

New DSP-based ultrasonic distance/level meter

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Abstract- The paper describes a prototype of ultrasonic distance/level meter. The meter is based on a digital signal processor (DSP), mandated to supervise its whole functioning. Besides driving the piezoelectric transducer, the DSP manages the digitization of the received ultrasonic signal, processes the acquired samples, according to a suitable measurement algorithm, and delivers the desired result to the final user. The measurement algorithm, already presented and validated [1],[2], grants functionalities typically provided by analog circuitry, with a consequent reduction of the impact of production tolerances of analog components on measurement accuracy. Meter's performance has been assessed through a number of laboratory tests involving known distances in different measurement conditions. A comparison of the experienced performance to that granted by other meters available on the market finally corroborate the reliability and efficacy of the proposed meter.

I. Introduction

Ultrasonic-based techniques are a common solution when the distance of a reflecting surface or level of liquids have to be measured [3]. Several examples of relatively cheap meters using ultrasonics and characterized by a satisfactory accuracy for a large number of applications has recently been released on the market [4]-[7]. Their success mainly relies on the straightforward principle usually exploited to achieve the desired distance information, i.e. the estimation of the time-of-flight (TOF) of an ultrasonic burst. TOF is defined as the time elapsed between the transmission of an ultrasonic burst by the transducer and detection of the echo produced by an obstacle the distance of which has to be measured. A simple relationship for time-to-distance conversion is finally applied to attain the unknown distance value.

TOF-based meters, however, present some drawbacks. In particular, measurement accuracy is mainly degraded by (i) additive noise, both externally and inherently generated, (ii) production tolerances of analog components, (iii) shape distortion of the received ultrasonic echo, and (iv) dependence on temperature of the propagation velocity of ultrasonics in the coupling medium [8]. Measurement noise has proven to be the main uncertainty source when threshold methods, generally adopted by the first ultrasonic meters, are used. Typical solutions based on analog processing (i.e. signal band-pass filtering or amplification with time-varying gain) suitably reduce the effect of noise, but introduce a harmful and unpredictable influence on the measurement because of their components tolerances. As for (iii), shape distortions cause measurement results to be affected by severe polarization (difference between estimated and actual TOF) when cross correlation estimator (optimal estimator according to the maximum likelihood criterion in case of additive white Gaussian noise) is adopted. With regard to temperature, its effects can easily be compensated by integrating a proper sensor in the meter project [8]; this way, last problem will be neglected in the following. Moreover, in the presence of hazardous environments or when low-power devices are described, ultrasonic transducer with a carrier frequency of 30-50 kHz are generally used. The use of low operating frequency does not allow high resolution to be attained and commercial devices can usually provide an accuracy not better than the wavelength of the used ultrasonic signal (5-10 mm in air) [9],[10]. Finally, measurement results are usually provided by meters in analog form (4-20 mA current loops or voltage differences functionally related to the measured distance), thus preventing their uncorrupted transmission on long distances.

The authors have recently proposed a digital signal-processing algorithm for ultrasonic TOF estimation [1],[2]. The algorithm processes the received ultrasonic echo, previously digitized, in such a way as to perform the same operations usually mandated to specific analog circuitry. Analog components are hence replaced by suitable digital signal-processing solution, with a consequent benefit on measurement accuracy. Moreover, thanks to a quadrature demodulation scheme, the proposed algorithm exhibits satisfactory performance also in critical measurements conditions, such as in the presence of severe shape distortions and high noise levels.

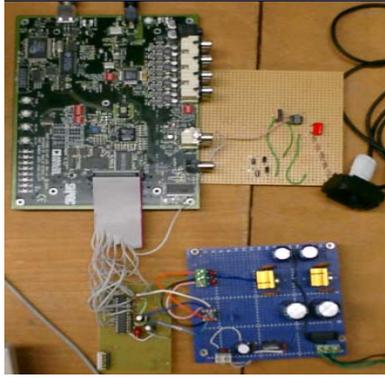


Fig.1. Current prototype of the proposed meter.

