J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

HIGH POWER ULTRASOUND

Ultrasonics is that part of acoustics dealing with the field of frequencies above the audible range. Therefore, the basic principles and equations of acoustics are adequate to explain the general behavior of the ultrasonic field. Nevertheless, the special characteristic of the ultrasonic waves of being inaudible establishes a fundamental difference in their applications with respect to the audio-frequency field.

Ultrasonic frequencies range from about 16 kHz up to 10^{10} Hz to 10^{11} Hz , that is, up to frequencies with associated acoustic wavelengths comparable to intermolecular distances. This very broad frequency range provides a great variety of ultrasonic applications. The range of power used in ultrasonics also varies widely: from less than 1 μW up to thousands of watts, depending on the applications. In fact, the applications of ultrasonics are generally divided into two categories: low and high intensity. Low-intensity applications are those wherein the purpose is to obtain information about the propagation medium without producing any modification in its state. On the contrary, high-intensity applications are those wherein the objective is to produce permanent changes in the medium as an effect of the ultrasonic energy.

High-power ultrasound is the part of ultrasound devoted to the study of high-intensity applications. The limit between low- and high-intensity is very difficult to fix, but it can be approximately established for intensity values which, depending on the medium, vary between 0.1 W/cm^2 and 1 W/cm^2.

High-intensity ultrasound waves are finite-amplitude waves and their effects are generally linked to nonlinear phenomena produced during their propagation. The term *finite amplitude* is used to describe high amplitude waves that contrast with the infinitesimal amplitude of the low intensity waves where the changes in the medium (pressure or density) due to the acoustic waves are of an extremely small order and the nonlinear phenomena are negligible. Therefore, in order to describe accurately the behavior of high-intensity ultrasonic waves, nonlinear equations of motion must be used. Nevertheless, nonlinear effects are not exhibited in all finite-amplitude waves but only in waves with sufficiently large amplitude.

The most relevant nonlinear effects related to high-intensity ultrasonic fields are wave distortion, acoustic saturation, radiation pressure, and acoustic streaming. In addition, cavitation in liquids and the formation and motion of dislocation loops in solids complete the group of the most characteristic nonlinear effects produced by high-intensity ultrasonic waves. Nonlinear effects are directly involved in the mechanisms that determine the broad field of the practical applications of high-power ultrasound.

Nonlinear Effects

Distortion of the Finite-Amplitude Waves.

The waveform distortion is the most characteristic nonlinear effect. Small- (infinitesimal-) amplitude signals propagate without change of shape because all points on the waveform travel with the same velocity c_0. In contrast, for a finite-amplitude wave the propagation velocity is a function of the local particle velocity, and therefore it varies from point to point on the waveform. The immediate consequence is that the relative position of the different points of the waveform changes during propagation and the wave becomes distorted.

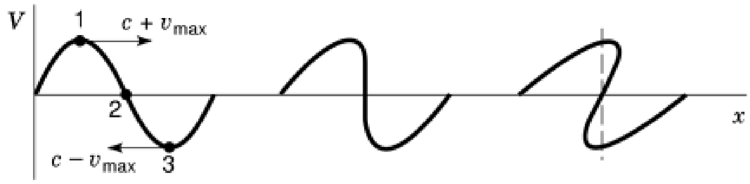

Fig. 1. Distortion of the finite amplitude waveform produced by the different local phase velocity at which each point of the profile moves along the propagation path.

From the basic relations describing the propagation of finite-amplitude plane progressive sound waves in nondissipative fluids results that the propagation velocity of such waves may be written as the summation of two terms, the velocity of sound c and the local particle velocity v (1):

$$\frac{dx}{dt} = c + v \tag{1}$$

It is to be noted that the sound velocity $c = (\partial p/\partial \rho)^{1/2}$ is not the same as the constant small-signal sound velocity c_0, but it is dependent on the nonlinear relation between pressure p and density ρ through the equation of state.

In consequence, the propagation velocity of finite-amplitude waves is affected, not only for the contribution of the particle motion (convective effect), but also for the nonlinearity of the equation of state (thermodynamic effect). The convective effect is generally more important in gases, while the nonlinearity of the p–ρ relation is usually more important in liquids. A simple illustration of the action of these effects to produce the distortion of the waveform is shown in Fig. 1, where the particle velocity is represented. It becomes clear that while point 1 travels with a speed $c + v_{\max}$, point 3 travels with $c - v_{\max}$ and point 2 with c. Consequently, the profile of the wave is gradually changing during propagation up to a certain distance where it becomes multivalued, a situation that is physically inadmissible and really implies the formation of a discontinuity or shock.

After the onset of the discontinuity, the motion of the wave becomes in general more complicated and the nonlinear basic equations for nondissipative fluids do not predict shock-wave propagation adequately. In addition, in a real viscous, heat-conducting fluid, the dissipative mechanisms play a determinant role and must be taken into account.

A model equation for plane progressive waves of finite amplitude in a thermoviscous fluid is the Burgers equation, which may be written in the form (2)

$$\frac{\partial u}{\partial \sigma} - u\frac{\partial u}{\partial(\omega y)} = \frac{1}{\Gamma}\frac{\partial^2 u}{\partial(\omega y)^2} \tag{2}$$

where $\Gamma = 2\epsilon$ Re is a dimensionless parameter, $\epsilon = (\gamma + 1)/2$ with $\gamma = B/A + 1$, where A and B are the coefficients of the first and second terms in a Taylor series expansion of the pressure as a function of density, that is,

$$A = \rho_0\left[\left(\frac{\partial p}{\partial \rho}\right)_s\right]_{\rho=\rho_0} = \rho_0 c_0^2, \qquad B = \rho_0^2\left[\left(\frac{\partial^2 p}{\partial \rho^2}\right)_s\right]_{\rho=\rho_0}$$

where s is the specific entropy and the subscript 0 refers to the equilibrium state. Re is the acoustical Reynolds number, $u = v/v_0$ is the ratio between the instantaneous value v and the maximum value of the particle velocity, $y = t - (x/c_0)$ with x and t the space and time variables, ω is the angular frequency, $\sigma = x/L$ is a dimensionless variable, with $L = 1/(k\epsilon M) = c^2{}_0/(\epsilon\omega v_0)$, where k is the wave number and $M = v_0/c_0$ is the acoustic Mach number. The parameter Γ, which is, together with M, the most important quantity for characterizing nonlinear fields, represents the relative contribution of nonlinear effects and dissipative effects. It is termed the Gol'dberg number.

