

**THEORETICAL MODELLING AND SIMULATION OF NON-IDEAL
VIBRATION EFFECTS IN PIEZOELECTRIC APPLICATOR FOR
ULTRASONIC DIATHERMY**

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ABSTRACT

Diathermy applicators emitting moderate ultrasonic power inside human tissues are widely employed for treatment of tissue lesions. Only limited theoretical studies have been made on patterns radiated by commercial physiotherapy applicators. Nevertheless, these studies are needed previously to optimize treatments over limited areas with accuracy and sufficient safety for patients and therapists. In this paper, possible origins of unexpected radiations, in near-field zones of diathermy devices, are experimentally and theoretically conjectured. A modelling of device vibrations, proposed by the authors, is applied to simulate radiated fields. Preliminary results, computed from our model, for real vibrations, explain partially some laboratory field patterns.

RESUMEN

Los transductores de diatermia emiten una moderada cantidad de potencia dentro de los tejidos humanos y son ampliamente empleados para el tratamiento de lesiones en estos. Hay escasos estudios teóricos acerca de los patrones radiados por los aplicadores de fisioterapia comercial. Sin embargo, estos estudios son necesarios para poder optimizar los tratamientos sobre áreas bien delimitadas con la suficiente precisión y seguridad, tanto para pacientes como fisioterapeutas. En este trabajo, posibles orígenes de radiaciones imprevistas, en zonas del campo cercano de dispositivos de diatermia, son investigados teórica y experimentalmente se propone una modelación de las vibraciones del dispositivo, y se aplica para simular los campos radiados. Resultados preliminares obtenidos mediante nuestro modelo para vibraciones reales, explican en parte algunos patrones de radiación obtenidos en el laboratorio.

INTRODUCTION

The ultrasound ability to interact with tissue to produce local heating has been known for a long time. Nowadays, ultrasound physiotherapy is widely used in health care to treat tissue injuries [1]. The ultrasonic diathermy applicators produces high frequency sound waves which travel deeply into tissue and create gentle therapeutic heat for the treatment of selected medical conditions such as pain, muscle spasms and joint contractures.

A detailed study of the field radiation patterns behavior is one of the most important tasks during the characterization of any ultrasonic physiotherapy transducer. The information of this behavior is needed in order to control and deliver prescribed doses to patients with a reasonable degree

of accuracy, and avoiding some undesired radiation outside of the treatment area. However, the insufficient knowledge, about the propagation of ultrasonic wavefronts and about the heating of the biological tissues, reduces the precision of the selected treatment area as well as the safety for patients and therapists. Additionally, they could irradiate some energy away the treatment zone, which could create undesired hot points or could attain healthy tissues, by insonifying neighbor tissues or transmitting some ultrasonic energy just in the direction of therapist's hand.

Many authors have been investigating theoretically and experimentally factors influencing the effective radiation patterns [2-6]. Various experimental works have been reported to study the ultrasonic radiation patterns during the treatment [7], and exist others studies based on the radiation of ultrasonic focalized arrays for therapy [8, 9]. The behavior of the real ultrasound radiation patterns generated by two commercial physiotherapy applicators, working in continuous mode, has been studied and analyzed previously by the authors [10-12]. Some anomalous unexpected radiations observed in the near zones have been analyzed and their origins have been discussed. In this work, another experimental procedure has been developed to explain the origin of these effects. Besides, an improved modelling of the device vibrations has been created to simulate the influence of non-ideal housing radiations in the expected radiation patterns.

