DEVELOPMENT OF INDUSTRIAL MODELS OF HIGH-POWER STEPPED-PLATE SONIC AND ULTRASONIC TRANSDUCERS FOR USE IN FLUIDS.

J. A. Gallego-Juárez, G. Rodríguez-Corral, E. Riera-Franco de Sarabia, F. Vázquez-Martínez, V.M. Acosta-Aparicio, C. Campos-Pozuelo
Instituto de Acustica, Serrano, 144, 28006 Madrid, Spain

Abstract

The extension of the high-power applications of sonic and ultrasonic energy in industrial processing requires the development of efficient and powerful transducers. Years ago some of the authors of the present paper proposed a new concept of ultrasonic transducer for use in fluids (more specifically in gases) based on a stepped-plate radiator. This concept was successfully applied to the design and development of a series of circular plate transducers of small and medium power capacities (lower than 1kW) and radiating surfaces smaller than 0.5 m^2. Nevertheless, the scale of a great part of industrial applications requires higher powers and larger radiating surfaces. Looking for such applications (i.e. fume precipitation, defoaming, drying and dewatering, etc.) we have designed and developed an industrial model of transducer with a rectangular plate radiator of double-stepped profile.

The design of the new model was made with the help of the finite element method (FEM) and the acoustic field was computed by the boundary element method (BEM). In such a way the distribution of displacements and stresses as well as the corresponding radiated field could be known previously to the real construction of the unit.

The industrial prototype of macrosonic transducer was designed with a radiating plate of 1.8 x 0.9 m^2 for an estimated power capacity of about 3500W. Previously a first scale model was developed and tested with a radiating plate of 0.6 x 0.3 m^2 for a frequency of 20 kHz and a power capacity of about 400 W. The industrial prototype was constructed by scaling up the first model in a factor of three.

Typical problems faced in the development of the industrial transducers were, the adequate selection and characterisation of the plate material, the excitation of the useful vibration mode without interference of the closer modes of the plate, the decrease of the maximum stress by improving the uniformity of the vibration amplitude, etc.

The industrial prototype, constructed initially with an aluminium plate and eventually with a titanium alloy plate, presents an electroacoustic efficiency of 67% and it has been operated in air with an applied power of two kilowatts in continuous wave.

I. INTRODUCTION

The applications of sonic and ultrasonic energy in industrial processing are very much dependent on the development of suitable high-power generators. In fact, the applications of high-power ultrasonics which have been well introduced in industry, such as plastic and metal welding or cleaning, are those where efficient reliable systems have been developed.

There exists a big potential for applications of sonic and ultrasonic energy in fluids and in multiphase media, as it has been demonstrated at laboratory and even at pilot plant stage for defoaming, fume precipitation, drying and dewatering, etc. [1] Nevertheless, the exploitation of this potential is presently hindered by the lack of adequate generators. Therefore, we have considered as one of the main objectives of our work the study, design and development of macrosonic generators for industrial applications.

The design of high-power transducers for reliable operation in fluid and/or multiphase

0-7803-7177-1/01/$10.00 © 2001 IEEE

media is focused on satisfying the following main requirements: good impedance matching between the transducer and the medium for efficient transmission of energy, high directional or focused radiation for energy concentration and high amplitude of the operating mode for intense acoustic radiation.

Looking at these requirements we have been involved during many years in the development of a new concept of ultrasonic transducers based on stepped-plate radiators [2, 3]. This concept was successfully applied to the design and construction of a series of circular plate transducers for small and medium power capacities (lower than 1 kW) with radiating areas smaller than 0.5 m^2. The different developed models implement very high electroacoustic efficiency (75-80%) and directivity (3dB beamwidth less than 2º). Nevertheless, the scale of the great part of industrial applications requires to work at higher powers and with larger radiating areas. To cover such additional requirements we have designed and developed an industrial model of transducer with a rectangular plate radiator of double-stepped profile and a surface area of 1.8 x 0.9 m^2 for an estimated power capacity of about 3500 W.

This paper deals with the design, construction and performance of this prototype.

II. GENERAL STRUCTURE OF THE STEPPED-PLATE TRANSDUCER

As before mentioned the new concept of high-power sonic and ultrasonic transducers is based on a particular type of vibrating plate radiator of stepped profile [4, 5]. The basic structure of these transducers is schematically shown in Figure 1. As it can be seen, it consists essentially of an extensive stepped plate radiator driven at its center by a piezoelectrically activated vibrator. The vibrator itself consists of a piezoelectric element of transduction in a sandwich configuration and a solid horn which acts as a mechanical amplifier. The extensional vibration, generated by the transducer element and amplified by the mechanical amplifier, drives the radiating plate which vibrates flexurally in one of its modes. All the parts of the transducer are calculated to be resonant at the operating frequency.

