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Characterization of an accurate phase measurement system using transmission lines

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***Abstract* – This paper deals with the experimental characterization of an accurate phase measurement system using transmission lines as phase reference. In particular, the used prototype implementing the accurate phase measurement system is also described. The prototype characterization aims of assessing the repeatability of the phase measurement and identifying the systematic effects affecting them. Several transmission lines, priory characterized by means of a Vector Network Analyzer, have been used as phase references. The obtained results demonstrated the standard deviation increases with the sine-wave frequency, while systematic effects are clearly visible at 10 kHz and 100 kHz. The maximum obtained standard deviation at 10 MHz is 0.30 °.**

I. INTRODUCTION

In several test procedures, sine-wave signal generators are adopted as sources of excitation for assessing the performance of waveform recorders [1], [2], [3], [4]. Those generators are often used to determine the magnitude and phase of the frequency response of waveform recorders (e.g., oscilloscopes) [5]. In this way, it is possible to compensate for the effect of the front-end on signal acquisition and to guarantee measurement traceability. For example, this is a very important step for calibrating electroshock weapons, as described in [6]. The frequency-sweep technique is the most accurate method used for estimating the magnitude of the frequency response of waveform recorders. However, for assessing the output phase spectrum of a sine-wave generator, the phase of the sine-wave should be measured. As stated in [7], several instruments are available on the market for measuring the phase difference between two isofrequential signals, however, few methods or instruments are available for measuring the phase of signals having different frequencies. Those methods and instruments cannot measure the phase over a wide range of frequencies with a low measurement uncertainty [7].

In [8], a method for accurately measuring the phase of a sine-wave signal is proposed. A proof-of-concept implementation of this method consisting of an Arbitrary Waveform Generator (AWG), an oscilloscope, and a universal digital counter is described in [9]. In this implementation, the AWG provides two outputs, i.e., the sine-wave under test and a pulse train signal synchronized with the sine-wave. Standard deviations in the order of 0.1 ° were obtained for frequencies ranging from 100 Hz to 10 MHz [9]. An improved hardware implementation using an analog multiplier and a voltmeter, is described in [10]. In this case, phase standard deviations of 0.017 ° and 0.0022 ° were obtained at 100 Hz and 1 MHz, respectively [10]. However, both the above-mentioned implementations require a signal generator under test having two output channels.

An implementation of the method [8] for a single input phase measurement instrument was proposed in [5]. In this case, a sampling pulse train signal is provided by a Field Programmable Gate Array (FPGA) board. The synchronization between the pulse train signal and the sine-wave under test is obtained through a 10 MHz reference clock. The obtained standard deviations are in the order of 0.01 ° at 5 $^\circ C$ for frequencies ranging from 100 Hz to 10 MHz, [5]. In the experimental setups used in [10], the standard deviation was assessed on 40 phase measurements by using a universal digital counter as a monitor to provide a coarse estimation of the phase. As reported in [7], the expanded uncertainty of the Keysight 53200A universal digital counter is 0.3 ° from 1 mHz to 100 kHz and 1.5 ° at 10 MHz. To the knowledge of the authors, there is no better reference counter on the market with a wide frequency range. However, it exhibits expanded uncertainties of one or two orders of magnitude higher than the standard deviations of the phase measurements provided by the proposed implementation. For this reason, the counter-based measurements cannot be used as reference. Therefore, the reference instrument has to be replaced with a reference method and reference objects presenting high repeatability phases.

In this paper, the performance of the prototype proposed in [10] is assessed against the measurements of phase deviation obtained by a Vector Network Analyzer (VNA) when the signal is passed through some transmission lines. The aim of the proposed analysis is to identify systematic effects and to assess the standard deviation of the phase measurements for frequencies ranging from 10 kHz to 10 MHz.

The paper is organized as follows. The phase measurement method is described in Section II. Section III reports the adopted prototype implementation. A compari-

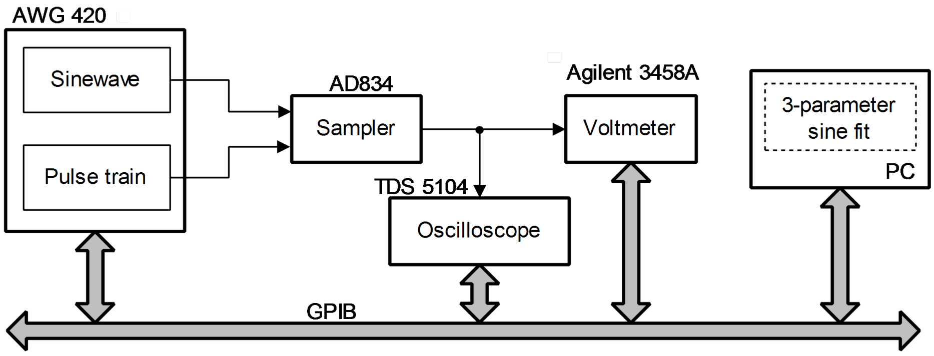

Fig. 1. Prototype implementation of the phase measurement method [10].

