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BEYOND THE GEOMETRICAL FOCUS IN FOCUSED ACOUSTIC BEAMS

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INTRODUCTION

The study of the acoustic field characteristics generated by focusing sources, both in linear and nonlinear regime, is an active field of research as they are relevant in most of the ultrasonic applications in medicine and industry. Particularly, the **linear shift** phenomenon (the distance between the geometrical focus of the focused source and the on-axis maximum pressure position in linear regime, real focus) was explained by Lucas and Muir in 1982 and corrected by Makov et al. in 2006 based on the parabolic approximation to the ordinary wave equation. Also, the **nonlinear shift** phenomenon (the movement of the pressure maximum position along the axis of focused acoustic beams under increasing driving voltages) has been related and interpreted in previous works. In this work we evaluate (experimentally and numerically) the nonlinear shift of an ultrasonic beam with medium Fresnel Number (NF = 6, some medical devices are in this focusing region), as well as we demonstrate that the nonlinear shift is able to move the on axis maximum pressure location beyond the geometrical focus.

MATERIAL AND METHODS

Experimental Setup

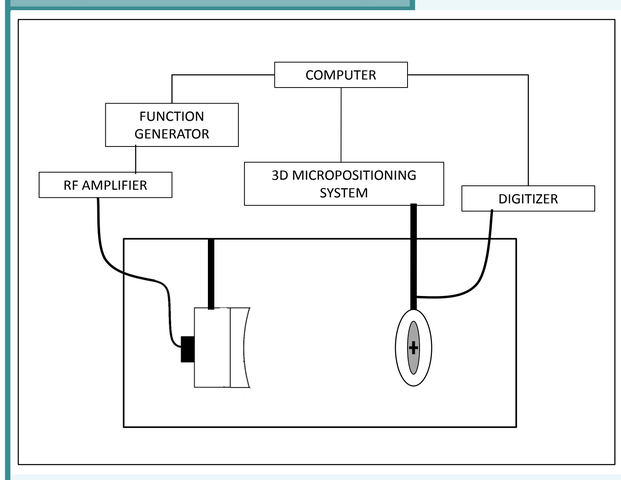


Figure 1. Experimental desing for acoustic pressure measuring in water.

- **Function Generator:** PXI5412, 14 bits, 100 MS/s, National Instruments.
- **RF Amplifier:** ENI 1040L, 400 W, +55 dB, Rochester.
- **Digitizer:** PXI5620, 64 MS/s, National Instruments.
- **Micropositioning System:** OWIS GmbH (Acuracy 10 µm)
- **Water Tank**: (60x40x38 cm).

- **TRANSMITTER:** PZ26 (Ferroperm Piezocerámics) + Methacrylate focused lens (diameter ϕ=50mm; radius of curvature R=70mm)
  - $\mathbf{f_0}$= 2.227 MHz
  - **2a**= 50 mm
  - **F**=157.0 ± 1.5 mm (Geometrical Focal Length)
- **RECEIVER:** Membrane Hidrophone (MH2000B, NTR/Onda Corp, 200µm active diameter)
- **Measurament Procedure:** Acoustic waveforms were evaluated in 25 transversal planes (6x6mm) to the transmitter axis with 0.25 mm spatial resolution

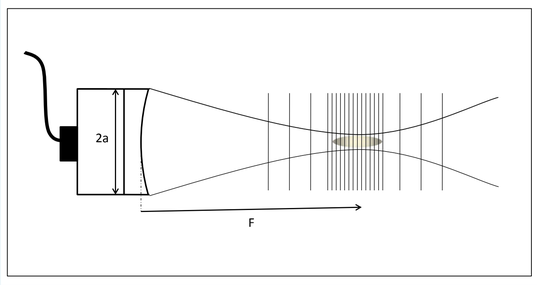


Figure 2. Measuring plan.

Numerical Model

- Numerical modelling of the experiment was performed using the **KZK equation** for axisymetric beams:

$$\frac{\partial^2 p}{\partial z \partial t'} = \underbrace{\frac{c_0}{2}\left(\frac{\partial^2 p}{\partial r^2} + \frac{1}{r}\frac{\partial p}{\partial r}\right)}_{\text{Difraction}} + \underbrace{\frac{\delta}{2c_0^3}\frac{\partial^3 p}{\partial t'^3}}_{\text{Absorption}} + \underbrace{\frac{\beta}{2\rho_0 c_0^3}\frac{\partial^2 p^2}{\partial t'^2}}_{\text{Nonlinearity}}$$

- $t'=t-z/c_0$: a retarded time
- c_0 : propagation speed
- δ : sound diffusivity
- β : coefficient of nonlinearity
- ρ_0 : ambient density of the medium

