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Adaptive matched filters for Contrast Imaging

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Abstract— The ultrasound (US) contrast imaging is a promising technique. Currently the scientific community of this field seeks US excitations which should make possible the optimization of the acoustic contrast. Two matched filters (MF) techniques are used to improve the image contrast. The first technique is an adaptive MF technique and the second is a RLS technique derived from identification theory.

The system proposed is a close loop system which optimizes the power backscattered by microbubbles. After having transmit a first signal, the backscattered power is optimized by transmitting the matched filtered signal at each iteration. This process is iterated until convergence.

Simulations are carried out for encapsulated microbubbles of 2 microns by considering the modified Rayleigh-Plesset equation for a 2.25MHz transmitted frequency and for various pressure levels (20 kPa up to 420kPa). *In vitro*, experiments are carried out by using two transducers a transducers which were placed perpendicularly. The signal was transmitted through a 2.25 MHz transducer. Responses of a 1/2000 diluted solution of SonoVueTM were measured by a 3.5 MHz transducer. Each experiment has been realized with three pressure levels (127, 244 and 370 kPa).

We show through simulations and through *in vitro* experiments that our adaptive imaging technique gives in case of simulations a gain which can reach 12 dB compared to the traditional technique and for *in vitro* experiments, the MF gives a gain which can reach 4.5 dB whereas the MF derived from identification theory can reach 6 dB.

Keywords— Matched filter, adaptive, contrast imaging, identification system.

I. INTRODUCTION

Conventional ultrasound contrast imaging systems use a fixed transmit frequency. However it is known that the insonified medium (microbubbles) is time-varying and therefore an adapted time-varying excitation is expected. Contrary to the work presented in [1] which optimized the transmit frequency of a fixed shape, we suggest here an adaptive imaging technique which chooses the wave shape

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that maximizes the contrast tissue ratio (CTR).

$$CTR = \frac{E_{bubbles}}{E_{tissue}}, \quad (1)$$

with $E_{bubbles}$ the microbubbles backscattered power and E_{tissue} the tissue backscattered power. This ratio (eq 1) can be maximized if the backscattered power of the microbubbles is maximized.

We tackled the problem by proposing an adaptive imaging technique derived from the identification theory[2]. The use of an adaptive technique is justified by the fact that:

1. during the clinical examination, the insonified medium perfused by the microbubbles is a non-stationary medium (the concentration and the size of microbubbles change...);
2. the pressure level is unknown because of the diffraction and attenuation effects which vary from one patient to another ;
3. the size and the distribution of the UCA are not precisely known and can differ from one sample to another.

Two matched filters (MF) techniques were used to improve the image contrast. The first technique was an adaptive MF technique and the second was a Recursive Least Squares (RLS) technique.

II. MATERIALS AND METHODS

A. Experimental Setup

Each method was compiled using Matlab® (Mathworks, Natick, MA). The resulting excitation signal was transmitted through a GPIB port (National Instruments, Austin, TX) to an arbitrary function generator (33220A, Agilent, Palo Alto, CA). The signal was then amplified using a power amplifier (Amplifier Research 150A100B, Souderton, PA) and transmitted to a 2.25 MHz PZT single element transducer (Sofranel, Sartrouville, France) focused at 55 mm and with a fractional bandwidth of 74% (fig. 1).

The responses of a 1/2000 diluted solution of SonoVueTM microbubbles (Bracco Research, Geneva, Switzerland) were measured by a 3.5 MHz PZT single element transducer with a fractional bandwidth of 63%, placed perpendicularly to the transmitter, also focused at 55 mm and used in receiver mode.

The echoes measured were amplified by 30 dB (Panametrics, Sofranel, Sartrouville, France) and then visualized on a digital oscilloscope (Tektronix, Beaverton, OR). Signals

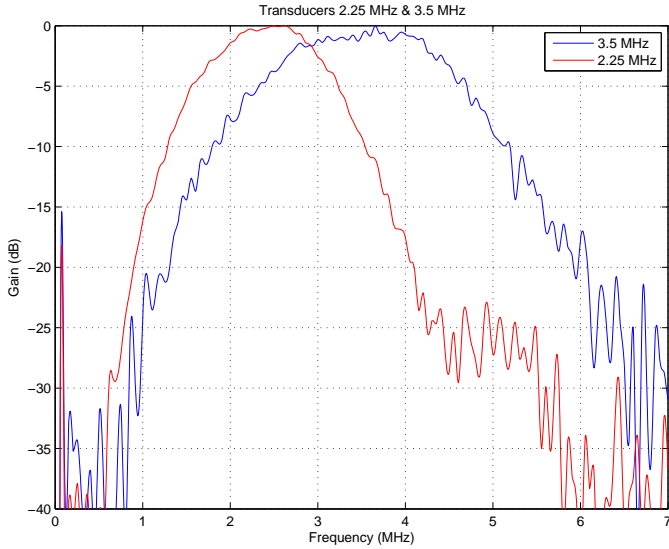


Fig. 1
BANDWIDTH OF TRANSDUCERS

were transferred to a personal computer through a GPIB port for further analysis.