In the derivation of Eq. (2) only second-order terms have been included in the series development of the state equation. Therefore, the use of the Burgers equation is restricted to Mach numbers less than 0.1. Nevertheless, this simplification does not exclude very large nonlinear effects because, even for very strong acoustic waves, generally $M \ll 1$. In water, for example, a sound-pressure level as high as 187 dB (or 0.1 Pa) corresponds to a Mach number less than 0.1. It should be noted that the conditions $M \ll 1$ and $\Gamma \gg 1$ are not contradictory but they do occur together in many real situations.

Equation (2) represents a good starting point to analyze the propagation of finite-amplitude waves. Considering an initially sinusoidal plane wave $v = v_0 \sin \omega t$ at $x = 0$ with sufficient intensity ($\Gamma \gg 1$), a solution of Eq. (2) may be written in the form (2)

$$\omega y = \arcsin(v/v_0) - \sigma\,(v/v_0) \qquad (3)$$

By means of this solution it is possible to analyze graphically the evolution of the waveform up to the formation of the discontinuity. After this point the motion could be more complex due to reflection at the discontinuity. However, for moderate wave amplitudes this effect is negligible and it is possible to deduce from Eq. (3) a useful relation to construct the waveform after the discontinuity. The complete evolution of the wave shape is shown in Fig. 2. It is apparent that, near the source ($0 < \sigma < 1$), the distortion is small. During propagation, the wave shape gradually changes, increasing the steepness profile and then the harmonic content. At point $\sigma = 1$ the wave profile, near the value $v = 0$, becomes vertical, and then the discontinuity is formed. The distance of formation of the discontinuity is $x = L$. After this point, the discontinuity increases up to $\sigma = \pi/2$, where the maximum value of the particle velocity reaches the discontinuity. The discontinuity produces a strong increase of attenuation due to the irreversible compression processes in the shock wave. Therefore, following shock formation the amplitude of discontinuity diminishes and the wave shape becomes a sawtooth. Because of dissipation effects the sawtooth wave gradually loses its steepness and eventually returns to its original sinusoidal shape.

In summary, the propagation path of an original sinusoidal wave of finite amplitude in a thermoviscous fluid may be divided into three regions. In the first region, which extends up to the shock formation, the nonlinear effect dominates. The second region, where nonlinear and dissipative effects are balanced, corresponds to the formation and propagation of a relatively stable sawtooth wave. Finally, in the third region, which is known as old age region, nonlinear effects are reduced by ordinary absorption, and the wave becomes again sinusoidal. The distortion of the wave shape can be described by various parameters. The ratio B/A, which provides a measure of the second-order nonlinearity of the pressure–density relation, is customarily used as a representative parameter. This ratio is generally called the acoustic nonlinearity parameter. Using measurements of B/A to infer properties of many different materials has been the subject of a large amount of works.

Finite-amplitude waves in solids has not been studied as extensively as in fluids. Recently interest in the nonlinear dynamic properties of solids has grown as a consequence of practical problems, such as the increasing power used in sonic and ultrasonic applications or the propagation of seismic waves in rocks. The equations applied in solids are similar to those developed for finite-amplitude waves in fluids. The one-dimensional propagation of longitudinal waves in an isotropic solid can be described by an equation of the form (3)

$$\rho_0 \frac{\partial^2 \xi}{\partial t^2} = Y_0 \frac{\partial^2 \xi}{\partial x^2} + Y_1 \frac{\partial}{\partial x}\left[\left(\frac{\partial \xi}{\partial x}\right)^2\right] \qquad (4)$$

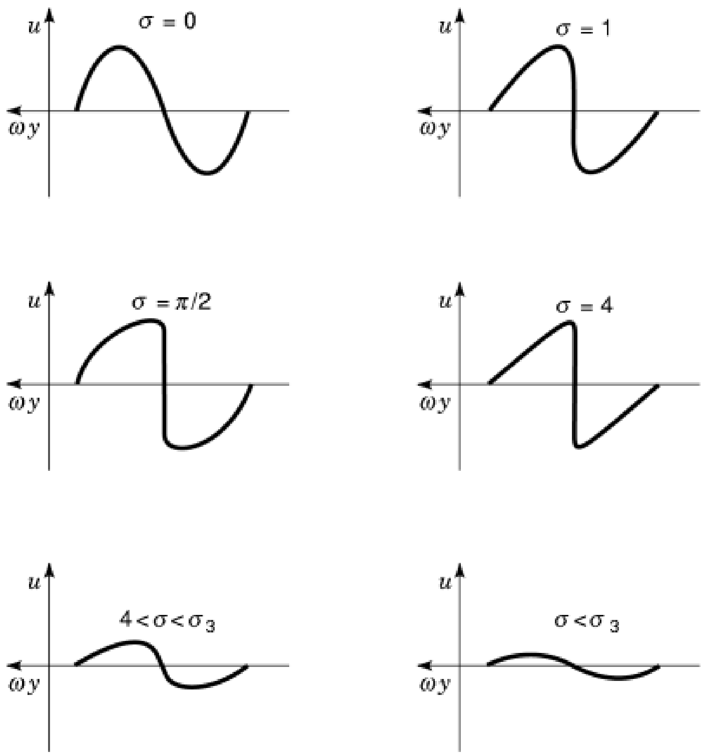

Fig. 2. Evolution of the waveform in nonlinear propagation at different distances of the source. The waveshape gradually increases the steepness profile up to the shock formation ($\sigma = \pi/2$). After this point, strong increase of attenuation causes a gradual decrease of discontinuity. Eventually, the wave returns to its original sinusoidal shape.

where ξ is the particle displacement, $Y_0 = C_1$ and $Y_1 = (3C_1 + C_2)/2$, with C_1 and C_2 the one-dimensional compressional, second- and third-order elastic constants. The nonlinearity parameter can be defined as the ratio of the coefficient of the nonlinear term to the linear term in Eq. (4), that is, Y_1/Y_0.

To study the nonlinear elastic properties of solids two main acoustic methods can be used. One typical method consists of measuring the nonlinear distortion of a progressive wave along the propagation path. The nonlinear elastic properties are inferred from the growth of harmonics according to the progressive wave solution of the wave equation. This procedure requires the use of high ultrasonic frequencies in order to generate progressive waves under bulk propagation conditions. Another more recently developed method consists of measuring the harmonic content in resonant rods subjected to high-intensity ultrasonic stresses and of comparing with theoretical models of finite-amplitude standing waves in solids (4). The experimental technique developed in this procedure additionally serves for nondestructive evaluation of the limiting strain of metals under high-intensity ultrasonic stresses by measuring linear and nonlinear attenuation (5).