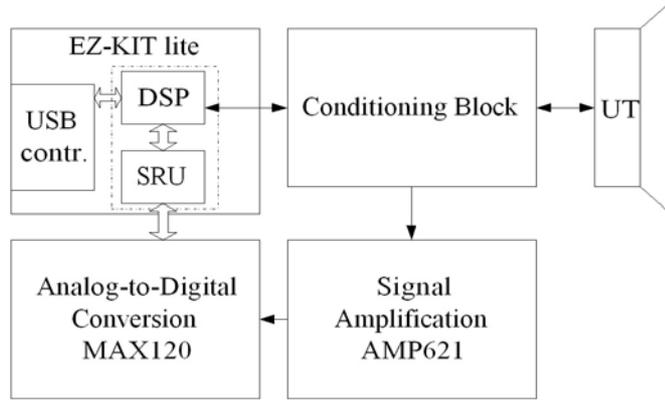


Fig.2. Schematic block diagram of the realized prototype.

The final goal of research activity is the realization of a prototype of a cost-effective distance/level meter implementing the aforementioned digital signal-processing algorithm. At this aim, the ADSP-21262, a 32-bit processor optimized for high precision signal processing applications, is adopted. The chosen processor is mandated to perform all the operations necessary to carry out the required measurement, from the generation of the electrical stimulus for the transducer to the digitization of the received ultrasonic signal, from the processing of the acquired samples to transmission of the measurement result. Only a minimal quantity of electronic components is used to complete the prototype, the tolerances of which do not affect the overall performance.

In the following, details about design issues of the proposed meter are given. Particular attention is focused on the specifications the chosen DSP satisfies in order to suitably implement the measurement algorithm. Results attained in tests conducted on simulated signals and actual measurements are, finally, presented and discussed.

II. Proposed meter

Hardware and software architecture of the proposed meter are described in the following. In this phase of the project, the components of the meter have been arranged on different boards (Fig.1), in order to assure design flexibility for improvements to be brought. The schematic block diagram is shown in Fig.2. In its final version, the meter will be realized on a unique board and will include a LCD display for result visualization; the corresponding layout is presented in Fig.3.

A. Hardware architecture.

The main element of the meter is the DSP, *Analog Devices SHARC-ADSP21262* (200 MHz core

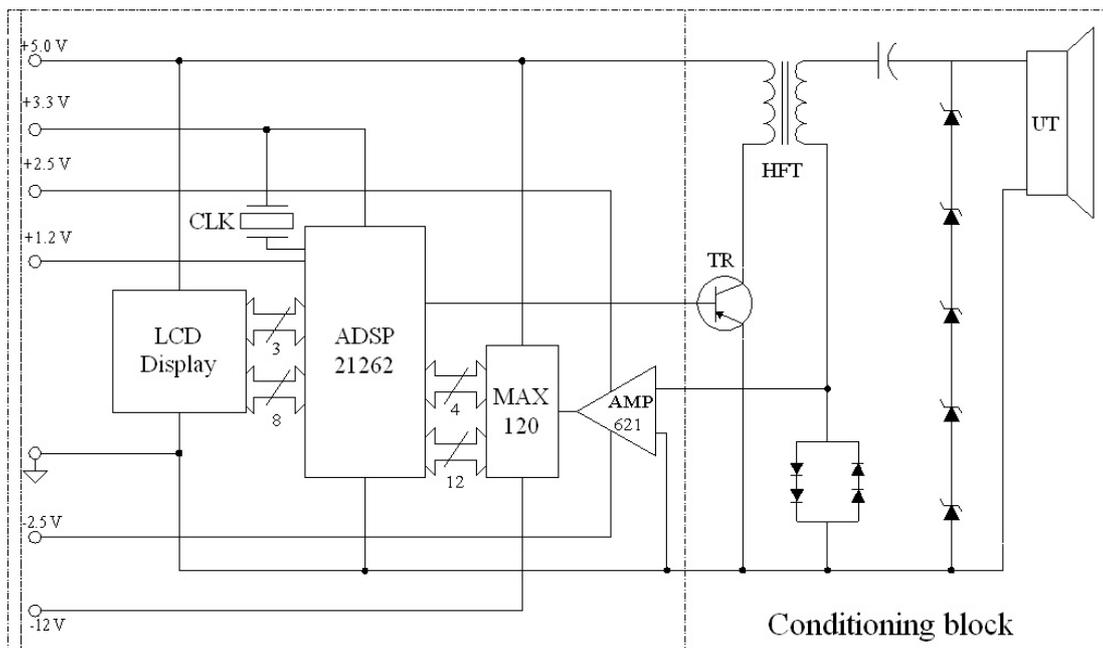


Fig.3. Layout of the final version of the proposed DSP-based distance/level meter.

instruction rate, 1.2 GFLOPS, 2 Mbits dual-ported SRAM, 4 Mbits mask-programmable ROM), a 32-bit processor optimized for high precision signal-processing application. EZ-KIT lite® board, namely the system provided by *Analog Devices* for evaluating SHARC® processors, has been used to access the I/O pins of the DSP. Thanks to a suitable front-end realized through spare electronic components, the processor is able to perform accurate and fast measurements of distance/level, providing results in digital form.

