Non Lineal Effects in The Radiation Force Generated by Amplitude-Modulated Focused Beams

Nuria González[1], Noé Jiménez[1], Javier Redondo[1], Bernardino Roig[1], Rubén Picó[1], Victor Sánchez-Morcillo[1], Elisa E. Konofagou[2,3] and Francisco Camarena[1]

[1]Instituto de Investigación para la Gestión Integrada de Zonas Costeras, Universidad Politécnica de Valencia, Grau de Gandia, Valencia, Spain

[2]Department of Biomedical Engineering, Columbia University, New York, NY.

[3]Department of Radiology, Columbia University, New York, NY, USA.

ISTU 2011NYC AIUM

Background

Abstract

- We present a numerical study of the nonlinear effects on the value of the radiation force and the location of its maximum in water.
- The radiation force is induced by a typical HMI [1] AM focused ultrasonic transducer (Gain = 18, carrier frequency of 1 MHz and modulation frequency of 25 kHz)
- This study shows that both the value and the location of the force peak are affected by the nonlinear propagation of the ultrasonic waves.
- The AM modulation of the signal affects the location of the radiation force produced, as some of the periods of the fundamental signal have low amplitude.

Linear shift vs. nonlinear shift

The *nonlinear focal shift*, i.e. the displacement of the pressure and intensity maxima position of focused acoustic beams under increasing driving voltages, has been studied numerically and experimentally in water [2]

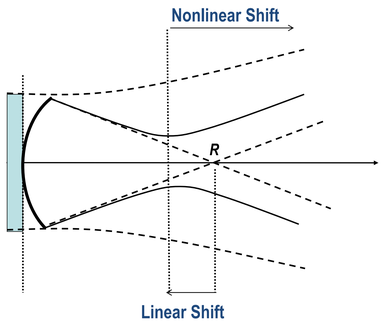


Fig1 Transversal representation of the acoustic field generated by a focused transducer.

Radiation Force

The radiation force in a viscous heat-conducting medium [3]:

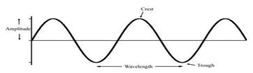
$$F_z = \frac{b}{c_l^5 \rho^3}\left(\frac{\partial p}{\partial t}\right)^2$$

$b = 0.0051$ Dissipation coefficient

$c_l = 1486\ \mathrm{m/s}$ Velocity of longitudinal waves

$\rho = 998\ \mathrm{kg/m^3}$ Density

In linear case (small-amplitude ultrasound) we obtain:



Sinusoidal wave

$$F_z^{lin} = \frac{\alpha p_0^2}{c_l^2 \rho^2} = \frac{2\alpha}{c_l \rho_0} I$$

$\alpha = 0.031\ \mathrm{Np/m}$ Absorption coefficient

I Wave intensity

p_0 Initial pressure

Methods

Beam Simulation

Numerical modeling was performed using the **KZK equation** for axis-symmetric beams [4]:

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

$t' = t - z_0$ Retarded time

δ Sound diffusivity

Linear focusing gain G	**18**
f-number	2.06
Fundamental Frecuency f_0	1 MHz
Carrier Frecuency f_m	25 kHz
Focal length d	144 mm
Radius of sound source	35 mm
Source pressure amplitud p_0	1-300 kPa

Table 1. Parameters used in the simulation

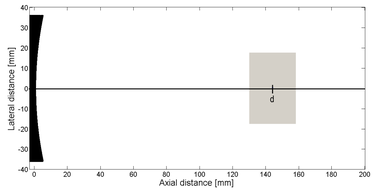


Fig. 2 Simulated transducer and studied area.

Excitation pulse:

$$p = p_0 \exp\left[-\left(\frac{\omega_0 t}{80\pi}\right)^{2000}\right]\left[1 + m\sin(2\pi f_m t)\right]\sin(2\pi f_0 t)$$

$\mathrm{m} = 50$ modulation index

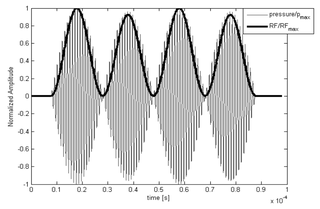


Fig. 3 AM excitation signal and its radiation force estimation (dark line)

Results

Radiation Force: Linear vs. nonlinear

The linear approximation for the radiation force underestimates the real value.

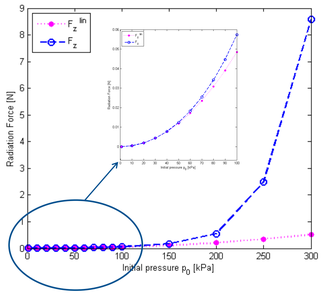


Fig. 4 Radiation force amplitude at different initial pressures.