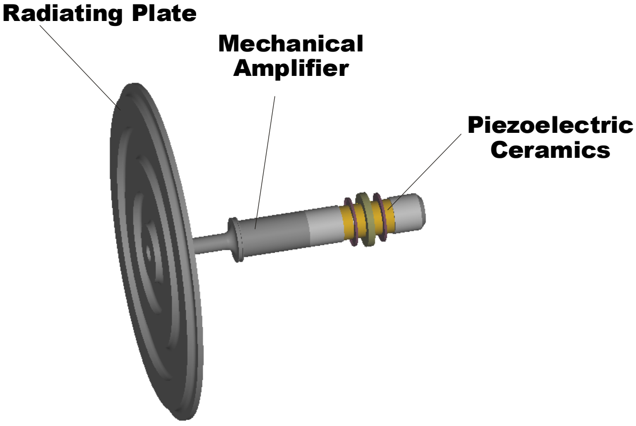


Figure 1: Scheme of the stepped-plate transducer

The extensive surface of the plate increases the radiation resistance and offers the vibrating system good impedance matching to the medium. The stepped profile of the plate permits to control the radiation pattern in such a way that high directional radiation can be generated to obtain energy concentration. In fact, a flat plate radiator vibrating in its flexural mode presents a poor directivity due to phase cancellation. Nevertheless, if the surface elements vibrating in counterphase on the two sides of the nodal lines are alternatively shifted along the acoustic axis to half a wavelength of the sound in the propagation medium, the radiation produced will be in phase across the whole beam and a directivity pattern equivalent to that of the theoretical piston will be obtained [6]. Following a similar procedure it is possible, with adequate displacements of the different plate zones, to achieve any acoustic field configuration. Focused radiators were also designed and constructed [7]. Different models of stepped-plate transducers were developed for frequencies in the range 10-40kHz and powers up to about 1 kW by using circular plate radiators.

III. THE DOUBLE-STEPPED RECTANGULAR PLATE TRANSDUCER

Basic Design Considerations

The use of rectangular plate radiators instead of circular radiators for the development of industrial transducers is due to several technical and practical reasons. First of all, the more uniform distribution of vibration displacements, which may be obtained in a rectangular plate [8], increases the power capacity of the transducer. In fact, such power capacity is basically determined by the maximum displacement we can get in the vibrating plate without breaking it off. In the case of circular plates the distribution of displacements, given by Bessel functions, presents high amplitudes in the inner area and much lower and decreasing amplitudes in the outer areas, making difficult to obtain high power capacities. As a consequence of the vibration distribution and the shape, more homogenous acoustic fields may be reached by using rectangular radiators. Finally, an important practical factor is the easier commercial availability of the radiator material (titanium alloy) as a rolled rectangular plate than as a forged disc even if both manufactured products are not exactly equivalent in their mechanical characteristics.

The rectangular plate radiator was designed with steps on both faces to obtain directional radiation also from the back face. The purpose is to use the back radiation in the forward direction by means of adequate reflectors.

The design, as in the case of circular radiators, was made by analytical methods in a first approach and it was further improved by the finite element method (FEM) [9].

Development and characterisation of the first transducer model

The main objective in developing the new model of stepped plate transducers was to reach a power capacity of some kilowatts in a single unit for industrial processing.

The development of the first prototype was made by following two steps. First, a scale model was constructed and tested with a rectangular plate of 0.6 x 0.3 m^2 for a frequency of about 20 kHz. The second step was to scale up the model. In both steps, at least two different units were constructed: one with the radiator made of aluminium alloy and other with the radiator made of titanium alloy.

The rectangular radiator was designed and constructed to operate at the working frequency in a resonant mode with 14 nodal lines parallel to its smaller side (Fig. 2). The driving system consists of a half a wavelength extensional vibrating piezoelectric sandwich joined to a stepped horn.

