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# INDUSTRIAL REQUIREMENTS IN HIGH-POWER ULTRASONIC TRANSDUCERS FOR DEFOAMING

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## ABSTRACT

Airborne stepped-plate focusing transducers have shown to be an efficient tool for breaking foams. The main characteristics of such transducers are their high efficiency and power capacity as well as their strong focusing effect. As a consequence, by using these power transducers it is possible to generate intensities in the focal area as high as 170 dB. However, for their application to industrial problems a special design has to be done covering specific requirements. The main requirements for industrial applications refer to efficiency, safety, durability and environmental resistance. This paper deals with the design and characterization of an industrial prototype of high power ultrasonic transducer for defoaming which is able to work in continuous operation under adverse environmental conditions, and high power excitation without the use of any cooling system. In addition, the transducer is designed to ensure the safe use of airborne high-power ultrasound according to the international recommendations for occupational exposure limits.

The industrial use of the transducers is for defoaming in bottling and canning lines and in fermenting vessels and other reactors.

## INTRODUCTION

Foams are produced in many industrial processes, and they cause, in general, difficulties in the process control and in operating the equipment. To eliminate foams, chemical antifoam agents are usually employed. They are generally, very effective but they contaminate the process. Other methods, such as thermal stresses or electrical fields are difficult to apply, expensive and scarcely effective. Mechanical methods, such as rotating devices, cyclones and air or liquid jets are also used but for the elimination of coarse foams.

Ultrasonic energy is another potential method for defoaming without introducing interferences in the process. High-intensity ultrasonic waves radiated through the air over the foam may destroy the bubbles as a consequence of the high acoustic pressures, the radiation force, the resonance of the bubbles and other secondary effects [1].The potential use of high-intensity ultrasound has never been introduced at industrial level, probably because of the lack of adequate and powerful airborne ultrasonic sources. The defoamers referred in the technical literature were based on aerodynamic acoustic sources of various types (whistles, sirens, etc) Such systems need for air flow generation that interacts with the liquid-foam and cause noise problems because they generally work at sonic frequencies.

We have developed a new ultrasonic defoamer based on the stepped-plate transducer [2]. Such is a powerful and compact piezoelectric transducer with no moving parts, no air flow and readily sterilizable. It is capable to generate in air acoustic intensities of about 10W/cm$^2$ (170dB) in its focus area. Such intensity is effective to break the foam almost instantly. The transducer is driven at resonance by an electronic equipment (power amplifier and oscillator with digital resonance controller) specifically designed.

This paper deals with the development of an industrial prototype of such transducer which has been prepared to work under the adverse conditions generally found in industrial environments.

## GENERAL CHARACTERISTICS OF THE INDUSTRIAL POWER TRANSDUCER

In an ultrasonic power transducer, a series of basic characteristics have to be analyzed in order to determine its capability and usefulness.
The kind of power transducer we have developed is the stepped-plate airborne transducer (Fig. 1). It basically consists of a stepped-plate radiator driven at its centre by a piezoelectrically activated vibrator. The vibrator itself it constituted by a composite piezoelectric transduction unit in a sandwich arrangement and a mechanical amplifier. The extensional vibration generated in the piezoelectric sandwich and amplified by the mechanical amplifer is used to drive the plate radiator with a stepped profile. The stepped profile of the plate is used to control the acoustic radiation field. In the use of the power transducer for defoaming, the stepped plate is designed to produce a focusing radiation. [3]

