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Fast simulation of nonlinear radio frequency ultrasound images in inhomogeneous nonlinear media: CREANUIS

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The simulation of ultrasound images is usually based on two main strategies: either a linear convolution or the use of an acoustic model. However, only the linear propagation of the pressure wave is considered on the simulation tools generally used. CREANUIS is a recent simulation tool (freely available on the Internet) which implements the nonlinear propagation of the wave to create realistic ultrasound images [1] and opens new simulations perspectives based on nonlinear propagation: amplitude modulation, pulse inversion, second harmonic inversion...

The nonlinear propagation in CREANUIS is simulated using a generalization of the angular spectrum method (GASM). This approach is implemented on a graphic processing unit (GPU) for a fast computation. Moreover, in GASM simulation, the possible inhomogeneity of the nonlinear parameter can be considered. It directly impacts the increase of the harmonics during propagation and consequently the resulting RF image. These resulting images perfectly translate the nonlinear parameter change in the medium. The link between echogenic or not areas and nonlinearity is conducted. Finally, the total computation time for CREANUIS (fundamental and second-harmonic image) compared to FieldII (fundamental image only) is reduced by a factor comprised between 2 and 4 according to the geometric considerations.

1 Introduction

The nonlinear ultrasound (US) wave propagation is used in tissue harmonic imaging (THI) since it increases the resolution of the US images [1], [2]. The natural increase of the harmonics can be enhanced by the use of contrast agents, in order to emphasize the nonlinear backscattering echoes from the media. Several methods have also been developed in order to measure this nonlinear echo such as amplitude modulation, pulse inversion, second harmonic inversion [3].

To simulate US images, two main strategies are reported in the literature: either a linear convolution model or the use of an acoustic one. In order to access to the more realistic US data, the use of an acoustic model, such as the famous FieldII software is required [4]. However, no simulation tool exists in order to simulate nonlinear radio frequency (RF) images, to test and improve the entire set of nonlinear methods.

In the literature, a large set of methods exist to simulate the nonlinear propagation of an US wave based on finite difference schemes [5], on spectral approaches [6], [7] or on coupled approaches [8], [9]. The main limitation of such tools is the total computation time which is really large. Only the spectral approaches proposed a limited computation time due to the consideration of only the fundamental and second-harmonic components. In term of nonlinear image simulation, two previous tools have been proposed in the literature based on simplified acoustics models. The common limitation for them comes from the non-consideration of the spatial impulse response of the transducer in the image reconstruction [10], [11].

In this paper, we propose to use a previously published generalized angular spectrum method (GASM) to quickly compute the 3D+t pressure evolution of the fundamental and second-harmonic components [12]. Then, a classical image reconstruction algorithm, similar to the one of FieldII, is used to create the complete nonlinear RF image [1]. The use of the GASM in CREANUIS (CREAtis Nonlinear Ultrasound Image Simulation) introduces the possibility to consider media with an inhomogeneous nonlinear parameter. Such a configuration is encountered when a contrast agent is injected in a biological tissue [13].

The paper is organized as follows. The general software overview and hypothesis made to reconstruct the image are first proposed. Then, CREANUIS is evaluated in comparison to FieldII for the fundamental component. Then, a third part is proposed to highlight the possible

image simulation of inhomogeneous nonlinear media. Then, discussions and conclusions are conducted.

2 Image simulation

The objective of CREANUIS is to generate nonlinear US images. The RF image is obtained by repeating the same basic operations for each simulated line:

- Compute the nonlinear pressure field
- Reconstruct the line
 - Compute the echoes for each scatterer
 - Perform the beamforming in reception

These steps are detailed hereafter.

2.1 Nonlinear field simulation

As presented in introduction, the nonlinear pressure field is computed thanks to the GASM [12]. The GASM compute the 3D+t pressure evolution for the fundamental and second-harmonic components. It also considers the possible frequency dependant attenuation of the media and the inhomogeneity of the nonlinear parameter.

In CREANUIS, the entire parameters are configurable such as the ultrasound frequency, the sampling frequency, the focus points, the transmitted pulse (windows, frequency, and shape), the apodization in transmission...

2.2 Image reconstruction

The image reconstruction scheme is based on a discretization of the medium done by the scatterers. Each scatterer is defined by a position and a backscattering echo that translates the quantity of the pressure field that is backscattered to the probe. Usually, the amplitude of the scatterers is defined according to a normal distribution with a standard deviation of 1, but any map can be imported into CREANUIS.