son of the obtained phase measurements with the reference ones derived from time propagation delay measurements of transmission lines is discussed in Section IV. The last Section concludes the paper and draws the future steps of the research.

II. PHASE MEASUREMENT METHOD

In this section, the phase measurement method proposed in [8] is summarized. In particular, the method is based on the coherent sampling of the sine-wave signal under test at instants defined by a pulse train signal (i.e., the pulse train and sine-wave signals are synchronized with each other). On the acquired samples, the 3-parameter sine fit method is applied to obtain the phase.

The phase measurement method relies on the following functional blocks: (i) a reference clock source, (ii) the sine-wave source under test, (iii) the pulse train source, (iv) a pulse delay, (v) a pulse selector, (vi) a sampler, (vii) an averaging and digitizing block, (viii) and the sine fit. The sine-wave source provides the signal under test, which is synchronized with the reference clock. Also, the pulse train source provides a signal synchronized with the reference clock, thus both sine-wave and pulse train signals are synchronized with each other. Then, the pulse train signal is delayed of a quantity that is an integer sub-multiple of the sine-wave period. The pulse selector is used for regulating the frequency of the pulse train signal driving the sampler. In particular, its frequency should be an integer sub-multiple of the sine-wave one. In this way, the sampler operates the sampling of the input signal (i.e., the sine-wave under test) in one instant for a sine-wave period and, being the frequency of the pulse train signal a sub-multiple of the sine-wave one, the output of the sampler is a pulse train having a time-integral value proportional to the amplitude of the sine-wave at the sampling instant defined by the pulse train. An averaging operation is performed on the sampler output before the final analog-to-digital conversion. The obtained samples are stored in a vector. A new time delay is imposed on the pulse train and another amplitude measurement is performed. When at least 3 amplitude measurements are acquired, the 3-parameter sine fit method is applied to the stored samples for estimating the phase of the sine-wave considering known its frequency.

III. PROTOTYPE IMPLEMENTATION

The prototype implementing the above-described phase measurement method is the one described in [10] (see Fig. 1). The AWG 420 by Tektronix [11] provides both the sine-wave and the pulse train signals working at the same frequency. The sampler is implemented with a commercially-available analog multiplier integrated circuit, i.e., AD834 [12]. The output of the sampler is a pulse train where the pulse amplitudes are modulated according to the sine-wave amplitudes in the time intervals defined by the pulse duration. In this way, the output signal has an energy proportional to the amplitude of the sine-wave at the instants defined by the pulse train. The Agilent 3458A voltmeter [13], configured for true-root mean square (true-rms) measurements, is used for quantifying this energy. The oscilloscope TDS 5104 by Tektronix [14] is used to acquire the sampler output signal, and by thresholding, to identify the sign of the associated true-rms measurement.

A MATLAB application has been developed for managing all the instruments, via General Purpose Interface Bus (GPIB), and for performing the 3-parameter sine fit on the true-rms measurements according to the imposed pulse train delays and the sine-wave frequency.

IV. PHASE MEASUREMENTS OF TRANSMISSION LINES

An experimental setup was implemented to investigate if the phase measurements provided by the prototype are affected by systematic effects. To this aim, transmission lines have been adopted for introducing phase shifts according to their exhibited time propagation delays. The test bench used for this analysis is depicted in Fig. 2. The Tektronix AWG 420 provides the sine-wave to the Quad Serial Loop Rev.B transmission line board by Xilinx. The transmission line board consists of five lines of nominal length

