This pattern repeats itself over a large number of successive periods, leading to what is known as **stable cavitation** (p.13).

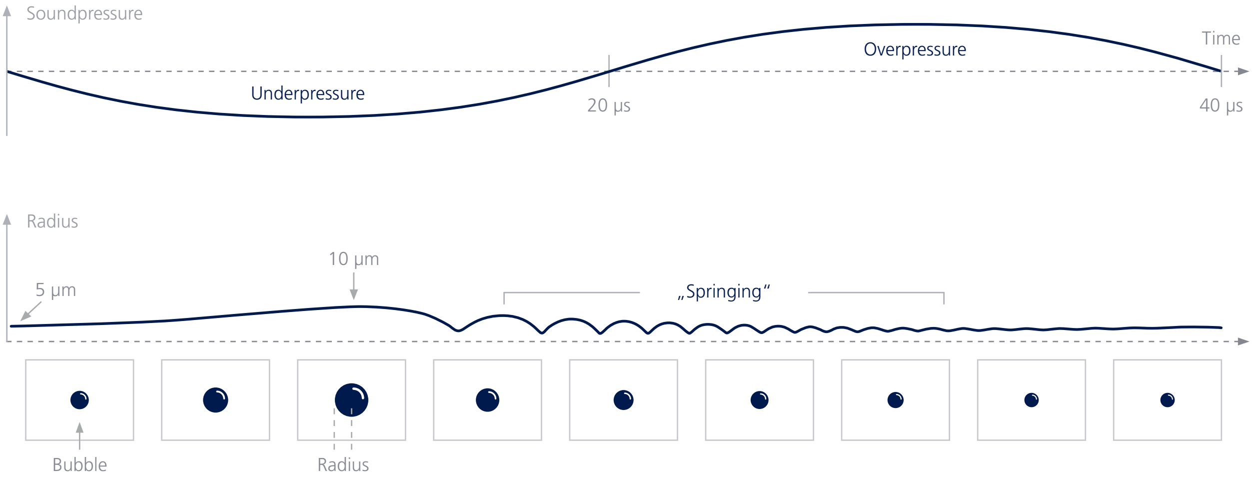
At higher sound pressures, such as 140 kPa in our example, a fascinating effect occurs known among experts as **inertial cavitation** or **transient cavitation** (p.13). The bubble expands to several times its initial radius due to increased pressure. As it rapidly pushes the liquid in front of it, it maintains its maximum size due to inertia until the acoustic pressure changes from negative to positive. The subsequent overpressure, combined with surface tension, causes the bubble to rapidly shrink to a minimum size. It can be assumed that the bubble wall reaches supersonic speed during this process. The rapid increase in internal bubble pressure leads to temperatures reaching several thousand °K within the bubble, causing it to collapse. This **collapse** is also referred to as **implosion**, generating a shock wave similar to an explosion. Particularly near boundary surfaces, such as the surface of the object being cleaned, a liquid jet forms alongside the bubble collapse, creating a small, fast-flowing stream of liquid in the direction of the surface.

Both stable cavitation and transient cavitation are useful mechanisms in ultrasonic cleaning. Oscillating bubbles in stable cavitation move the liquid around the object to be cleaned, ensuring a continuous exchange of the media at the interface. This is particularly effective for ultrasonic-assisted rinsing, often one of the final steps in a cleaning process. The shock waves and liquid jets generated by transient cavitation are more suitable for the cleaning step, effectively „blasting" contaminants on the surface of the object and carrying away the dirt.

There is a known threshold behavior between stable cavitation and transient cavitation, referred to as the **cavitational threshold**.

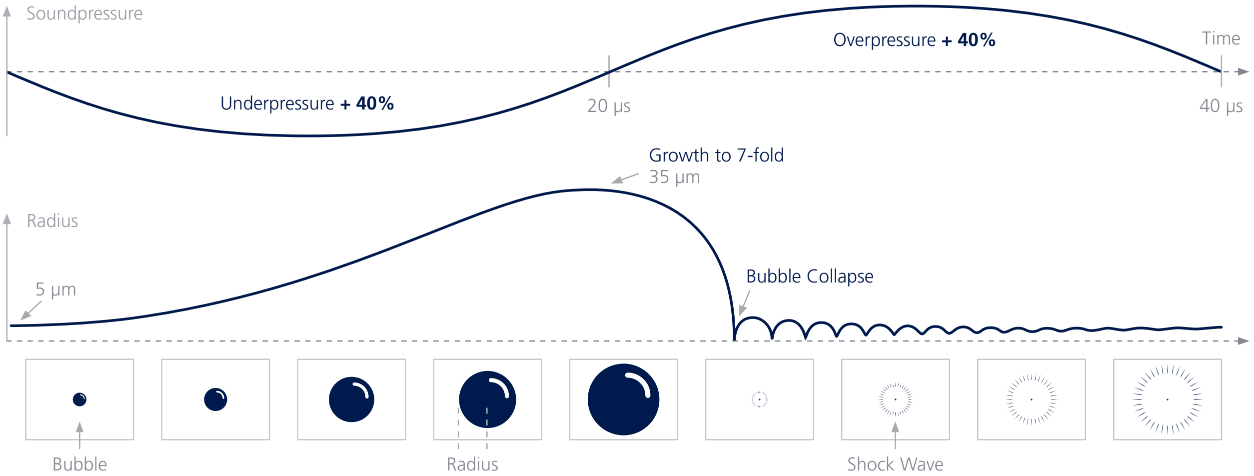
Stable Cavitation

Bubble Dynamics



Transient Cavitation

Bubble Dynamics



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CHAPTER 3

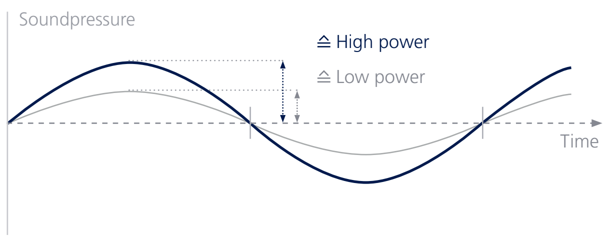
Ultrasound: Frequency and Power.

