BOLETIN DE LA SOCIEDAD ESPAÑOLA DE
Cerámica y Vidrio
ARTICULO

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Ultrasonic transducers with resonant cavities as emitters for air-borne applications

A. OCTAVIO MANZANARES*, F. MONTERO DE ESPINOSA FREIJO

Instituto de Acústica, Consejo Superior de Investigaciones Científicas (CSIC), Serrano, 144, 28006 Madrid, Spain

In this work a new proposal to improve the emission efficiency of air-borne ultrasonic transducers is introduced. A theoretical ultrasonic transducer design is studied using a piezoelectric membrane and a Helmholtz resonator with two acoustic ports. The resonator provides radiation in the acoustic ports in phase with that of the membrane. Several finite element simulations and experimental results are used to study the device. The finite element models were used to compare its behaviour with that of conventional vacuum-cavity transducers. These results show an improvement in the bandwidth reaching a quality factor value of 19. Furthermore, the experimental measurements were used to study the effects of the resonant cavity in the response. Several measurements for different cavity depths were performed. The results show an improvement of 25 dB in the emitted pressure through tuning the transducer.

Keywords: cMUT; pMUT; air-borne transducer

Transductores ultrasónicos con cavidades resonantes como emisores en aplicaciones en aire

En este trabajo se presenta una nueva propuesta para mejorar la eficiencia de transductores ultrasónicos acoplados a aire. Para este estudio se ha empleado un diseño teórico de transductor ultrasónico que utiliza una membrana piezoeléctrica y un resonador de Helmholtz con dos puertos acústicos. El resonador hace que la radiación en los puertos acústicos se encuentre en fase con la producida por la membrana. Para estudiar el dispositivo se utilizaron resultados obtenidos mediante programas de elementos finitos y resultados experimentales. Por un lado, los modelos de elementos finitos se utilizaron para comparar el comportamiento del dispositivo con el de transductores convencionales con cavidades al vacío. Estos resultados indican una mejora en el ancho de banda alcanzando valores de factor de calidad de 19. Por otro lado, los resultados experimentales se emplearon para identificar los efectos de la cavidad resonante en el funcionamiento del dispositivo. Para ello se realizaron varias medidas utilizando ciertas profundidades de cavidad. Los resultados muestran una mejora de 25 dB al afinar el transductor utilizando la cavidad más apropiada.

Palabras clave: cMUT; pMUT; transductor acoplado a aire

1. INTRODUCTION

Ultrasonic transducers employ different physical principles. Particularly, piezoelectric (1-2) and electrostatic (3-4) ultrasonic transducers have been made and used for many air-borne applications. Authors such as Schindel et al. (5) or Adamowski et al. (6) developed electrostatic ultrasonic transducer designs based on grooved back plates. Schindel et al. designed a micromachined silicon back plate allowing higher frequency transducers. These have several holes in the back plate defining the resonance frequency at approximately 1 MHz. Higher frequency devices such as capacitive micromachined ultrasonic transducers (cMUTs) (7) and piezoelectric micromachined ultrasonic transducers (pMUTs) (8-9) have been developed in recent years. Nevertheless, most of them have been used for immersion applications (10-12). Working in the ultrasonic range in air is problematic due to the attenuation in the medium.

In this work, a frequency scaled prototype made to study how to improve the acoustic behaviour in air for high frequency ultrasonic transducers is reported. The device basically consists of a thin PZT membrane (the diaphragm) mounted over one end of a short duct closed at the opposite end to form an enclosured cavity (Fig. 1). This frequency scaled transducer was made to avoid the manufacture of an expensive micromachined ultrasonic transducer (MUT) for this study. This is because the transducer that would be required to perform the measurements described here on a conventional MUT would need to have an aperture size of approximately one micron. Such transducers are not available. A PZT based device is used instead of an electrostatic transducer to make the measurements and the fabrication easier. The diaphragm is a squared shaped membrane which has special boundary conditions. It has two free opposite edges while the others remain clamped. This geometry provides two acoustic ports at the open edges of the membrane acoustically connecting the medium to the cavity. This transducer works like a Helmholtz resonator (13). This is basically an enclosure with an open hole where a resonance is produced due to the spring effect of the air in the cavity. Using this idea, improvements in the efficiency and bandwidth can be obtained by fixing the size of the acoustic ports at the free edges of the membrane and adjusting the volume of the cavity. A device working under the same principle was described by Horowitz et al. (14) but using a PZT disc mounted at the back of the enclosure. This device works as a part of an energy harvester. It converts acoustic energy into electric energy through the vibration of the PZT disc in the enclosure. Moreover, if this device worked as an emitter the acoustic radiation would be only produced in the acoustic port of the resonator. The device presented here has significant differences. In this case, the acoustic radiation will take place from the membrane as well as from the acoustic ports. Furthermore, the resonator provides radiation from the acoustic ports in phase with that of the membrane. This is possible by equalling the resonant frequency of the membrane f_m with the frequency of the resonator f_H. This frequency is named as Helmhotlz frequency and is given by