When the measurement starts, sixteen rectangular pulses, generated through the PWM module of DSP, are used to switch the base of the transistor TR, *FMMT720*, (50 V maximum voltage, 2 A maximum collector-emitter current). The high-frequency transformer, HFT, *6500 ranging transformer*, (5.0 ± 0.1 DC pulsed primary excitation, 580 ± 30 peak-to-peak output voltage amplitude) amplifies the voltage signal up to the values needed to drive the piezoelectric transducer (UT), *Polaroid 9000 Series*, (17°x35° beam angle, 45±2 kHz operating frequency, 108 dB transmitting sensitivity and -78 dB receiving sensitivity). In particular, the electrical stimulus is characterized by a frequency and peak-to-peak voltage amplitude equal respectively to 44.8 kHz and 400 V.

Both generated and received ultrasonic signal are digitized by an analog-to-digital converter (ADC), *Maxim MAX120*, (12-bit resolution, 500 kS/s maximum sample rate, ±5 V bipolar input range, 1 LSB maximum DNL/INL error) with a sample period, T_0 , of 4 μs. The analog input of the ADC is firstly clipped by means of a diodes bridge, in order to cut the high voltage values associated to the signal generation step. Since typical peak-to-peak amplitude values of received ultrasonic echoes are always lower than 20 mV, the signal passes through an operational amplifier, *Analog Devices AMP621* (0.015% total gain error, 125 μV total offset voltage, 200 kHz bandwidth) characterized by a gain equal to 100, in order to properly exploit the ADC dynamic range. With regard to timing relationship, the ADC communicates with the DSP through a dedicated 4-bit bus, while the digitized data are exchanged through a 12-bit bus provided by I/O pins of the Signal Routing Unit (SRU). The ADSP-21262's on-chip DMA controller allows zero-overhead data transfers without processor intervention; the DMA operates independently and invisibly to the processor core, allowing DMA operations to occur while the core is simultaneously executing its program instructions (in particular, ADC interrupt sub-routines). Digitized samples are collected in the data memory (DM) of the DSP; in order to achieve a measurement range of 1.7 m, a number of samples covering an observation interval of at least 10 ms is acquired.

B. Software architecture.

The EZ-KIT lite® evaluation system has been used in conjunction with Visual DSP++ development environment in order to (i) implement the measurement algorithm and the control software in mixed code, (ii) program and debug the DSP, and (iii) exchange data from the DSP memory to the personal computer by means of USB connection. With regard to (i), it is worth noting that the control routine mandated to set DSP's registers on power up and supervise the digitization phase is written in assembly, in order to suitably use the nice property of the DMA module. On the other hand, the measurement algorithm, mandated to process acquired signals, is written in C++; details of the algorithm are given in the following.

After the digitization phase, some preliminary operations have to be executed in order to perform TOF estimation. In particular, the portion of digitized record, roughly covering 2 ms and accounting for the ultrasonic transmission burst, is firstly cut. Moreover, the main echo (i.e. the echo corresponding to the first reflection of the transmitted ultrasonic signal) is primarily located through a straightforward peak-location algorithm and subsequently extract in order to provide a more limited set of samples to be analyzed; a number, k , of samples equal to 300 proved to be a proper length to assure satisfying results. In the literature the echo waveform is usually modelled as