How to regulate the ultrasonic effect.

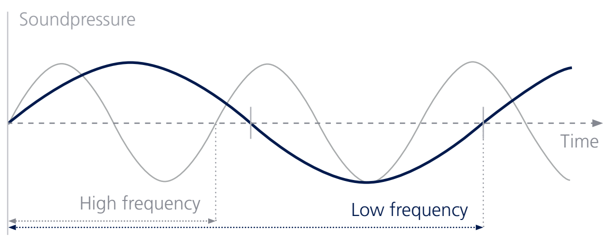
In previous chapters, we've learned that the choice between a wire brush or paint brush can significantly impact the mechanical action used for cleaning. Depending on the contamination type, cleanliness requirements, and the cleaning material's nature, it's beneficial to consider different tools. In ultrasonic cleaning, the tool at our disposal is the cavitation bubbles. The question at hand is how we can manipulate their behavior to either act aggressively or with a gentle touch. Let's examine the typical adjustments available on an ultrasonic tank to answer this question:

Many ultrasonic cleaners offer **power** adjustments, which can be equated to the volume or strength of the sound pressure. When set to high power, cavitation bubbles behave transiently, generating stronger shock waves and jets that exert more force on the contamination and cleaning material. At lower power levels, the cavitation bubbles display a stable behavior, gently pulsating and thereby transporting the cleaning media across the material to be cleaned. It should be noted, however, that even at lower power levels, there may occasionally be unwanted bubble collapse events.

A more effective means of achieving gentle cleaning is by regulating the ultrasonic **frequency**. Assuming a constant ultrasonic power, it follows that as the frequency decreases (e.g. 25 kHz), the cleaning effect becomes more forceful; conversely, as the frequency increases, the effect diminishes in intensity.



Comparison: large vs. small sound pressure.



Comparison: low vs. high frequency.

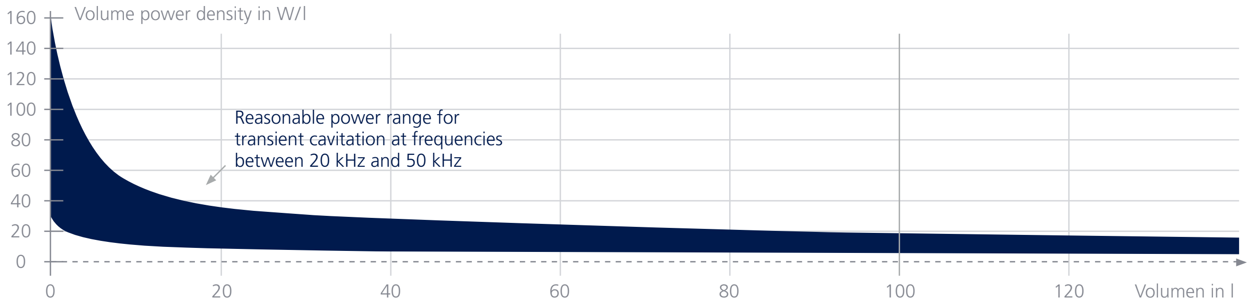
Set parameters correctly.

For many standard applications, a „medium-hard brush" is sufficient, and, of course, the correct choice of the remaining parameters of Sinner's circle (Chapter 1). For common ultrasonic cleaning devices, this then corresponds to a frequency in the range between 35 kHz and 45 kHz. The power is selected depending on the filling volume of the liquid so that transient cavitation occurs. For very fine and gentle cleaning, as well as for rinsing after cleaning, frequencies of 70 kHz and higher are then used. It is also possible to generate transient cavitation at high frequencies, but the higher the frequency, the higher the power required, and in some cases, the transducers have to be designed completely differently. Thus, it is considerably more expensive and therefore rarely makes economic sense.

When choosing an appropriate ultrasonic device, one often comes across the volume-related power, referred to as „**watts per liter**" or „**W/l**" for short. It is important to consider this factor in the selection process. A common misconception here is that you always need a volume power density of at least 20 W per liter of liquid. This assumption is generally not valid!

There is an admittedly non-intuitive relationship between the filling volume and the required **volumetric power density**. The smaller a tank is, the more W/l are needed. The larger, the less! However, 'a lot helps a lot' does not apply here either. Too much power leads to cavitation events in the immediate vicinity of the ultrasonic transducers or at the sound-emitting surface. In the worst case, this leads to inefficient cleaning and also to significantly faster wear of the ultrasonic tank. Yes, even stainless steel, which is what ultrasonic tanks are typically made from, cannot withstand the effects of cavitation indefinitely.

One must still note here: This is only a rough estimate which is subject to certain limitations. If the ultrasonic tank is shallow and long or very narrow and, therefore, high, then it should be designed, in particular, considering the direction of the sound-emitting surface and the position of the ultrasonic transducers. Elma already pays attention to the ideal ratio between power and filling volume during the specification and development of the ultrasonic units, especially considering the tank geometry.



Rough orientation for a reasonably chosen specific volume power density.

CHAPTER 4

Wavelength and Sound Field.

Propagation of sound.
Another important factor to consider in relation to frequency is the resulting **wavelength** and its impact on the spatial distribution of sound pressure and cavitation bubbles. Let's break this down step by step.

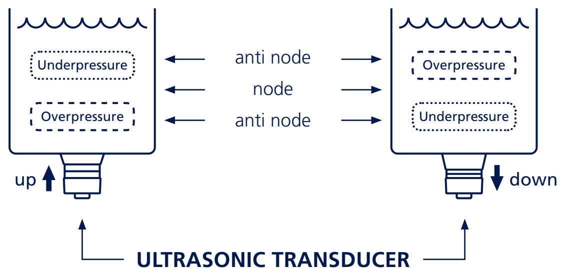
In Chapter 2, we have already established that wavelength and frequency are interdependent. You can calculate the wavelength by dividing the **sound propagation speed** of the liquid (in this example, 1480 m/s) by the frequency. At 25 kHz, the waves are, therefore, approximately 5.8 cm long. However, for the sound waves in the ultrasonic tank, this is only half the truth – and, as we will see in a moment, in the truest sense of the word: The waves originating from the transducer are reflected on the water surface at the latest. They make a 180° turn and travel back in the direction of the transducer.