$$f_H = \frac{c}{2\pi}\sqrt{\frac{A}{V\left(l+\delta\right)}} \qquad [1]$$

where c is the speed of sound in air, A is the equivalent area of the aperture formed by the acoustic ports, V is the volume of the cavity, l is the length of the port or in this case the thickness of the membrane, and δ is an end correction of the aperture that forms the two acoustic ports (13). The radiation occurs out of phase when a difference between f_m and f_H exists. For instance, when the cavity is much smaller than the wavelength, the phase shift reaches 180 degrees. For this reason, a previous calculation of the dimensions of the cavity and the resonant frequency of the membrane is required to make the device work properly. Finite element (FE) modelling is used to calculate the dimensions necessary to tune the system.

2. DEVICE DESCRIPTION

A schematic of the transducer is depicted in Fig. 1. The membrane was manufactured from a commercial piezoelectric speaker (CERAMITONE®). This consists of a 0.05 mm thick, 25 mm diameter PZT-5A disc bonded on a 0.1 mm thick, 50 mm diameter brass plate. The soft type PZT-5A ceramic generally presents higher mechanical losses which imply a greater bandwidth. This suits the requirements of the final transducer which has to generate short time signals for its application. The speaker was cut to obtain a square membrane with 30 mm sides. Lateral 0.5 mm wide holes on the two opposite edges of the membrane were cut to form the acoustic ports. This membrane was bonded at one end of a 100 mm long aluminium duct with square cross section with 30 mm sides using Araldite® Rapid. The rigidity of this adhesive will affect the membrane resonance frequency value; the more rigid

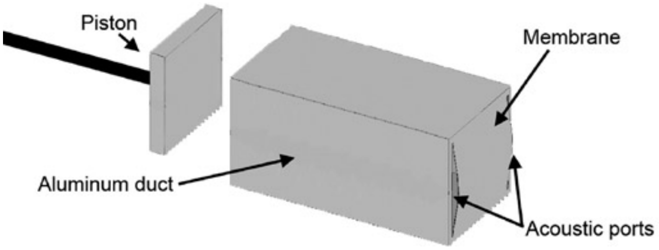

Fig. 1. Schematic of the transducer prototype.

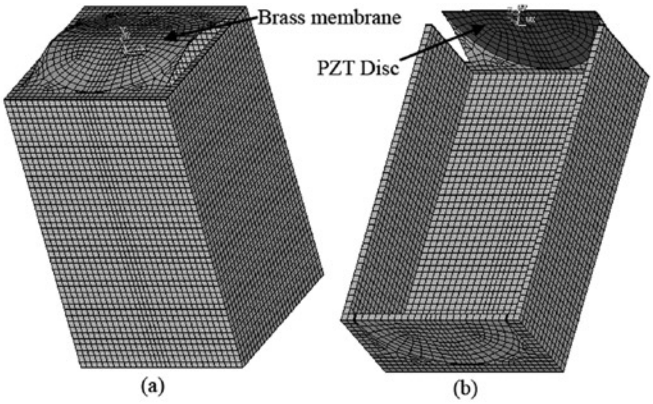

Fig. 2. (a) FE model of the studied device (HR_MUT). (b) Section of the transducer showing the PZT disc underneath the membrane

