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Nonlinear Effects in the Radiation Force Generated By Amplitude-Modulated Focused Beams

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Abstract. Harmonic Motion Imaging (HMI) uses an amplitude-modulated (AM) beam to induce an oscillatory radiation force before, during and after ablation. In this paper, the findings from a numerical analysis of the effects related with the nonlinear propagation of AM focused ultrasonic beams in water on the radiation force and the location of its maxima will be presented. The numerical modeling is performed using the KZK nonlinear parabolic equation. The radiation force is generated by a focused transducer with a gain of 18, a carrier frequency of 1 MHz and a modulation frequency of 25 kHz. The modulated excitation generates a spatially-invariant force proportional to the intensity. Regarding the nonlinear wave propagation, the force is no longer proportional to the intensity, reaching a factor of eight between the nonlinear and linear estimations. Also, a 9 mm shift in the on-axis force peak occurs when the initial pressure increased from 1 to 300 kPa. This spatial shift, due to the nonlinear effects, becomes dynamic in AM focused beams, as the different signal periods have different amplitudes. This study shows that both the value and the spatial position of the force peak are affected by the nonlinear propagation of the ultrasonic waves.

Keywords: Radiation Force; Amplitude modulated; Harmonic Motion Imaging; Non linear Shift
PACS: 62.65.+k, 81.70.Cv, 43.35+d, 02.70.Bf

INTRODUCTION

Harmonic Motion Imaging (HMI) [1,2] is a radiation-force technique that induces oscillatory displacements at the focal zone of an amplitude-modulated (AM) focused ultrasound (FUS) transducer for the detection of localized stiffness changes. The acoustic radiation force (RF) is defined as a period-average force exerted on a medium by a sound wave [3]. When an ultrasonic wave experience absorption and scattering in the course of its propagation, it transfers part of its momentum to the medium. As a consequence, an amplitude-modulated wave can be used to generate low frequency elastic stresses in the medium [4]. When the transverse dimension of the beam is much smaller than the absorption length, we can ignore the transverse component of the force F_r because of its smallness in comparison with the longitudinal component F_z. In

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this case, the force of radiation pressure, in a viscous heat-conducting medium, can be written in the form [5]

$$F_z = \frac{b}{c_0^5 \rho_0^3} \overline{\left(\frac{\partial p}{\partial t}\right)^2} \tag{1}$$

where c_0 is the velocity of the longitudinal waves, p is the acoustic pressure and b is the dissipation coefficient.

When small-amplitude sinusoidal ultrasound is used we obtain from Eq. 1:

$$F_z = \frac{2\alpha I}{c_0 \rho_0} \tag{2}$$

where α is the ultrasonic absorption coefficient and I the average acoustic intensity.

In this paper, a numerical analysis of the effects related with the nonlinear propagation of AM focused ultrasonic beams in water on the radiation force and the location of its maximum will be presented. The RF is generated by a 1 MHz focused ultrasound transducer (Gain G=18) using a 25 kHz amplitude-modulated wave. Thus, we verify if the radiation force is affected in the same way that the pressure and intensity, by the nonlinear shift described in Ref. [6]

NUMERICAL METHOD

Numerical modelling of the experiment was performed using the KZK equation for axis-symmetric beams:

$$\frac{\partial^2 p}{\partial t' \partial z} = \frac{c_0}{2}\left(\frac{\partial^2 p}{\partial r^2} + \frac{1}{r}\frac{\partial p}{\partial r}\right) + \frac{\delta}{2c_0^3}\frac{\partial^3 p}{\partial t'^3} + \frac{\beta}{2\rho_0 c_0^3}\frac{\partial^2 p^2}{\partial t'^2} \tag{3}$$

where $t' = t - z/c_0$ is a retarded time, c_0 the propagation speed, δ the sound diffusivity, β the coefficient of nonlinearity, and ρ_0 the ambient density of the medium. Eq. 2 is valid in the paraxial approximation ($ka >> 1$) and takes into account nonlinearity, diffraction and thermoviscous absorption. The focusing effect is considered through initial conditions and the numerical scheme used to solve the equation is based on a time domain algorithm described in Ref. [7].

SIMULATIONS

It was simulated the propagation in water of an AM beam radiated by a focused transducer (aperture 35 mm, geometrical focal length 144 mm and resonant frequency f_0=1 MHz) with different initial pressures (15 simulations with p_0 from 1 kPa to 300 kPa).

The pressure field $p(r,z)$ was calculated in a region around the focus of 28 mm (axial) × 35 mm (lateral) with a resolution of 0.1 mm × 0.5 mm.

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The transducer excitation signal, shown in Fig.1, can be expressed as:

$$p = p_0 \exp\left[-\left(\frac{\omega_0 t}{80\pi}\right)^{20000}\right]\left[1 + m\sin(2\pi f_m t)\right]\sin(2\pi f_0 t) \tag{4}$$

where f_0 =1 MHz is the carrier frequency, f_m =25 kHz is the modulation frequency and m=50 is the modulation index.