On their way, wave crests (overpressure) and troughs (underpressure) sent out later will intersect them. When two wave crests meet at a specific location, they reinforce each other. The same applies to two wave troughs.

However, when a wave crest and a wave trough meet, they cancel each other out, effectively reaching zero. In physics, this whole behavior is also known as wave interference.

Now, let's imagine we would be as small as a cavitation bubble and be in the location in the ultrasonic tank where, at a particular moment, the sound overpressure doubles due to the addition of two wave crests.

We will observe that the pressure gradually decreases with time and then, half an oscillation period later, there is twice the negative pressure around us. At this moment, exactly two wave troughs complement each other. Then the pressure increases again until it corresponds to double the sound overpressure, and the cycle repeats. This location is referred to as the sound **pressure anti node**.



Formation of a standing wave field with nodes and anti nodes.

Processes in the ultrasonic bath.

Ultrasound and cavitation drive contamination out of the links of a watch strap.

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Areas in the ultrasonic tank.

If we now move to a second location, which is a quarter of a wavelength further (in our example, 1.45 cm), we will find that here the sound pressure remains constant over time. This location is referred to as a **sound pressure node.**

A quarter of a wavelength further away, there is another sound pressure anti node, then another node, and so on. When viewed from a distance, it appears as if there are no propagating waves at all. This is why we refer to this phenomenon as a standing wave or a **standing wave field**.

What you should take away from this chapter is that there are **stationary sound pressure zones** in the ultrasonic tank. The distance between these zones depends on the frequency.

: **High frequency** ≙ small distance
: **Low frequency** ≙ large distance

Now, if we look at what was presented about cavitation formation in Chapter 2, it leads us to the following consideration: Cavitation cannot occur at all in the sound pressure nodes, which may then result in uneven mechanical cleaning effects.

Indeed, that is true, and this is why it is advisable to move the part to be cleaned slowly back and forth within the sound field in the direction of the sound-emitting surface. In ultrasonic cleaning terminology this often is referred to as mechanical oscillating of the parts.

In Elmasystem cleaning tanks and larger Elmasonic floor-standing units, this movement can be achieved automatically using a mechanical device. In smaller units, commonly there is no (automatic) movement of parts. In such cases, a basket or product carrier is inserted or hung in a fixed position. In the following chapter, we will discuss how to effectively solve this issue by applying what we have learned so far.

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CHAPTER 5

Ultrasonic Operating Modes.

Multiple functions.

In many common ultrasonic cleaning tanks, various ultrasonic operating modes can be selected. When one selects such an operating mode, either the frequency or the power, or both, they are controlled by the ultrasonic generator. The variation of frequency or power then occurs on a much slower time scale than the actual ultrasonic signal. To understand this, we first have to clarify how we can describe an ultrasonic signal on the time scale at all. So far, we have mainly talked about the frequency and the „spatial" length of a wave. But there is also a simple relation between the duration of a wave and its frequency. This is already derived from the known unit Hertz (Hz) mentioned in Chapter 2.

One hertz means that one oscillation, one wave crest and one wave trough, lasts exactly one second. At a typical ultrasonic oscillation frequency such as 37,000 Hz (37 kHz), one oscillation lasts only 27 µs. That's 0.000027 s. Pretty fast, isn't it?

Eco Mode.

For a long time, the motto was „the main thing is lots of power". Although high power ensures strong cleaning effects, it also has disadvantages. High power promotes wear on the ultrasonic tank and means high overall energy consumption. Modern ultrasonic units (Elmasonic Select, Med, Easy) are therefore equipped with a so-called Eco mode. This is a reduced power sweep mode which, under standard conditions (degassed water with surfactant detergent, approx. 20 - 70 °C), produces transient cavitation and thus a sufficient mechanical cleaning effect. This mode is therefore perfectly adequate for many cleaning tasks. It is quieter, more energy efficient and ensures a longer service life.

Sweep Mode.

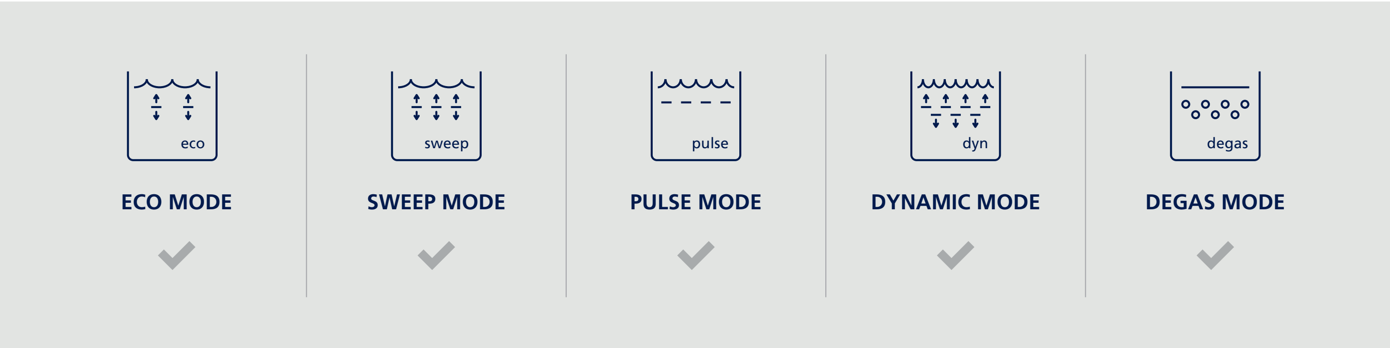
A typical modulation mode is the so-called sweep mode, sometimes also called „frequency wobble". Especially with tabletop units (e.g. Elmasonic Select, Med, Easy), this mode is the standard mode and does not have to be selected separately. This is simply due to its advantages. This sweep mode generates modulation in the form of a recurring change in frequency, also known in technology as frequency modulation. This can be understood as a second oscillation combined with the ultrasonic oscillation. As already indicated, this supplementary oscillation is significantly slower or lower-frequency than the actual ultrasonic signal, approximately in the range between 1 s and 100 ms, or 1 Hz and 10 Hz. And what is the point of this? Quite simply, we have learned that a change in frequency also causes a change in wavelength in the tank. So, if you change the frequency cyclically, the place where cavitation bubbles are generated also changes with the same cycle. This is how the ultrasonic tank moves the cleaning effect. However, the maximum possible shift in wavelength that accompanies the frequency shift is unfortunately not quite wide enough to obtain a completely homogeneous cleaning pattern. Mechanical oscillation should therefore still not be dispensed with, especially in larger tanks.