The location of the on-axis maximum radiation force changes with exciting power.

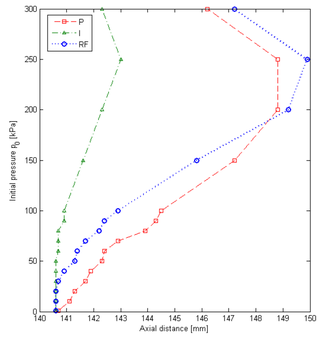


Fig. 5 Non linear on-axis focal shifts for pressure (8 mm), intensity (2.5 mm) and radiation force (9mm).

The waveforms

In AM signals, only the central periods are distorted during propagation:

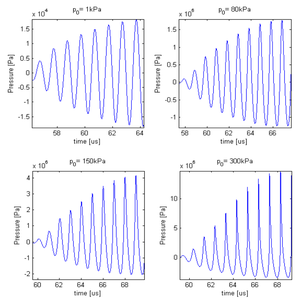


Fig. 6 Distortion of the waveform profile for p_0=1,80,150 and 300 kPa.

Modulation effects

Axial displacement of the radiation force maximum location during AM signal application.

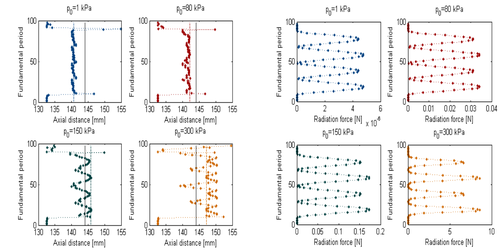


Fig. 7 On-axis location (left) and amplitude (right) of the radiation force maximum in each period at different initial pressures (p_0= 1,80,150 300 kPa).

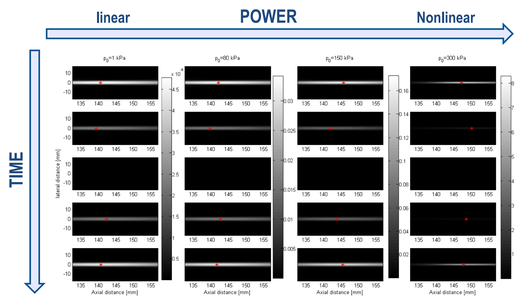


Fig. 8 2D simulated map of the acoustic radiation force shown every 5 μs at different initial pressures (p_0= 1,80,150 300 kPa. The red * marks the location of the axial maximum at each instant.

Conclusions

- Radiation force is affected by the nonlinear propagation, both in value and location.
- Regarding the nonlinear wave propagation, the force is no longer proportional to the intensity:
  - ✓ linear estimation differs by **an order of magnitude** when shock waves appear.
- As Intensity and Pressure, Radiation force is affected by the nonlinear shift (9 mm):
  - ✓ **Exceed geometric focal 5,5 mm**
  - ✓ **Backward motion of 2 mm**
- This spatial shift, becomes **dynamic** in AM focused beams.
- The nonlinear focal shift and the modulation of the exciting pulse can be used to affect the amplitude and the location of the radiation force.

Acknowledgements

This work was supported by the Spanish Government, under the Project FIS2008-06024-C03-03 and Programa de Apoyo a la Investigación y Desarrollo of the Universidad Politécnica de Valencia PAID-06-10-002-295, Spain.

References

[1] C. Maleke, M. Pernot, E.E. Konofagou. "Single Element focused US transducer method for HMI". Ultrasonic Imaging 28, 144-158, 2006.

[2] Y. N. Makov, V.J. Sánchez-Morcillo, F. Camarena, V. Espinosa "Nonlinear change of on-axis pressure and intensity maxima positions and its relation with the linear focal shift effect" *Ultrasonics* (2008), doi:10.1016/j.ultras.2008.03.007

[3].Y. A. Pishchalnikov, O. A. Sapozhnikov, and T. V. Sinilo, "Increase in the Efficiency of the Shear Wave Generation in Gelatin Due to the Nonlinear Absorption of a Focused Ultrasonic Beam". *Acoustical Physics, Vol. 48, No. 2, 2002, pp. 214–219*

[4].Y. S. Lee "Numerical solution of the KZK equation for pulsed finite amplitude sound beams in thermoviscous fluids" Ph. D. Thesis, The university of Texas at Austin, 1993.