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Development of a method to characterize CMUT receiver behavior

M. Städler[1], *J. Kober*[1], *T. Trittler*[1], *M. Kircher*[2], *M. Herzog*[1], *H. Heuer*[3], *and J. Hampe*[1]
[1] *TUD Dresden University of Technology, Else Kröner Fresenius Center for Digital Health, Dresden, Saxony, Germany*
[2] *Fraunhofer, Institute for Photonic Microsystems, Dresden, Saxony, Germany*
[3] *Fraunhofer, Institute for Ceramic Systems and Technologies, Dresden, Saxony, Germany*
merit.staedler@tu-dresden.de

Abstract: This study presents a method of characterizing the performance of a capacitive micromachined ultrasound transducer (CMUT) as receiver using a chirp signal on the transmitter. This approach enables the spectral analysis of key characterization parameters - sensitivity, bandwidth, and noise equivalent pressure within a single-shot measurement. To assess the effectiveness of the chirp-based approach relative to conventional single-tone excitation, both signal types were applied in a pitch-and-catch experiment involving two distinct CMUT probes. The results demonstrate a higher-resolved bandwidth and improved robustness against uncorrelated acoustic noise when employing the chirp excitation signal.

Keywords: Capacitive Micromachined Ultrasonic Transducers, Ultrasound, Receiver Characterization, Experimental Setup, Synchronized Swept-Sine Technique

Introduction

Capacitive micromachined ultrasound transducers (CMUTs) are attracting increasing interest due to their design flexibility, cost-effective mass production and their capability of monolithic integration within receiver electronics. With high receive sensitivity and broad bandwidth, they are particularly promising for use as receive elements in ultrasonic sensing and imaging applications. To evaluate the influence of different designs on their performance, a characterization of their receiver behavior is essential. To isolate and analyse the receiving performance, the “pitch-and-catch” setup adapted from Klemm et. al [1] is employed. This setup includes two line-of-sight configurations: one with a CMUT and a transmitter facing each other, and another where a hydrophone captures the emitted pressure from the transmitter. This dual approach allows comprehensive sensitivity assessment by comparing the CMUT output with the hydrophone-recorded pressure. In contrast to other studies, particular emphasis is placed on characterizing the receive behavior across a wide frequency spectrum, which is critical for broadband sensitivity analysis and the evaluation of the noise equivalent pressure (NEP). As these information are vital for optimizing CMUTs as the ultrasound transduction mechanism for a wide range of applications [2]. To cover the desired frequency range, common pulse and single-tone (ST) for discrete frequencies or a broadband chirp signal can be used. Whereby multiple STs and a chirp signal can be better compared due to the precisely controlled frequency of a ST [3]. In this work, we present an exponential chirp excitation as an efficient alternative, enabling broadband characterization in a single measurement. This method reduces the need for multiple tone-by-tone acquisitions, allowing sensitivity and NEP to be derived from a single dataset. Two CMUT probes, differing in their diameter of the membrane, are used to be characterized with both signal methods in the "pitch-and-catch" configuration. The results obtained using the exponential chirp are compared with those from conventional ST measurements, using the generated derived characteristics sensitivity, bandwidth and NEP as metric.

Methods

Two excitation signals were employed in the pitch-and-catch experiments: an exponential chirp spanning a bandwidth of 1...16 MHz with a duration of 1 ms, and 32 single sinusoidal tones ranging from 1...16 MHz in 500 kHz steps, each with a duration of 100 µs. Both signal types were recorded using the CMUT probes and a hydrophone. The experimental configuration, illustrated in Fig. 1, consists of a water tank and two independent pitch-and-catch configurations. In both setups, a piezoelectric transmitter (SONOTEC SONOSCAN IK-10-6) was used, driven by a high-bandwidth power amplifier (Mini-Circuits ZHL-32A+) in combination with coaxial fixed attenuators (Mini-Circuits VAT-A-SERIES). As receivers, either a hydrophone (HGL-0400, preamplifier: AH-2010-100; ONDA Corporation) or one of the CMUT