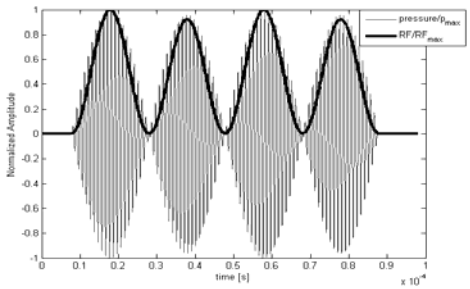


FIGURE 1. AM signal used as excitation, and RF obtained by Eq. 1.

The radiation force was evaluated from the pressure field *p(r,z)* simulated, according to the more general equation 1 (with b=0.0051 Kg/ms, c_0= *1486* m/ s and ρ= *998* Kg/m^3) or taking into account the linear expression given by Eq. 2 (with α = *0.031* Np/m).

RESULTS

The results of this work can be understood in the framework of the nonlinear theory. High amplitude waves are nonlinearly distorted in the course of their propagation (see Fig. 2). In a small nonlinear regime, this distortion generates higher harmonics of the fundamental frequency, but in the stronger nonlinear regime, with the formation and development of the shock fronts on the waveform, a great absorption occurs.

Figure 3 shows that at low amplitudes (linear regime) the locations of the on-axis pressure, intensity and radiation force maxima match at 140.6 mm. That is because for a sinusoidal wave the intensity is maximum when the pressure is maximum, and the radiation force is proportional to the intensity and the maxima positions also match. When we increase the initial pressure applied to the transducer these locations change. First moving away from the transducer, and after, when shock waves appear in the focus, moving back to the transducer. This effect, called *nonlinear focal shift*, can be explained from the self-refraction of the wave at nonlinear regime [8]. In our simulation, the beginning of shock front formation starts when the initial pressure level is 250 kPa, at this point the motion of the axial maximum inverts its direction.

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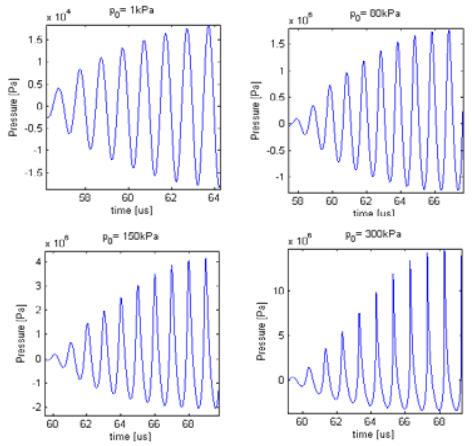


FIGURE 2. Distortion of the waveform profile at the focus for p_0=1, 80, 150 and 300 kPa.

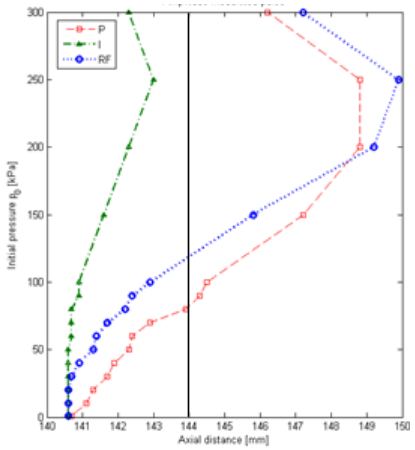


FIGURE 3. Nonlinear focal shift for pressure (8 mm), intensity (2.5 mm) and radiation force (9mm). 15 simulations from p_0=1 to 300 kPa.

The shifts of pressure, intensity and radiation force maxima under increasing nonlinearity have a different behavior. The magnitude of the RF shift (distance from the initial focus position to the return point) is about 9 mm. It starts being moderate, as the intensity, but its behavior changes when the waveform starts to be distorted, exceeding the maximum pressure position and the geometrical focus (around 5.5 mm), with a backward motion of 2 mm. The different location of the RF and intensity maxima that can be seen in fig 4 shows that the RF is only proportional to the intensity in linear regime, as it was expected. But this is not the unique difference, when the waveforms are nonlinearly distorted an amplification of the RF value occurs. Figure 4 shows the RF amplitude calculated according to Eq. 1 and Eq. 2 (linear approximation) versus pressure applied to the transducer (p_0). Fig 5 shows the ratio of both amplitudes, which differ in more than an order of magnitude. This behavior can be also observed in Fig. 6, where the axial distribution of the RF maximum obtained from both expressions for several initial pressures is represented. In linear regime both distributions match, but when the initial pressure increases, both the RF value and the location of the maximum on axis differ.