Each final RF line is obtained through the following operations. For a given spatial position of the scatterers, the backscattering amplitude of the fundamental and second-harmonic components are computed. Then, for each active element of the probe and according to the geometry of the transducer, the interaction between the pressure wave and the surface of the elementary transducer has to be calculated thanks to the spatial impulse response proposed by Stepanishen [14] and reuse by Jensen and Svenden [4]. Once the different pre-beamformed RF lines are created,

they are combined using a dynamic focalization and a specific apodization in order to create the final RF line. These operations are summarized in Figure 1.

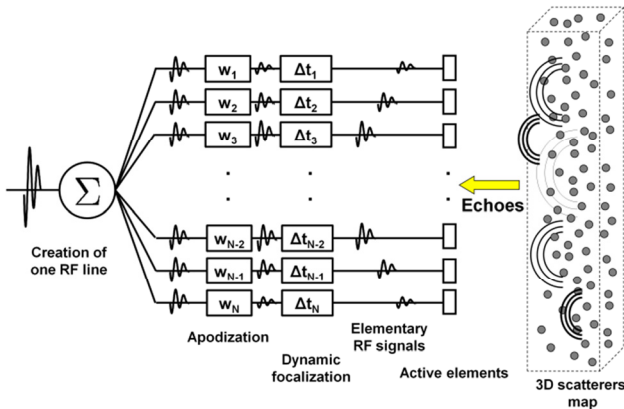


Figure 1: Illustration of the beamforming strategy of CREANUIS [1].

2.3 Software implementation

CREANUIS has been implemented in C++. To quickly compute the nonlinear propagation field, a GPU version of GASM has been used [15]. The quantity of used memory strongly depends on the different dimensions used in the simulation such as the sampling frequency, the number of scatterers, the number of simulated lines... In order to save computation time, the nonlinear pressure field is saved and reused.

3 Evaluation of CREANUIS

The evaluation of CREANUIS software for the fundamental component is made by comparison with the obtained FieldII images. The probe parameters used in both simulations are summarized in Table 1.

Table 1: Summary of the probe parameters used in simulations.

Parameter	Value
Pitch	245 μm
Kerf	30 μm
Height	6 mm
Elevation focus	23 mm
Number of active elements	64

3.1 Comparison to FieldII

To evaluate the performance of the linear process of the CREANUIS software, a homogeneous phantom composed of 600 000 scatterers (30 scatterers/ mm^3) has been simulated. Hanning windowed 3-cycle sinusoidal burst at 5 MHz were transmitted in the medium. Hanning apodization was used in both transmission and reception. The resulting log-compressed images are presented in Figure 2.

To evaluate the differences between the two models, a mean deviation (MD) criterion has been used between the Field image and the CREANUIS image. The MD criterion is expressed as:

$$MD = \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m |I_{i,j}^{\text{FieldII}} - I_{i,j}^{\text{CREANUIS}}| \quad (1)$$

where $I_{i,j}^X$ the (i, j) is the pixel intensity in the X image of dimension (n, m) . The mean deviation between the two proposed images was 8.1% corresponding to very similar images and models. To go further in the model estimation, the speckle distribution and the probability density function (pdf) of each image has been evaluated on each images and compared to the theoretical Rayleigh distribution. The root mean square error (RMSE) between the theoretical and obtained distribution has been evaluated:

$$RMSE = \frac{1}{N} \sum_{i=1}^N (R_i - X_i)^2 \quad (2)$$

where R_i is the probability density of intensity i in the Rayleigh distribution, X_i the probability in simulated X image, and N the number of bins of the distributions. The obtained pdf are displayed in Figure 2.c-d. The RMSEs obtained are 7.7% and 2.1% for the FieldII and CREANUIS images, respectively. The CREANUIS image is closer to the theoretical Rayleigh distribution which completely validates our approach for the fundamental component.