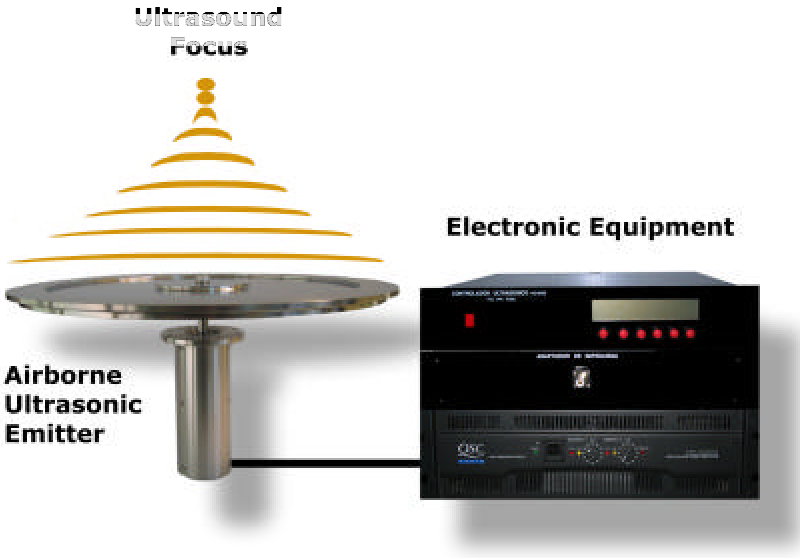

Figure 1: Ultrasonic focusing system for defoaming

The main factors to bear in mind for the industrial use of such transducers are: power capacity, electrical impedance, efficiency and energy losses, durability for long term operation, safety, environmental effects and specific requirements for particular industrial sectors.

In this paper we will analyze all these factors for the case of our stepped-plate transducers for defoaming.

**Power capacity**

The stepped plate radiator determines the power capacity of the transducer. In fact, the limitation is given by the maximum displacement which is possible to get in the plate radiator without breaking it off. It means that the limiting stress of the plate material ($T_{max}$) is a fundamental parameter. The material used for the construction of the plate radiator is a titanium alloy (Ti6Al4V) which has a $T_{max}$ = 200MPa at the frequency in the range of 20-30 kHz [3]. By using this value and the distribution of displacements computed by finite element methods and measured by a laser vibrometer (Fig. 2) it is possible to determine the maximum acoustic power which the transducer is able to radiate ($W_{Rmax}$). Bearing in mind that the plate radiates by both faces the total acoustic power that it is possible to obtain from the transducer will be $2W_{Rmax}$, To determine the maximum electric power applied to the transducer the electroacoustic efficiency (?) has to be taken into account. Then the maximum electric power applied $W_{Emax}$ will be

$$W_{E\max} = \frac{2W_{R\max}}{h}$$

In practice the operating electrical power is applied with a safety factor of 1.5 in such a way that

$$W_{Eop} = \frac{2W_{R\max}}{1.5h}$$

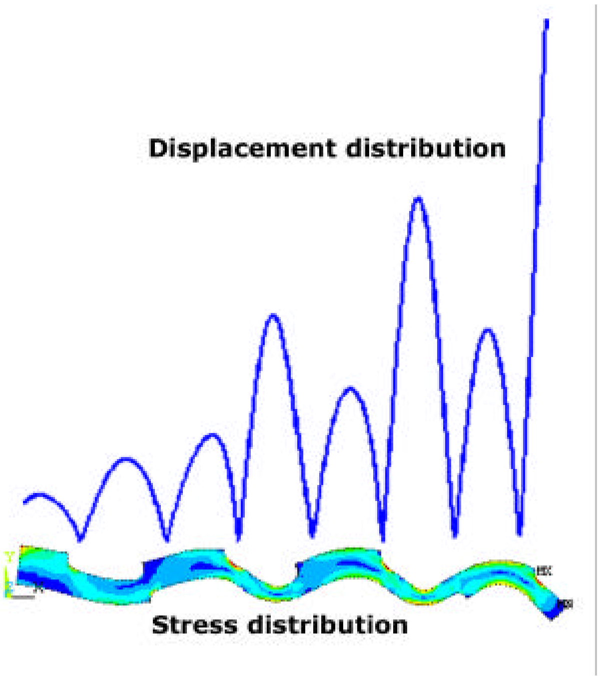

Figure 2: Vibrating Plate. Displacement distribution and stress distribution

**Impedance**

The impedance of the transducer mainly depends on the distribution of vibrating displacement of the plate radiator, the amplification factor of the mechanical amplifier and the number of piezoelectric ceramics used in the sandwich arrangement.

The amplification factor of the mechanical amplifier which is a stepped horn, is defined by the ratio of the areas of the ends of the horn, with the higher amplitude being at the smaller area.

If I is the current intensity measured at the terminals where the electric power $W_E$ is applied, the electric impedance measured will be

$$Z = \frac{W_E}{I^2}$$

Such intensity is directly related with the displacement of the piezoelectric ceramics (d) by the piezoelectric transformation factor

$$a = \frac{Y_{33} d_{33} S}{h}$$

where $d_{33}$ is the piezoelectric constant, $Y_{33}$ is the stress component, $I$ =a.2p fd

If we design the transducer with a stepped plate of a diameter of the order of 40-50 cm, for a frequency (f) of about 20-25 kHz, with a mechanical amplifer factor of about 7 and a sandwich arrangement with two pairs of piezoelectric ceramics, the electrical impedance of such transducer will be in the range of 500-800 ohms. This is an acceptable value to drive the transducer by an electronic generator.

