Macrosonics: Phenomena, transducers and applications

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Abstract

The field of high-power sonics and ultrasonics is presently known as macrosonics. It comprises a great variety of applications which are generally related with the exploitation of nonlinear phenomena associated to the high amplitudes.

Advances in macrosonic applications are very much dependent on the development of suitable transducers and systems for the efficient generation of the effects to be exploited. Thus, applications in solids generally require high stresses to produce friction, heat and other secondary effects. Applications in liquids are generally based on cavitation and require transducers able to reach a certain sound pressure level (cavitation threshold) through a liquid volume. Applications in gases, which are generally based on particle velocity and radiation pressure, require high vibration amplitudes and good impedance matching.

This paper deals with some basic aspects of the macrosonic field and makes special emphasis on the transducers used and phenomena exploited for the development of new applications.

Resumen

E1 campo de los sonidos y ultrasonidos de alta intensidad es conocido en la actualidad con el nombre de macrosonidos. Este campo comprende una gran variedad de aplicaciones que están en general relacionadas con la explotación de los fenómenos nolineales asociados a las altas amplitudes.

Los avances en las aplicaciones de los macrosonidos están muy ligados al desarrollo de transductores y sistemas adecuados para la generación eficiente de los efectos a utilizar. Así las aplicaciones en sólidos generalmente requieren altas tensiones para producir fricción, calor y otros efectos segundarios. Las aplicaciones en líquidos se basan generalmente en la cavitación y requieren transductores capaces de producir en cierto nivel de presión acústica (umbral de cavitación) a través del volumen líquido. Las aplicaciones en gases, que se basan generalmente en la velocidad de vibración y en la presión de radiación, requieren amplitudes de vibración elevadas y un buen acoplamiento de impedancias. Este trabajo presenta algunos aspectos básicos del campo de los macrosonidos y hace especial énfasis en los transductores empleados y en los fenómenos explotados para el desarrollo de nuevas aplicaciones.

Introduction

The field of high-intensity applications of sonic energy, regardless of frequency, is presently known as macrosonics. As well known, acoustics may be divided in three main branches according to the frequency spectrum and the hearing characteristics imposed by the frequency, i.e., infrasonics which is the branch dealing with frequencies below those within the hearing range of the average person (0-20 Hz), sonics which refers to the audible range (20Hz-20kHz) Ultrasonics which covers the very wide range of vibratory waves from 20 kHz up to the frequencies associated to wavelengths comparable to intermolecular distances (about 10” Hz).

The basic principles and equations of acoustics are adequate to explain the general behaviour of the three branches. Nevertheless, the special characteristic of the ultrasonic and infrasonic waves of being inaudible establishes a fundamental difference in their applications with respect to the audiofrequency field. However, besides frequency other wave parameters, as intensity, may influence broadly the phenomena related to the production, propagation and application of acoustic waves. As a consequence other classification of the acoustic field could be adopted, such as low and high-intensity acoustics. From the point of view of applications, low-intensity waves are those wherein the primary objective is transmitting information through or about the medium, without modifying it. On the contrary, high-intensity waves are those which may produce changes in the propagation medium and that, generally, are applied with this purpose.

Macrosonics is then the part of acoustics devoted to high-intensity waves and their applications. The limit between low and high-intensity is difficult to fix, but it can be approximately established for intensity values which, depending on the medium, vary between 0.1W/cm^2 and 1W/cm^2.

High-intensity waves are finite amplitude waves and to describe their behaviour the equations of the nonlinear acoustics must be used. The applications of high-intensity waves are based on the adequate exploitation of the effects linked to nonlinear phenomena produced during their propagation.

The history of macrosonics is a part of the history of acoustics and, more specifically, can be considered as a part of the history of ultrasonics because macrosonics and high-power ultrasonics are in a great part coincident. The physical effects of intense waves were firstly noticed by Paul Langevin in 1917 making tests to develop an ultrasonic technique for the detection of submarines during the First World War. He realized that small fishes placed in the ultrasonic beam in the neighbourhood of the source were killed. Such tests were done by using a quartz plate sandwiched between two metal pieces, a new kind of piezoelectric transducer which is still considered a fundamental transducer for high-power applications. Following Langevin's work, which can be considered the birth of macrosonics, another important event that marked the initial development of macrosonics were the experiments of Wood and Loomis during the 1920s. Using a high-power oscillator and a quartz plate transducer, they conducted interesting experiments with high-intensity ultrasonic waves (200-500 kHz) such as formation of emulsions and fogs, flocculation of particles suspended in a liquid, levitation of matter, killing or damaging of small fish, etc. [1]. Following this pioneering work, the interest in the study of macrosonic effects increased steadily. More than 150 studies were published in the period 1927-1940 about different effects related with the high intensities. The main effects studied were emulsification and dispersion, coagulation, atomisation, chemical and biological effects and metallurgical applications [2]. In the period 1940-70 the development of new transducer materials (piezoelectric and ferromagnetic ceramics) and transducer structures (horn and prestressed piezoelectric sandwich) as well as the rapid advances in electronics made possible the production of commercial macrosonic systems for practical applications such as cleaning, plastic and metal welding, machining, emulsification, etc. Since 1970, the field of macrosonics, after the explosion of possibilities of the early periods, have grown more in terms of extension of the use of applications commercially introduced than in the development of new applications. Nevertheless, some specific topics have continued to be the object of the attention of research groups in such a way that new applications have been opened or are in the way to be opened. To be mentioned as representative topics the studies and applications in multiphase media, sonochemistry and medical therapy.