Pulse Mode.
Another useful modulation mode affects the power of the ultrasonic tank. We have already learned that higher power also produces stronger cavitation. At the same time, we also know that stronger cavitation leads to more wear to our ultrasonic tank. Let's say we have a device that can generate 100 W of ultrasonic power. But we need a stronger cavitation effect and therefore actually a power of, for example, 130 W. Now here's the trick: We divide the power into the time, emit 70 W ultrasonic power for 10 ms and in the next 10 ms, 130 W, then again 70 W, and so on. In time average, we still have 100 W power, but for half of the time, we have the strong cavitation effect with 130 W. This is exactly what is achieved with the so-called pulse mode.

Dynamic Mode.
So, if you want the most homogeneous cleaning possible and at the same time a strong cleaning performance, one chooses a mode that combines both the previous ones we have discussed. Alternating Pulse and Sweep results in the so-called Dynamic Mode.

Degas Mode.
A specific effect that is not actually intended for cleaning is the so-called Degas mode. In this mode, the ultrasound is switched on and off cyclically. This is particularly efficient for removing gas dissolved in the media from the tank. We will learn why this is useful and why it works best this way in the following chapters.

The degassing mode is mainly used for tank preparation, i.e. before the actual cleaning process.



CHAPTER 6

Why Cavitation Bubbles Can Change their Size.

Insight into physical processes.
We have already established, at least in broad strokes, how the cavitation bubbles are created and act: At lower sound pressures, the cavitation bubbles oscillate after they have been created. They cyclically compress and expand with the ultrasound and then tend to rebound. At higher sound pressures, combined with the suitable ultrasonic frequency, the bubbles expand so much in the vacuum phase that they subsequently collapse with the onset of overpressure.

In science, this is known as the so-called **dynamic Blake threshold**. How this behaves exactly cannot be described well without the use of higher mathematics. Nevertheless, we can assume the following relationships: If the expansion within an overpressure phase exceeds more than three times the original size, then the bubble will probably collapse violently.

Whether the bubbles collapse or oscillate depends not only on the sound pressure, but also on their initial size and the ultrasonic frequency. Very small bubbles will not respond to the ultrasonic excitation and will dissolve over time. Large bubbles can perform so-called non-linear oscillations, but tend not to collapse. Only if the bubbles have the right initial size will it follow with a violent bubble collapse. So far, we have talked about the dynamics of a bubble within one or perhaps a few oscillation periods.

What complicates the matter is that the bubbles, stimulated by the ultrasonic effect, change their size even, or especially, over long periods of time. Two **bubble growth effects** are responsible for this:

Rectified Diffusion.
The first effect is called rectified diffusion. This is a transport mechanism for gas particles dissolved in the media – essentially air: i.e. nitrogen, oxygen, carbon dioxide and argon. Let's imagine again what a bubble is like in the first place: Inside, the bubble is filled with gas particles. Around these particles, a bubble wall encloses them and shields them from the water. If the bubble is compressed by overpressure, the gas particles enclosed inside are also compressed.

However, it then becomes a little too narrow for them, which is why some gas particles „escape" through the bubble wall into the water. If, on the other hand, the bubble is expanded, more space becomes available inside the bubble, and thus, some gas particles dissolved in the water pass through the bubble wall into the interior of the bubble. This effect is called diffusion.

The behavior is such that more gas is always transported into the bubble in the negative pressure phase than out of the bubble in the positive pressure phase. As a result, the bubble continues to grow over the duration of several ultrasound cycles due to this, now directed diffusion.

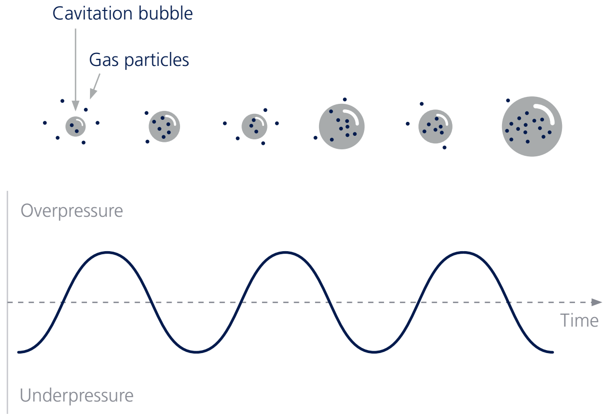
Coalescence.

The second known effect is called coalescence. You can imagine the behavior similarly to soap bubbles in the air. It can happen that two soap bubbles meet and unite to form a larger bubble. This is similar to what happens with cavitation bubbles, although another effect plays an important role here. And we will deal with this in the next chapter.

Rectified Diffusion

Bubble Growth Dynamic

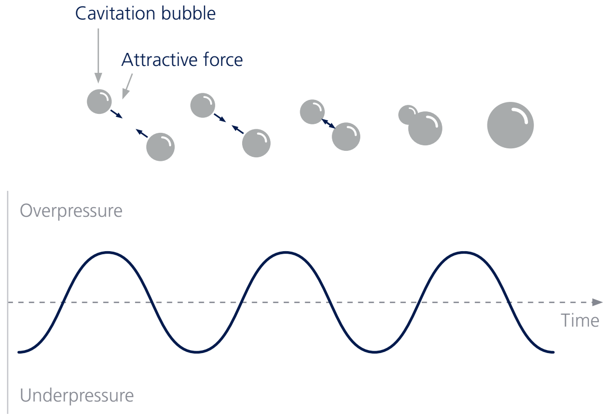
Over time, more particles diffuse into the bubble than out! Result: **The bubble grows**.