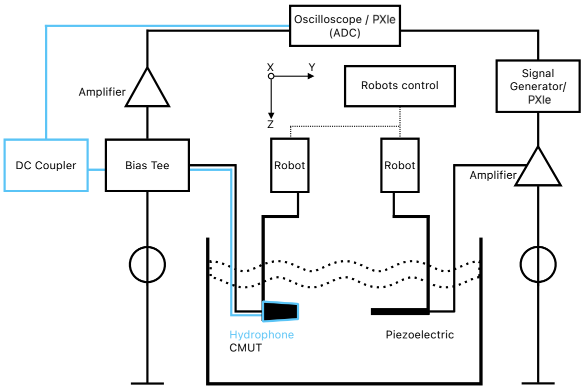


Fig. 1: Schematic presentation of the "pitch-and-catch" measurement setup with both line-of-sight options either an applied hydrophone (in blue) or a CMUT (in black). Figure adapted [1].

probes was aligned with the transmitter at a distance and depth of 60 mm. Each CMUT probe, provided by Fraunhofer IPMS, featured an active area of 250 µm × 250 µm and included an integrated circuit. Therefore, this characterization method inherently reflects the combined performance of both the integrated circuit and the CMUT. Two CMUT variants were evaluated: *CMUT1*, with a nominal frequency (f_0) of 6.5 MHz and a DC bias of 64 V, and *CMUT2*, with a nominal frequency of 8 MHz and a bias voltage of 72 V. These nominal frequencies were determined based on impedance measurements. For consistent comparison, both CMUTs were supplied with 90% of their maximum bias voltage using a custom-designed Eval-Kit ($R = 50\ \Omega$) [4]. Signal generation and data acquisition for the chirp measurements were performed using a National Instruments system consisting of an FPGA controller (NI PXIe-8133) and a FlexRIO transceiver module (NI FlexRIO-5781R). To automate the ST measurements, we used Python-controllable devices. A signal generator (SDG 1062X, SIGLENT) transmitted sinusoidal excitation signals with an amplitude of 1 V_{pp}, while a digital oscilloscope (PicoScope 3406B, Pico Technology) handled data acquisition. Both instruments were synchronized via a trigger. Each ST measurement was recorded 32 times and averaged to reduce noise, whereas the chirp measurement was recorded only once. As the applied chirp signal includes fade-in and fade-out phases, the data corresponding to the first and last frequencies were excluded. This led to a bandwidth range of 2...14 MHz ($[f_1;f_2]$) being considered for the comparison. The chirp data was analyzed using the synchronized swept-sine technique (SST) as described by Novak et al. [5], which allows the separation of individual harmonic orders in the CMUT response. The sensitivity was determined based on the first harmonic to isolate the linear response and eliminate nonlinear effects. It is defined as the ratio between the CMUT's recorded output signal and the reference pressure measured by the hydrophone (Eq. (1)) [1]. The pressure values were derived from the measured voltage, converted to pressure using the calibration data specific to the hydrophone employed.

$$S = \frac{U_{CMUT}}{P_{hydrophone}} \tag{1}$$

To determine the 6 dB bandwidth, the sensitivity spectrum was converted into the dB domain, and the frequency range within 6 dB of the peak sensitivity was calculated as schematically presented in Fig. 2 b) with eq. (2).