This work is aiming to review some advances in macrosonic applications developed on the last period. These advances will be framed within the progress made in the knowledge of basic phenomena and in the development of new transducer technology.

Nonlinear phenomena

As before mentioned, high-intensity acoustic waves are finite-amplitude waves and their applications are generally based on the adequate use of the nonlinear phenomena associated to the high amplitudes. The most relevant nonlinear phenomena related to high-intense acoustic waves are wave distortion, acoustic saturation, radiation pressure, streaming, cavitation in liquids and the formation and motion of dislocations in solids.

Length limitation of this article prevent a detailed study of these phenomena. For further knowledge about them, interested readers are referred to Ref. [3].

Transducers

Macrosonic transducers are narrowband transducers working generally at frequencies within the range 10 to 100 Khz with power capabilities of a hundred watts to several kilowatts and large vibration amplitudes. At present, most high-power transducers are of the piezoelectric type. Therefore, we will mainly focus our attention on this kind of transducers. Nevertheless, it is interesting to point out recent developments of new and promising magnetostrictive materials (rare earth compounds), which show a great potential for high-power transducers. [4]

Transducers are typically composite devices in which the core is a piezoelectric (or magnetostrictive) element, which changes dimensions in response to an electric (or magnetic) field. Other passive components complement the transducer structure to improve energy transfer. These components are generally made of metallic alloys.

In modern transducers, the piezoelectric materials generally used are piezoelectric ceramics. It can be shown that piezoceramics offer the highest electromechanical conversion and efficiency, and have, in general terms, the most favourable properties for high-power ultrasonic transducers [5].

The most characteristic piezoelectric transducer for high-power applications is the well-known sandwich transducer, which is reminiscent of the Langevin transducer. When ceramics for narrow-band low-frequency applications were first used, the transducers consisted of simple piezoceramic blocks. However, this plain arrangement did no prove to be very useful, especially for high power applications, due to the low tensile strength of the ceramic and to the physical dimensions of the single-piece needed for such a low frequency. Because of these difficulties, Langevin's design was re-investigated and adapted to the new circumstances. The sandwich transducer is a half-wave resonant length-expander structure, which, in its simple version, consists of a disc, or of paired discs, of piezoelectric ceramics sandwiched between two identical metal blocks [6].

High-intensity applications of sonic and ultrasonic energy in solids such as machining, welding, metal forming, etc. are based on mechanical effects as a result of particle motion. In these processing applications, the sandwich transducer is also used, but it also includes a metallic transmission line of special shape, which produces a displacement amplification at the working end. These transmission lines are formed by half wavelength resonant elements, called mechanical amplifiers or horns, which are generally stepped, conical, exponential or catenoidal. The horn must be designed to resonate at the same frequency as the transducer which is to drive it. A schematic drawing of a typical processing transducer with one exponential horn is shown in Fig. 1 [7].

Most high-power ultrasonic devices are designed on the basis of different kinds of multi-element sandwich transducers and they are constructed very often in arrays of a number of elements in order to cover a large working area and to obtain the desired total power.