The attenuation of finite-amplitude waves is not constant: it depends on the source distance and increases with the wave amplitude. These effects are directly linked to the production of acoustic saturation, a phenomenon that limits the real ultrasonic energy that can be transported at a certain distance from the source. In fact, the wave distortion at a fixed point in the radiation field increases when the source amplitude increases. Consequently, the wave energy is transferred to higher-order harmonics, which, since the absorption increases as the square of the frequency, are absorbed more intensely, causing an excess of attenuation of the wave. This behavior will determine that, over a certain range, any increase of the wave amplitude at the source will be compensated by its decay in the considered point. Therefore, there exists a limiting magnitude of the wave amplitude that can be reached at a fixed distance from the source in a given medium. For instance, in air at a frequency of 20 kHz the maximum sound pressure level that can be transmitted to a distance of 2 m away from the source is 135 dB (or 0.0002 μbar), and at 5.7 m the level is only 121 dB (6). Therefore, the great significance of the limiting value due to acoustic saturation in practical applications of high-power ultrasound should be emphasized.

Interested readers will find an excellent review on nonlinear acoustics in Ref. 7.

Radiation Pressure. Steady forces acting on obstacles in a sound field are usually caused by a physical quantity known as the acoustic radiation pressure. Radiation pressure is characteristic of any wave process because it is related to the change in the magnitude of the momentum carried by a wave at a target. The resulting forces are generally weak for small-amplitude waves. The nonlinearity of finite-amplitude waves introduces corrections that notably increases the magnitude of the effect. In this way, radiation pressure can be considered a nonlinear effect. The radiation force acting on a single obstacle in a medium is determined by the momentum flux through it, and the constant component of this force is obtained by averaging it with respect to time. The calculation of the radiation pressure yields to different results depending on the conditions of the obstacle and the acoustic field. Thus, the radiation pressure exerted on a plane target by an ultrasonic beam confined by rigid walls preventing inflow of fluid into the beam is known as the Rayleigh radiation pressure. Instead, if the target is placed in the path of an unbounded ultrasonic beam, the time-averaged force per unit area acting on it is called the Langevin radiation pressure. The action of radiation pressure forces on different obstacles or interphases in multiphase media represents one important mechanism in many effects produced by high-power ultrasound.

A great amount of literature about radiation pressure has accumulated, and in general there is certain confusion about the subject. In Ref. 8 many of the basic concepts are clarified and expressions for the radiation pressure under different conditions are derived.

Acoustic Streaming. Acoustic streaming is a nonlinear acoustic effect in which steady fluid flows are induced by finite-amplitude acoustic waves. In a high-intensity ultrasonic field steady flows are produced both in the free ultrasonic beam and near obstacles. In the latter case, the boundary layer has a significant influence in the development of the steady flows. Outside the boundary layer, in a travelling wave, the fluid flows away from the source at the center of the ultrasonic beam and in the opposite direction at the periphery. In a standing wave, a series of closed vortices are established between maxima and nodes.

Acoustic streaming seems to be mainly induced by radiation forces set up by the absorption of the acoustic waves in the medium. However, other mechanisms, such as diffraction and nonlinearities of the acoustic field, may also contribute to this effect.

The streaming generated in the boundary layer near obstacles gives rise to vortices smaller than the wavelength, and their dimensions are determined by the thickness of the boundary layers. The vortex scale of the streaming in the free ultrasonic beam depends on the confined volume where the beam is generated and generally is higher than the acoustic wavelength. The velocity of the streaming is smaller than the particle velocity in the ultrasound wave.

An interesting review about acoustic streaming may be found in Ref. 9. Streaming is another nonlinear effect that may influence various high-power ultrasound applications, particularly, those where mass and heat transfer play a determinant role.

Acoustic Cavitation. Acoustic cavitation may be defined as the formation, pulsation, and/or collapse of vapor or gas cavities in a liquid under acoustic stresses. Ultrasonic waves of a certain intensity applied to a liquid may produce small cavities or bubbles because of the fluctuations of hydrostatic pressure they produce. In fact, during the rarefaction phase of the cycle the bubbles or cavities may be formed and during the compression phase they may collapse. Cavitation is a very complex process where a series of remarkable phenomena take place. Two types of cavitation are generally considered: stable and transient cavitation. In stable cavitation, usually produced at moderate acoustic intensities, bubbles inside the liquid oscillate, generally in a nonlinear way, around their equilibrium size. This situation may be kept stable during many acoustic cycles and gas bubbles may grow. In fact, during the positive-pressure half-cycle the gas inside the bubble will be compressed and then diffuse into the liquid. During the negative half-cycle, the effect is just the opposite: the bubble expands and gas diffuses from the liquid into the bubble. Nevertheless, the rates of these two processes are not equal because the surface area of the bubble is greater during expansion. Consequently, the bubble acquires some additional gas during each cycle. This process, which is called rectified diffusion, is applied for ultrasonic degassing of liquids: the bubbles grow, trapping the dissolved gas, rise to the surface of the liquid, and escape.

The second type of cavitation, which is known as transient or inertial cavitation, is generated under high-intensity acoustic fields. During the negative-pressure half-cycle, the effect of the restoring force produced in the bubble by the gas and liquid vapor becomes negligible with respect to the acoustic pressure and the bubble expands to several times its original size. Then during the compression half-cycle the bubble collapses violently and generally disintegrates into many smaller bubbles. The collapsing bubble develops very high localized temperatures (estimated as high as ten thousand degrees) and pressures (estimated as high as five thousand atmospheres), which are important in many effects of high-power ultrasound. The high pressures produce erosion, dispersion, and mechanical rupture, while the high temperatures are responsible for sonoluminescence and sonochemical effects. In transient cavitation the motion during collapse is essentially inertia-controlled: empty cavities will collapse completely while in gaseous cavities the motion is cushioned by compression of the residual gas.

Besides the two types of cavitation already mentioned, we may consider an additional subclassification related to the gas or vapor content of the bubble. In a transient cavity it is assumed that there is no time for gas diffusion into or out of the bubble, while condensation and evaporation may happen. Therefore, the collapse of a vaporous bubble will be more violent than the collapse of a gaseous bubble, because of the lack of a residual gas to cushion it. In fact, the activity of a cavitation field produced in a gas-free liquid is generally stronger than in a gassy liquid. In reality, a cavitation bubble can be assumed to be filled with a vapor-gas mixture.