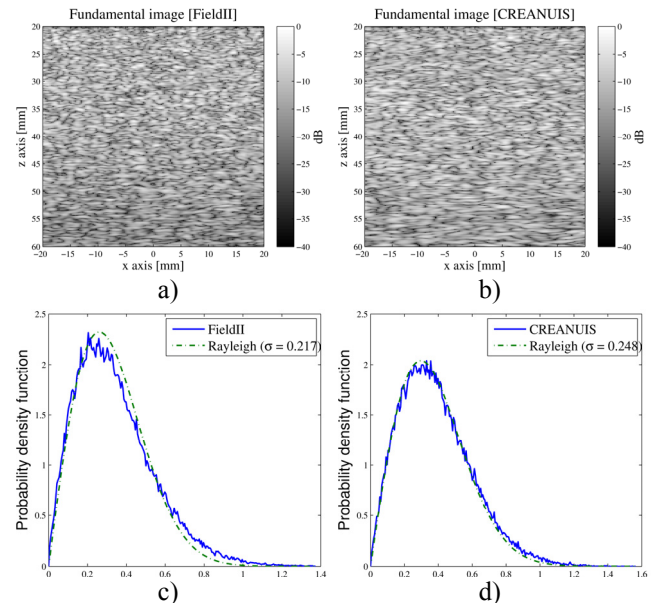


Figure 2: Illustration of the obtained linear log-compressed images with FieldII (a) and CREANUIS (b) and their corresponding probability density function (c-d).

3.2 Nonlinear image simulation

CREANUIS offers the possibility to simulate, in the same time, second harmonic images. The cyst phantom, defined in [16], has been used with 100000 scatterers randomly placed in the medium (3.3 scatterers/ mm^3). Their amplitudes have been adapted to create hyper- and hypo-echoic regions. Hanning-windowed 3-cycle sinusoidal burst at 3.5 MHz focused at 60 mm was transmitted in the medium. Hanning apodization has been used in both transmission and reception. The fundamental images are proposed in Figure 3.a for the FieldII image and in Figure 3.b for CREANUIS. The second-harmonic image is displayed in Figure 3.c. On such image, it is clearly visible that the resolution has been increased in both axial and lateral directions.

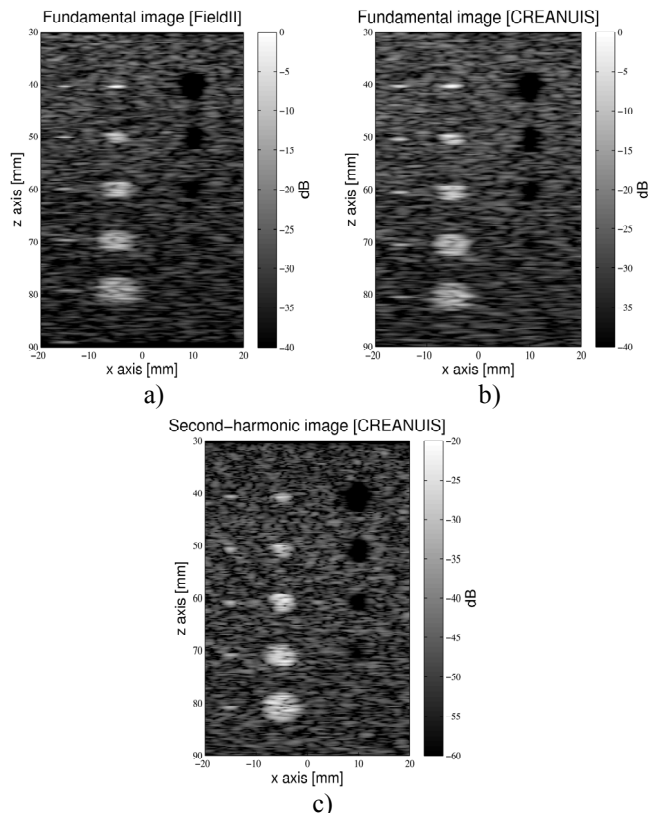


Figure 3: Fundamental images obtained with FieldII (a) and CREANUIS (b). CREANUIS also provide the second-harmonic image (c) of the medium.

3.3 Computation time

To compare the computation time between CREANUIS and FieldII, the same phantom composed of 100 000 scatterers has been used. The computation has been conducted on the same laptop computer (Intel Core2 Duo T9400 at 2.53GHz, 3.48 GB of memory). The reference time, for FieldII, was assumed at 160 minutes for the entire phantom. In order to decrease the total computation time of the nonlinear pressure field computation, the GASM algorithm has been implemented on a GPU. Then, two cases have to be considered: homogeneous or inhomogeneous nonlinear medium. In the latter case, multiple pressure field computations are required. In function of the discretization of the medium and the GPU type use, CREANUIS requires about 33 minutes for the homogeneous nonlinear medium case and between 47 and 87 minutes for inhomogeneous one. A summary of the total simulation time and speed-up are summarized in Table 2.