B. Explored Medium

The ultrasound contrast agent composed of SonovueTM microbubbles. The microbubble gas was composed of sulfur hexafluoride (SF₆) and the bubble shell was a phospholipid monolayer [3]. The mean diameter was 4.5 μm [4] and the shell thickness (d_{Se}) was 1 nm [5]. The mechanical shell properties were the shear modulus G_s 46 MPa [6] and the shear viscosity 1 Pa.s.

Numerical simulations for encapsulated contrast microbubbles were solved using Bubblesim [7] from the modified Rayleigh-Plesset equation (eq. 2):

$$\ddot{R}(t)\dot{R}(t) + \frac{3}{2}\dot{R}(t)^2 + \frac{p_0 + p_i(t) - p_L(t)}{\rho_L} - \frac{R(t)}{\rho_L c_L} \dot{p}_L(t) = 0, \quad (2)$$

with R the instantaneous radius of the microbubble and their derivatives, p_0 the static pressure, p_i the instantaneous acoustic pressure, p_L the liquid pressure on the surface of the microbubble, ρ_L the liquid density and c_L the velocity of sound in the liquid. The SonovueTM properties were used for the microbubble parameters.

The transducer effects were considered: each transmitted and received signal was filtered by the bandwidth of the transmitter and the receiver transducers, respectively.

C. Methods

Improve the CTR consists in maximizing the power backscattered by the microbubble. This maximisation problem can be seen as an optimal command issue for which the best excitation is seeking. In optimal command and for linear system, the best excitation is obtained by

time reverse the backscattered signal of the microbubble. We propose two techniques : a standard time reversal technique and a filtered time reversal technique.

C.1 Matched Filter - Time Reversal Technique

This technique is described in the figure 2 and consisted in :

1. sending through the transducer and the medium a sinus wave train;
2. measuring the backscattered signal of the microbubble;
3. time-reversing the signal;
4. normalizing the excitation to ensure the same power in the first step.

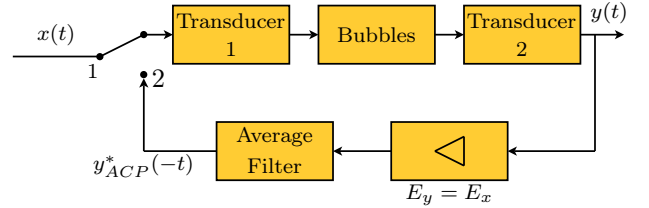


Fig. 2
SCHEME OF THE BUBBLE SYSTEM ASSOCIATED WITH THE MATCHED FILTER

C.2 Recursive Least Squares Filter

The signal $x(t)$ was injected into the bubble system and into the autoregressive model. The switch was in position 1 in figure 3. The discretized signal $y(n)$ was modeled by a fourth-order RLS filter (AR-4). This filter minimized the error $e(n)$ between the input and output such as:

$$e_n = y_n - x_n^T \theta_{n-1}, \quad (3)$$

where x was the input of the bubble system, y_n the filtered signal at the time n and θ the vector of filter coefficients. We therefore obtained the filter coefficients θ [8] by the following equation:

$$\theta_n = \theta_{n-1} + K_n e_n x_n, \quad (4)$$

with

$$\begin{aligned} K_n &= \frac{1}{\lambda} (K_{n-1} - s(v_n v_n^T)) \\ s &= \frac{1}{\lambda + x_n^T v_n} \\ v_n &= K_{n-1} x_n \end{aligned} \quad (5)$$

where λ was the forgetting factor and T was the symbol of the transpose.

The signal $y(n)$ is compared to the one built by the model $\hat{y}(n)$ in order to minimize the error between the two signals. The optimization adapted itself over time.

Finally, the switch was to position 2. The modeled signal $\hat{y}(n)$ is reversed and amplified so that the power of $x(n)$ was equal to the energy $\hat{y}(n)$.