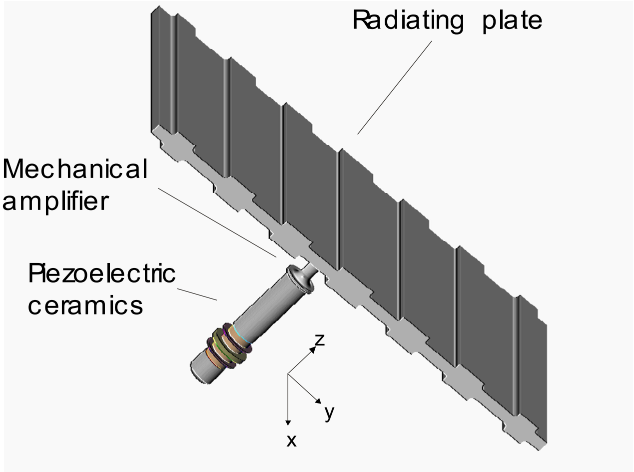


Figure 2: Scheme of the double-stepped rectangular plate transducer

The amplitude distribution of the plate radiator was computed by FEM. Figure 3 shows the predicted vibration mode for a quarter of the plate which, for symmetry reasons, represents the behaviour of the full plate.

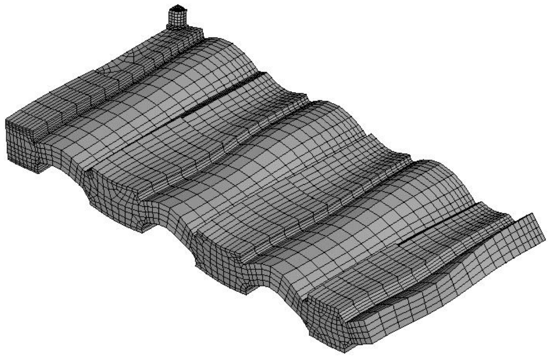


Figure 3: Vibration mode of the plate with FEM

Experimental tests were carried out to characterise the transducer scale model. First of all the amplitude distribution of the plate radiator was measured by means of a Laser Scanning Vibrometer (Polytec PSV-200) and, as the result, the FEM simulation was validated. Afterwards, the electrical impedances in air and in vacuum were measured to determine the electroacoustic efficiency. The acoustic field was both measured in a semi-anechoic environment and computed by the boundary element method (BEM). In such a way the numerical method was validated. The obtained electroacoustic efficiency was of 75% for an operating frequency of 19.5 kHz.

To estimate the power capacity of the transducer scale model, the limiting strain of the plate material was determined by a resonant method previously implemented [10]. As a result an estimated power capacity of about 400W was determined.

The good performance of the scale model transducer gave us the first confirmation of the feasibility of our project. Therefore, the transducer was scaled up by applying a scale factor of three. As a consequence, the transducer dimensions resulted multiplied by three while the frequency reduced in 1/3. The power capacity should be increased by a factor of 3^2 and the distribution of displacements, the impedance and the efficiency should remain unchanged [11, 12].

In this way, an industrial prototype of a macrosonic transducer was designed and constructed with a double-stepped rectangular plate of 1.8x0.9 m^2. In the development of the industrial transducer a few practical modifications were introduced such as for example, to diminish the ratio between the two diameters of the stepped horn and to increase the number of piezoelectric ceramics. The purpose was to keep the impedance as low as possible in order to avoid very high voltages and to cope with the high electric power applied.

The radiating plate was placed in a frame where it was supported by small rubber holders at the nodal lines. A photograph of the industrial and the scale model transducers is shown in Figure 4.

The material of the plate was a titanium alloy. The measurement of the efficiency of the industrial transducer was different from that of the scale model transducer because of the difficulties of measuring the losses resistance in a vacuum environment. Therefore, the procedure was to measure the vibration displacements of the plate radiator by laser scanning vibrometry in order to calculate the radiating power and then to compare it with the electric applied power to determine the efficiency. The impedance was measured by means of an impedance bridge. In such a way values of 67% for the efficiency and of about 500 Ω for the input impedance were obtained. The near acoustic field along the central axis of the plate radiator was measured and compared with the BEM calculation (Fig. 5)