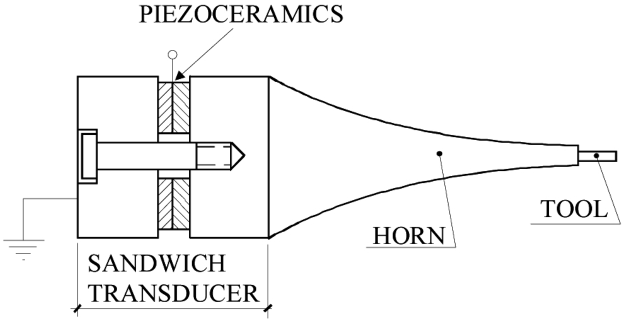

Fig. 1: Schematic structure of a typical ultrasonic processing transducer

A new concept for the generation of ultrasonic energy in fluids has been introduced in recent years by means of the so-called stepped-plate transducer [8, 9]. Generation of ultrasonic energy in fluids presents problems related to the low specific acoustic impedance and high absorption of the medium. Therefore, in order to obtain an efficient ultrasonic transmission and to produce high pressure levels, it is necessary to achieve good impedance matching between the transducer and the fluid, large amplitudes of vibration and highly directional or focused beams for energy concentration. In addition, for large-scale industrial applications, high-power capacity and extensive radiating area would be required in the transducers. The existing high-power commercial transducers have many limitations to cover all the above-mentioned requirements. The development of a new type of stepped-plate transducer, in which these prerequisites have been attained, opens up new possibilities. The new transducer consists essentially of an extensive circular flexural vibrating plate of stepped shape driven at its center by a piezoelectrically activated vibrator. The special shape of the plate permits, despite its flexural vibration, a piston-like radiation to be obtained. As is well known, a flat-plate radiator vibrating in its flexural modes shows a poor directivity, due to phase cancellation. Nevertheless, if the surface elements vibrating in counterphase on both sides of the nodal circles are alternately shifted along the acoustic axis, half a wavelength of the radiated sound, the radiation produced will be in phase across the whole beam. Following this procedure, it is possible, with adequate modifications of the plate surface, to obtain any acoustic field configuration. Focused radiators have also been constructed [10]. Stepped-plates vibrating up to seven nodal circles and diameters up to 70 cm have been designed and constructed [11]. In the latest version of this transducer, efficiencies of around 80%, beam width (at 3 dB) of 1.5 degrees and power, capacities of 1 kW have been attained for the frequency range 10-40 kHz. Looking for industrial applications and in order to increase the power capacity, a new model of transducer has been recently developed by using rectangular plate radiators with double-stepped profile. (Fig. 2). Rectangular plates offer a more uniform distribution of vibration, and therefore higher power capacity, and the material needed for their construction (rolled titanium alloy) is more easily available than the forged titanium needed for the construction of circular plates.

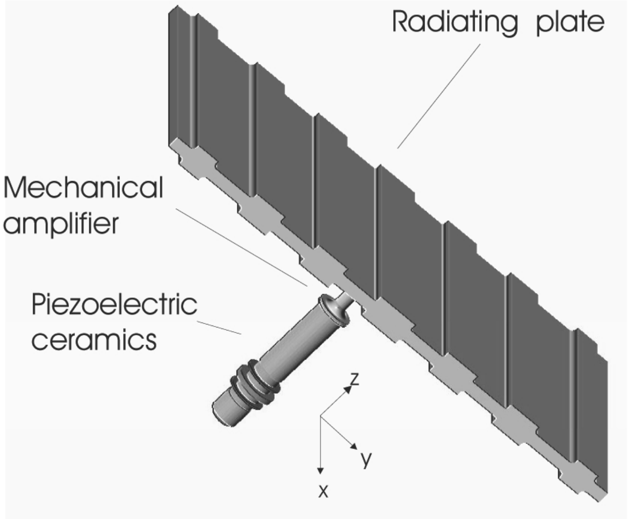

Fig. 2. Double stepped rectangular plate transducer

Applications in multiphase media

As a consequence of the development of a new technology of high-power sonic and ultrasonic generators for use in fluids and in multiphase media, we have been able to treat some specific industrial problems as: fine particle removal from industrial fumes, defoaming of fermenting vessels and canning lines, dehydration of vegetables, dewatering of slurries, washing of textiles. We will review briefly these applications and the nonlinear phenomena involved in their mechanics.

Fine particle removal from industrial fumes

Removal of fine particles (smaller than 1-2 microns) from industrial flue gas emissions is one of the most important problems in air pollution control and the conventional filtration systems, such as the electrostatic filters, are inefficient for these sizes.

The application of high-intensity acoustic fields to an aerosol may induce collision and agglomeration of the suspended particles, giving rise to larger particles.

For more than 20 years we have been working on the theoretical and experimental aspects of this problem. After the construction and testing of numerous laboratory devices we developed a multifrequency agglomeration chamber of 3.5 m long and 0.5x0.7m in section, with four circular stepped-plate transducers of 10 and 20 kHz and an electrical applied power of about 350 W each one (Fig. 3). The chamber was designed for flow rates up to 2000 m3/h and was tested in a pilot installation together with an electrostatic filter for the treatment of fumes produced by a fluidised bed coal combustor.

