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Modified Digital Correlation Technique for Accurate Phase Measurement in Multi-Frequency Bio-Impedance Analysis

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Abstract

In bio-impedance analysis (BIA), high-frequency low-amplitude alternating current (AC) signals can incur time delays due to the capacitive nature of human cell membranes, and the characteristics of human tissues can be assessed from these delays in terms of phase changes. To accurately measure the phase changes, this work proposes a modified digital correlation-based phase measurement method. The accuracy of the general correlation technique is improved through digital direct synthesis (DDS) and digital correlation of unipolar square input signals. The proposed method is established through memory management and frequency adjustment. The result shows that, compared to the existing methods, the proposed method needs fewer hardware components, has better accuracy of 0.2° and higher frequency compatibility from 5 kHz to 1 MHz, and requires lower cost (140 USD). The method can be applied for the BIA of all types of tissues (recently used in COVID detection and care) and for the applications where efficient phase measurement is required.

Keywords: phase measurement, bio-impedance analysis, direct digital synthesis, unipolar square signal, digital correlation

1. Introduction

Time delays can occur when signals pass through different media. These delays are depicted as the phase differences of the propagated signals with respect to the original signals generated from sources. The measurement of phase differences can efficiently help assess the characteristics of the media. Thus, the delays between test signals and reference signals need to be determined precisely [1]. Interferometry, phase Doppler anemometry (PDA) and ultrasound imaging, signal demodulation of bio-signals, surface acoustic wave (SAW) sensing, Coriolis mass flowmetry (CMF), space systems, etc. are some of the applications which demand a precise measurement of phase differences. A phase measurement system should be analyzed based on its accuracy, sensitivity, simplicity, portability, response time, operating frequency, and noise immunity. In the case where synchronous detection/frequency synchronization is to be carried out to test the reliability of phase measurement techniques, the test signals and reference signals are generated from the same source.

In bio-impedance analysis (BIA), high-frequency low-intensity sinusoidal alternating current (AC) signals are applied to the tissue under test (TUT) through electrodes by a drive module, and the voltage response of TUT is measured by a sense module through electrodes, as shown in Fig. 1. The signal used for excitation suffers phase alteration while traveling through TUT. This is caused due to the capacitive nature of cell membranes of the cells constituting tissues. The signal used for excitation is an ultra-weak signal which also gets affected by additive noise sources like motion artifacts, other bio-signals, etc. [2]. It is essential to employ a precise AC constant source to excite tissues [3]. For a very weak signal, the detection system should be highly sensitive and accurate. Three dispersion mechanisms (α, β, and γ) are used to characterize the anomalous electric properties of

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bio-materials when subjected to the external AC signals of low frequency to very high frequency. Due to the capacitive nature of cell membranes, the tissue characteristics including intracellular, extracellular, and membranous properties are obtained only in the β dispersion range (5 kHz to 1 MHz) [2, 4]. Recently, the BIA during COVID care is a hot topic of research [5-6].

The purpose of the study is to devise a digital correlation-based phase measurement method for BIA. The method is intended to be simple, portable, cost effective, accurate, and high frequency compatible. For the first time, the phase measurement for bio-impedance signals by using digital correlation method is demonstrated.

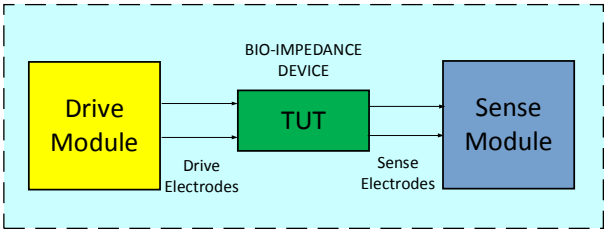


Fig. 1 Simple block diagram depicting BIA

2. Related Work

Conventional phase measurement methods in BIA, such as Lissajous pattern analysis [7], virtual vector voltmeter [7], XOR-filter [8], sine fitting [9], and zero crossing detectors [10], are easy to implement but are outdated. They are not feasible in portable devices and have frequency limitations. Yang et al. [11] used an off-the-shelf chip AD8302 for bio-impedance phase measurement since it directly gives the magnitude and phase of the signal under study. This technique is expensive and is sensitive to direct current (DC) components, so it is not effective. Olivarez et al. [12] utilized an LCR meter to measure bio-impedance; the meter is expensive and bulky, and is not application specific.

Analog phase measurement systems are characterized by bulky outdated designs, long-term voltage drifts, non-linearity, and cross talks at high frequencies. Digital electronics and ARM-based computational methods could minimize the effect of these characteristics, leading to an ultraprecision measurement. An accurate phase measurement is traditionally realized by using digital signal processing (DSP). The typical digital-type phase measurement schemes include digital zero crossing detector, fast Fourier transform (FFT), quadrature detection, phase-locked loop (PLL), and correlation.

Hu et al. [13] used a zero-crossing algorithm for the sake of simplicity and accuracy, but it is done in an off-line manner due to hardware constraints. Also, the digital zero crossing detection is influenced by harmonic distortion and high computation time. Kamat et al. [14] used a discrete Fourier transform (DFT) based off-the-shelf AD5933, and controlled the system using field programmable gate array (FPGA) which is computationally efficient. The DFT based measurement is affected by additive noises as it involves inverse tan function. Also, the frequency-domain method suffers from spectral leakage. The quadrature detection adds an additional phase shift of 90° followed by the use of sophisticated multipliers leading to complexity [1]. PLL is also employed to lock into the phase of low amplitude signals, but PLL is available as an off-the-shelf (analog and digital) and built-in module (in FPGA, software, and neuronal) and requires high quality external circuits [15]. Bertotti et al. [16] suggested a peak detection-based phase measurement, but it requires two reference sources increasing hardware complexity. The state-of-art devices such as Sine-phase [17] and Eliko [18] have focused on the accuracy compromising the cost. Therefore, it is necessary to devise a phase measurement method which is simple, compatible with portable devices, cost effective, accurate, and high frequency compatible. These features lead to effective phase measurement.

