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Analog Cancellation of Unwanted Reflections for Enhanced Ultrasound Microscopy

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***Abstract*—Our scanning acoustic microscope uses coded excitation. The excitation signal consists of linear chirps of 1 µs duration. Parts of this signal are reflected from the internal structures of the lens, which causes high signal amplitudes in the recorded signal. The signals from the lens reflections can be 5 to 10 times larger than the signal from the sample. As coded excitation utilizes long modulated signals, the signals originating from the lens reflection will overlap with signals originating from the sample. The frequency encoding combined with the pulse compression method enables the reconstruction of the time resolution and allows the separation of the reflections.**

Pulse compression works properly only if the full duration and the full amplitude of the signal is captured. Therefore, the amplifier and the gain of the analog-to-digital converter (ADC) resolution needs to be adjusted to the amplitude of the strongest reflection present, i.e. the lens echoes. This results in quantization of the small-amplitude echoes from the sample.

To overcome these limitations, we implemented an analog signal cancellation method. The signal of the lens reflections was first recorded. During measurements, the signal containing lens reflections was inverted, then reproduced by an arbitrary waveform generator, and finally combined with an analog signal combiner to the measurement signal from the microscope. The maximum signal amplitude was reduced by 80 %, which made it possible to change from the 1000 mV-range to the 200 mV-range of the ADC, thus improving the dynamic range. This reduced the quantisation noise and led to a 3 times lower noise-level in the image.

Keywords—Ultrasonic microscope, signal filtering, signal suppression

I. INTRODUCTION

Recently, we built an ultrasonic microscope that uses coded excitation [1-3]. Coded excitation utilizes long modulated signals that allows increasing the transmission energy compared to conventional acoustic microscopes, by spreading it over a long time. The received signals are cross-correlated [4] with the transmitted signal waveform to compress the pulse. The use of long signals increases signal-to-noise ratio (SNR) compared to conventional burst excitation. The frequency-modulated signals have large bandwidth and thus high temporal resolution after pulse compression [5, 6].

The drawback is that the transmitted signal and received echoes might overlap before cross-correlation. In practice, strong reflections occur at fixed times (e.g. lens echoes), overlapping the small signal of interest with their large amplitude. In theory, this is not problematic, because the frequency coding allows separation of these signals. However, the analog-to-digital converter (ADC) needs to capture the full range of the strong reflection signal and, at the same time, have a sufficient voltage resolution to resolve the slight changes introduced by the weaker signal of interest, i.e. the sample echo. In practice, this limits the detectability of weak signals [7].

In this study, we present a way to overcome this limitation: We cancel the internal echoes from the measured signal by analog means before digitisation. The cancellation signal is the inverted signal of the large and stationary reflections (lens echoes). This signal eliminates the dominant reflection signal, leaving only the weak signals of interest. The voltage range of the ADC can therefore be reduced, improving the detectability of weak signals by reduction of quantization noise.

We designed a system for the existing ultrasonic microscope and experimentally evaluated the performance.

II. METHODS

A. Simulation

First: a numeric simulation was performed with MATLAB to test the general concept. A linear frequency sweep of a sine signal was created, (1).

$$f(t) = \sin\left(\left(2\pi f_{start} + \frac{f_{stop} - f_{start}}{2 t_{sweep}} t\right) t\right) \tag{1}$$

$f_{start} = 300\ \text{MHz}$, $f_{stop} = 500\ \text{MHz}$, $t_{sweep} = 1\ \mu\text{s}$. This chirp was enveloped with a Gaussian window.

To simulate a measurement signal, this chirp signal was convolved with three Kronecker delta functions with an amplitude of 0.001, 0.01, and 1, 300 ns apart. The delta function with amplitude 1 was assumed to be the undesired reflection, which should be cancelled. The sample echo and second lens reflection were the delta functions with amplitude 0.001 and 0.01, respectively. The time was discretised with a time increment of 0.1 ns, corresponding to the sampling frequency in our system.

Two signals were generated in this way: the reference signal S_{Ref}, where only the reflection with the value 1 is present, and the signal S_{Sig}, containing all components. To take the quantisation process of an n-bit converter into account, a function was used that quantises the voltage interval [-U,U] of each signal into 2^n-1 discrete values, symmetrical around zero. For this simulation $n = 8$ was used to match the ADC of our microscope. The required voltage interval was matched to maximum signal amplitude, considering the same (and largest) interval in the case that S_{Ref} and S_{Sig} are quantised separately.