$$s(t) = A(t - \tau) \sin(2\pi f_0 t + \phi) \quad , \quad (1)$$

where $A(t)$ stands for echo envelope, τ is the TOF, f_0 is the ultrasonic carrier frequency, and ϕ is a constant phase term. A suitable scheme of quadrature demodulation is applied to the extracted samples in order to recover the envelope $A(t - \tau)$ (Fig.4). At this aim, the extracted signal is multiplied by the two orthogonal sinusoidal carriers, the frequency of which is equal to the nominal operating frequency, f_0 , of the adopted ultrasonic transducer. Since the number of samples, k , the carrier frequency of the ultrasonic signal, f_0 , and the sample period, T_0 , are fixed in design phase, values of the carriers can once be evaluated off-line and transferred in DM. The multiplication gives rise to both a base-band component and a high-frequency component. A low-pass filtering is carried out to retain only the base-band components (respectively called in-phase and in-quadrature component). At this aim, the method of Fast Fourier Transform (FFT) convolution has been used. The signals are thus transformed into the frequency domain using the FFT, multiplied by the frequency response of the filter kernel, and then transformed back into the time domain using the inverse FFT. In order to calculate their FFT, the

signals arising from the multiplication by the orthogonal carriers are zero-padded up to N equal to 512 elements. Once again, twiddle factors for complex-FFT evaluation of the signals and the frequency responses of the filter are determined off-line and memorized in DM. This choice allows the computational time to be hardly reduced by preventing to evaluate their values for each measurement and granting the possibility of exploiting some nice properties of ADSP-21262. In fact, the chosen processor features an enhanced Harvard architecture based on separate program and data memory buses and on-chip instruction cache. The processor can thus simultaneously fetch four operands (two over each data bus) and one instruction (from the cache), all in a single cycle. As an example, the simultaneous evaluation of complex-FFT for the in-phase and in-quadrature components has been performed according to this scheme. Filtered signals are subsequently processed in order to obtain the signal envelope and remove the dependence on the phase constant, ϕ .

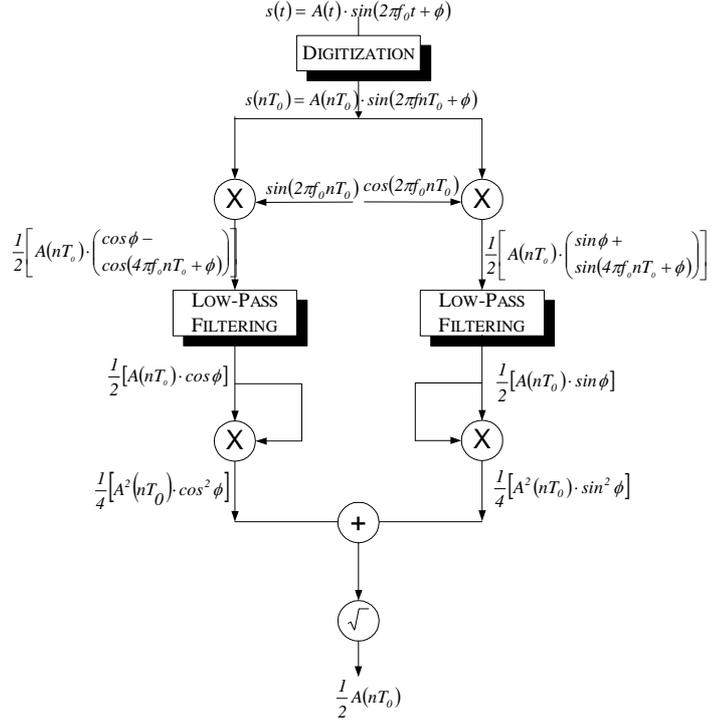


Fig.4. Quadrature demodulation scheme.

Filtered signals are subsequently processed in order to obtain the signal envelope and remove the dependence on the phase constant, ϕ .

A standard least-mean-square algorithm is then applied to determine the straight line mandated to fix the TOF estimate. At this aim, the time value t_{max} associated to the maximum of the derivative calculated on the rising edge of the envelope is determined; intercept, b , and slope, a , of the regression line are thus evaluated by selecting a set of 20 points around t_{max} . The desired estimate of TOF is finally achieved according to the expression $TOF = -b/a$. It is worth noting that the chosen DSP along with the aforementioned processing strategies grant a measurement time never greater than 15 ms, thus allowing a measurement rate up to 60 readings/s to be achieved. Moreover, measurement results can be collected in the DSP's memory for further processing.