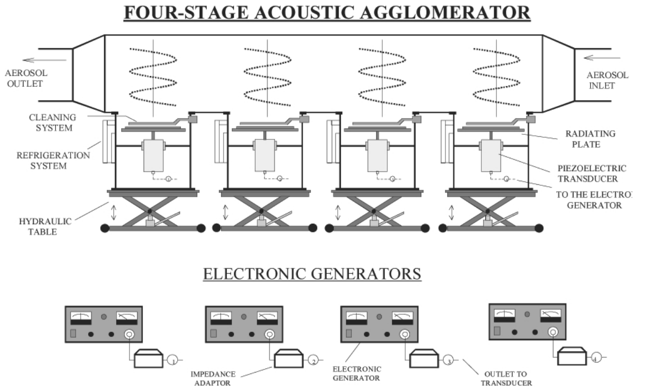

Fig. 3: Multifrequency agglomeration chamb

The results of these tests showed that the introduction of the acoustic system improved the precipitation efficiency of the electrostatic filter, obtaining additional reductions of the fine particle of the order of 40% (in certain cases this value arrived up to 70%). [13]

Defoaming of fermenting vessels and canning lines

Foams are frequently produced during various manufacturing processes and they cause, in general, difficulties in process control and in handling equipment. A typical example is in the fermentation industry where foam represents one of the biggest problems.

High-intensity sound and ultrasound is a clean means for breaking foams.

A new ultrasonic defoamer has been developed by using the stepped-plate transducer and it has been successfully applied to control of foam in fermenting vessels and on high-speed canning lines of carbonic beverages. The picture shows the application of the new system for the treatment of foam in reactors where the transducer rotates to increase the defoaming area (Fig.4). [14]

Dewatering of slurries

Solid/liquid separation is a topic of permanent industrial interest.

Dewatering is a process in which the water is removed from a product without changing its phase while in drying processes the moisture is removed by vaporization.

Solid/liquid separation in finely dispersed slurries is a process generally made by using a porous filtration medium and applying a driving force (vacuum, pressure or centrifugation) to achieve flow through it. The solid particles are re-

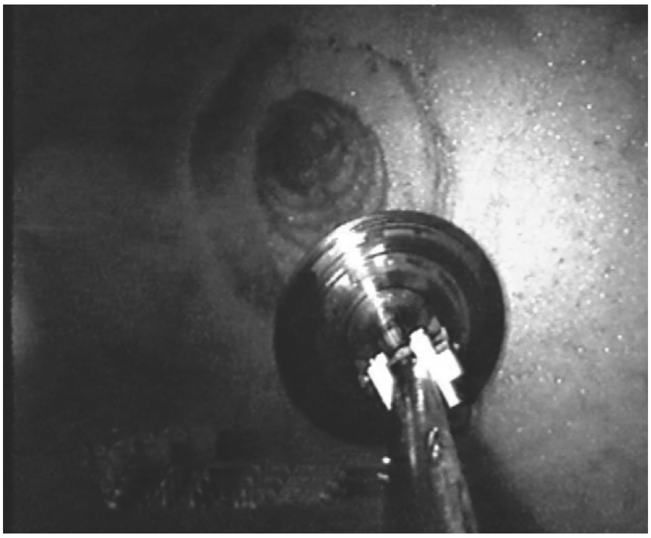

Fig. 4: Defoaming of a fermenting vesse

tained over the surface of the filter medium while the liquid passes through it. In such a way the free water is separated but a certain moisture content remain in the interstitial spaces. This interstitial moisture is very difficult to remove.

We have developed an ultrasonic procedure for post filtration dewatering in ceramic rotary filters to release the remaining interstitial moisture. The ultrasonic process basically consists in applying the acoustic vibration generated by a plate transducer, directly in contact with the material to be dewatered and under a soft static pressure (Fig.5) [15].