Coalescence

Bubble Growth Dynamic

Two or more bubbles attract and unite to form a **larger bubble**.



Simplified illustration of the effects of bubble growth.

Why Cavitation Bubbles Move in the Ultrasonic Tank.

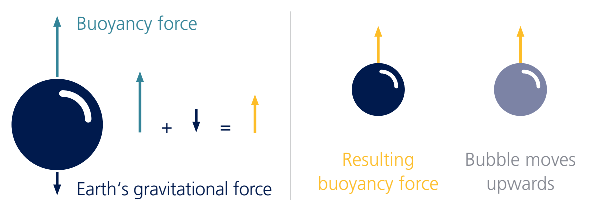
The translational force.
Cavitation bubbles oscillate, collapse, disappear, grow, split, or unite. As if that weren't enough, cavitation bubbles also move through the tank. To set an object in motion, a **force** usually has to be applied. Such a force is also called a translational force. Several forces act on gas bubbles underwater.

: **Gravitational force** = volume of the bubble * density of the gas in the bubble * gravitational acceleration

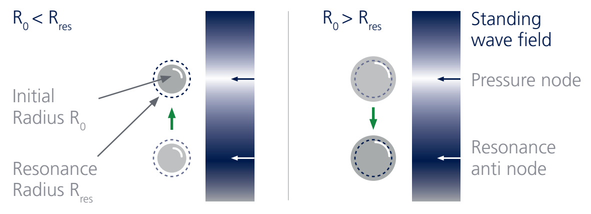
: **Buoyancy force** = volume of the bubble * density of the water * gravitational acceleration

The first force is the force of gravity and this is counteracted by the so-called buoyancy force. Since these forces oppose each other, the stronger force will always win. You can imagine this as in a tug-of-war. The team with more force ensures that the rope keeps pulling in its direction. The resulting force from the two opposing forces is the actual translational force. Since the density of water in our case is always higher than the density of gas, the buoyancy force will be stronger than the gravitational force, causing the buoyancy force to win in the tug-of-war and the bubble to rise to the surface.

However, if you look closely in the ultrasonic tank, you can often observe bubbles that do not rise to the surface during ultrasonic operation but appear to float in the middle of the water. When the ultrasound is then switched off, these bubbles rise directly to the surface of the tank.



Buoyancy force – the stronger force.



Primary Bjerknes force: The sound field moves the bubbles.

Why does the sound fixate the bubbles? This is obviously due to another force that counteracts the previously discussed buoyancy force. This is called the Primary **Bjerknes force** (named after the physicist Vilhelm Friman Koren Bjerknes).

: **Primary Bjerknes force** = (-1) * sound pressure gradient * volume of the bubble

The **sound pressure gradient** here describes the change in sound pressure over a certain spatial range of the sound field. Let's imagine that we are as small as a cavitation bubble and that we are located in the sound pressure node of the sound field. We learned in Chapter 4 that there is no pressure change at this location. If we now move bit by bit towards the sound pressure anti node, the pressure change gets stronger and stronger.

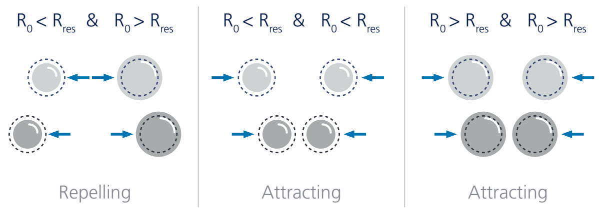
The course of our path, i.e. the change in the pressure change amplitude, is called the sound pressure gradient. However, the gradient alone is not sufficient to exert a force on the bubble, provided that the bubble is assumed to have a constant size. However, as we have already learned, the radius of the bubble and thus its volume, changes over the course of an oscillation period. Here we need another relation: the so-called resonance radius (Minneart radius). As a related example, let's take a weight suspended from the ceiling by a mechanical spring. If we pull the weight down a bit and release it, it will vibrate up and down at its natural resonant frequency. A bubble underwater also has such a resonance frequency.

Small bubbles, or more precisely bubbles that are smaller on average than their so-called resonance radius (Minneart radius), are moved in the direction of the sound pressure antinode. Bubbles that are larger on average than the resonance radius move in the direction of the sound pressure node.

Since we call the force just discussed the „**Primary** Bjerknes force", it is not surprising that a „**Secondary** Bjerknes force" also exists. It is not only the sound field that causes bubbles to move: Neighboring bubbles also influence each other.

Here, in a first approximation, we can assume that bubbles of different sizes will repel each other. We assume here that one bubble is smaller and one larger than the resonance radius. Bubbles of approximately the same size, i.e. two bubbles which are both smaller or both larger than the resonance radius, attract each other.

For the sake of completeness, the following should be noted: It can happen that the translational effect of the Bjerknes forces is reversed at very high sound pressures. This is due to the so-called nonlinearity of the dynamic behavior. However, we will not discuss this further here.



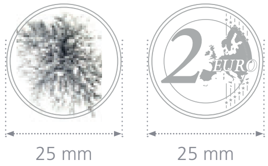
Secondary Bjerknes force: Neighboring bubbles influence each other.