The difference in the signal was calculated by simulating the subtraction (cancellation) in the analog domain (before quantisation, D_{analog}) (2) and the subtraction in the digital domain (after quantisation, $D_{digital}$) (3).

$$D_{analog}=\text{quantisation}\left(S_{sig}\text{-}S_{ref}\right) \tag{2}$$

$$D_{digital}=\text{quantisation}\left(S_{sig}\right)\text{-quantisation}\left(S_{ref}\right) \tag{3}$$

B. Experiment

For the experimental verification, we modified the ultrasonic microscope according to the schematic shown in Fig. 1. The main signal path is the same as described in [2], where further information about the hardware can be found. The arbitrary waveform generator (AWG) transmits a chirp signal from channel 0 (CH 0). The signal is amplified and then directed to the ultrasonic transducer with a TX/RX switch. The switch is controlled by a digital channel of the AWG. The echoes from the transducer are then recorded with an oscilloscope.

In the modified setup, the AWG transmits an additional signal from channel 1 (CH 1). It replicates the waveform of the reflected ultrasonic signal, which contains strong signals from internal reflections from the transducer lens. This signal is inverted so that combining the signals with an RF signal combiner will cancel the transducer internal echoes. A 10 dB signal attenuator adjusts the power level of the synthesised signal to the level of the reflected signal. Afterwards, the output signal of the combiner is amplified and digitised by the oscilloscope in CH 0. CH 1 of the oscilloscope is used to monitor the signal that is used for cancellation during the optimisation process. All measurements were done with a SASAM lens (Sa15#05-15#0040, Kibero GmbH) transducer with a central frequency of 400 MHz.

The amplitude of the signals reflected from the transducer is 8 times larger than the signal of interest (sample echo). The analog cancellation reduces the amplitude of the internal reflections. Therefore, a lower voltage range of the oscilloscope can be used, and this increases the dynamic range for the signal of interest.To demonstrate the effectiveness of the method regarding the image quality, a 1951 USAF target (ThorLabs R1DS1P) was imaged with the original configuration and with the analog signal cancellation. In the first measurement, the original configuration was used (cfr [2]). This was done to get a reference for the performance of the device. The voltage range of the oscilloscope was set to ±1000 mV to allow capturing the full amplitude range of the signal. Next, the hardware was changed to the configuration shown in Fig. 1. To capture a reference for the internal lens echoes, the transducer was defocused (far away from the sample) to have no focal echoes in the signal. Finally, the cancellation signal was combined with the received signal. The amplitude and phase of the cancellation signal were optimized by minimizing the amplitude of the residual signal.

III. RESULTS AND DISCUSSION

A. Simulation

Fig. 2 shows the result of the quantization simulation of the cross-correlated signals. It is apparent that the analog subtraction gives a higher SNR as the range of the ADC can be utilised in an improved way, which reduces the quantisation noise.

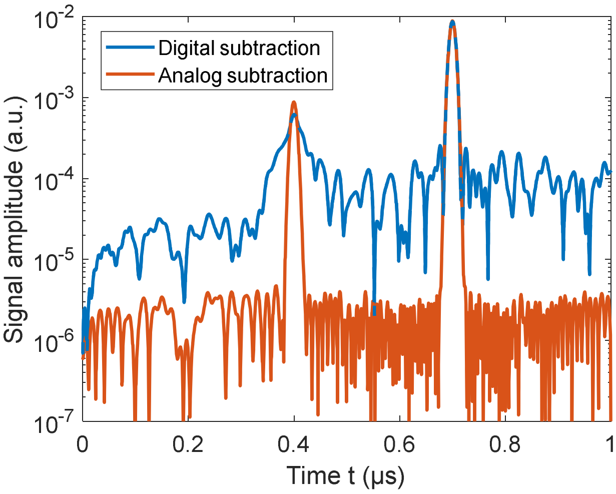

Fig. 2. Simulated signals after cancellation of the reference signal from the measured signal. Subtracting the digitized signal causes artefacts due to the quantisation noise. By subtracting the signals before the quantisation step, a higher SNR can be achieved.