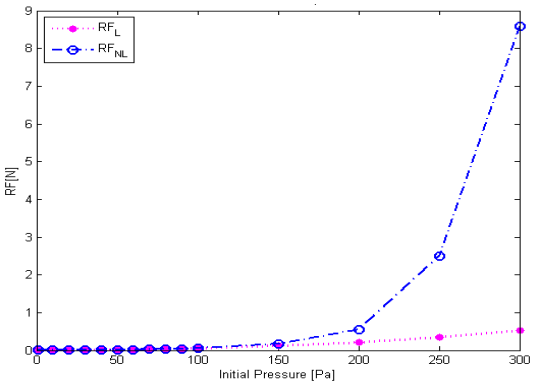


FIGURE 4. RF maxima values obtained for initial pressures simulated. Points: linear approximation, Eq. 2. Circles: general expression, Eq. 1.

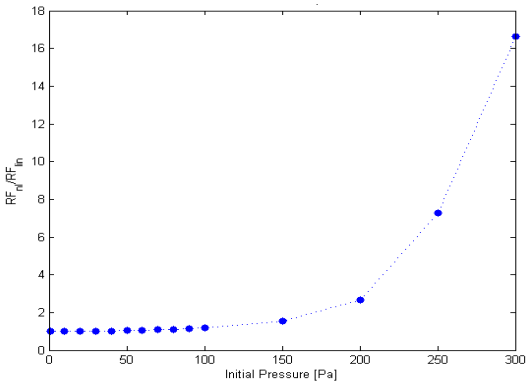


FIGURE 5. Ratio of the moduli RF_{NL}/RF_{LIN}

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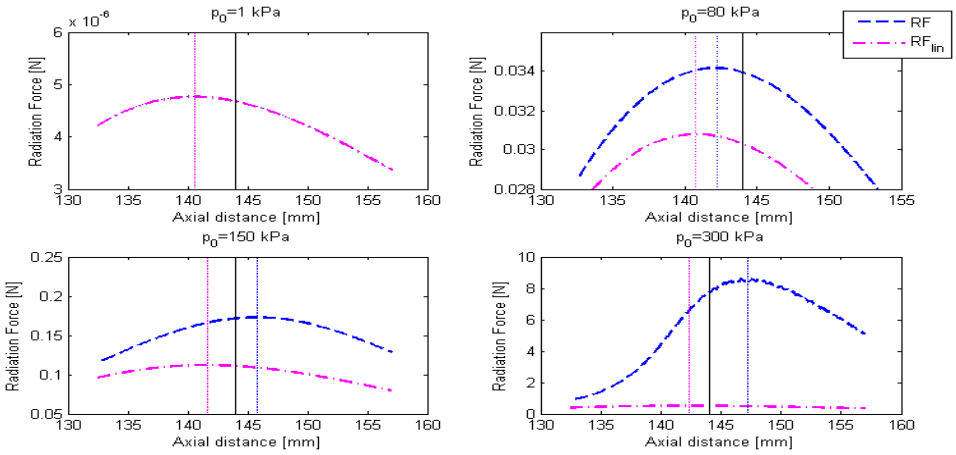


FIGURE 6. On-axis radiation force distributions obtained from numerical solutions of KZK equation. (p_0= 1, 80, 150 and 300 kPa).

As it has been shown above, the value and location of the RF maximum depend on the excitation of the transducer. So, what happens if the excitation signal is amplitude modulated (AM)? Can the nonlinearity affect the RF generated by these kinds of signals and therefore to the techniques that make use of it?

The amplitude variation along the temporal profile of the AM signal involves two main effects: first, it produces a dynamic radiation force whose magnitude changes over time (see Fig. 7 right); Secondly, as it is shown in Fig. 2, with the increasing of the initial pressure on the transducer, it coexists a linear regime propagation (without distortion) for periods with small amplitude and a nonlinear regime propagation (with distortion) for the central periods with a large amplitude. Figure 7 (left) shows the RF maximum location for each period in the considered AM signal. It is noted that in linear regime, all periods of the RF focus at the same point. With the increasing of the initial pressure on the transducer, the nonlinear focal shift becomes more pronounced and can be differentiated for each period. Finally, when the formation of shock waves occur, the RF presents, for each carrier half cycle, a behavior similar to the one presented in Fig. 3, showing an advance and a backward motion of the location of RF maximum.

Figure 8 shows the force field each 5μs (5 equally-spaced temporary cuts) between the central periods of the first and second half-cycle of carrier. It can be noted that in addition to the nonlinear shift, when we increase the initial pressure on the transducer, the force field is narrowed around the axis and the dynamic range of the amplitude increases.