The practical distinction between the different types of cavitation is not an easy task. For example, the separation between the stable and transient forms of cavitation is sometimes rather indeterminate, and the transition from one to another may happen through simple changes in the acoustical or environmental conditions. It is usual to establish thresholds to pinpoint the onset of each type of cavitation. Nevertheless, one of the most controversial points in relation to cavitation is to ascertain clear criteria to determine the thresholds. In particular, it is important to know the threshold for transient cavitation, which is the type of cavitation related to the majority of high-power ultrasound applications in liquids.

A suitable framework to study acoustic cavitation is furnished by the Gilmore equation describing the dynamics of a single cavity under an acoustic field (10):

$$\begin{aligned} R\left(1-\frac{U}{c}\right)\frac{d^2R}{dt^2}+\frac{3}{2}\left(1-\frac{U}{3c}\right)\left(\frac{dR}{dt}\right)^2 \\ -\left(1+\frac{U}{c}\right)H-\frac{U}{c}\left(1-\frac{U}{c}\right)R\,\frac{dH}{dR}=0 \end{aligned} \tag{5}$$

where R is the bubble radius, $U = dR/dt$, c is the sound velocity, and H is the specific free enthalpy on the bubble surface. If the process is considered adiabatic, the expression for the free enthalpy will be

$$\begin{aligned} H=\frac{n}{n-1}\frac{A^{1/n}}{\rho_0}\Bigg\{\left[\left(P_0+\frac{2\sigma}{R_0}\right)\left(\frac{R_0}{R}\right)^{3\gamma}-\frac{2\sigma}{R}+B\right]^{(n-1)/n} \\ -(P_0-P_m\sin\omega t+B)^{(n-1)/n}\Bigg\} \end{aligned} \tag{6}$$

and the sound velocity

$$c = [c_0 + (n-1)H]^{1/2} \tag{7}$$

where A, B, and n are constants (for water $A = 3001$ atm, $B = 3000$ atm, $n = 7$) P_m is the pressure amplitude of the acoustic field, P_0 is the static pressure, R_0 is the equilibrium bubble radius, ρ_0 is the equilibrium density of the liquid, c_0 is the sound velocity in the unperturbed liquid, ω is the angular frequency, σ is the surface tension, and γ is the ratio of specific heats. These equations take account of the compressibility of the medium, but viscosity and mass transfer are not included. The solution of Eqs. (5) to (7) will determine the motion of the bubble and the conditions under which the transient cavity will be produced. Under real conditions the cavitation bubble is not alone but exists simultaneously with a set of other bubbles. One can study cavitation in a liquid containing a wide distribution of bubbles by considering the bubble resonance radius R_r as a critical parameter. From the numerical solution of Eqs. (5) to (7) and by using the equation of state for water in the form $P = A(\rho/\rho_0)^n - B$, the radiated sound pressure near the cavity wall can be computed for different bubble sizes. The curves of the radiated sound pressure as a function of the applied sound pressure show a sudden change of the slope at a certain point, tending to infinity (11). The applied acoustic pressure that produces such a change for each bubble size can be identified as the transient cavitation threshold for the corresponding bubble. In fact, the bubble wall velocity calculated at this point is found to be of the order of or even higher order than sound velocity, which represents another indication for transient cavitation. Figure 3 shows the thresholds computed for single bubbles of radii below and above the resonance radius for an applied acoustic field of 20 kHz. Three different characteristic groups of bubbles can be observed corresponding to three different shapes of the threshold curve. Bubbles with radii far below the resonance radius (between about 0.001 cm and 0.012 cm) exhibit a similar threshold pressure (about 0.9 atm). Bubbles just below the resonance radius (between about 0.012 cm and 0.016 cm) show a different threshold pressure for each bubble size, and all the threshold values are generally lower than the threshold value for the previous bubble group. Finally, there is another group of bubbles, with radii above the resonance radius, which need a much higher applied acoustic pressure to produce transient cavitation. In conclusion, in a gassy liquid with a wide bubble size distribution three different cavitation thresholds can be found and consequently three levels of cavitation activity may be reached.

Cavitation near solid-liquid interfaces differs from cavitation in pure liquids. In fact, the presence of a boundary causes asymmetry of the motion, and instead of a spherical symmetrical collapse, a deformation in the cavity is induced during collapse. As a consequence, a liquid jet is produced to which most of the available energy is transferred. This jet can reach velocities of hundreds of meters per second, and if it makes an impact on the boundary, it could produce severe erosion of the surface because of the high energy concentration.

Factors that affect cavitation are numerous. The most important are the frequency and the intensity of the acoustic field, the temperature and the static pressure in the liquid, the number and size of bubble nuclei (undissolved gas bubbles, gas trapped in microscopic cracks, etc.), and the physical characteristics of the liquid. In spite of the fact that acoustic cavitation is one subject more extensively studied within the field of ultrasound, many important questions about the dynamic of this phenomenon still remain unanswered. Interested readers are referred to Refs. 12 and 13 for further learning.

Applications of High-Power Ultrasound

The field of applications of high-intensity sonic and ultrasonic waves is currently termed *macrosonics.* The use of high-power ultrasound in practical applications is based on the exploitation of the nonlinear effects previously examined and of a series of secondary effects such as heat, agitation, interface instabilities and friction, diffusion, and mechanical rupture. These effects are employed to enhance a wide range of processes that depend

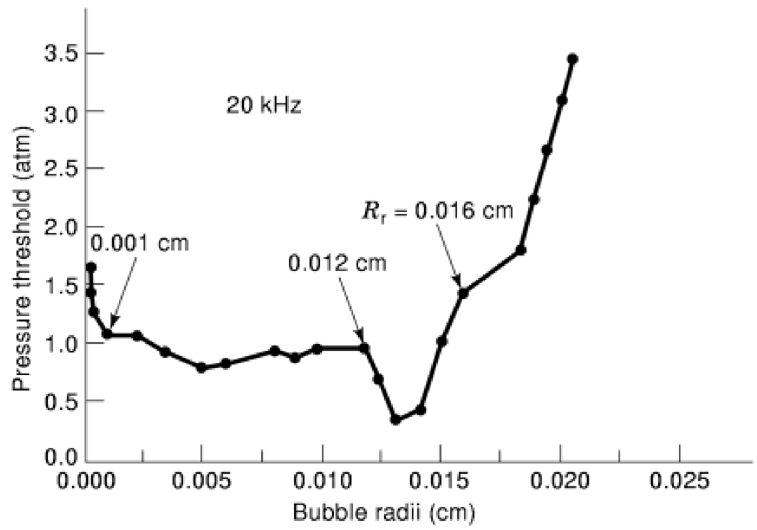

Fig. 3. Cavitation thresholds computed for single bubbles of different radii for an acoustic field of 20 kHz. The bubble resonance radius corresponds to $R_r = 0.016$ cm.