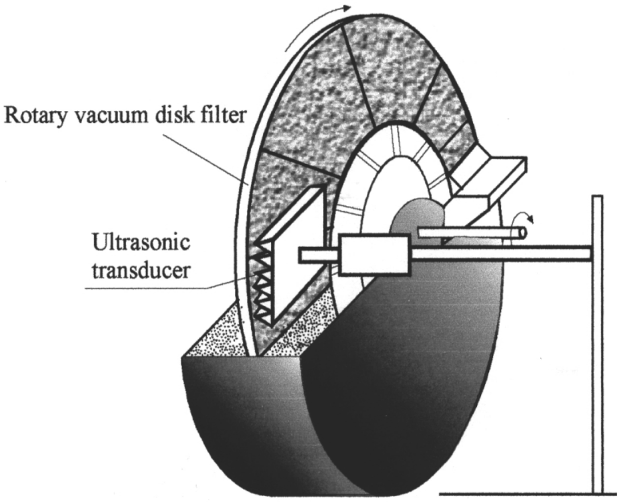

Fig. 5: Rotatory filter assisted by ultrasound

Dehydration of vegetables

Dehydration is a method of preserving food. High intensity ultrasonic waves can be used for the dehydration of food materials following similar mechanisms to those applied for dewatering. We have developed a procedure based on the application of the ultrasonic vibration in direct contact with the samples and together with a static pressure. An air flow at about 1m/s and 22ºC was also applied to facilitate the removal of moisture. The results obtained with vegetable (carrot) slices of 2 mm in thickness and 14 mm in diameter by using ultrasound in comparison with the effect obtained by using forced hot-air at different temperatures showed clearly that the dehydration effect remarkably improved. In addition, by using ultrasonic energy the product quality is very well preserved. [16]

Cleaning of textiles

Cleaning of solid rigid materials is probably one of the best known applications of high-power ultrasound. Nevertheless, the use of acoustic energy in cleaning textiles offers more problems than in solid rigid materials. The fibres are more flexible, then the erosion effect is smaller. In addition, the structure of the fabric favours the formation of air bubble layers which obstruct the penetration of acoustic waves.

During several years we investigated the use of ultrasonic technologies for cleaning textiles we developed a continuous washing system in which textiles are exposed to the acoustic field in a flat format and in almost direct contact to the radiating element of a high-power transducer. The textile items are transported in a conveyor belt, passing them underneath the acoustic source. The washing results obtained with the new system showed that the wash performance of a series of representative stains as well as test monitors was significantly better than those obtained with the conventional methods [17].

Other current macrosonic applications

major research initiatives carried out recently by other groups have been mainly devoted to son chemical and biomedical applications generally based on the exploitation of cavitation effects. Length limitation of this article prevent a detailed discussion of all developing research lines. However, we will briefly describe here some of the most relevant developing topics.

Synthesis of manostructured materials and the formation of very fine particle matter is an interesting and promising area with a wide field of possibilities for industrial applications (catalytic devices, recording materials, colloidal suspensions, etc) and biomedical uses (nanocapsules of proteins for transporting therapeutic compounds, genes or other agents). Bubble collapse in liquids creates unique high-energy conditions in such a way that volatiles compounds decompose inside a collapsing bubble and the resulting atoms agglomerate from nanostructured materials. Also cavitation implosion causes particles to drastically reduce in size [18].

The use of sonic energy for water treatment is another growing area of application. High intensities produced by cavitation implosion destroy bacteria by disrupting biological cell walls. In addition, macrosonic energy may enhance the effects of chemical biocides by breaking up and dispersing bacterial clusters [19]

New options for commercial applications are offered by thermoacoustic engines and refrigerators [20]. The variations of pressure and velocity produced in a gas by an acoustic wave are also accompanied by temperature variations which can be used for the production of thermoacoustic effects.

In medical applications the already well established technique of lithotripsy is a landmark in the use of sonic energy in therapy. Extracorporeal shock wave lithotripsy is based on the generation of high-intensity acoustic pulses outside the body and focusing them through the skin and body wall onto the stone [21]. Focusing is done by reflection on ellipsoids or paraboloids, by acoustic lenses or by direct focusing. The mechanism of shock wave lithotripsy is not completely understood but it seems that compressive and tensile forces together with cavitation are the main effects to be considered. A similar technique to lithotripsy has been used for cancer therapy. The acoustic energy can be focused on cancerous tissue within the body to destroy it.

Finally, some words about the application of macrosonic waves for hemostasis, a recent therapeutic technique which offers excellent prospects. It has been demonstrated that high-intensity ultrasonic beams focused on a small area, can be used to induce coagulative necrosis in tissues where bleeding is produced in such a way that punctures and laceration in animals can be successfully closed. The intensities needed are higher than 1000W/cm^2 [22].

Conclusions

Macrosonics is a wide and expanding field. Nevertheless, up to the present moment only a restricted number of applications have been introduced in industry and probably the most promising fields of application are yet to be developed. In this paper we have reviewed some recent advances which in a great part are in the intermediate stage between laboratory and industry. The future of this field is very much dependent on three main factors: the knowledge and control of the nonlinear phenomena involved in the mechanisms of the different applications, the development of adequate and specific transducer technology, and the capacity to scale-up the systems.

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