Additionally, the rim radiations have been previously considered among the main causes of the perturbations on the real field patterns. To explain better the implication of this cause in the perturbations, an experimental measurement of the acoustic patterns was realized. For a diathermy applicator, an aperture in an opaque screen (made of materials that possess a higher attenuation) is placed close to the applicator's rim, allowing the propagation of the ultrasonic field radiated by the transducer face and inhibiting the radiation coming from the rim. The measurement results of the radiations patterns will be shown and compared with results obtained without using the screen. Although we have previously developed a preliminary theoretical model to explain the possible origin of the anomalous radiation, an improved modelling of the device vibrations is still needed. This modeling will help to a better understanding of the real radiation patterns behavior in this commercial therapy applicator. A computer simulation of the acoustic field radiated by this applicator has been developed, under continuous wave (CW) excitation, and considering the radiation from the nominal aperture and also from their rim zone (simulated by a number of radiant rings located at distinct depths). The effects on the radiation field caused by the applicator rim, the number of those rings, and their width, will be studied in this work. Figure 1 (a) shows the diathermy applicator's shape considered here and the coordinates used in this work.

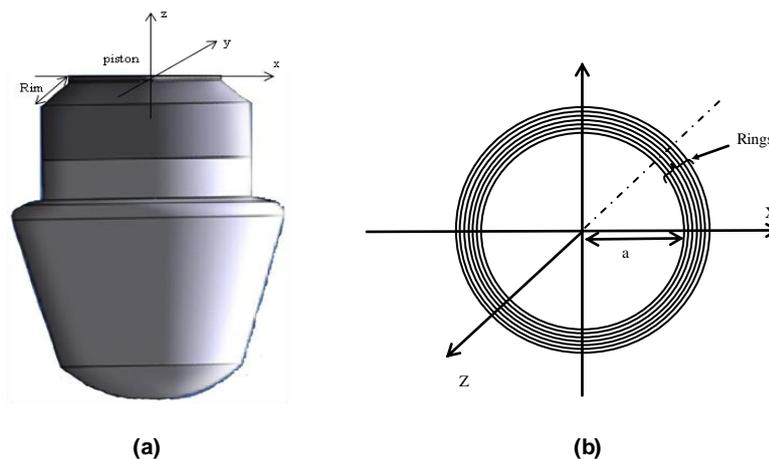


Figure 1. (a) A diathermy applicator and coordinate system used in this study, (b) cross-sectional representation of applicator approaching piston and rings.

EXPERIMENTS

The diathermy applicator used in the experiments and simulations was a Carin model LOT99137 device (diameter of 32 mm, and operating frequencies: 1 MHz). The measured

effective working frequency of this applicator was 1.15 MHz when it was efficiently driven. The acoustic pressure amplitudes were measured in a water tank by a scanning 0.6-mm-diam PZT needle hydrophone that includes a pre-amplifier. Its sensitivity is close to -127 dB, referred to 0.1 μ Volt / Pascal; and it presents a quasi-plane frequency response in the considered frequency range (MHz). The applicator was driven by a 50 μ s tone burst, to provide a close approximation to CW behavior.

A 3D scanning automated system, containing the diathermy emitter and a miniature hydrophone, was used to measure the acoustic pressure amplitudes. The hydrophone was moved along x, y and z axis with a step resolution of 20 μ m. The acquired data were recorded for posterior analysis, using a computer-compatible electronic receiver-amplifier (suitable to obtain a good signal-to-noise ratio) and an acquisition/A-D converter system. A gated detector to acquire the peak values of the field signals envelopes (during the entire scanning process) was also employed.

NUMERICAL MODELLING OF THE ACOUSTIC FIELD

The acoustic pressure field, p , at any position in the case of a plane piston vibrating in a sinusoidal way, immersed within an infinite plane rigid baffle, is given by the Rayleigh-Sommerfeld diffraction integral:

$$p(x, y, z) = \frac{j\rho ck}{2\pi} U_0 \int_S \frac{e^{j(\omega t - kr')}}{r'} dS \quad (1)$$

Where $j = \sqrt{-1}$, ρ is the density of the medium, c is the speed of sound in the medium, k is the real wave number, U_0 is the vibration velocity amplitude of the piston, ω is the angular frequency, t is the time, r' is the distance from a point on the transducer surface to the field point of interest, and S is the area of the whole transducer. Figure 2 shows the coordinates of the transducer being considered [13].