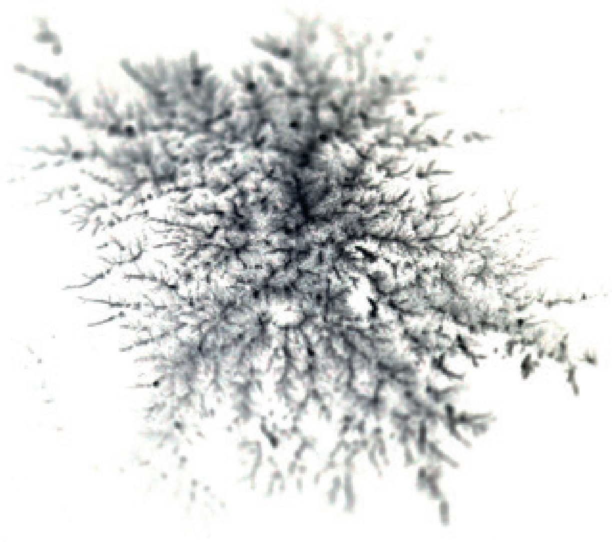
CHAPTER 8

The Emergence of Cavitation Structures.

Insights into the microscale.
Cavitation bubbles are only a few micrometers in size and occur in an incredible variety. All of the aforementioned effects, such as the formation, dynamics, growth, translation and interaction of cavitation bubbles, result in so-called cavitation structures. There are many different types like star structures, jellyfish structures, smoker structures, veil structures and many more.

The right image shows a star structure about the size of a **two euro coin**. The interesting thing about these cavitation structures is that they actually only appear to us as „structures“. For the human eye, less than 100 frames per second are sufficient to perceive an observed motion as fluid. Since the ultrasonic range only begins at 20,000 vibrations per second, we cannot perceive individual cavitation events at all. So if you want to see what is really happening, point a high-speed camera with a recording frequency that is faster than the ultrasonic frequency at such a cavitation structure. If you then play back the video very slowly, you can see that the individual branches of a structure are actually individual bubbles moving cycle by cycle along the branch paths.





Cavitation image in star structure (enlarged view).

CHAPTER 9

Temperature, Water Quality, Gas Content, Cleaning Chemistry.

Key influencing factors.

We already know that the formation of cavitation bubbles benefits from imperfections in the water structure. This type of nucleation or bubble nucleation is called **heterogeneous nucleation**. In conjunction with this, it can be stated that the mechanical effect in ultrasonic tanks with water containing mineral salts from tap water is stronger than, for example, with re-osmosis or deionized water. Another, more important influencing factor is the **gas content** of the liquid. Usually, there is relatively a lot of gas (air) dissolved in water, especially after a fresh fill. At the same time, a lot of air means that the growth effects already mentioned in Chapter 6 will produce very large bubbles. And here lies a problem: Large bubbles do not collapse, ergo: **Freshly filled water does not clean well**. For this very reason, tanks should always be „degassed" (see page 21). This works most efficiently with Elma Degas modes: these cyclically turn on the sound, causing bubbles to grow (see page 23), which are then held in place by the primary Bjerknes force. In the subsequent phase, the ultrasound is switched off, allowing the buoyancy force to gain the upper hand and the bubbles to rise to the surface of the tank. Over time, more and more dissolved gas escapes until a certain state of equilibrium is reached. Once this is reached, the bubbles are the right size: about 2 µm to 10 µm. We have already learned by looking at the Sinner's circle that, in addition to the mechanics, the Elmaclean cleaning chemistry used is also decisive. In addition to the actual task of dissolving the impurities, this also has a significant influence on the cavitation effect. In particular, the surfactants are decisive here. These lower the surface tension, which significantly changes the cavitation bubble dynamics. The reduction in surface tension facilitates the formation of bubble nuclei and makes the cavitation bubble „softer", causing bubbles to collapse even at lower acoustic pressures. Thus, surfactants not only help us dissolve the contaminant, but also make the mechanical impact more efficient. Let's stay with Sinner's circle and take a closer look at the temperature of the medium.

For many – but be careful – not all contaminants, higher temperatures are beneficial. For example, greases clean better when they are liquid in liquid form, i.e. when they are heated above their melting temperature. It is certainly not surprising that temperature also has a corresponding influence on cavitation. Basically, different parameters oppose each other here. As the temperature increases, the speed of sound and the vapor pressure become higher, while the viscosity decreases. All in all, the optimum range for the cavitation effect in aqueous media can be assumed to be between 30 °C and 70 °C. Higher temperatures are rather disadvantageous, at least from the cavitation point of view, due to the high vapor pressure. Sometimes, though, there will be processes that need higher temperature and that's fine – remember: cleaning is not only determined by the mechanical parameter.

CHAPTER 10

The Cleaning Process: Cleaning, Rinsing, Drying.

Smart Automation.

We started our journey with a simple cleaning example, the grill grate. Admittedly, for a one-off cleaning of a grill grate, ultrasonic cleaning is probably too complex, technically. Also too expensive and, therefore, disproportionate. Let us therefore imagine a „professional" cleaning task. We find this, for example, in the industrial manufacturing process of surgical instruments.

Such instruments are often made of stainless steel and are ground, milled and polished during manufacture. There is no question that the chips, coolants/lubricants and polishing paste must be removed to create as residue-free a component as possible. Subsequently, the instruments are rinsed and passivated. To carry out all these steps manually, in high volume, would be an absurd amount of work. This is where the range of automated **ultrasonic cleaning systems** comes into their own. Let's take a closer look at the system process:

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*Step 1: **Preparing**.*

The manufactured instruments are positioned in the basket in such a way that they are all fixed at a certain distance next to or behind each other, sometimes also one above the other. During positioning, care should be taken to ensure that the instruments are fixed in the most drainage-friendly way possible for subsequent drying.

*Step 2: **Loading**.*

The basket is now placed on a conveyor, which brings the basket into a position where a gripper lifts it from above. The gripper then moves the basket over the first cleaning tank and lowers it into the tank, at the receptacle of a so-called oscillation unit. This automatically moves the basket up and down by about 3-5 cm per minute during treatment.