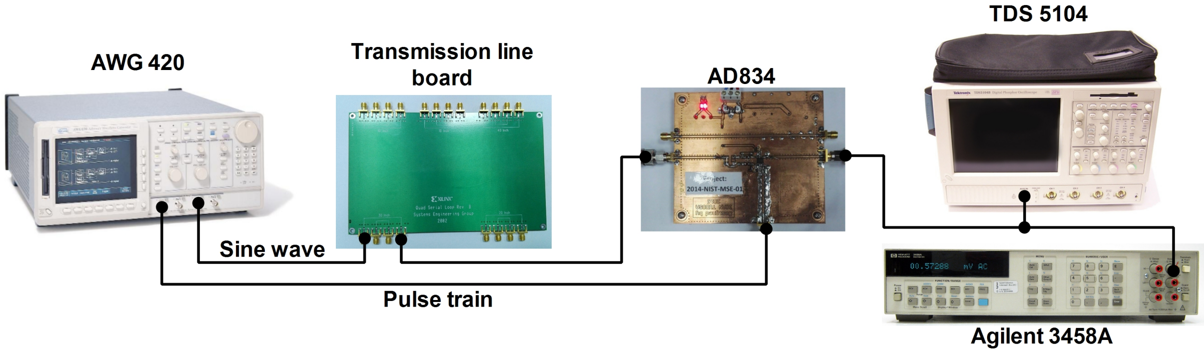

Fig. 2. Experimental setup used for the phase measurements using the transmission lines.

254 mm, 381 mm, 508 mm, 762 mm, and 1016 mm, that allows imposing five phase delays to the sine-wave. The phase measurement prototype based on the analog multiplier is used for measuring the sine-wave phase at the output of the transmission line. All the phase measurements have been referred to the one obtained by considering a short circuit instead of the transmission line. To characterize the transmission line, the Agilent E5071B network analyzer [15] has been used. In particular, for each transmission line, magnitude, phase, and propagation delay measurements for S_{21} parameter have been performed. The measurements are provided with respect to the magnitude, phase, and propagation delay measurements with the port wires of the network analyzer in a short circuit.

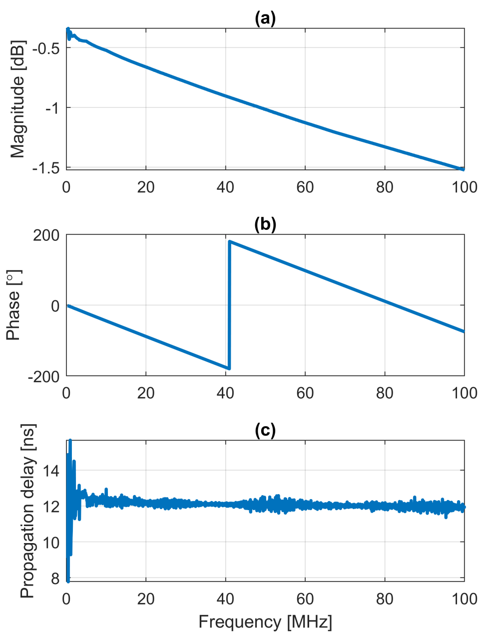

Fig. 3. Results of the S_{21} characterization of the 1016 mm transmission line: (a) magnitude, (b) phase, and (c) propagation delay.

For example in Fig. 3, the magnitude, phase, and propagation delay measurements for 1016 mm transmission line are depicted up to 100 MHz. As reported in [15], the VNA can perform measurements from 300 kHz to 8.5 GHz, thus, since the phase measurements are performed at 10 kHz, 100 kHz, 1 MHz, and 10 MHz, they have been derived from the propagation delay, by considering it constant with the frequency, as follows:

$$\phi = \Delta_T \cdot f, \tag{1}$$

where Δ_T is the measured propagation delay, and f is the frequency. The VNA exhibits a low accuracy for propagation delay measurements at frequencies up to 10 MHz, [15] (i.e., it is around 1 ns at 300 kHz, and decreases to 0.1 ns at 10 MHz). Thus, considering the propagation delays of the transmission lines constant in the bandwidth of analysis, the propagation delay measurements were obtained as the mean of the delays in the frequency range of 10 MHz to 90 MHz, and their variabilities were assessed from their standard deviations. In Tab. 1, the obtained propagation delay measurements and their type-A uncertainties for each transmission line are summarized. The uncertainty for the phase measurement has been assessed by applying the law of propagation of uncertainty to (1):

$$u_\phi = \phi \cdot \sqrt{u^2_{\Delta_T}/\Delta^2_T + u^2_f/f^2}, \tag{2}$$

Table 1. Propagation delays measured with the Agilent E5071B network analyzer.