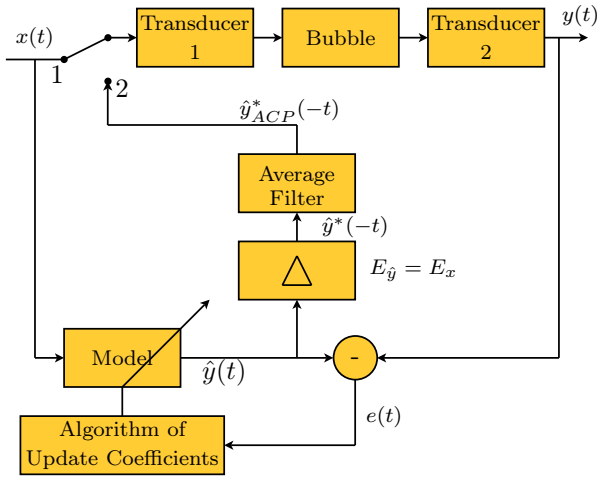


Fig. 3

SCHEME OF THE BUBBLE SYSTEM ASSOCIATED WITH THE IDENTIFICATION SYSTEM

C.3 Average Filter

As the signal to noise ratio (SNR) of the filtered signal $y(t)$ was low (due to the incoherent variations between each echo), we proposed to increase the SNR by building the signal $y_{ACP}(t)$ from a linear combination of the filtered signal $y(t)$, *i.e.* principal component analysis (PCA) [9] such as :

$$\mathbf{y}_{ACP} = \mathbf{A}' \mathbf{y}^*, \quad (6)$$

where \mathbf{y}_{ACP} was the principal component score, \mathbf{A} was composed of the eigenvectors of the correlation matrix and \mathbf{y}^* was the matrix composed of the vectors of the standardized \mathbf{y} . The new signal $y_{ACP}(t)$ from which the power was evaluated in the optimization process corresponded to the first column in the matrix \mathbf{y}_{ACP} .

III. RESULTS & DISCUSSIONS

A. Simulation Without Noise

The bubble was initially excited by a sinusoid modulated by a Gaussian amplitude of 137 kPa (figure 4). The

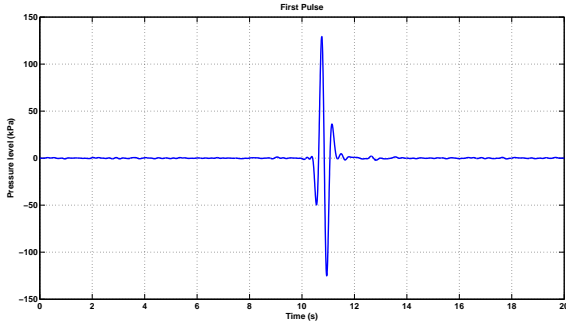


Fig. 4

INITIAL PULSE WITH A PRESSURE LEVEL OF 137 kPa

backscattered signal was modeled by the RLS algorithm (figure 5).

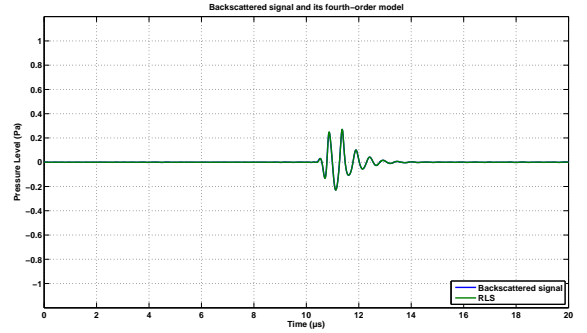


Fig. 5

SIGNAL BACKSCATTERED BY THE MICROBUBBLE

The model of the signal was reversed and amplified so that its power was equal to that of the initial sinusoidal excitation. The signal of figure 6 was the best signal.

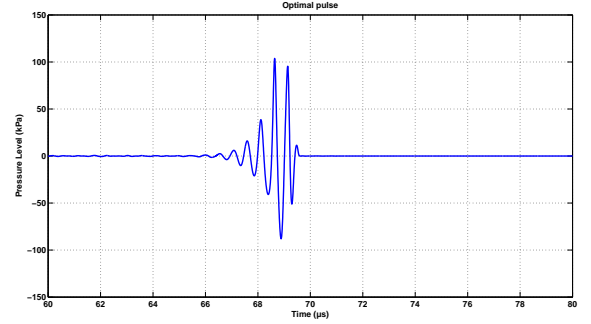


Fig. 6

OPTIMAL PULSE WITH THE SAME POWER THAN THE INITIAL PULSE

When the bubble is excited by the optimal pulse (figure 7), the backscattered power achieves a gain of 17.68 dB compared to the backscattered power without optimisation process.

The identification of the bubble system as a filter allowed us to optimize the power response of the microbubble. This optimization did not require *a priori* knowledge of the system. It optimized the system bubble constituted by a cloud of microbubbles and the transducers.

B. Simulation With Noise

The initial pulse is a sinus wave with a white noise which had the same power than the sinusoidal signal modulated by a Gaussian presented in figure 4. The signal to noise ratio (SNR) was 4.74 dB. The order of the RLS filter was compared to find the optimal order in an empirical way. The experiment is repeated for several different orders. The optimal order was 4 (figure 8).