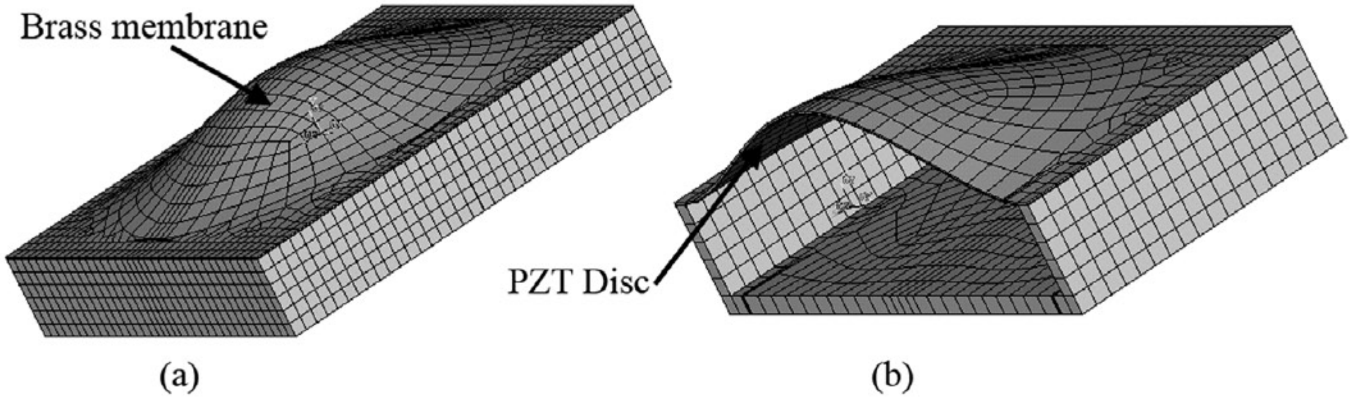

Fig. 3. (a) FE model of the conventional MUT type transducer (FS_MUT) with the brass membrane clamped on all edges. (b) Section of the transducer showing the PZT disc underneath the membrane.

the adhesive is, the higher the frequency is. An electrical connection was made to the exposed surface of the PZT-5A using a 4mm-wide silver sputtered line across the diameter of the disc. This electrode shape is made to enhance the pure cylindrical first resonance mode of the membrane. The cavity is closed by a piston capable of sliding along the length of the duct to change its volume. The capability of changing the cavity volume facilitates the study of the most important issues that must be taken into account when designing devices such as MUT transducers using a resonator. Due to its dimensions, this device works in the audio range. However, it is possible to extrapolate the results of this macro-scaled transducer to a micro-scaled device assuming that the micro-scaled device fulfils the relation in Eq [1], and the membrane boundary conditions and the mode shape both remain the same.

3. RESULTS AND DISCUSSION

3.1 FE modelling

Two FE models were built using a commercial package (ANSYS 8.0, ANSYS Inc., Canonsburg, PA). The first model was made to study the behaviour of the transducer with the Helmholtz resonator (denoted HR_MUT) in air (Fig. 2). The other model represents a frequency scaled design of a conventional MUT transducer (denoted FS_MUT) (Fig. 3). The FS_MUT was built with a vacuum underneath a square shaped PZT membrane clamped on all edges. Using both models, it is possible to calculate the electrical impedance, displacement and the emitted pressure of each transducer.

First, the HR_MUT model was used to calculate the appropriate dimensions necessary to tune the membrane with the resonator. A conventional method of tuning a Helmholtz resonator consists of calculating the electrical impedance and adjusting the cavity volume or the acoustic port length until two resonance peaks appear in the real part of the impedance spectrum. This occurs when f_H is approximately the same value as the membrane resonance frequency f_m. In this situation, the frequency of the null between peaks corresponds to f_H. This effect is shown in Fig. 4(a) for a cavity depth of 45 mm in the HR_MUT model. This figure also shows the simulated electrical impedance of the FS_MUT transducer. A 1 volt amplitude sinusoidal driving signal was applied to both models. The impedance of the tuned HR_MUT transducer presents a lower value of resistance and a wider bandwidth. This means that as f_m reaches f_H, the velocity of the membrane tends to zero (Fig. 4(b)). At frequencies around the resonance, the displacement of the FS_MUT membrane is approximately ten times larger than that for the studied device. However, this difference is not as large when analyzing the sensitivity (Pa/V) for both transducers (Fig. 4(c)). The sensitivity was evaluated at 30 mm from the centre of each membrane in order to reduce near-field effects. The HR_MUT transducer has a maximum sensitivity of -8.5 dB with respect to the maximum obtained with the FS_MUT transducer. Nevertheless, a wider band is seen in air for the HR_MUT transducer. It has a quality factor, Q, of approximately 19 while the conventional MUT type presents a Q value of around 80. Moreover, if both models were electrically driven to obtain the same membrane peak displacement, the emitted pressure would be as depicted in Fig. 5. The HR_MUT model was driven with a 1 volt amplitude continuous wave while a 0.1 volt amplitude was used to excite