Table 2: Summary of the total computation time and speed-up obtained between FieldII and CREANUIS.

Simulator	Time	Speed-up factor
FieldII (linear medium)	160 minutes	-
CREANUIS (homogeneous nonlinearity)	33 minutes	4.8
CREANUIS (inhomogeneous nonlinearity)	[47 ; 87] minutes	[1.8 ; 3.4]

4 Simulation of inhomogeneous nonlinear media

Thanks to the use of the GASM simulation in CREANUIS, it is now possible to simulate media with inhomogeneity nonlinear parameter. The only request is to give to CREANUIS the initial nonlinear coefficient map. In inhomogeneous nonlinear coefficient case, the GASM simulation has to be conducted for each simulated RF line because the nonlinear map, in front of the active elements is changing depending on the RF line.

In the following example, a homogeneous medium composed with 100 000 scatterers ($4.5 \text{ scatterers/mm}^3$) is considered. The nonlinear coefficient map has been chosen to have $\beta = 7$ for the negative x axis and $\beta = 3.5$ for the positive x axis (Figure 4.a). The resulting images, proposed in Figure 4, highlight the nonlinear behaviour of the medium. In the fundamental image (Figure 4.b), the inhomogeneous nonlinear coefficient impact is not visible on the B-mode image. Indeed, in the GASM model, the inhomogeneity of the nonlinearity is not considered on the fundamental component. However, on the second-harmonic component, Figure 4.c, the evolution of the echoes, only due to the nonlinear coefficient change, is clearly visible on the B-mode image. CREANUIS offers now the possibility to simulate medium with inhomogeneity in the backscattering amplitude but also in the nonlinear behaviour, and to study the impact of each case with respect to the other.

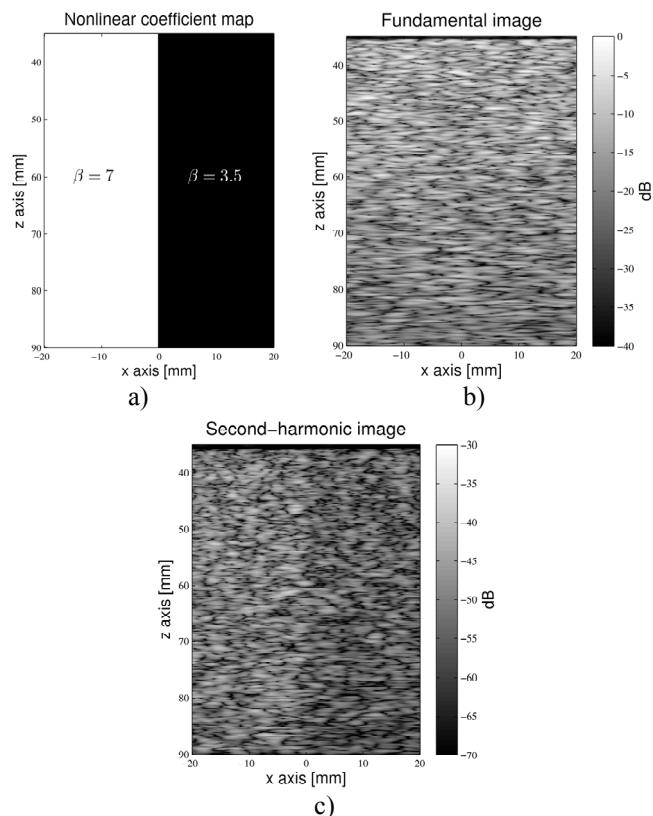


Figure 4: Illustration the inhomogeneous nonlinear parameter medium (a) with the corresponding fundamental (b) and second-harmonic (b) images.