Figure 4: Scale model and industrial stepped-plate transducers

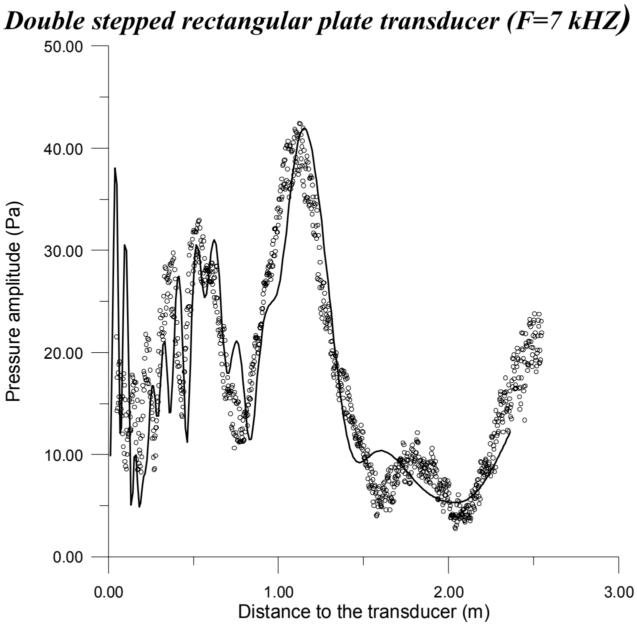
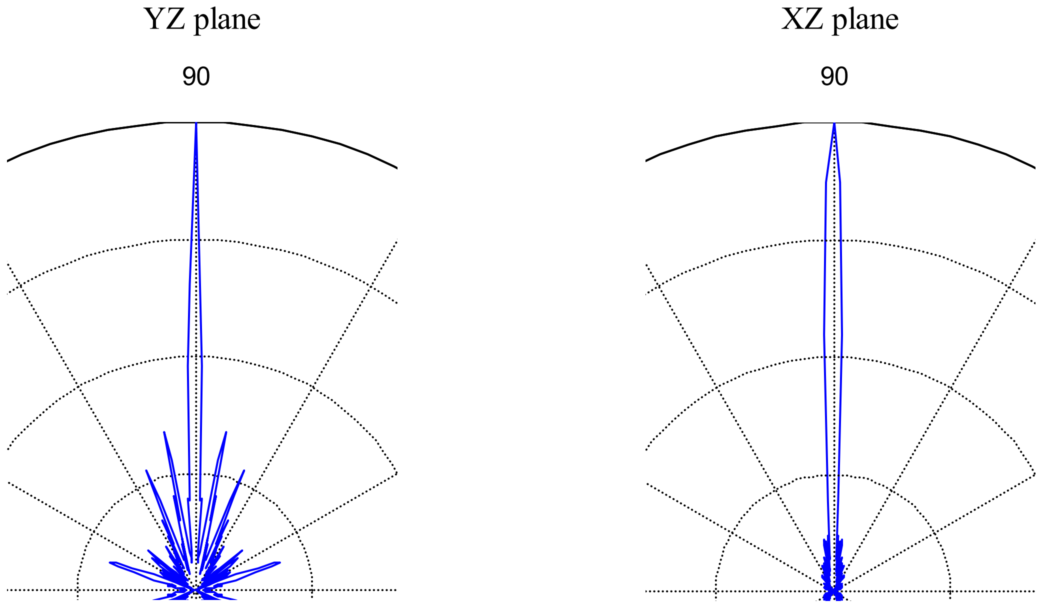


Fig. 5: Numerical (BEM) – Experimental comparison of the acoustic field along the central axis

The directivity patterns computed in the far field are shown in Figure 6. Table 1 summarises the main characteristics of the scale model and the industrial transducers measured at low excitation signals.


YZ plane

XZ plane

Figure 6: Directivity diagrams

Table 1 Main characteristics of the double-stepped rectangular plate transducers at low signal operation.

Radiating plate (m^2)	Frequency (kHz)	Bandwidth (Hz)	Efficiency (%)
0.6 x 0.3	19.5	2.5	75
1.8 x0.9	7.6	1	67

IV. IMPROVEMENTS IN THE PLATE RADIATOR DESIGN FOR HIGH POWER OPERATION

The reliable and safe operation of a stepped plate high-power transducer in a fluid medium, and more specifically in air, requires to analyse and optimise the characteristics of the radiating plate which have a direct influence in the power capacity, such as the fatigue failure of the material, the distribution and location of the stresses and the isolation of the operating vibration mode from other close non-tuned modes.

Fatigue failure of the plate material

The performance of the industrial transducer very much depends on the behaviour under high strain levels at sonic and ultrasonic frequencies of the material used in the construction of the plate radiator. In fact, the power capacity of the transducer is determined by the limiting strain of this material. As a consequence, we use special titanium alloys and determine their high strain behaviour by a resonance procedure [10].

The titanium alloy selected for the construction of the plate was Ti-6Al-4V which is considered the most adequate material to our purposes. Nevertheless, the performance of a material for high-intensity high-frequency stresses is not only dependent on its composition but it is very much linked to its microstructure. The problem is to quantify the ultrasonic fatigue strength of different commercial microstructures, an information which is not provided by the titanium manufacturers.