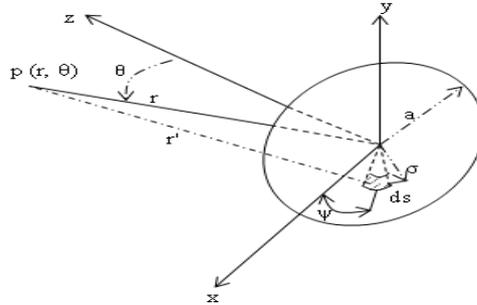


Fig. 2. Coordinate system used in calculating the sound-pressure field of a circular transducer

For the diathermy applicator used in this work, Fig. 1 (a), the pressure at the observation point will be the total contribution from the circular transducer and a group of several external annuli, located at distinct planes, modeling the rim of this applicator, as presented in the Fig. 1 (b).

The total pressure can be written as

$$p(x, y, z) = \frac{j\rho ck}{2\pi} U_0 \int_S \frac{e^{j(\omega t - kr')}}{r'} dS + \sum_{n=1}^{Nr} \left(\frac{j\rho ck}{2\pi} U_0 \int_{S_n} \frac{e^{j(\omega t - kr'_n)}}{r'_n} dS_n \right) \quad (2)$$

Where r'_n is the distance from a point on the n_{th} ring to the field point of interest, and S_n is the area of the n_{th} ring. The integrals in equation (2) are evaluated using Huygen's principle and summing the contributions from incremental areas composing the circular transducer and the rings [13,14]. The first term in the Eq. (2) corresponds to the acoustic pressure field due to a circular transducer and the second term corresponds to the acoustic pressure field due to the applicator rim.

In the area very close to the rims of these type of applicators, it has been experimentally appreciated that the pressure amplitudes of the ultrasonic field, coming of the rim zone, are weaker, while the hydrophone is moving away from the radiation face. For this reason, different amplitudes of the pressures over the rings, emulating the applicator rim, have been used during the acoustic field computation. In order to approach these non-uniform radiations over the rim zones, the second term of Eq. (2) has been multiplied by the expression (3).

$$a(n) = e^{-5(n/Nr)^2} \quad (3)$$

where, n ($n=1, 2, \dots, Nr$) refers to each peripheral ring, and Nr is the total number of rings. The first ring is located close to the radiating face perimeter.

The Eq. (2) becomes,

$$p(x, y, z) = \frac{j\rho ck}{2\pi} U_0 \int_S \frac{e^{j(\omega t - kr')}}{r'} dS + \sum_{n=1}^{Nr} a(n) \cdot \left(\frac{j\rho ck}{2\pi} U_0 \int_{S_n} \frac{e^{j(\omega t - kr' r'_n)}}{r'_n} dS_n \right) \quad (4)$$

The Eq. (4) was used to simulate the acoustic field radiated by such diathermy applicator, approaching the complex observed real acoustic field. The integrals in this equation were evaluated numerically in a similar way to that of Zemanek [13]. The aperture radius of the circular transducer is 16 mm; the speed of sound in water used is 1500 m/s; the applicator nominal frequency is 1.15 MHz. We have supposed the rim of our particular ultrasonic transducer was composed by a number of thin rings, Nr , with a width, w_r , separated among them a depth (Sep), emulating a conical surface as the rim of the ultrasonic applicator.

RESULTS AND DISCUSSION

The authors have previously studied the behaviour of radiation patterns radiated by two commercial ultrasonic therapy applicators, of the same manufacturing series and model, when they are radiating into water. One of those applicators, LOT99137, was considered to have a relatively regular amplitude distribution over all the radiating aperture [12]. We have considered this applicator, to be studied in this work. The most important region of interest to be analyzed in the diathermy applicators field is the near zone. A transverse cross-sectional scanning at the very near zone has been performed for the applicator under quasi-CW ultrasonic pulses. Fig. 3 (a,b), shows the contour representation in an area of (75X75) mm at a depth close to the emitting surface ($z=3$ mm), obtained without and with an opaque screen having an aperture for the nominal emitting surface, and that is placed in front of the irradiating surface.