III. Performance assessment

A. Noise sensitivity assessment

Meter's sensitivity to noise has been assessed through a number of tests on simulated signals. At this aim, numeric signals have been generated off-line and downloaded into the DSP memory through the EZ-KIT lite system. According to the expression (1), ultrasonic echo envelopes have been synthesized in the hypothesis of a sample rate equal to 250 kS/s. As for $A(t)$, it has been modelled as

$$A(t) = \left(\frac{t}{T}\right)^m e^{-\frac{t}{T}}, \quad (2)$$

where m is the slope of the echo envelope in the proximity of the onset and T is a time constant depending on the particular transducer. The values of the shape parameters m and T , respectively equal to 2 and 140 μ s, were chosen as similar as possible to those characterizing the actual signals involved in the successive experimental tests. The obtained envelopes have then modulated a sinusoidal carrier, the frequency of which matches that of the ultrasonic transmitter (44.8 kHz) adopted in the proposed meter. The resulting signals have been corrupted by additive, white, Gaussian noise. The corresponding signal-to-noise ratio, SNR , has been calculated according to the expression:

$$SNR = 10 \log \left(\frac{E_S}{\sigma_n^2 t_s} \right) \quad (3)$$

where E_S is the energy of the ultrasonic simulated signal, and σ_n^2 stands for the noise variance.

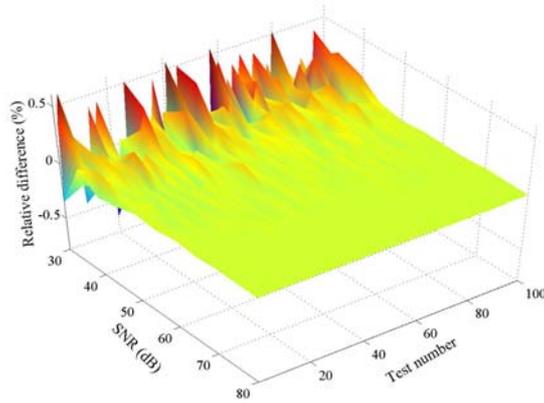


Fig.5. Relative differences provided by the meter.

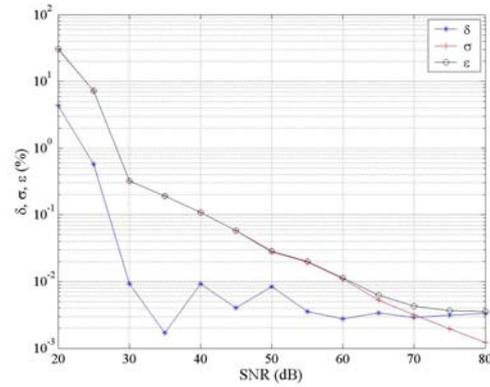


Fig.6. Results obtained on simulated signals.

Several tests have been conducted for different values of *SNR* (*SNR* within 20-80 dB), in order to simulate diverse noise conditions of the measurement chain. For each values of *SNR*, 100 ultrasonic signals have been analyzed; Fig.5 shows the surface of the obtained differences (expressed in percentage relative terms) between the estimates of TOF and the nominal one. Furthermore, bias, δ (difference between the mean value of the TOF estimates and the imposed one), experimental standard deviation, σ , and combined error, $\varepsilon = \sqrt{\delta^2 + \sigma^2}$, on TOF estimates have been evaluated. With specific regard to the interval 30-80 dB, values of δ , σ , and ε lower respectively than 0.02%, 0.3% and 0.3% have always been experienced (Fig.6). Meter's performance rapidly decreases for *SNR* values within 20-30 dB, giving rise to values of combined error up to 20 %. Such low values of *SNR* are associated to very critical noise conditions, usually characterizing the ultrasonic signal reflected by external plane located at distance greater than the meter range. If this is the case, received ultrasonic echo is fully buried in the noise floor.

B. Tests in free-space propagation

A number of experimental tests in free-space propagation have been conducted to assess the performance of the meter. During the tests, the temperature of the coupling medium has duly been checked in order to compensate its effect on the propagation velocity of the ultrasonic signal; a standard RTD probe has been adopted. Meter's capability of measuring the distance of a reflecting plane characterized by orthogonal alignment with the transmitted ultrasonic signal has firstly been investigated. At this aim, the piezoelectric transducer has been mounted on a movable plane, which slides on a distance reference, and different distances ranging inside the interval 400-1000 mm have been considered. For each distance, δ , σ , and ε , related to about one hundred acquisitions, have been evaluated. The obtained results, expressed in percentage relative terms, are given in Fig.7; values lower respectively than 0.3%, 0.15% and 0.4% have always been experienced.