**Efficiency and losses**

The electroacoustic efficiency is determined from the equivalent circuit as the ratio between the radiation resistance ($R_R$) and the total resistance (radiation resistance plus losses resistance $R_L$)

$$h = \frac{R_R}{R_R + R_L}$$

The efficiency is quantified by measuring the impedance at resonance with the transducer radiating in air and vacuum.

The efficiency of these transducers is of about 75% . Therefore the 25% of the applied energy is going to produce heating of the transducer. Such heating will be mainly concentrated in the radiating plate, which is vibrating with very high displacements, and in the piezoelectric ceramics which have high internal losses (in comparison with the metallic parts). The transducers should be designed to minimize the losses in the piezoelectric sandwich because, for practical reasons, such part will be encapsulated without any cooling system and the piezoelectric ceramics need to operate under 70ºC to keep stable their properties. To that purpose, the selection of the piezoelectric elements constituting the piezoelectric sandwich requires a specific process [4]

**Lifetime**

The estimated durability for long time operation depends on the fatigue problems of the material in which the radiating plate is made of. This plate supports the maximum displacements and therefore such displacements are conditioned by the limiting strain of the material, as already mentioned.

In order to obtain a safe operation we have developed, in connection with the manufacturer, a procedure to obtain a titanium alloy with a high fatigue limit for ultrasonic vibrations. It has to be noted that the ultrasonic fatigue limit is about ¾ of the standard fatigue limit of the material. In addition, it is also necessary to bear in mind that for high-frequency acoustic vibrations in classic tests the minimum number of cycles established for fatigue tests are about $10^7$. Nevertheless, for our transducers working at ultrasonic frequencies higher than $2x10^4$ cycles/s such number is still very low because it represents less than one hour working. Therefore in order to assure the long term lifetime we have established a minimum number of 100 hours working at the maximum power capacity. It means that the transducer has to be subjected to $10^{10}$ cycles of fatigue tests. Such tests are carried out at the "safe maximum power" which corresponds to the applied power in which the maximum strain in the plate radiator is about 80% of the limiting strain of the material for ultrasonic frequencies.

For industrial prototypes the durability after 1000 hour tests have been confirmed by increasing the time of the fatigue tests in one order of magnitude. The fatigue tests are carried out by controlling the electrical, acoustical and thermal parameters of the transducers

**Environmental safety**

For the safe use of ultrasound there is no presently established limiting standards as for the audiofrequency noise. Nevertheless in the recent years a few countries (Japan, Canada, USA, Sweden,...) have established some recommendations about human exposure limits for ultrasonic airborne radiation up to the frequency of 50kHz [5]. Such recommendations are given in 1/3 octave bands and the sound pressure levels (SPL) for the most strict cases are: 75dB in 20kHz band and 110 dB in the 25kHz to 40kHz bands. Such limits are independent of time.

Protective measures are simpler in the ultrasonic range than in the audible range because of the higher absorption of the ultrasonic frequencies and the easier way to isolate by enclosures. However, the first point to be considered is the selection of the operation frequency. If such frequency is chosen over 25kHz an increase in the limit of 35dB is obtained. Other measures, if needed, are isolation enclosures and/or ear protectors. Our transducers focalize the radiation in a small area in front of the plate radiator at about 50 cm where the SPL is of around 170dB. Therefore such area has to be out of the human exposure. In fact this is the defoaming area to be placed over the foam. However around the transducer in a radius of 1m, where sporadically could be located an operator, the levels we have measured are still above the limit in about 20-30 dB. Therefore the use of ear protectors with an attenuation higher than 30dB will be necessary.

If the transducer is used inside a reactor the container acts as an enclosure to isolate the ultrasonic radiation from the external environment.

In many industrial applications it is not possible to operate the electronic equipment close to the point where the ultrasonic energy is applied. Therefore the electronic equipment was designed and constructed in such way that it can be located at about 100m from the transducer.