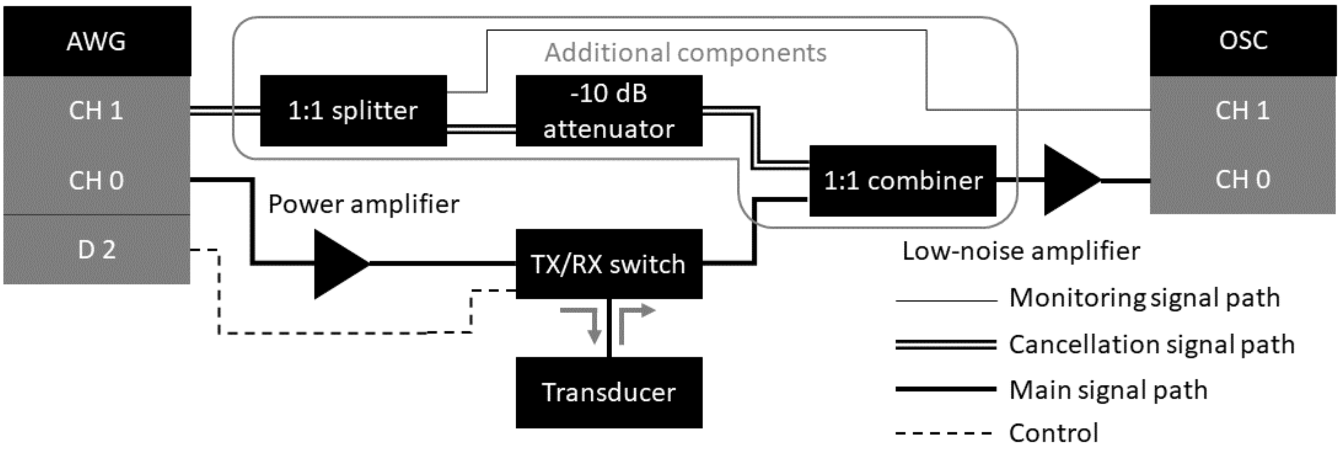

Fig. 1. Block diagram of the new configuration. The additional components for the signal cancelation are encircled by the gray line.

B. *Experiment*

We performed the analog signal cancellation and a reduction of the peak-to-peak amplitude by 80 % (from 1.35 V to 0.27 V) was achieved. Thus, the more sensitive ±200 mV range of the oscilloscope was used without saturation of the signal. The quantisation steps affecting the signal of the original setup is seen in Fig. 3. The improved setup allows a higher voltage resolution and therefore reduces the effects of the quantisation error.

The 1951 USAF sample imaged with both methods is seen in Fig. 4. To quantify the noise-level in the image, the area of flat glass surface above the target pattern without any features was selected. The area covers 275×100 µm^2 (upper left coordinate of the area in Fig. 4 is at (X = 0.2 mm, Y = 0.1 mm)). From all 110751 points within the area, the mean value µ and standard deviation σ were calculated. The ratio σ/µ was improved from 4.9×10^{-3} to 1.6×10^{-3} (Fig. 5). This is an improvement by a factor of 3. To get the same improvement by signal averaging, 9 repeated measurements would be necessary. This corresponds to increasing the length of the coded signal by a factor of 3.

As seen in Fig. 3, the signal of the first lens echo is not completely cancelled. The reason is, that the RF components have a nonlinear behaviour as well as non-flat frequency response. To improve the cancellation efficiency, one approach would be to iteratively record and cancel the residual signal with the same optimization steps as was done here.

The challenges in signal cancellation are that the temporal accuracy of the signal needs to be in the hundreds of picoseconds range. The thermal drift of the transducer alters the time delays, which requires readjustments of the cancellation signal delay. Therefore, we plan to automate the adjustments in a future version of the setup, which will allow us to perform measurements even with a change of temperature of the transducer.

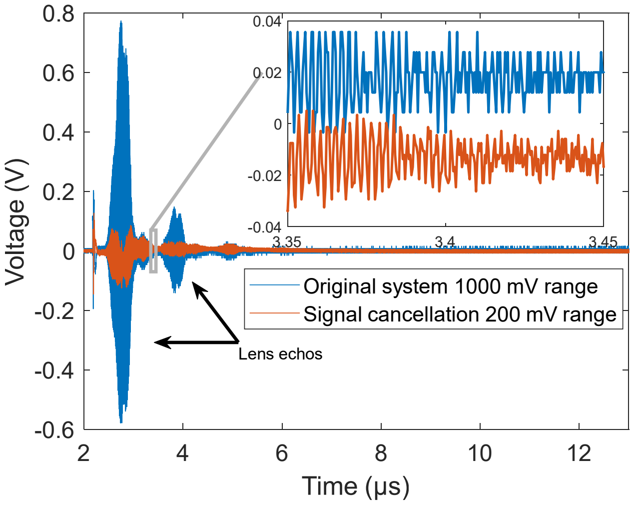

Fig. 3. Signal of the original system and signal after cancellation. The signal amplitude from the lens echoes is reduced so that a smaller voltage resolution of the oscilloscope can be used. In the inset, focal echoes with both methods are shown. By changing the voltage resolution, the quantisation error can be reduced, which, in the end, improves the quality of the image.

This method could be beneficial for low-contrast biological samples that require sensitive and low-noise imaging systems to have quantitative results, especially in applications where fast scanning is required. For example, to image fresh samples from plants, where the different structures have a weak contrast as they consist mainly of water.