RESULTS

Linear Characterization of the beam

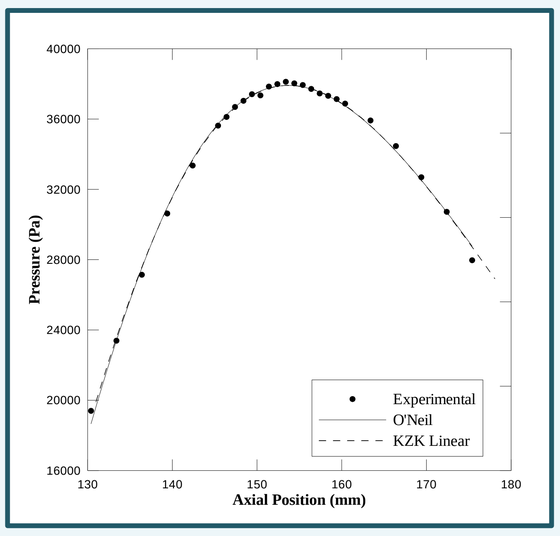


Figure 3. On axis pressure distribution in linear regime. Experimental values, analytical O'Neil expression and KZK simulation.

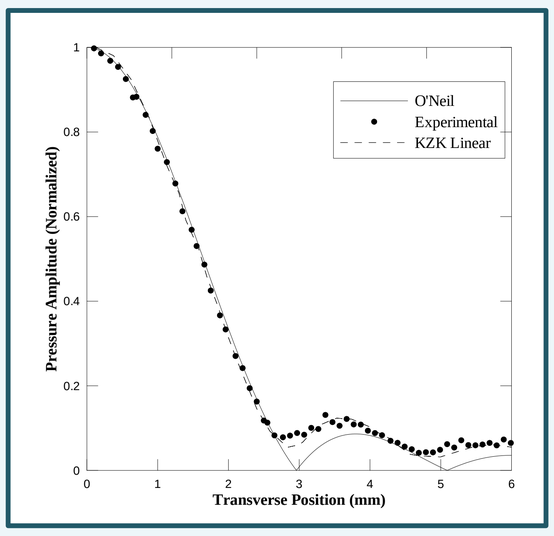


Figure 4. Transversal normalized pressure. Experimental values, analytical O'Neil expression and KZK simulation.

The linear characterization of the beam allows us to know the characteristics of our acoustic source (aperture and geometrical focus) and the position of the on-axis maximum pressure, i.e., the **LINEAR SHIFT**.

1. Nominal values ⟶ F=157 mm; 2a=50 mm; N_F=5.9; G=19
2. Analitic O'Neil Solution ⟶ F=158.2 mm; 2a=51.6 mm;
3. Numerical Simulation KZK ⟶ F=157 mm; 2a=50.2 mm

The **on axis maximum pressure** obtained from the analytic expression is located at 153 mm from the transducer, i.e. the 96.7 % of the geometrical focal length, what is in good agreement with the value of the linear shift predicted by Makov et.al.

Beamwith

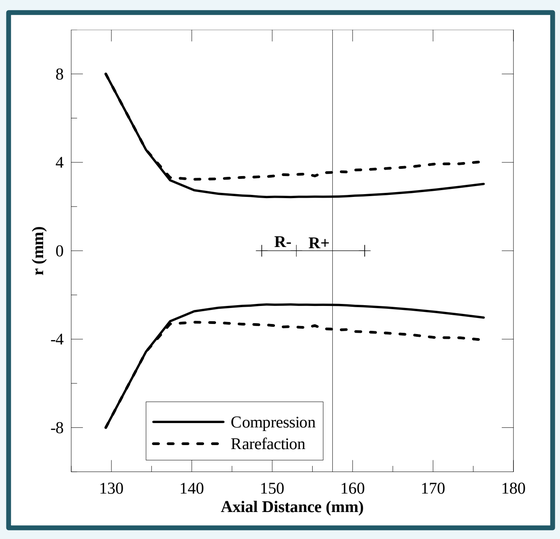


Figure 7. Half amplitude beam shapes, for positive (solid lines) and neative pressures (dashed lines). Experimental values, p_0=67 Kpa. R+ y R- denote the movement range of maximun and minimun pressure respectively.

Figure 7 shows the two beam pressure profiles for compression and rarefracción. The beam width was defined at -6 dB of the maximum pressure in the plane. R + and R-denote the movement range of maximum and minimun pressure respectively with increasing voltage.