Other special requirements for industrial equipments refer to each specific industrial sector. For the food industry the transducer has to be all made of selected materials such as stainless steel or titanium alloy and the electrical contacts have to be well protected as well as the piezoelectric ceramics to allow the unit to be cleaned without introducing moisture in these parts. In this case transducer must be encapsulated with special protection (isolation standards IP66 or IP67) (Fig. 3)

Figure 3: Industrial Ultrasonic Emitter

## TECHNOLOGICAL DEVELOPMENT

### Development

The main problems in the development of this kind of transducer structure are related with the vibrating plate radiator, and its connection with the piezoelectric vibrator. Such vibrator is an extensional resonator which drives the flexural plate radiator. Therefore the coupling between the plate and the vibrator is a very sensible operation which is difficult to determine theoretically. The basic procedure we follow starts with a primary analytical calculation which is only approximated and is completed by finite element methods. In general, the objective to reach is to obtain for the transducer assembly the same frequency that for the single plate alone. The practical problems generally appear in the junction between the vibrator and the plate radiator where heating is produced when the coupling is incorrect.

Another important and frequent problem in our transducer structure refers to vibration mode interactions. It means than the proximity of other vibration modes may disturb the operating mode. As a consequence the flexural axysymmetric mode we want to get from the circular radiating plate may be distorted giving rise, at high power operation to nonlinear interactions and chaos. That is a difficult problem that has to be solved by means of modifications of the plate design to move away the undesired modes.

We have designed and constructed transducers for 25.7kHz with a plate radiator of about 400 mm in diameter and a power capacity of 200W. By using this transducer it is possible to obtain a focus area of about 25mm in diameter with an intensity of 170dB. For higher frequencies, about 42kHz, we have designed and constructed a transducer with a plate radiator of 240mm in diameter and a power capacity of 75W. The focus area is of about 15mm in diameter and the intensity is again of 170dB.

### Applications

The transducer here presented has been specifically developed for its application to industrial defoaming. This is a very wide field of application and the problems related with the elimination of the excess of foam are very varied. Therefore, we have developed our system only for two representative types of defoaming: defoaming of big reactors (fermenter vessels or chemical reactors) and control of the excess of foam in high speed bottling and canning lines of beverages.

The scheme of the set-up for the application of the new system for the treatment of foam in reactors is shown in the Figure 4. The defoaming system is constituted by one or two focalized high-power ultrasonic transducers mounted in a rotation system to increase the defoaming area. The position and the path of the focus may be controlled by varying the rotation speed.

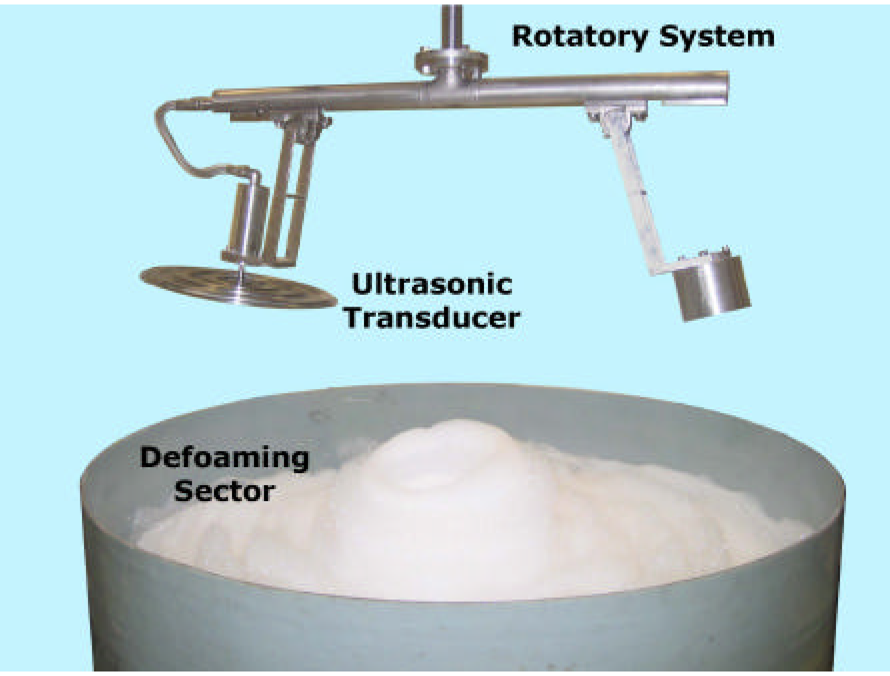

Figure 4: Ultrasonic transducer in rotatory system

In canning lines, the airborne ultrasonic radiation is focused on the working area where the foam excess is quickly destroyed to avoid liquid losses.

The ultrasonic defoaming system has been successfully applied to control foam in the filling operation of cans and bottles of commercial beverages at speeds as high as 20 cans per second. The system has also been applied in fermenter vessels of up to 8 m in diameter.

## Acknowledgments

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