Transmission line length [mm]	Propagation delay [ns]
254	2.01 ± 0.04
381	2.91 ± 0.04
508	3.84 ± 0.04
762	5.65 ± 0.04
1016	7.47 ± 0.04

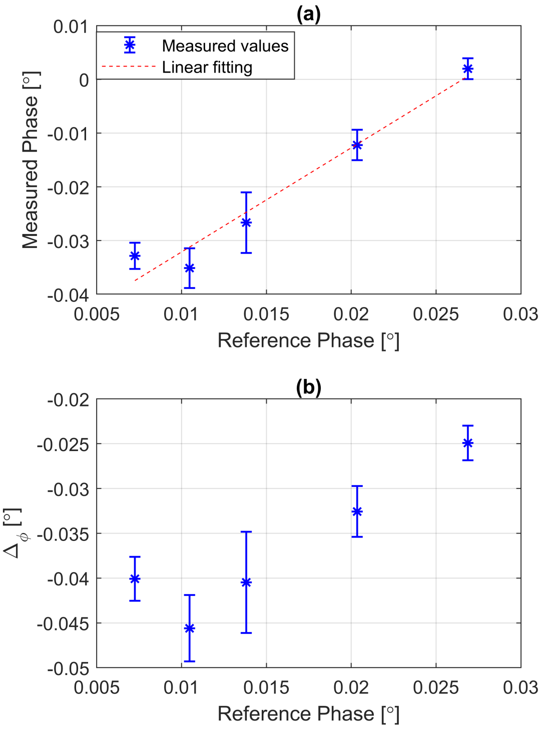

Fig. 4. Obtained phase measurements vs. reference phase measurements at 10 kHz with the five transmission lines.

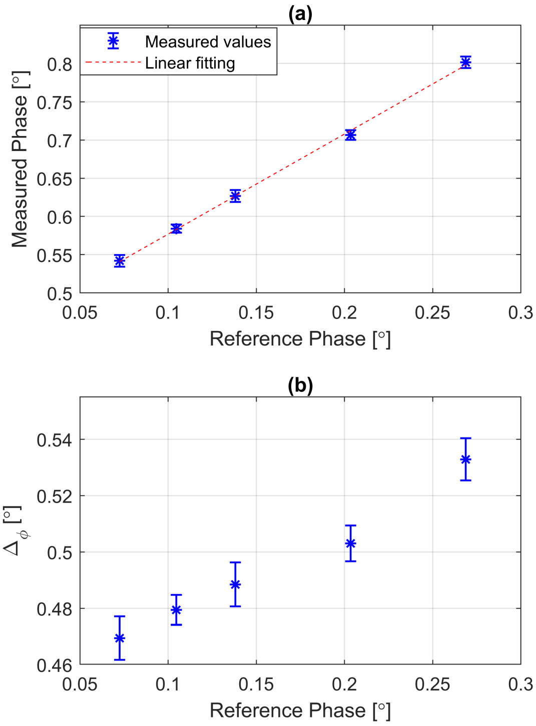

Fig. 5. Obtained phase measurements vs. reference phase measurements at 100 kHz with the five transmission lines.

where u_{Δ_T} is the type-A uncertainty reported in Tab. 1 and u_f is 5 ppm of the measured frequency f as reported in [15]. For assessing the repeatability of the phase measurements provided by the phase measurement prototype, 40 phase estimates are performed for each transmission line.

In particular, for the sine-wave frequency of 10 kHz, the following parameters were used to configure the phase measurement: the pulse duration was 10 μs, the sine-wave and pulse train amplitudes were 2 V, and the integration time for the true-rms measurements was 2 s. In Fig. 4a, the measured phases against the reference ones derived from the propagation delay measurements are depicted. The maximum obtained standard deviation is 0.0019 ° for the transmission line of 508 mm length, against the uncertainty of 0.00014 ° of the reference phase measurements obtained according to (2). Fig. 4b shows that the differences between the measured phases and the reference ones (i.e., Δ_ϕ) clearly increase with the reference phase, thus concluding that systematic effects affect the performed phase measurements at 10 kHz.

Fig. 5 reports the results obtained at 100 kHz with a pulse duration of 1 μs. Even in this case, the phase measurements are affected by systematic effects, and the maximum obtained standard deviation is 0.0026 ° for the transmission line of 508 mm length.

At the sine-wave frequency of 1 MHz, the maximum obtained standard deviation increased at 0.047 °, which is obtained for the transmission line of 762 mm length. In this case, the phase measurements do not show clear systematic effects (see Fig. 6).

Even for the sine-wave frequency of 10 MHz, the phase measurements seem not affected by systematic effects as depicted in Fig. 7. However, as expected, the maximum standard deviation increases by one order of magnitude with respect to the sine-wave frequency of 1 MHz (i.e., 0.30 ° for the transmission line of 254 mm).