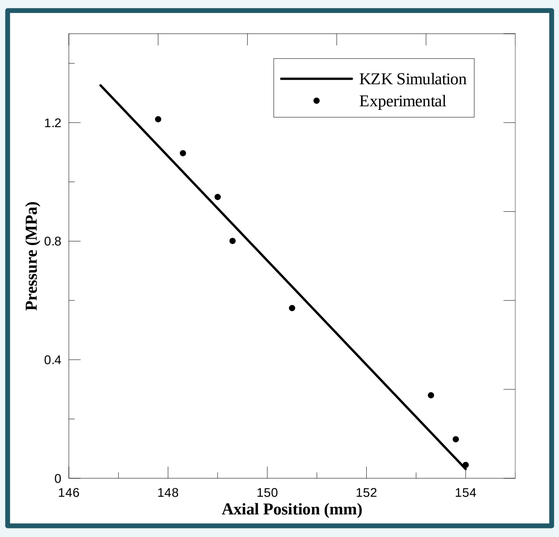


Figure 6. On axis minimun pressure. Experimental values (points) and KZK simulation (solid line). Input values are 2, 9, 21, 45, 65, 85, 100 and 125 V_{pp} from bottom to the top.

Nonlinear Behavior

Experiment and **simulation** show (Fig.5) the same conclusions:

1. The on axis maximum pressure position **moves away** from the transducer when exciting power increases.
2. These positions can **surpass** the position of the **geometrical focus.**

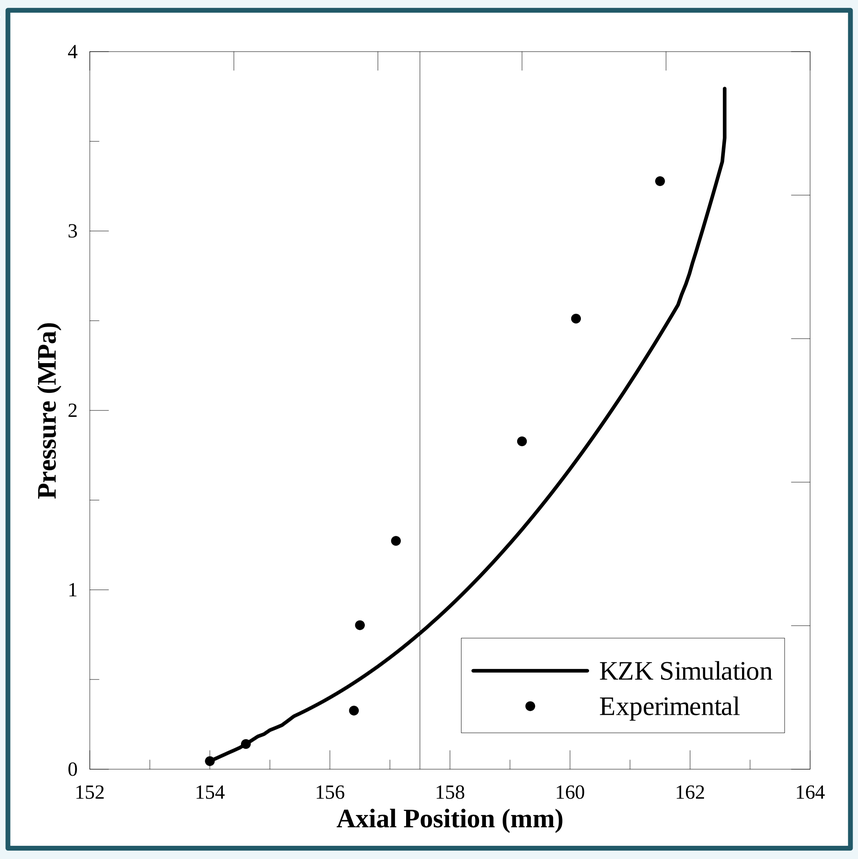


Figure 5. Variation of the on axis maximum pressure with the input voltage. Experimental values (points) and KZK simulation (solid line). Vertical line denotes the geometrical focus site in 157.5 mm. Input values are 2, 9, 21, 45, 65, 85, 100 and 125 V_{pp} from bottom to the top.

CONCLUSIONS

The acoustic field of a medium focused transducer (N_F = 6) has been studied in order to fix the characteristics of the **linear** and **non linear shift**. In linear regime it has been observed that the maximum pressure is located at 153 mm from the transducer, which indicates a **linear shift of 4.5 mm**. This agrees with Makov et al. results in their study about the dependence of the linear shift with the Fresnel number. In **nonlinear conditions** it has been observed a maximum pressure position displacement (both in experiment and simulation) due to the increasing input voltage, even **exceeding the geometric focus**. When maximum power is applied to the transducer the on axis maximum pressure position exceed the geometrical focus in 4 millimetres, and the separation between the on axis maximum and minimum positions is as far as 13.7 millimetres.

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