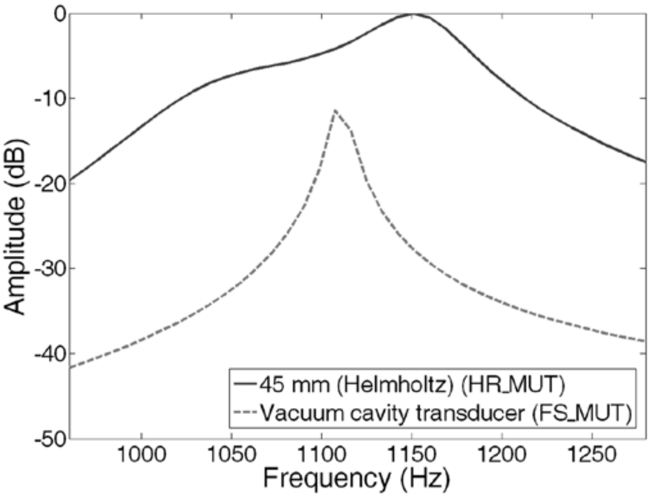

Fig. 5. Amplitude of the simulated emitted pressure for the same membrane peak displacement for both transducers

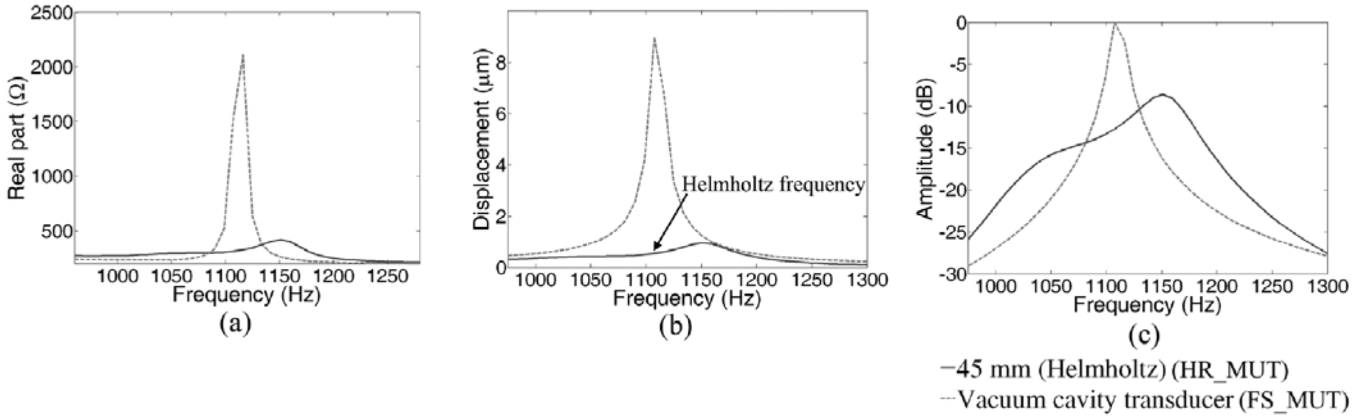

Fig. 4. (a) Real part of the simulated electrical impedance of the tuned HR_MUT transducer with a cavity depth of 45 mm and that for the FS_MUT transducer. (b) Displacement at the membrane centre of both transducers. (c) Amplitude of the simulated sensitivity (Pa/V) in dB for both transducers.