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*Step 3: **Cleaning**.*

In this first tank, we now get down to the rough stuff. The wire brush, i.e. 25 kHz in pulse mode, is selected as the ultrasonic frequency. The tank temperature is 60 - 70 °C. Since a strong mechanical cleaning effect is more important than the water quality in this first cleaning stage, towns water or softened water is often utilized here. 2 % by volume of the surfactant-containing, alkaline **Elma lab clean A25** is used as the cleaning agent. The treatment time is set to ten minutes per stage. The gripper then lifts the basket out of the first tank and places it in the second. Meanwhile, a filtration unit starts filtering out the dirt particles in the first tank. The individual tank stations in a system are also called treatment chambers, or simply chambers. The second chamber also has an oscillation unit, as do all those that follow. The first rinsing process takes place in chamber two. For this purpose, the tank is filled with 50 °C softened water (EH water).

ELMASYSTEM EVO

Lines with a system – built for flexible and expandable cleaning processes.

PREPARING Cleaning basket → **LOADING** Conveyor → **CLEANING** Chamber 1 → **RINSING** Chamber 2-4 → **DRYING** Chamber 5 → **UNLOADING** Conveyor

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The ultrasonic frequency used here is 45 kHz. Here, the entrained particles and residues of the cleaner are now removed. This first rinse is now followed by two more tanks. These are arranged in a special configuration: A so-called cascade recirculation. Here, chamber four has a higher liquid level than chamber three.

Step 4 - 6: ***Rinsing****.*
Freshly treated deionized water (DI water) is permanently fed into chamber four. This originates from a treatment system within the circuit that takes water from tank three. Via an overflow weir section, the water from tank four flows back down into tank three. This little refinement ensures maximum purity in the last tank in a particularly efficient manner. The water temperature here is also 50 °C in each case, with 37 kHz being used in tank three and 130 kHz in tank four, i.e. figuratively speaking the fine brush.

Step 7: ***Drying****.*
The tanks are now followed by drying in chamber five. A hot air dryer is used here. In terms of design, this is quite similar to an ultrasonic tank and, in keeping with its name, dries the items with hot, flowing air.

Step 8: ***Unloading****.*
At the end of this cleaning line, the gripper places the baskets on an unloading unit, from where they can be further processed or packed. It should also be noted that all tanks must be well run in, i.e. degassed, before use. This can usually be cleverly achieved during the heating phase.

This process example, which is used for many „hard surfaces" of this type, already shows the variability of such a cleaning process. Not only can the sinner circle parameters be varied, but there are also additional features, such as rotating units that turn the material to be cleaned during treatment. Some systems are equipped with a „lift-out". This special mechanical unit lifts the basket out of the tank very slowly after the last rinse (in the above-mentioned example at chamber four), thus achieving the maximum possible drainage. There are many different filtering techniques, both in terms of the filters themselves and in terms of the specific flow of the liquid, such as so-called laminar flow. Special explosion-proof system designs allow the use of various flammable solvents and special hermetic enclosures with laminar flowing air allow the use in clean room environments. In addition to warm air, infrared light or, in the case of narrow recesses in the cleaning material, vacuum can also be used for drying.

By skillful use of all these opportunities, virtually any cleaning task can be mastered.

Processes in the ultrasonic bath.

Ultrasonic cleaning effect of a sprocket set covered with grease and dirt from the rear wheel of a bicycle.

CHAPTER 11

Ultrasonic Devices Can Do More than just Clean.

Expert knowledge for your application.
Cavitation is obviously ideal for professional cleaning, but not only cleaning! Especially in the laboratory environment, there are tasks that can be tackled amazingly efficiently with cavitation and ultrasound. One important sub-area concerns **homogenization**.

This refers to the uniform mixing of, for example, a powder and a liquid. A general example of this is the mixing of cocoa. You know it: You put milk into a glass and then add one or two spoons of cocoa powder. The cocoa is only partially absorbed and lumps form. You have to stir vigorously to obtain a „homogeneous" cocoa liquid. But it works much better with ultrasound and cavitation. The pressure waves, sound radiation forces and jet formation drive the individual cocoa particles apart and mix them perfectly into the liquid. In technical jargon, the dispersal is called **deagglomeration** and the mixing or distribution is called **dispersion**.

The same cavitation effects also help when mixing liquids that separate into two or more phases without further intervention. You know the effect from salad dressing; the salad oil floats on top of the vinegar. If you stir or shake vigorously, the oil is divided into fine droplets and an emulsion is formed. Ultrasound and cavitation can be used to form much finer droplets and thus finer **emulsions**.

Another broad area of application is what is known as **sonochemistry**. Cavitation effects are able to intensify and improve chemical reactions. This makes manufacturing processes more efficient and environmentally friendly.

We have already learned about the **degassing** of liquids with ultrasound as an effective instrument for tank preparation. However, there are processes in which the media has to be degassed in a targeted manner, independently of cleaning. This is used, for example, in water and wastewater treatment to improve the quality of the water by removing dissolved gases such as oxygen, carbon dioxide or nitrogen.

Acoustic cavitation can be used to create **nanoparticles** and **nanostructures**. Cavitation intensively mixes and breaks up the liquid and the materials within it, which can lead to the formation of nanoparticles. These nanoparticles find application in nanotechnology, catalysis, medicine and other fields.

Cavitation can be used to destroy and thus enable **defoaming** in industrial processes such as food and beverage production, chemical processing and the oil and gas industry.

In biological research and medicine, acoustic cavitation can be used to perform cell **disruption (lysis)**. This involves breaking cell membranes to access the cellular contents. This can be used, for example, to extract proteins, DNA or RNA from cells. The destruction of viruses and bacteria is also currently being researched.

Another field of application is the triggering of **crystallization**. Cavitation nucleation sites serve here as crystallization nucleation sites, which then trigger the growth of crystals.

75 YEARS

FINAL WORD

Leading Cleaning Technology has been the engine of our success for 75 years now. These 75 years have been characterized by outstanding inventive talent, incredible curiosity and the relentless pursuit of the highest quality and perfection. The accumulation of experience and knowledge over many years, including close contact with fundamental research, enables us to develop outstanding products and solutions based on fascinating physical phenomena. Most importantly, these are products and solutions tailor-made for **your individual cleaning task**.

GLOSSARY

The Most Important Terms Aptly Explained.