$$FBW = \frac{f_{high} - f_{low}}{f_0} \tag{2}$$

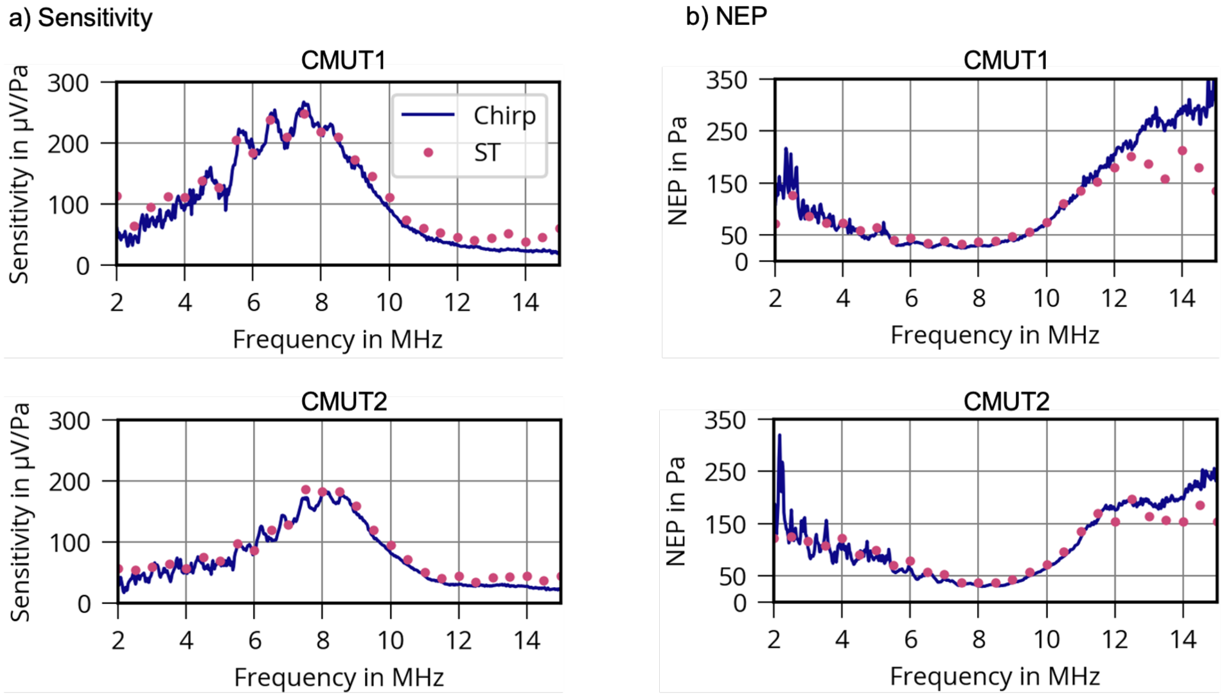
The NEP was derived as the ratio of the recorded noise level to the calculated sensitivity and the recorded frequency range ($f_{PXIe} = 100MHz, f_{PicoScope} = 125MHz$) (Eq. (3), Fig. 2).

$$NEP = \frac{U_{noise}}{S \cdot \sqrt{\Delta f}} \tag{3}$$

Noise measurements were conducted in the same water tank environment, with no excitation signal applied. The noise levels observed for the two signal types differ due to variations in the electronic acquisition configurations and the applied averaging methods. Since the absolute noise level of the PXIe system is three times higher than that of the Picoscope, the chirp-based measurement acquired with the PXIe was normalized by a factor of three to ensure comparability. Both spectra, sensitivity and NEP, of both signal types are compared through a deviation calculation. Therefore, the ST dataset is interpolated, and for each frequency in the recorded chirp signal, the difference between the ST amplitude and the chirp amplitude is calculated. Finally, the average of these deviations is computed. As the difference between the sensitivity and NEP spectrum is only a constant factor, only the deviation of the sensitivity spectrum is considered.

Results

The SST of Novak et al. [5] showed that only a second harmonic component was present in the CMUT probe signals, located around the –30 dB level. As a result, no separation of higher harmonic orders was conducted in subsequent calculations. Fig. 2 presents the sensitivity and NEP spectra for both signal excitation methods. Over the full recorded bandwidth,



a) Sensitivity

b) NEP

c) Characterization parameters

	CMUT1		CMUT2	
	Chirp	ST	Chirp	ST
S in $\frac{\mu V}{Pa}$	267.35	247.7	183.35	187
f_0 in MHz	7.5	7.5	8.11	7.5
B_{-6dB} in %	63.73	53.33	47.84	46.67
B_{-6dB} range	[4.74; 9.52]	[5.5; 9.5]	[6.08; 9.96]	[6.5; 10]
NEP in $\frac{mPa}{\sqrt{Hz}}$	3.40	3.73	4.13	4.35