on the irradiated medium. In fact, a typical characteristic of high-intensity ultrasonic waves is their ability to produce different phenomena in different media in such a way that these phenomena seem to be opposite at times. This is, for example, the case of the application of power ultrasound to liquid suspensions for particle dispersion and to gas suspensions for particle agglomeration. The explanation of this apparently contradictory behavior can be found in the different media where the ultrasonic energy is acting and, consequently, in the different effects that are activated. In liquids, the great majority of the applications of high-power ultrasonics are associated with cavitation, a nonlinear effect that is not possible to induce in gas or solid media.

Another characteristic of high-intensity ultrasonic waves is their capacity to work synergistically with other forms of energy in order to promote, accelerate, or improve many processes. This is the reason why many practical applications of high-power ultrasound are not exclusively ultrasonic processes but ultrasonically assisted processes.

In high-power ultrasonic (or macrosonic) processing a certain amount of mechanical energy is introduced into the processed medium to produce permanent changes in it. Nevertheless, the onset of the high-intensity ultrasonic processes often requires one to go beyond an intensity threshold, and in these cases it makes no sense to discuss total energy. Intensity threshold, intensity level, and treatment time are the main three parameters to be considered in an ultrasonic process together with frequency. Typical macrosonic processes are generally carried out at intensities in the range of 1 W/cm^2 up to thousands of watts per square centimeter and frequencies between 10 kHz and 100 kHz.

A large number of high-power ultrasound effects have been produced in the laboratory. Nevertheless, only a restricted number of ultrasonic processes have been introduced in industry. This situation is mainly attributed to the problems related with scaling-up of the ultrasonic processing systems.

The main applications of high-power ultrasonics for industrial processing are collected in the following list.

Applications in Fluids Cleaning, atomization, emulsification and dispersion, soldering, degassing, sterilization, extraction, diffusion, crystallization, sonochemical reactions, dewatering and drying, defoaming, particle agglomeration

Applications in Solids Plastic and metal welding, machining and cutting, material forming, fatigue testing, friction reduction

In the following sections a brief explanation about each application will be presented.

Applications in Fluids.

Cleaning. Ultrasonic cleaning is one of the oldest and best known applications of high-intensity ultrasound. The cleaning action of ultrasonic energy is mainly due to cavitation and microstreaming. These effects give rise to (1) high stresses at the interface between the cleaning liquid and the dirty solid, which favor the soiled material separation, (2) liquid agitation, which contributes to the dispersion of contaminants, (3) penetration of very small pores in the dirty material, which promotes a very effective and unique cleaning, and (4) sonochemical reactions, which can help the detergent action.

Cleaning baths normally operate at frequencies in the range of 20 kHz to 60 kHz and with intensities within the range 0.5 W/cm^2 to 6 W/cm^2, which correspond to the cavitation thresholds of the solvents used. Ultrasonic cleaners generally consist of rectangular section tanks driven by ultrasonic transducers placed at the bottom. The main practical problem with ultrasonic cleaners lies in obtaining a cavitation field over all surfaces to be cleaned. In addition, cavitation clouds produce shadowing effects that prevent full-field cleaning. Therefore, this is a very difficult or almost impossible task, but there are some methods that permit one to alleviate the problem. Moving the pieces to be cleaned or using multifrequency systems are two examples of subsidiary procedures.

Ultrasonic cleaners from hundreds to thousands of watts are customarily used in industry with tank capacities from a few liters to hundreds of liters. Usually the tanks are equipped with temperature-controlled heaters to heat the washing liquor.

Typical objects that undergo ultrasonic cleaning include engine parts, ball bearings, filters, electronic printed circuits, heat exchangers, and surgical instruments.

Ultrasonic cleaning is a procedure that has been shown to be very useful in cleaning solid rigid materials. Nevertheless, the application of this method to soft materials such as textiles presents more problems. In textiles, the fibers are flexible; then the erosion effect is less strong, and the proper reticulated structure of these materials favors the formation of air bubble layers that hinder the penetration of ultrasonic waves. These and other technological reasons have limited the application of high-power ultrasonics for domestic or industrial cleaning of textiles in spite of the anticipated advantages of this technology in time, efficiency, and energy consumption. Recently, new attempts have been made in this area and the preliminary results have shown to be promising. The procedures developed are based on either degassing of the wash liquor or the use of plate transducers working in contact with or very close to the textiles (14).

Information about ultrasonic cleaning may be found in almost all books about ultrasonics. Interested readers are referred to Refs. 15 and 16, Vol. 1.

Atomization. The production of fine droplets by means of high-intensity ultrasound is a process that may be mainly attributed to radiation pressure and the formation of capillary waves on the surface of a liquid. Cavitation may also play a positive role. The ultrasonic irradiation of the liquid surface from the liquid phase gives rise to capillary waves on the surface produced by the radiation pressure. Over a given acoustic intensity range the capillary waves generate droplets of about the same size in the air. The droplet size is related to the exciting frequency in such a way that higher frequencies produce smaller droplets. There are several theories giving quantitative relations to be applied under restricted conditions. The role of cavitation in atomization may be associated with the production of droplets from the walls of cavitation bubbles at the liquid surface.

Ultrasonic atomization is applied to the formation of fogs or mists with a fine and relatively uniform distribution of droplet size. This procedure is used to produce medical inhalants, to atomize fuels in combustors, to manufacture metallic powders from molten metals, etc. To obtain very fine fog droplet sizes, frequencies up to several megahertz have been applied. A thorough discussion about the mechanisms of atomization can be found in Ref. 16, Vol. 2.

Emulsification and Dispersion. High-power ultrasound could be very effective in obtaining uniform solid/liquid and liquid/liquid dispersions. The basic mechanisms to enhance this process are cavitation and streaming. The high stresses produced by bubble collapse impinge on the particles around the bubbles, which are thus impelled to mix. The successive collapses also make the droplets or particles smaller and facilitate the fusion. Acoustic streaming contributes to the homogeneity of the mixture. Stable emulsions of immiscible liquids have been obtained without the use of additives. This process is being used in the food and pharmaceutical industries and recently in the production of water-oil mixtures that may produce a lower-contaminant fuel alternative to oils. Ultrasonic dispersion of solid particles in a liquid is generally very effective and is used in many industrial applications where clusters of particles have to be broken up. Dispersions of zinc oxide, titanium dioxides, and other industrial particles are frequently made by using high-power ultrasound.