CONCLUSIONS

The present work describes, by the use of a KZK based numerical code, the spatiotemporal behavior of the radiation force induced by a 1 MHz FUS transducer excited by an AM pulse modulated at 25 kHz with different initial pressures (from 1 to

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300 kPa). We examined the connection between the linear and nonlinear stages of the RF focal shift compared with the pressure and intensity one's. We find that every maxima location agrees in linear regime, and have a different behavior in nonlinear regime. The location of the maxima follows the same tendency (away from the transducer with increasing power and suffering a backward motion with shocks wave formation), but the interval of axial motion is different. The RF presents a moderate shift (as intensity) in linear regime, but is strongly affected by nonlinear regime, exceeding the geometric and the pressure focal. The distortion of the temporal profile also affects the amplitude of the force, obtaining an amplification of the module when shocks fronts appear. Consequently, the radiation force is no longer proportional to the intensity and equations 1 and 2 results differ by an order of magnitude. Finally, the difference amplitude over the AM signal implies the existence of a focal shift during the application of the signal because for moderate initial pressures not all the periods are equally distorted and therefore they are not focused at the same point.

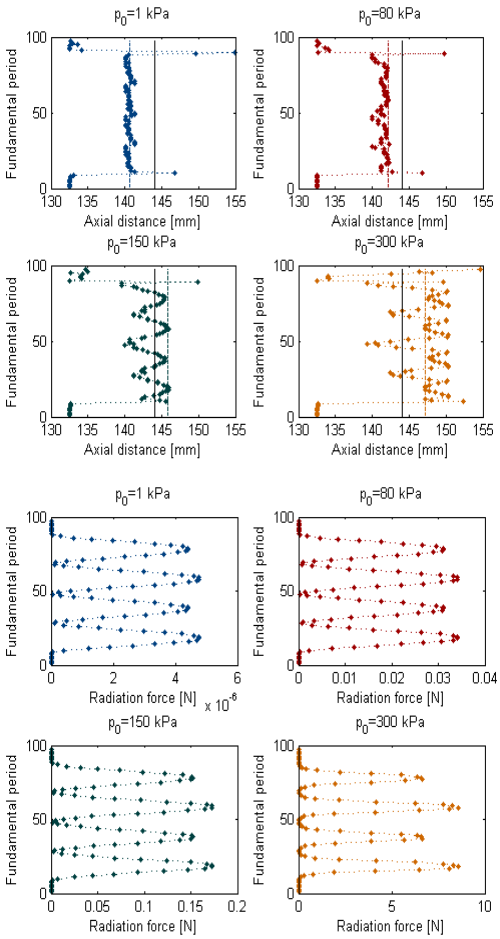


FIGURE 7. Location (left) and amplitude (right) of the RF maxima for each fundamental period at different initial pressures (p_0= 1,80,150 300 kPa).

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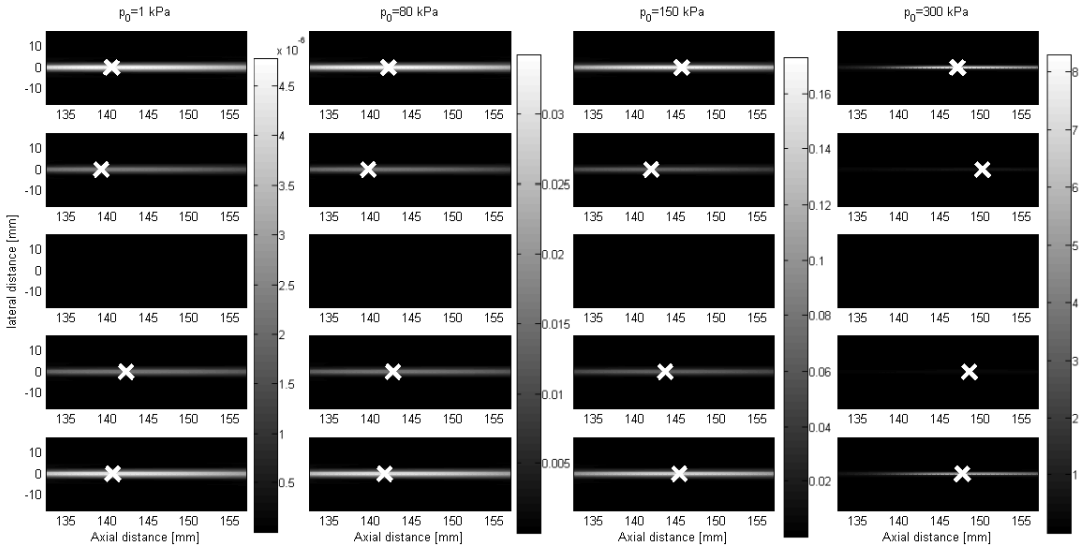


FIGURE 8. Map of the acoustic radiation force simulated. Initial pressures (p_0= 1, 80, 150 and 300 kPa). The force field is shown every 5 μs (top to bottom). The white x marks the location of the axial maximum at each instant.

ACKNOWLEDGMENTS

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