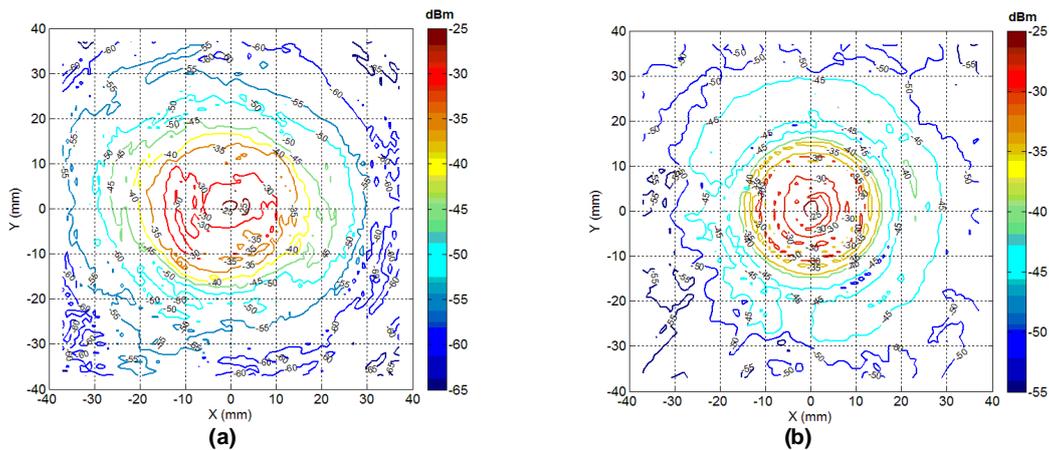


Fig. 3. A contour representation of experimental pressure field distribution, measured at the plane $z=3$ mm, radiated by Carin LOT99137 in a water tank ($f=1.15$ MHz, 32 mm in diameter applicator, and a quasi-CW excitation with 50 μ s tone burst). a) without screen. b) with an opaque screen having an aperture.

In Fig. 3, it can be appreciated a clear behavior differences between two contour representations of the radiation patterns at this distance ($z=3$ mm). The pressure levels in the radiating distribution, over the aperture plane, have a range around -12-15 dBm in both cases.

Further, the maximum radiation levels can be observed at the central zone of the nominal aperture decaying toward the periphery of the emitting surface. Fig. 3 (b), shows the distribution of the acoustic field with the presence of an opaque screen with an aperture located in front of the irradiate surface, have a good symmetric behavior in the amplitude distribution over the entire radiating aperture. In contrast to it, in Fig. 3 (a), the pressure field distribution, obtained without using the opaque screen, has a very notable and anomalous irregularity, as well as a poor symmetric behavior in the amplitude distribution over the aperture plane. According to the experimental results, we can emphasize that the radiations coming from the applicator's rim have been attenuated in the screen opaque and the acoustic field distribution has not been affected by those anomalous radiations. The experimental results obtained with an opaque screen having an aperture, may explains the existence of the possible anomalous radiations, coming outside of the nominal aperture, which are involved in the perturbation of the effective radiation patterns. Even so, the distribution of the radiation patterns at this distance is not as that theoretically predicted for a plane piston. We still can observe in Fig. 3(b) the non-uniform radiations distribution from the aperture plane, and some notable lateral lobes around the nominal aperture. It would be produced, possibly, by some radiation coming from a non-ideal radiator part, or by anomalous vibration modes in PZT resonator, or by certain extra-vibrations induced on the applicator external structure. Considering this, further experimental research efforts must be made to explain in detail the origins of those anomalous radiations.

For calculating the ultrasonic field radiated by this abovementioned applicator, an improved modelling of the device vibrations has been used, approaching the complex real acoustic field. Although we have previously studied the influence of the rings in the effective acoustic fields, the influence of the numbers of rings, N_r , considering different sizes in their widths, w_r , on the radiation patterns behavior, had not been reported.