The effect on measurement results of misalignment between the reflecting plane and the piezoelectric transducer has then been investigated. At this aim, a suitable measurement apparatus has been set up. It consists of the same sliding plane of the previous test and a target plane that rotates around its own axes (Fig.8); the angular position of the rotating plane has been measured through a reference goniometer

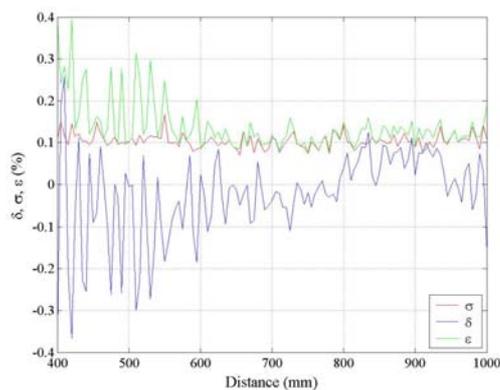


Fig.7. Results obtained in actual tests highlighting the satisfying performance of the meter.



Fig.8. Measurement apparatus to assess the effect of misalignment on meter's performance.

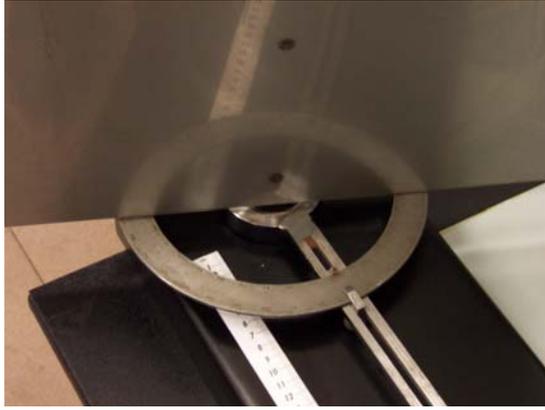


Fig.9. Detail of the rotating plane and the reference goniometer. Accuracy lower than

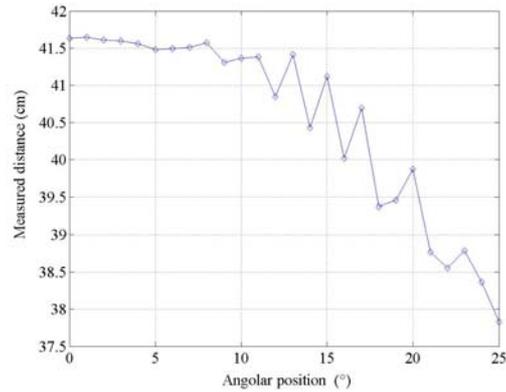


Fig.10. Results obtained for a distance of 41.5 cm. As expected, a reduction of the measured value for increasing angular positions has been experienced.

(Fig.9). Due to the lack of orthogonality between sensor and target, only a portion of the transmitted signal will come back to the meter; the amplitude of the received echo decreases upon the increasing of the tilt angle or distance. As an example, results obtained for a reference distance of 41.5 cm are given in Fig.10. Measured distance decreases upon the angular position's increasing in the interval 0-25°; this outcome is justified by the reduction of the quantity $L \left(1 - \cos \left(\frac{\alpha \pi}{180} \right) \right)$, where L is the nominal reference distance, which the orthogonal transmission path of the ultrasonic signal undergoes, given an angular position α .

IV. Conclusions

The paper describes a cost-effective, distance/level meter based on the TOF estimation of an ultrasonic pulse. Its core is a digital signal processor, ADSP-21262, managing the whole measurement process. Thanks to a digital signal-processing algorithm based on a quadrature demodulation scheme along with a spare quantity of electronic components, the proposed meter grants very satisfying results. Values of bias and experimental standard deviation never greater than 0.3% have, in fact, been experienced during experimental tests in free-space propagation. Taking into account that its expected final cost will be lower than 70 €, the meter shows itself very competitive in terms of quality-to-price ratio with the respect to other solutions already available on the market [4]-[7].

The ongoing activity is mainly devoted to (i) experimentally assess the resolution of the meter, (ii) realize the prototype on a unique board with the inclusion of a sensor for temperature compensation, and (iii) investigate the performance of the meter in the presence of reverberations (as an example, in closed-tank configuration).

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