Soldering. Ultrasonic soldering is one of the applications of high-power ultrasonics that has been known for many years. The conventional soldering process consists of joining two metals with a filler metal called the solder, its liquid point being below that of the metals to be joined. When soldering, the joints are submerged in the solder in such a way that it wets the surface of the metals. In addition, a soldering flux is used to remove surface contaminants. Ultrasonic soldering consists of applying high-intensity ultrasound in the molten solder to produce cavitation. The effect of cavitation is the cleaning of the surfaces, bringing them into direct contact with the solder. The main advantage of ultrasonic soldering is the ability to solder difficult materials without the need for flux. Ultrasonic soldering has been used to solder difficult materials such as aluminum. The frequencies used are in the range 20 kHz to 30 kHz. A review of this application may be found in Ref. 17.

Degassing. The ultrasonic degassing of liquids is mainly based on the phenomenon of rectified diffusion caused by stable cavitation. Streaming and radiation pressure also contribute to small-bubble coalescence and mass transport. Ultrasonic degassing is used for the removal of gas from melts in metals and glass manufacture. One of the most complete studies about degassing can be found in Ref. 16, Vol. 1.

Sterilization. Bacterial spores are the most resistant life-form. Therefore, their destruction constitutes the best indication to evaluate the efficiency of a sterilization process. Ultrasonic sterilization has been studied as an alternative to other conventional methods. Nevertheless, the sterilization by ultrasound alone is, in general, very difficult. The usefulness of ultrasonic energy improves in combination with other agents such as ultraviolet radiation, heat, or chemical bactericides. The ultrasonic synergistic effect increases the bacterial killing rate of conventional sterilization methods. The action of high-intensity ultrasonics in liquid sterilization may be mainly attributed to cavitation and streaming, which facilitate the separation and dispersion of clusters of bacteria and thus the action of other agents. Frequencies in the range 20 kHz up to 250 kHz have been used. Application of high-power ultrasonics is not restricted to the liquid phase but is also extended to the gas phase where the time required for conventional gas sterilization could be greatly reduced. The ultrasonic action is mainly due to the effect of acoustic streaming in the diffusion and penetration of the sterilizing gas. Airborne sterilization has been applied at about 20 kHz with intensity levels of the order of 160 dB. Ultrasonic sterilization has been studied for application as a method of milk pasteurization and also for sterilization and decontamination of medical instruments. The procedures of thermosonication have attracted growing interest recently in food preservation (18, Chap. 10).

Extraction. Ultrasonic cavitation can produce the disintegration of biological and vegetable cells and releases their content. This process is applied to biological cells for extraction of active antigens for making vaccines and to laboratory studies. The frequency employed is generally 20 kHz and the intensities range from 2 W/cm^2 to 35 W/cm^2. Ultrasonic extraction from plants has been applied to numerous processes in food, pharmaceutical, and cosmetic manufacture. Typical examples are the extraction of fruit juices, sugar, proteins, alkaloids, glucosides, and scents.

Diffusion. Diffusion of fluids through membranes and porous bodies can be accelerated ultrasonically. The diffusion rate increases when ultrasound is applied in the direction of diffusion. Acceleration of diffusion is a function of acoustic intensity: higher intensity leads to greater positive effects. Nevertheless, when intensity becomes very high, cavitation is produced and then extreme turbulence at interfaces may retard diffusion. The main effect contributing to diffusion seems to be acoustic streaming. The acoustic streaming velocity plays a significant role in the mass flux. In addition, acoustic radiation reduces the diffusion boundary layer as a result of acoustic microstreaming. The diffusion effect depends on the frequency and in general increases as the ultrasonic frequency increases. Frequencies in the range 20 kHz to 1 MHz have been applied. Interested readers are referred to Ref. 16, Vol. 2.

Crystallization. Crystallization from melts or from solutions can be promoted and helped by applying high-power ultrasound. The main effects involved are cavitation and streaming. Growth of cavitation bubbles during the expansion phase causes liquid evaporation into the bubble. The evaporation and expansion reduce the temperature in the bubble. If the magnitude of the local cooling is enough, crystal nucleation can occur and microcrystals are produced. During the compressive phase, the crystals may be impelled into the melt volume. Acoustic streaming influences the distribution of temperature and increases diffusion. Cavitation also may induce the breakup of larger crystals. The capability and efficiency of ultrasound to produce metals with uniform and highly refined grain structure have been experimentally demonstrated. Further information on this topic can be found in Ref. 19.

Sonochemical Reactions. The chemical effects of high-power ultrasonics are mainly related with the very high pressures and temperatures produced during cavitation. Other effects such as the acoustic streaming can also contribute positively. Sonochemistry is presently one of the faster growing fields within high-power ultrasonics. The treatment of the nature and applications of sonochemical reactions would require a special chapter. The readers are referred to the reviews published in Chapters 4 and 5 of Ref. 20.

Dewatering and Drying. Solid/liquid separation represents a topic of permanent industrial interest. The application of ultrasonic energy may contribute to improving the efficiency of conventional dewatering and drying processes. Dewatering processes generally refer to removal of water from a product without producing a phase change of the liquid, while in drying processes the moisture is removed by vaporization.

Different effects seem to play a role in the application of high-intensity ultrasound to porous media to be dewatered and/or dried. When the material is completely covered with moisture and evaporation takes place only at the surface, high-intensity airborne ultrasound introduces pressure variations at gas-liquid interfaces and increases the evaporation rate. The compressions and rarefactions caused by the ultrasonic waves help to keep open the channels of the porous medium in such a way that the moisture removed during rarefaction does not reenter during compression. The friction produced between solid and liquid parts vibrating at high frequencies and at high intensities may produce local heating that decreases the surface tension and the viscosity of the liquid. Small liquid droplets retained inside the capillaries of the solid can be separated if the ultrasonic stresses become greater than the surface stress. When ultrasonic waves propagate, the air bubbles present in the liquid trapped in micropores and capillaries can grow as a result of rectified diffusion and produce the displacement of the liquid out of these micropores. Finally, cavitation at very high intensities can separate the colloidal and chemical attached liquid from the solid phase. Ultrasonic assisted drying has a practical use in drying heat-sensitive materials such as food and pharmaceutical products (see Ref. 18, Chaps. 7 and 11). Ultrasonic dewatering combined with other forms of energy seems to be a promising method for solid/liquid separation in high concentrate suspensions such as sludges. The frequencies employed in these procedures are in the range of 10 kHz to 30 kHz. A review about this application can be found in Ref. 21.