In the second example, 100 000 scatterers have been randomly place into the medium ($3.5 \text{ scatterers/mm}^3$). However, the amplitude of 4 distinct areas has been multiplied by 3. These regions are represented in black

circles in Figure 5.a. Moreover, an inhomogeneous nonlinear egg-shaped medium has been considered and represented with a red-dashed line on the same Figure. This inclusion interacts with the high backscattering region in order to visualize the impact of the medium in terms of echoes and nonlinearity. The same signal as in the previous simulation has been considered. In Figure 5, the resulting fundamental (b) and second-harmonic (c) images are presented. On the fundamental image, only the impact of the scatterers' amplitude is visible in the echogenic area whereas, on the second-harmonic image, a coupled effect exists between backscattering regions and nonlinearity. The deeper inclusion has a strong echo although it is not really contained into the nonlinear region. However, once the second-harmonic component has been created, it is not immediately lost after the inclusion and the second-harmonic echoes remains important.

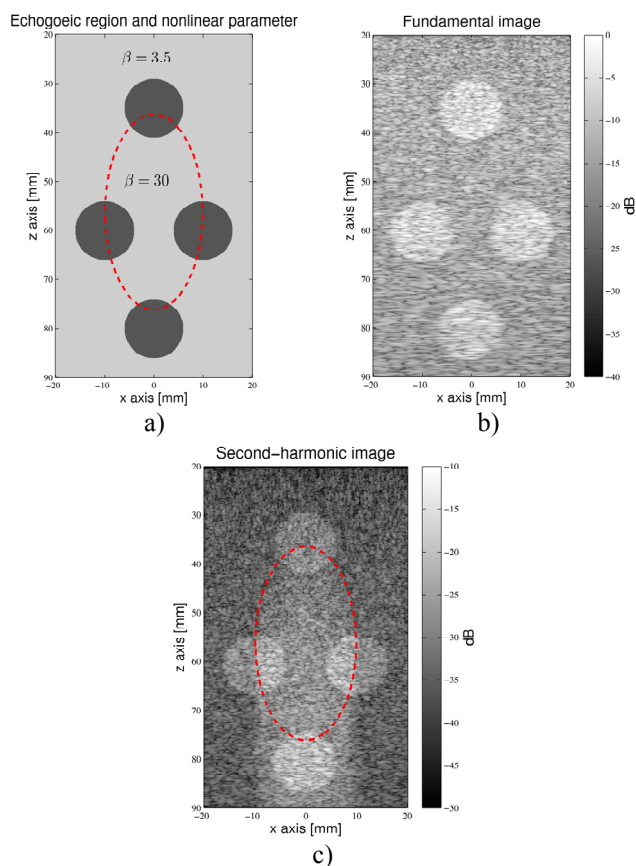


Figure 5: Illustration of an inhomogeneous echogenic medium with an inhomogeneous nonlinear coefficient (a). The red-dashed line displays the border of the high nonlinear inclusion. The gray scale modelled the backscattering amplitude intensity of the area. The corresponding fundamental (b) and second-harmonic (c) images translate the coupled effect.

5 Discussions and conclusions

In conclusion, CREANUIS combines a nonlinear propagation software and an image reconstruction algorithm in order to simulate nonlinear RF image. The utilisation of GASM opens new perspectives: a fast simulation tool to compute the total pressure field and the possibility to consider inhomogeneous nonlinear medium. These two main points are crucial to be able to simulate complex nonlinear media in a reasonable computation time.

The fundamental image provided by CREANUIS has been validated in comparison with FieldII. Indeed, in addition to the weak mean deviation between the two obtained models, the CREANUIS image is closer to the theoretical Rayleigh distribution. This study validates our approach compared to the classical FieldII approach.

Currently, some limitations are still present in CREANUIS. First, only the fundamental and second-harmonic are computed. This limitation is of importance when new capacitive transducer (cMUT) are considered because they propose large bandwidth in transmission and reception [17]. However, the pressure field computation step can be easily changed in the CREANUIS software and new tools can be used in order to overtake this limitation. A second limitation comes from the fact that only the attenuation is considered during the back propagation. However, the backscattering echoes are weak and a linear propagation can be considered in a first approximation.

The total computation time strongly depends on the number of scatterers, but CREANUIS shows major improvements compare to the FieldII software. However, efforts can be continued by proposing a complete GPU version of CREANUIS. Indeed, all the scatterer's echoes calculation and RF line creation repeat the same operations and can be massively parallelized. Previous work have been conducted on the spatial impulse response GPU computing [18]. A valorisation project is in progress in the CNRS in order to freely distribute CREANUIS on the Internet.

Acknowledgments

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