As before mentioned, one of the reasons to construct rectangular radiators was the easier commercial availability of the rectangular rolled material instead of the forged discs we used for the circular radiators. However, when we have studied the fatigue limit of the rolled material with the microstructure currently supplied by the manufacturer we have found that this material showed values of fatigue strength which in average are of about 20% lower than the strength value of the forged titanium alloy. As a consequence, we have to analyse several different microstructures in rolled rectangular plates in order to find the best possible material. The limiting strain we can expect from the titanium alloy we are presently using could be established within the range of 200 MPa. This limit should be improved.

Distribution and location of the stresses

To maximise the power capacity of the transducer, uniformity of the stresses at the radiating surface is needed. This is impossible in a flexural vibrating plate. Therefore, the objective should be to diminish as much as possible the maximum stress in order to reach a balanced stress distribution. In addition, such maximum stress should be located out of the driving area where the change from the extensional to flexural motion gives rise to erosion problems which can contribute to fatigue failure.

To reach these objectives, three modifications were introduced on the original design of the plate. First, the steps were slightly grooved in their central part. This modification improved the uniformity of the vibration without affecting at the directional characteristics of the radiator.

The second improvement was made by introducing small changes in the mass of the central and the outermost steps. The purpose was to move the maximum stress from the driving point to the outermost nodal lines in the plate by increasing the height of the central step with respect to that of the outermost steps. In contrast this modification decreases the response of the operating mode compared to the other closer modes.

Finally, the maximum stress could be still diminished by making the border of some steps chamfered instead of curved. This modification changes the rigidity of the steps and therefore the stress distribution.

It is to be noticed that the detailed analysis of the influence of all these modifications was achieved by using the finite element model of the plate, previously validated with the scale model transducer and also with the aluminium plate version of the industrial model.

Isolation and/or magnification of the operating mode

The plate radiator presents a high density of vibration modes in the range of the operating frequency and some of them may occur dangerously close to the operating mode. This fact is particularly important at high excitation when the driving signal may suffer distortion and the band experiments some increase. In practice, there are two vibration modes very close to the operating frequency. They are also flexural modes but with different distribution of displacements. Hence, it is necessary to avoid any interference of those modes with the operating mode.

The isolation in frequency of the operating mode is achieved thanks to the very narrow band of the transducer. In fact, the closer modes at both sides of the operating mode are separated of about 250 Hz and 100 Hz respectively while the band of the transducer is as small as 1 Hz. Therefore, the frequency separation seems to be within a reasonable safety margin even for high power. It is to be mentioned that to drive such a very narrow band transducer a special electronic system was designed to produce a signal lying all the working time within the band and following automatically the resonance frequency if it slides during operation [3].

Another important question is the amplitude of the close modes compared with the operating mode. As before mentioned, the mass of the central step was increased with respect to the others to force the maximum stress to move from the excitation area. As a consequence, the impedance of the operating mode increases and its response diminishes compared with the close modes. It means that these modes can be more easily excited and modal coupling can be produced, affecting transducer performance. The procedure to mitigate this problem was again to adjust very finely the balance between the masses of the central and outer steps in order to magnificate as much as possible the response of the operating mode without modifying other characteristics. By this way we reached to pass from a situation where the impedance of the working mode was of 2.6 and 2.5 times that of the two closer modes, up to another situation where this factor was of 1.3 and 2 respectively. At the same time the separation of frequencies were kept in about the same range. By this modification we were able to pass from an applied power to the transducer of about 1200 W up to 2000W without problems of modal coupling.

CONCLUSIONS

The need of transducers with high power capacity and extensive radiating surface for new industrial applications of sonic and ultrasonic energy in fluid and multiphase media has promoted the development of a prototype of industrial transducer based on a double stepped-plate radiator. This development required very careful component design in order to guarantee continuous operation at very high power and, in certain cases, under difficult environmental conditions (fume precipitation, industrial defoaming, etc). The result is a new powerful unit which has been tested working during thirty hours (about 10^9 cycles) with an applied power of 2 kW in continuous wave.

Significant improvements in the design of the stepped plate, over the original model, were introduced to keep at high power the good performance of the transducer. In fact, the transducer is able to operate at high power with a reasonable uniformity in the vibration amplitude, an adequate distribution of the stresses, and without modal coupling. Such achievements can be considered an important step in the development of these new huge devices. Nevertheless further longer tests either in the laboratory or under real industrial conditions have to be carried out.

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VI. ACKNOWLEDGEMENTS

This work has been supported by the research project PIE-131095 (ENDESA/OCIDE). The authors want to recognise the very valuable assistance of Mr. A. Blanco in the development, adjustment and operation of the electronic system to drive the transducer and of M. E. Andrés in the design and construction of mechanical structures.