First, the influence of the number of rings, without taking in consideration the non-uniform pressure radiation over the rim, was examined. Fig. 4. (a,b), shows the axial pressure fields for various rings with two different widths. The separation between the rings in depth, Sep , is 1 mm for $w_r=1$ mm, (Fig. 4. a), and 2 mm for $w_r=2$ mm, (Fig. 4. b).

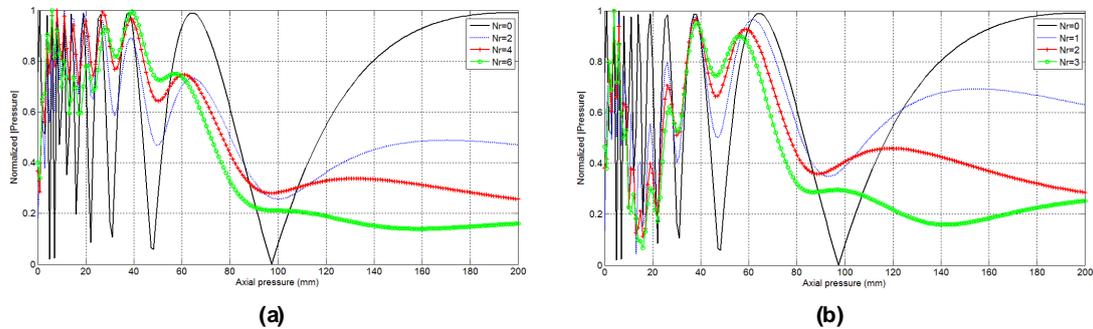


Fig. 4. Normalized axial pressure fields with uniform pressure over the rings, under continuous cw-excitation, $f=1.15$ MHz, radius=16 mm. (a) $w_r=1$ mm and $Sep=1$ mm. (b) $w_r=2$ mm and $Sep=2$ mm.

In Fig. 4 (a,b), it can be appreciated that, in both cases, the influence of N_r on the axial pressure fields, is very significant. A comparison of these two figures shows little differences in the behavior of the axial pressure fields.

A numerical calculation of the axial pressure fields, taking into account non-uniform pressure radiation over the rim, has been made, considering the same conditions as presented in Fig. 4 (a,b). The behaviors of these axial pressure fields are plotted in Fig. 5. (a,b).

The influence of N_r on the axial pressure fields for this case, is still present. Also, some differences in the behavior of the axial pressure field, have been observed, comparing Fig. 5 (a) and Fig. 5 (b). Besides, along the propagation axis, there is a much better agreement for the non-uniform case than for the uniform case, for the maxima and minima of the axial pressure.

The values of the maxima and minima of the axial pressure decrease and increase respectively, in general, when the numbers of rings increase.

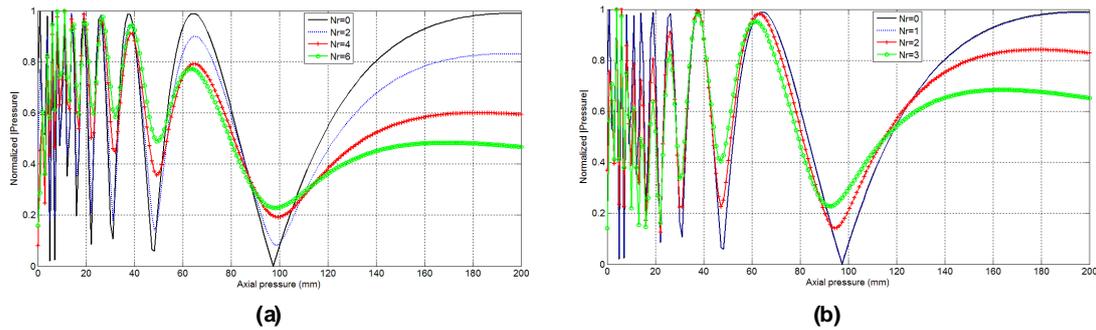


Fig. 5. Normalized axial pressure fields with non-uniform pressure over the rings, under continuous cw-excitation, $f=1.15$ MHz, radius=16 mm. (a) $w_r=1$ mm and Sep=1mm. (b) $w_r=2$ mm and Sep=2mm.