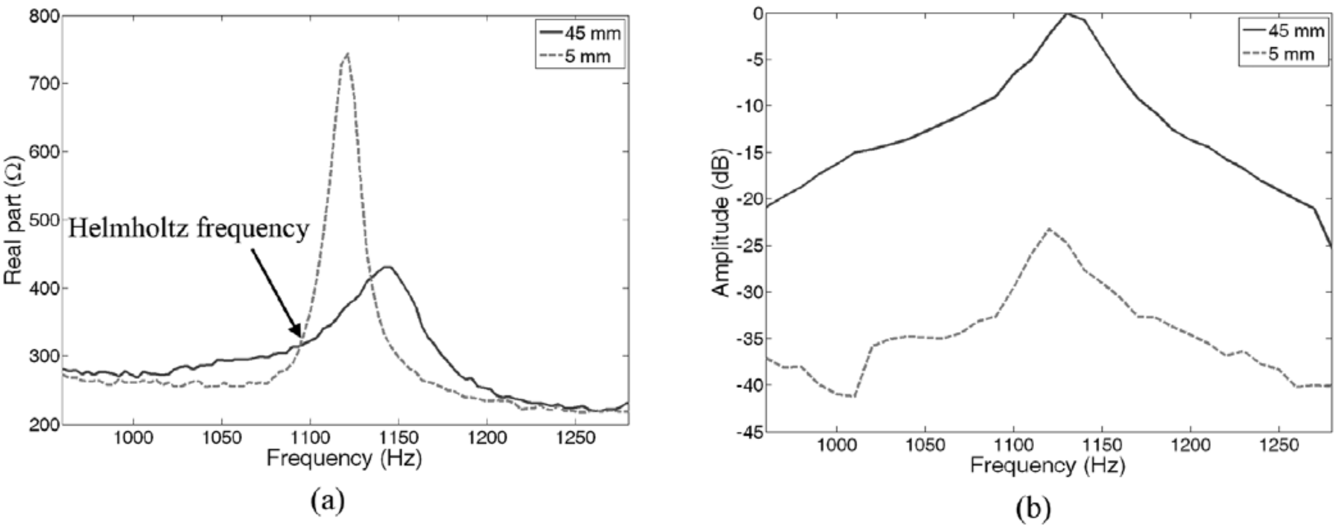

Fig. 6. (a) Experimental measurement of the real part of the electrical impedance of the device with a cavity depth of 45 mm (corresponding with the Helmholtz frequency) and with a cavity depth of 5 mm. (b) Amplitude of the emitted pressure for both cases.

the FS_MUT. Under these conditions, the FS_MUT transducer emits a pressure wave with maximum amplitude -15 dB with respect to that emitted by the HR_MUT transducer. This demonstrates that the proposed design has a greater effective active surface. As seen in the next section, this occurs because in the tuned HR_MUT transducer, the acoustic radiation predominantly comes from the acoustic ports. Moreover, the radiation is in phase with that of the membrane.

3.2 Experimental results

The performance of the HR_MUT transducer prototype was studied using three measurements. First, the electrical impedance was measured to identify the cavity size required to match f_m with f_H. An Agilent 4294A precision impedance analyzer was used for this purpose. A 1 volt amplitude continuous wave driving signal was applied to perform this measurement. When there is a difference between the frequencies, a single resonance peak appears (Fig. 6(a)). Nevertheless, when the system is tuned two impedance peaks appear. This occurs for the same cavity depth obtained with the FE simulations (45 mm). Once the system was tuned, the second measurement was performed. The pressure at 25 mm from the centre of the piezoelectric membrane was measured using a Fonestar electret condenser microphone FOX-2214. A 1 volt amplitude sinusoidal signal was used to excite the transducer. A comparison between the pressure emitted from the tuned system and that of an untuned system (shown here with a cavity depth of 5 mm) is illustrated in Fig. 6(b). An improvement of 25 dB is seen when the system is tuned and approximately the same bandwidth in both cases. Finally, a linear scan of the pressure over the membrane in both cases was performed to measure the radiated pressure near the surface using the same microphone mounted on a motor controlled translation stage. The transducer was excited by a 1 volt sinusoidal wave of frequency f_H. The results are shown in Fig. 7. A change in the grey scale from white to black in front of the acoustic ports can be observed along the x-axis in Fig. 7(a) indicating a change of phase of 180º at these locations. This means that the pressure emitted from the acoustic ports is out