Defoaming. Foams are frequently produced during various manufacturing processes, and generally they cause difficulties in process control, in handling equipment, and in the adequate use of reactors. A typical example is the fermentation industry, where foam represents one of the biggest problems. There are several conventional defoaming methods employing thermal, chemical, and mechanical effects. Thermal methods involve heating and cooling the foam, which is generally difficult and expensive. Chemical defoaming agents are usually very effective but they contaminate the process. Mechanical devices such as cyclones, air or liquid jets, and vacuum systems are effective for coarse foams.

High-intensity sonic and ultrasonic waves are a clean means of breaking foam. The mechanism of acoustic defoaming may be a combination of the following: high acoustic pressures, high radiation pressure, resonance of the foam bubbles, and acoustic streaming. The potential use of high-intensity ultrasound for defoaming has been known for many years. Nevertheless, a few acoustic defoamers have been reported and apparently none of them have been used in industrial plants. Recently, a powerful defoamer has been developed by using a new type of airborne power ultrasonic transducer with a stepped-plate radiator. The new ultrasonic defoamer has been successfully applied to the control of foam excess produced on high-speed canning lines and in the dissipation of foam in reactors. Interested readers are referred to Chap. 7 of Ref. 18.

Particle Agglomeration. The application of a high-intensity sonic or ultrasonic field on a suspension originates an agglomeration process of the suspended particles. This phenomenon, which had been experimentally known since 1931, has been studied and discussed by many investigators. A variety of effects are involved in the process of acoustic agglomeration. It is generally accepted that orthokinetic and hydrodynamic interactions are the predominant mechanisms, while other effects such as acoustic streaming can contribute to promote these interactions. An orthokinetic interaction occurs between two or more suspended particles of different sizes when they are located within a distance approximately equal to the displacement amplitude of the acoustic field in the suspending medium. Due to the differential fluid and inertial forces, the particles follow the acoustic oscillation with different amplitudes and phase, and such differential motion greatly increases the probability of particle collision. The hydrodynamic interactions are mainly caused by the radiation pressure and by the hydrodynamic forces resulting from the mutual distortion of the flow field around the particles.

The phenomenon of the acoustic agglomeration of aerosols (solid or liquid particles in a gas) has recently become of renewed interest in connection with energy and environmental problems. One of the most important causes of air pollution is the presence of micron and submicron particles in the air. These tiny particles, which cause most of the physiological damage due to adhesion in the respiratory tissues, are very difficult to remove, and conventional particle collection devices (cyclones, electrostatic precipitators, etc.) are generally inefficient. A new legislation, more stringent about the number concentration of these particles, is now being introduced in the U.S.A. and in the European Union, and as a consequence improved technology will be necessary. High-intensity acoustic energy represents a new means capable of increasing conventional filter collection efficiencies, by agglomerating the particles and shifting their size distribution into a larger range. This can be achieved by applying sound pressure levels between 140 dB and 165 dB at frequencies in the range 10 kHz to 20 kHz. A macrosonic system for fine-particle removal has recently been developed at a semi-industrial stage (22).

From the mechanisms of acoustic agglomeration it seems evident that the same process developed in aerosols can be induced in particles suspended in a liquid. Nevertheless very few experimental results have been reported on liquid media. The reason is that agglomeration in liquids may be prevented by the occurrence of cavitation, which just produces the opposite effect. In addition the orthokinetic effect is not very effective in liquids because the entrainment factor (the ratio between the amplitude of the aerosol particle velocity and the vibration velocity of the medium) has similar values for a wide range of particle sizes, and consequently the differential motion among particles becomes small. The most efficient way for agglomeration and particle separation in liquids is to apply standing wave fields, where the particles are driven by radiation forces to the nodes or antinodes, depending on their density and size. The concentration of the particles favors agglomeration, which can be stable if particles tend to coalesce and flocculate (23).

For an extensive review of acoustic agglomeration, interested readers are referred to Ref. 24 even if some statements may be controversial. To understand fundamentals of particle agglomeration, readers should consult Ref. 25.

Applications in Solids.

Plastic and Metal Welding. Ultrasonic plastic welding is a well-known technique that is widely used in commercial applications. In fact, high-intensity ultrasonics is probably the most common method for thermoplastic assembly, particularly for products that are difficult to join by microwaves due to their low dielectric loss. In ultrasonic welding, the parts to be welded are clamped together and then exposed to the ultrasonic vibration, generally applied perpendicularly to the weld plane. Two types of welding techniques are used: direct welding, where the tool is in direct contact with the material to be bounded, and transmission welding, where the bond area is at some distance from the tool. Joining of plastic surfaces is possible because the surface friction develops localized heating and the yield strength of the material diminishes. The bonding effect depends on the attraction between adjacent polymer molecules. The intensities required are of the order of a few kW/cm^2, and the frequencies employed are typically 20 kHz to 40 kHz even if some recent works have been done at frequencies as high as 90 kHz. The exposure times, which usually are very short (less than 1 sec), are followed by a brief period without ultrasound to allow the excess of heat to be conducted out and the bond to solidify.

Ultrasonic metal welding is a technique generally used for applications where conventional methods are not adequate. The welding mechanism is based on the frictional forces between the parts induced by the transfer of vibrational energy. Some heat is produced in the pieces as a consequence of the shearing stresses at the interface. This mechanism may be associated with the formation of a molten layer in the interface. However, in the majority of cases the local heating is not enough to melt the materials and the welding mechanism can be attributed to diffusion, and the surfaces being brought together under pressure and solid-state bonding taking place. Thus ultrasonic metal welding can be considered as a relatively cold process. The intensities and frequencies currently employed are, respectively, in the ranges 1 kW/cm^2 to 3 kW/cm^2 and 20 kHz to 60 kHz. The industrial applications of ultrasonic metal welding are in electric and electronic industries. One typical application is aluminum wire bonding to metallized surfaces and other nonmetallic materials. Recently developed techniques show that frequencies in the range of several hundred of kilohertz are adequate for bonding very thin wires (0.1 mm diameter). In addition, the required vibration velocities are smaller and the welding time shorter than the conventional 60 kHz systems (26). For more information see Ref. 16, Vol. 1.