The behavior of the axial pressure field calculated with $N_r=6$ mm, and $w_r=1$ mm, taking into account the non-uniform vibration over the rings, seems to be more correlated with the experimental measurements in the LOT99137 device, reported in [12].

In order to analyze better the influence of the number of rings in the radiation patterns, transversal cross-section at $z=3$ mm with dB-contour representations of pressure field radiations are presented. Fig. 6. (a,b) shows these representations, for an ideal circular piston and for a circular transducer with six external annuli, considering 1mm for both values of w_r and Sep. The vibration over the rings has been non-uniform.

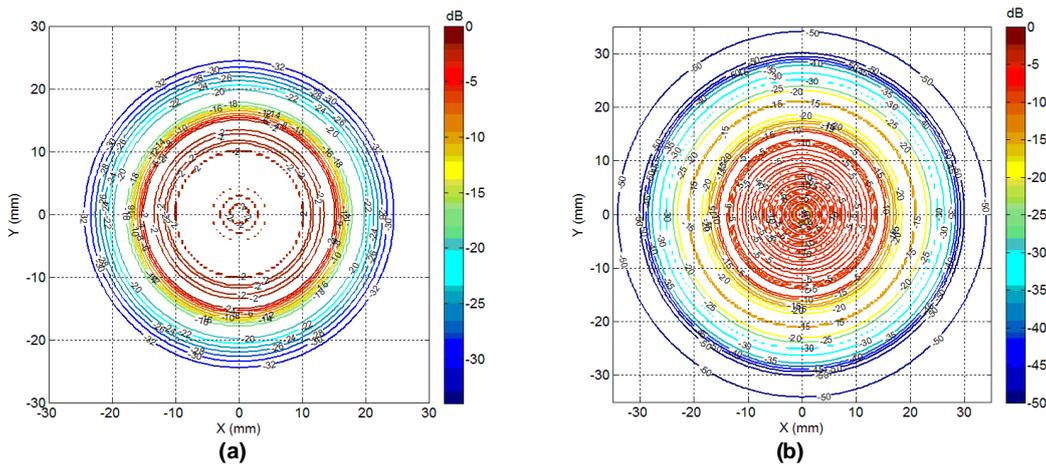


Fig. 6. dB-Contour representations of pressure fields distribution at the plane $z=3$ mm, under continuous cw-excitation, radiated by (a) ideal circular piston and (b) circular transducer and 6 rings elements, with non-uniform pressure over the rings. $f=1.15$ MHz, radius=16 mm, $w_r=1$ mm and Sep=1mm.

A comparison of these two figures (Fig. 6 (a) and (b)), shows a strong influence of the rings on the pressure field distribution. Further, it can be appreciated that the width of the radiation patterns increases with the rings presence. Finally, the numerical calculations show that the rings added to a circular transducer affects their effective acoustic field. Taking in account this fact, this type of radiations have to be avoided, in order to use any physiotherapy applicator in a more effective and proper way.

CONCLUSIONS

Anomalous radiations coming from the rim of a commercial physiotherapy applicator, and observed in their near field, have been analyzed and discussed. These radiations were studied using, as an obstacle against them, a screen with an aperture in front of the radiator surface.

The experimental procedure used in this work, shows the implication of these radiations in the effective acoustic fields radiated by this applicator. Numerical calculations show a strong influence of the rings number on the acoustic fields, with uniform radiation and also for non-

uniform radiations. These anomalous radiations coming from the rings could reduce the accuracy in order to predict the selected treatment areas, as well as they could create undesired radiations attaining healthy tissues.

An improvement in therapy applicator design is necessary. Additionally, further research efforts must be made to explain more in detail the origins of the observed anomalous radiations.

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