Moreover, we tested two possible configurations. The first was the standard time-reversal technique. This opti-

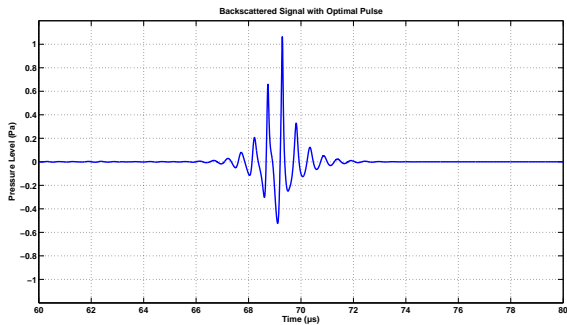


Fig. 7

SIGNAL BACKSCATTERED FROM THE OPTIMAL PULSE

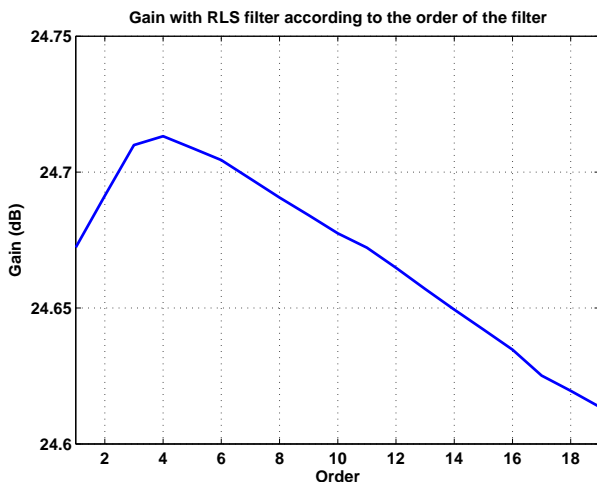


Fig. 8

GAIN OF THE OPTIMIZATION ACCORDING TO THE ORDER OF THE RLS FILTER

mization allowed us to reach a gain of 10.85 dB compared to the signal backscattered from the initial pulse. The second was an identification system using modeling filter with the RLS filter. This second optimization allows us to obtain a gain of 24.72 dB.

This last simulation confirmed that the identification system optimized the power backscattered by the bubble. Moreover, this simulation showed that the gain was increased by 13.87 dB using a filter such as the RLS filter. The RLS filter was able to extract the essential information to identify the bubble system.

C. Experiment

The experiment consisted in transmitting, through the cloud of microbubbles, a sinusoid modulated by a Gaussian with a pressure of 137 kPa with the same characteristics as the stimulus presented in figure 4. Both identifications were compared: the first used the data from the backscattered signal while the second used the signal modeled by the filter RLS. The identification system was performed several

times, which corresponds to iterations. The backscattered signal at iteration n was again used as initial pulse for the next iteration $n + 1$.

The gain of the optimization can reach 4.6 dB (figure 9) compared to the backscattered power of sinus pulse in the case of the matched filter. If the identification by RLS filter was used, the gain could reach 6.3 dB.

As in our simulations, the RLS filter can increase the gain of the optimization. The experimental results are not exactly identical because of the non-stationarity of microbubbles. To cancel the fluctuation due to their motion, we have repeated the experiment. Since a high number of repetition and a high value of iterations number could destroy the microbubbles and thus induce a backscattered power reduction, a trade-off must be found to avoid the destruction of the microbubbles.

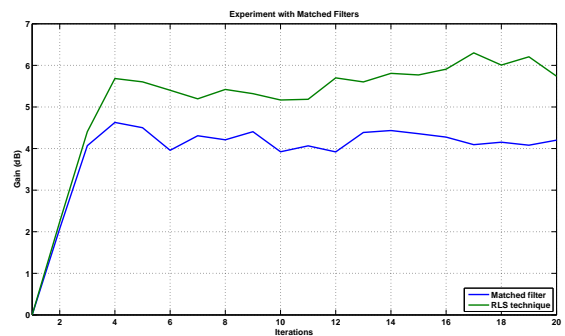


Fig. 9

EXPERIMENT REALIZED WITH AN INITIAL SINUS PULSE OF PRESSURE LEVEL OF 137 kPa

IV. CONCLUSION

The use of matched filter (time reversal technique) seems a good choice to optimize the CTR. Among the two proposed techniques, we suggest to use the RLS time reversal technique.

We can carry on modeling the signal by nonlinear filters like Volterra filter and implementing the RLS filter in an echograph with an programmable generator.

V. ACKNOWLEDGEMENT

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