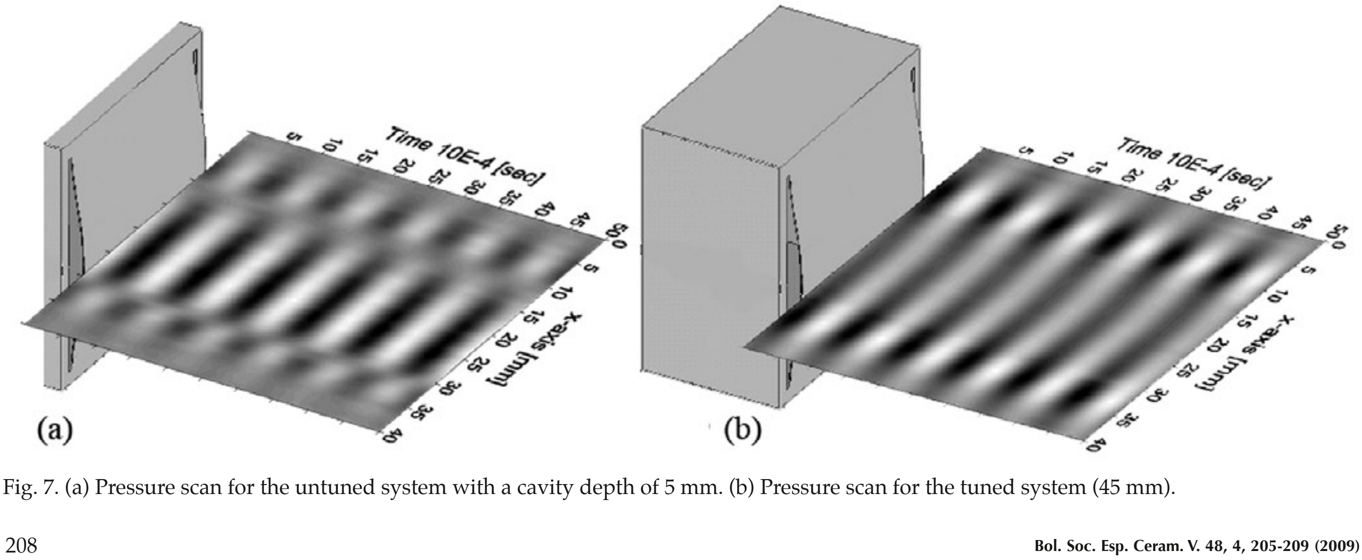

Fig. 7. (a) Pressure scan for the untuned system with a cavity depth of 5 mm. (b) Pressure scan for the tuned system (45 mm).

of phase with that from the membrane in this case. The result of the scan when the system is tuned is shown in Fig. 7(b). In this case, the emitted pressure from the acoustic ports is in phase with that from the membrane. This demonstrates that the proposed design effectively has a greater active surface. This figure also shows a higher pressure at the acoustic ports. This demonstrates that at f_H, the velocity of the membrane decreases causing the radiation to be predominantly from the acoustic ports.

4. CONCLUSIONS

In this work, a new proposal of air-borne ultrasonic transducers has been presented. A theoretical ultrasonic transducer design has been made to study how to improve the acoustic behaviour in emission. FE simulations and several electric and acoustic measurements have been performed to study the prototype. The membrane presents a large active surface due to its boundary conditions. Moreover, the effect of the Helmholtz resonator effectively makes this active surface increase. This is because the pressure emitted from the acoustic ports is in phase with the radiation from the membrane. Comparing the experimental measurements of the tuned device with that of the transducer with a smaller cavity volume, an improvement of 25 dB is seen in the amplitude of the emitted pressure for the tuned device. Furthermore, FE models have been used to compare the tuned device and a frequency scaled conventional MUT type transducer (FS_MUT). The bandwidth in air increases reaching values corresponding to a quality factor of approximately 19. The FS_MUT transducer has higher sensitivity (Pa/V) but it is seen that for the same membrane peak displacement, the presented transducer improves the emitted pressure of the conventional transducer by 15 dB. All these indicate that it is possible to improve the acoustic performance in air of ultrasonic transducers such as cMUTs or pMUTs. For the particular case of a cMUT transducer, a special design of the transducer cavity with a fixed bottom electrode is required. Further work is needed to develop an electrostatic ultrasonic transducer using this idea.

ACKNOWLEDGMENT

The authors acknowledge funding from Grant DPI2007-65408-C02.

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Recibido: 5-6-09
Aceptado: 15-7-09

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