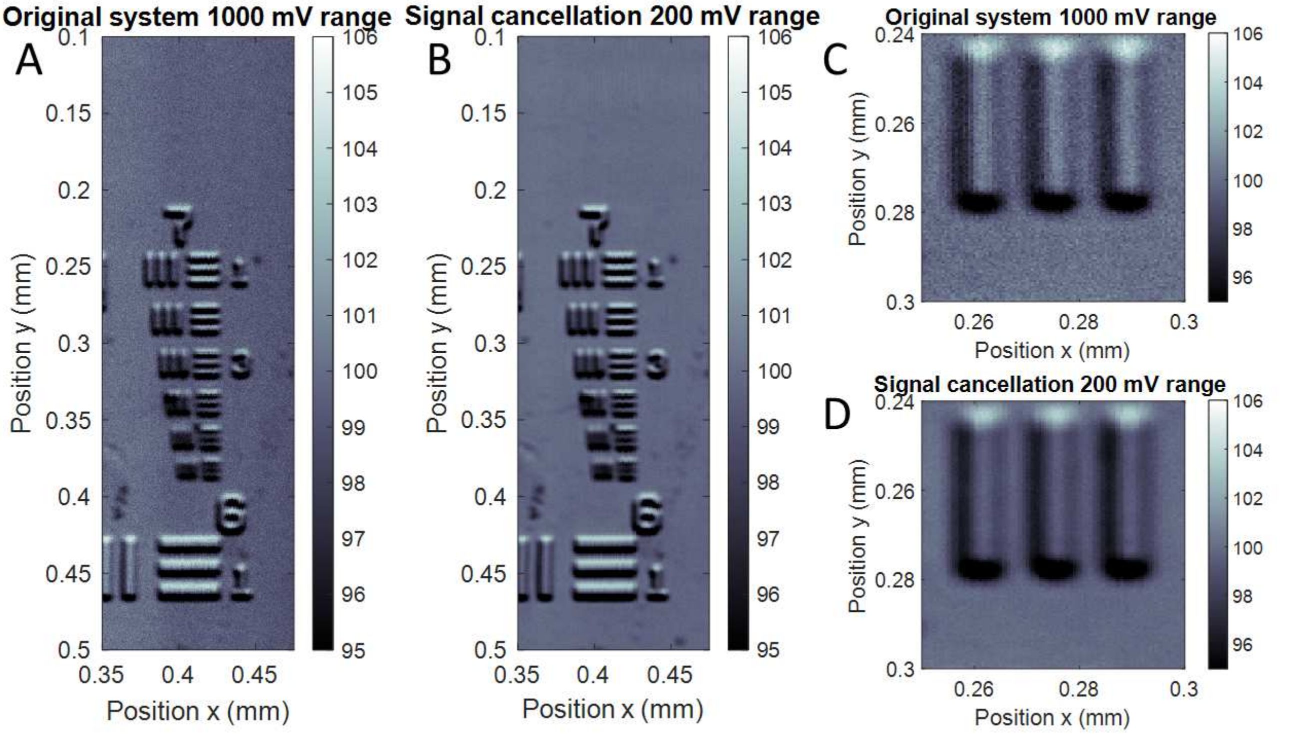

Fig. 4. A & B: Comparison of a 1951 USAF target showing the group numbers 7. C & D: The reduction of the noise level is shown on group 6 element 2. The features became more apparent, even though the physical resolution was not changed.

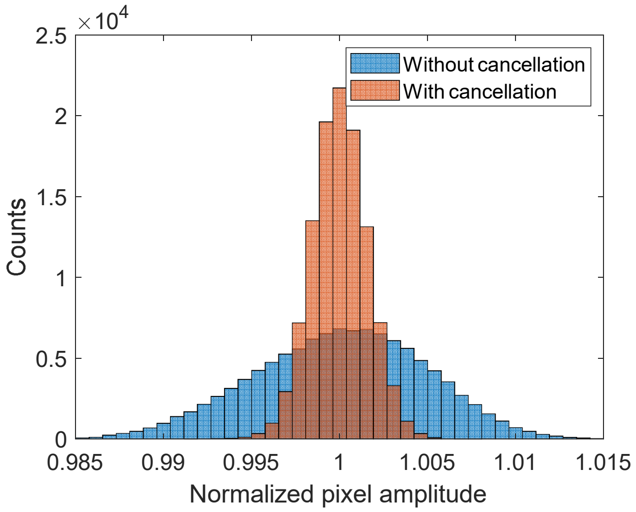

Fig. 5. The histogram shows the amplitude distribution of a uniform area in the image, normalised to the mean value. 110751 points were evaluated.

IV. CONCLUSION

We upgraded our CESAM system with analog lens echo cancellation. This increased the SNR by a factor of 3, which increases the imaging quality of the system.

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