Ultra-clean speak.
Shine with your newly acquired knowledge. Below are the most important key terms in ultrasonic cleaning for quick reference.

Amplitude:
Describes the amount of deflection of an oscillating physical quantity (in this case, sound pressure).

Bjerknes forces:
Named after the physicist Vilhelm Friman Koren Bjerknes. They are divided into primary and secondary Bjerknes forces and describe translational forces which move cavitation bubbles. The Primary Bjerknes force describes the influence of the sound field on the movement of the bubbles and the Secondary Bjerknes force describes the influence of two or more bubbles on each other.

Bubble growth effects:
Cavitation bubbles grow over several oscillation periods. Two effects in particular are responsible: directed gas diffusion (rectified diffusion) and the union of two or more bubbles into a larger bubble (coalescence).

Cavitation structures:
Multiplicity of cavitation bubbles moving along certain trajectories (paths) within microseconds. The inertia of the eye then makes this appear as structures. The trajectories of the bubbles can differ due to different physical influences, resulting in different structures such as „starfish structures", „jellyfish structures", and many more.

Cavitation Threshold:
Boundary between stable and transient cavitation. The cavitation threshold can be overcome by increasing the ultrasound power (implicitly the sound pressure). Lower powers are required to overcome it at low ultrasonic frequencies rather than at high ones. The use of surfactant-containing cleaning chemistry can facilitate overcoming the threshold.

Cavitation:
Formation of micrometer-sized bubbles filled with water vapor and gas due to strong pressure fluctuations. These oscillate or collapse, move through the medium, grow or disappear, and form cavitation structures.

Cleaning effect:
The cleaning effect results from the parameters: media, temperature, time and mechanics. A graphical representation of

these parameters is the so-called Sinner's circle. The correct choice of parameters determines the cleaning success.

Degassing:
Expulsion of gas particles dissolved in the media (nitrogen, oxygen, carbon dioxide and argon). Important for tank preparation prior to ultrasonic cleaning and most effective with the degas mode.

Frequency:
Physical quantity that describes how many times an oscillation occurs in one second. The frequency has the unit Hertz (Hz). One Hz is equal to one vibration per second.

Nucleation:
Describes the formation of cavitation bubbles. Mostly cavitation bubbles are formed at weak points in the molecular structure of the media. These weak spots can be salts, dust, micro- /nano-bubbles or even gas pockets on surfaces.

Oscillation period:
Duration in which an oscillating physical quantity (here sound pressure) has passed through the minimum once and the maximum once. The period of oscillation is the arithmetic reciprocal of the frequency: period = 1 / frequency.

Sinner's circle:
Graphical representation of the cleaning parameters media, temperature, time and mechanics, named after the surfactant chemist Herbert Sinner (* 1900 in Chemnitz, † 1988 in Hilden).

Sound field:
Usually a three-dimensional description of the sound pressure distribution (usually the sound pressure distribution) in a medium.

Sound pressure gradient:
Describes the course of the change in sound pressure over a certain spatial range of the sound field.

Sound pressure:
Characteristic physical quantity representing the strength of sound waves in a media. It is measured in the unit Pascal (Pa). The sound pressure indicates how strongly the molecules in the media are compressed and expanded due to sound vibrations.

Speed of sound:
Usually refers to the speed of sound propagation. It describes how fast sound waves travel through media. In air, this is approx. 343 m/s, in water approx. 1480 m/s. The speed of sound propagation varies with temperature and, in water, especially with the existence and density of bubbles.

Stable cavitation:
Cavitation bubbles that resonate with the ultrasound at lower sound pressures or oscillate non-linearly but do not collapse at slightly higher sound pressures.

Standing waves:
One describes predominantly a so-called standing wave field (see sound field). Reflection of the propagating sound waves results in a wave field with locally fixed sound pressure zones, so-called sound pressure nodes and sound pressure anti nodes.

Surfactants:
Chemical compounds used in cleaning agents. They lower the surface tension and thus increase cavitation. For cleaning, surfactants bring the great advantage that they lower the interfacial tension between different media and thus make wetting out and cleaning off the contamination possible in the first place.

Transient cavitation:
Is also called inertial cavitation and describes cavitation bubbles that collapse due to strong ultrasound. The bubbles grow to over 3 times their initial size in the negative pressure phase and collapse abruptly in the positive pressure phase. This produces a pressure wave and, near surfaces, usually also a liquid jet.

Ultrasonic generator:
Electronic circuit that generates strong electrical vibration signals to cause an ultrasonic transducer to vibrate.

Ultrasonic transducer:
An ultrasonic transducer converts electrical vibration signals into mechanical vibration, thereby emitting ultrasonic waves into a medium. The physical principle is related to the classic loudspeaker. However, ultrasonic transducers usually use piezoelectric transducers, instead of electromagnetic ones.

Ultrasound:
Sound waves emitted at more than 20,000 vibrations per second (20 kHz). Ultrasound is above the range of human hearing and therefore cannot be perceived.

Wave propagation:
Wave propagation is distinguished on the basis of the orientation of the direction of propagation and the direction in which the individual particles vibrate. Sound waves in water or air are predominantly so-called longitudinal waves, which propagate in the direction of excitation. A guitar string, on the other hand, vibrates transversely.

Wavelength:
Describes the length (spatial) of a wave period. The wavelength depends on the speed of sound propagation: Wavelength = speed of sound propagation / frequency. The higher the frequency, the shorter the wavelength.

YOUR NOTES

YOUR NOTES

75
YEARS

About the Author

David Holly

Principal Engineer (Ultrasonic / Cavitation)

He has been part of the Elma crew for several years and is thoroughly fascinated by ultrasound and cavitation. In his daily work, he develops strategies to transform the latest scientific findings into groundbreaking technologies.

For this to succeed, communicating knowledge about these complex systems to a broad audience is incredibly important.

Elma

Elma Schmidbauer GmbH
Gottlieb-Daimler-Straße 17
78224 Singen (Germany)

www.elma-ultrasonic.com

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