In conclusion, the phase measurements are clearly affected by systematic effects at 10 kHz and 100 kHz, while at 1 MHz and 10 MHz, due to the increased standard deviations, the Δ_ϕ trends could be covered by the variability of the phase measurements.

V. CONCLUSION AND FUTURE WORK

In this paper, an experimental setup for measuring the phase delay introduced by transmission lines using a hardware prototype for measuring the phase of a sine-wave signal provided by at the output port of generator and was described. To guarantee measurement traceability, the propagation delays for all the transmission lines were measured

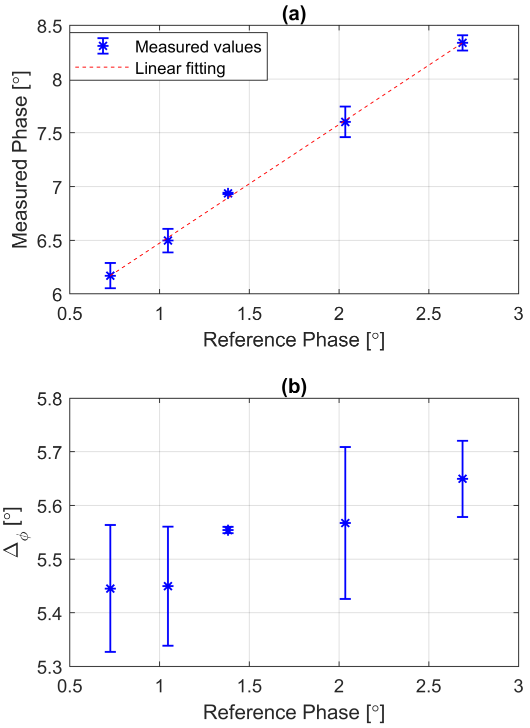

Fig. 6. Obtained phase measurements vs. reference phase measurements at 1 MHz with the five transmission lines.

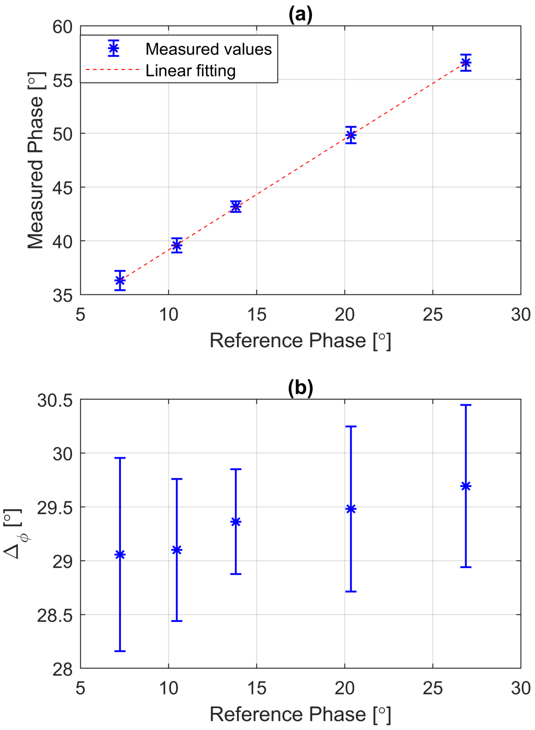

Fig. 7. Obtained phase measurements vs. reference phase measurements at 10 MHz with the five transmission lines.

by means of a network analyzer, a commercially available bench-top instrument. The obtained results for a sine-wave frequency from 10 kHz to 10 MHz were discussed. From the obtained results it was demonstrated that systematic effects affect the phase measurement performed by the prototype at 10 kHz and 100 kHz, while they were not clearly visible at 1 MHz and 10 MHz. Furthermore, the obtained standard deviations of the phase measurements were increased with the sine-wave frequency. In particular, at 10 kHz, it was 0.0019 °, while at 10 MHz, it has reached the value of 0.30 °. In particular at 1 MHz, the maximum obtained standard deviation is 0.047 ° against the value of 0.0022 ° reported in [10]. This growth of one order of magnitude of the standard deviation could be due to the fact that the phase delay measurement is obtained from two phase measurements one with the transmission line and the other with the short circuit. Furthermore, when the transmission line is inserted, the sinewave amplitude at the input of the analog multiplier is attenuated with respect to the one used in [10]. Future work will be directed to: (i) investigate the cause of systematic effects at 10 kHz and 100 kHz, (ii) implement a compensation method for the systematic effects, and (iii) to reduce the standard deviation of the phase measurements at 1 MHz and 10 MHz.

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