Machining and Cutting. Ultrasonic vibrations are used in machining hard and brittle materials that are difficult to cut by other methods. There are several ways of using ultrasound in machining. The oldest method consists in applying the ultrasonic tool together with a suspension of abrasive particles. The motion of the tool and the cavitation developed in the suspension produce the erosion effect needed to remove the material. The problem with this procedure is that the tool, in the course of working, also becomes eroded. Another procedure of ultrasonic machining is by introducing the vibration into the tool to reduce the cutting resistance. This is a dry technique that is adequate for soft materials. The action of the ultrasonic vibration in the cutting process is characterized by the periodic changes due to the high-frequency movement, which substantially reduces the power required for the cutting process. The main characteristics of ultrasonic machining processes are efficiency, precision, and surface quality. The parameters that have a major influence in the process are vibration amplitude and frequency. The machining efficiency increases almost linearly with increase in vibration amplitude. Typically the vibration amplitudes are in the range 50 μm to 150 μm and the frequencies are around 20 kHz. The ultrasonic technique is extensively used in many specific industrial processes such as cutting, machining and drilling semiconductor materials, ceramics, glass, quartz, and similar brittle materials. In the aeronautic industry this technique is being used for cutting glass and carbon fibers in composite manufacture. A recent interesting application is in food cutting. Commercially, food is cooked or baked in large sheets or blocks and it must be cut in portions for selling it to consumers. Ultrasonic cutting blades have been demonstrated to be very efficient in bakery and frozen products and even in fresh products such as meat, fish, and vegetables (see Chap. 14 of Ref. 18).

Interested readers on the mechanisms of machining and cutting are referred to Ref. 16, Vol. 1.

Material Forming. High-power ultrasonics is being used as a means to improve operation efficiency in material-forming processes such as wire, bar, and tubing drawing, extrusion of metals, and extrusion and molding of plastics. The effects of ultrasonic vibration seems to be attributable to a reduction in the internal friction of the material and in the external friction between the die and the workpiece. The vibration can be supplied in the direction of the drawing, transversely to the drawing direction, or in both forms at the same time. The advantages of the process are a reduction of the drawing force, an increase of drawing rates, and an improvement of the shape, surface quality, and dimensions of the pieces. The frequencies employed in the forming processes are typically 20 kHz to 30 kHz and the powers are of several kilowatts.

Interested readers are referred to Ref. 27.

Fatigue Testing. Application of high-power ultrasonics allows acceleration of fatigue testing of materials. The failure of dynamic structural elements is related to the fatigue of the material. Therefore, the evaluation of fatigue life is a very important problem and the determination of the curves relating stress level to number of cycles to failure is a time-consuming procedure, because it is conventionally done at frequencies in the range of a few cycles per second. The application of high stresses at ultrasonic frequencies clearly represents a means to shorten the process. Nevertheless difficulties arise in establishing the correlation between the results of ultrasonic fatigue testing and low-frequency testing. This is an interesting research topic because there are significant differences between both processes. For wider information, see Refs. 15 and 27.

Processing Systems, Parameters, and Standards

The very wide field of applications of high-power ultrasonics implies a great variety of practical systems with different characteristics. These characteristics depend mainly on the effect to be exploited. Liquid processes generally are based on cavitation and they require to be over a certain sound pressure level (cavitation threshold) throughout a determinate volume. Gas processes may be based on radiation pressure and particle velocity, as, for instance, in the case of aerosol agglomeration and they require adequate vibration amplitudes and treatment times over a volume. Solid processing is generally carried out directly on the material where the high stresses give rise to friction, heat and other suitable secondary effects. Sometime solid processing has to be done into a liquid to produce cavitation.

In spite of the variety of effects, any processing system should be mainly constituted by a treatment chamber and a power transducer coupled to it. Therefore, the feasibility of the applications depends on the efficiency of the transducer–chamber system. The knowledge of the influence of geometry and dimensions of the processing chamber as well as the effect of the excitation transducer requires an extensive and complex study, which today is possible to do in some cases by using numerical methods. As a general rule, the high-power systems operate in continuous wave and the chamber dimensions are large compared to wavelength. The environment is usually reverberant and a diffuse or standing-wave field is established. In a diffuse field the energy is equally distributed and all directions of the energy flux are equally probable. However, values of pressure levels at individual points may deviate significantly from the average values. A diffuse field requires a chamber with irregular shape. Under ideal conditions a diffuse field seems to be optimum for a regular and uniform treatment of all the fluid inside the volume. Nevertheless, those conditions will require too much power to be delivered to the system. Frequently, a standing wave field is more desirable because the pressure or the particle velocity can be amplified at determinate areas (nodes or loops) where the treatment takes place. To set up standing wave fields the surface of the chambers should be parallel. If the two dimensions of the chamber cross section are smaller than the wavelength, a one-dimensional standing wave can be obtained by placing the transducer face parallel to the opposite surface of the chamber and at a distance adjusted to a resonance length. The transducer will be loaded with an impedance, which depends on this length. In the case in which the three dimensions of the chamber are higher than the wavelength, the standing-wave pattern become very complex and it is determined by the eigenmodes of the chamber and the directional characteristics of the transducer. In addition, the finite-amplitude waves generated in a real high-power ultrasonic processing system introduce nonlinearities in the standing-wave pattern, which make the calculation of the acoustic field still more difficult. Consequently, the design of practical ultrasonic processing systems constitutes a topic of current research.

The performance of a processing system can be defined as the ratio between the energy stored in the chamber and the total energy loss in the system averaged on a period. The energy loss must be equal to the electric energy consumption while the stored energy can be calculated from the energy density. Besides the acoustic field characteristics of a processing system, a series of parameters related to the specific process must be considered. These parameters include frequency, time of treatment, total power, pressure amplitudes, volume of radiation, and losses in the processed medium. The extreme difficulties inherent to the characterization of high-power ultrasonic systems is thus evident. Furthermore, when cavitation occurs in a liquid, new additional problems have to be considered. Cavitation bubbles not only scatter the ultrasound from the source but will act as additional sources of sound. This situation may explain the small number of measurement techniques developed and that the majority of them are related to medical uses where there is a strong demand for safety. Interested readers are referred to a very recent paper, where the existing high-power ultrasonic measurement methods are reviewed (28).

An extensive bibliography about applications of high power ultrasound can be found in Ref. 29.

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