d) Bandwidth calculation

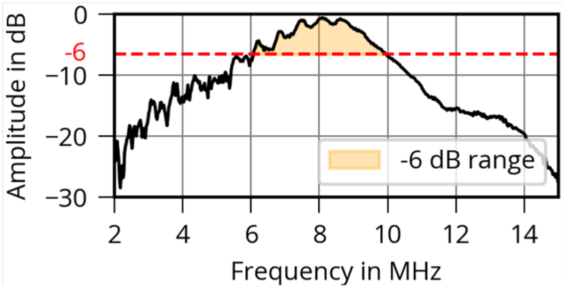


Fig. 2: Comparison of both signal types recorded by the two CMUT probes. Results of the sensitivity (a) and the NEP (b) calculation based on Equation(1) (3) and the characterization parameters (c). (d) Schematic presentation of the bandwidth calculation.

the difference between the signal types amounts to 19.3 % for the *CMUT1* and 14.6 % for the *CMUT2*. When the bandwidth is restricted to a ±4 MHz range around the resonance frequency, the probes exhibit a deviation of 8.9 % and 11.5 %. Even closer, within a ±2 MHz range, the *CMUT1* shows a deviation of 1.7%, and the *CMUT2* showed a deviation of 7.5%. The maximum recorded sensitivity values differed by 7.3% for the *CMUT1*, with both signals showing the maximum at 7.5 MHz. For the *CMUT2*, the deviation in maximum sensitivity between signal types was 1.9% but the resonance frequencies differ. A broader bandwidth was conducted by *CMUT1* (10.4%) and by *CMUT2* (1.17%) when the chirp signal was used. After applying a linear correction factor, the NEP values for *CMUT1* differed by 0.33 mPa/$\sqrt{Hz}$, and for *CMUT2*, by 0.22 mPa/$\sqrt{Hz}$.

Discussion

The chirp-based measurement offers higher frequency resolution within a single acquisition, enabling a more precise determination of the absolute characterization parameters such as resonance frequency and bandwidth range, as illustrated in Fig. 2a. In contrast, the ST measurement required averaging over 32 individual acquisitions to achieve comparable accurate values at a reduced frequency resolution. Despite this, the level of disruption in the lower frequency range is comparable, suggesting that the disturbances are inherent to the measurement setup or probe behavior rather than random noise. In the higher frequency

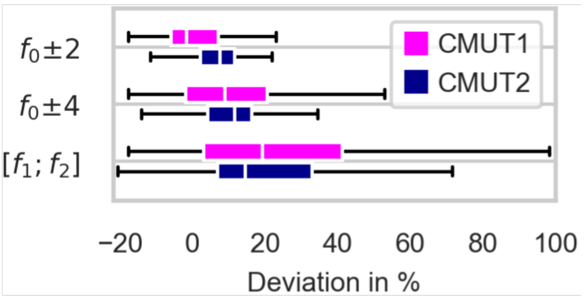


Fig. 3: The percentage deviation of the calculated sensitivity from ST and chirp signal measurements of the CMUT probes is shown in box plots across different frequency ranges.

range, the ST method appears more susceptible to disturbances, leading to a higher number of outliers in the recorded data. Although using smaller frequency steps in the ST approach could improve resolution, it would also significantly increase measurement time. As the improvement of the resolution by a factor of n would require n × m measurements, where m is the number of repetitions for each measurement. Furthermore, from a practical implementation and noise robustness perspective, it is important to note that chirp-based measurements require an excitation and acquisition system with sufficient transmission buffer capacity and an adequately high sampling rate to generate, transmit, and accurately capture chirp waveforms. These requirements may not be met in all hardware setups, potentially limiting feasibility.

Conclusion

The measurements using the chirp signal proved beneficial in terms of reduced acquisition time and higher spectral resolution, enabling a more precise analysis of parameters relevant for receiver behavior characterization. The observed response of the CMUT receivers was consistent across both excitation methods, suggesting that the use of a chirp signal represents a valid and effective alternative for CMUT receiver characterization.

Acknowledgment

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