Knapp et al. [19] introduced a generalized cross correlator (GCC) based method to estimate phase differences by locating the cross-correlation peak of filtered versions of two received signals. The optimum performance is attained only when the signals and noises are Gaussialy distributed [19]. On the basis of accuracy, the correlation-based phase measurement tends to yield better results if modified in an application specific way. Drawing inspiration from their work [19], Liu et al. [20], Luo et

al. [21], Shen et al. [22], Liang et al. [23], etc. utilized the correlation method for time delay/phase difference measurement. Till now, the correlation method has been applied to the estimation of time delay in the field of PDA, interferometry, and remote sensing. However, the digital correlation-based phase measurement is not employed in many viable applications due to certain limitations, such as frequency drift errors and phase errors.

This study proposes a digital correlation-based phase measurement method, which is simple, portable, cost effective, accurate, and high frequency compatible. For the first time, the phase measurement for bio-impedance signals by using digital correlation method is demonstrated. The experimental functionality and reliability of this method is supported by simulation and analytical treatment. The exhaustive error analysis is carried out, and the remedial measures are suggested and implemented. Finally, the proposed setup is compared with the existing ones.

3. Hardware Realization for Phase Measurement Using Digital Correlation

In a bio-impedance system, a drive module offers a high-frequency low-amplitude excitation current to TUT through drive electrodes, and a sense module measures the impedance of TUT from the voltage response through sense electrodes. The tissue impedance is to be obtained as magnitude and phase. The methodology employed here for bio-impedance phase measurement is a part of a bio-impedance measurement device whose development is under progress. The excitation signal can incur phase changes while passing through a biological tissue. The phase difference between the excitation signal and the response signal is measured by the sense module to give bio-impedance phase. The accurate measurement of phase has always been critical. For testing the reliability of digital correlation, synchronous measurement approach is used. It requires the introduction of the phase difference between the reference signal (like excitation signal) and test signal (dummy bio-impedance signal). These signals can then be processed by digital correlation method, and the phase difference can be obtained.

3.1. Experimental setup for phase measurement

The controllers used in DSP boards do not accept negative signals. Hence, a DC offset is often added before processing them. A typical method of introducing a delay in signals is to propagate the signal through resistor capacitor (RC) networks. RC networks are unfavorable in the present application as they remove DC components and also entail the use of variable passive components with changing frequencies. Another option is to use a two-channel programmable function generator, which can produce two sine waves with a DC offset. The phases from 1° to 360° and the frequencies from 5 kHz to 1 MHz can be set using it. However, such generator is bulky and cannot be a part of portable devices. As such, direct digital synthesis (DDS) chips are employed to produce the reference signal and the test signal in this work. The experimental setup for performing the phase measurement is as shown in Fig. 2.

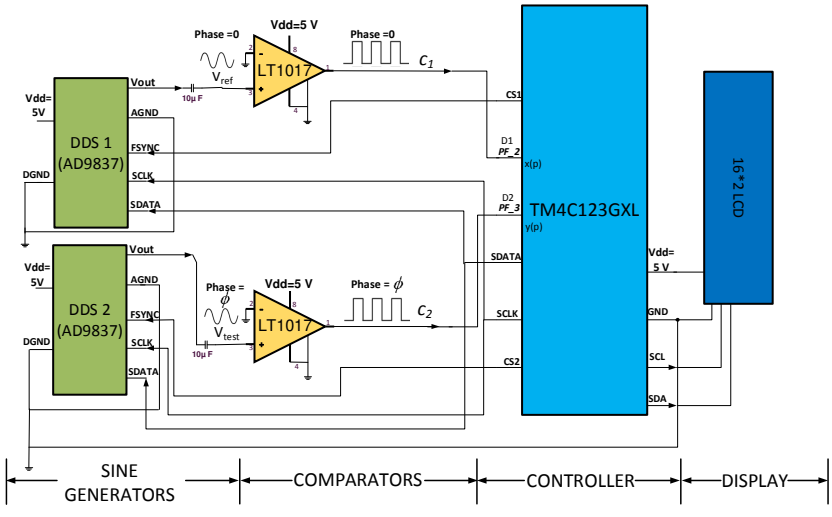


Fig. 2 Schematic diagram of hardware realisation for phase measurement

The reference (V_{ref}) and test (V_{test}) sinusoidal signals of 0.624 mV_{pp} and the frequencies from 5 kHz to 1 MHz are generated using DDS chips. The phase measurement using digital correlation method is performed using ARM Cortex M4 based Texas board TM4C123GXL [24]. The board can accept signals through analog and digital pins. The analog pins of the board receive the signals and convert them to digital signals before processing them. However, sampling the signals with a 10-bit analog-to-digital converter (ADC) can affect the phase information and can add A/D quantization noise. In order to avoid this, the conversion of sine waves to unipolar square waves is done and then given to the digital pins of the board. DDS (AD9837 from Analog Devices, Inc.) are employed to produce the reference signal and the test signal.

DDS ensures faster switching between output frequencies. Additionally, it has fine frequency resolution of 0.06 Hz, wide spectrum of operation till 8 MHz, and signal-to-noise ratio (SNR) of -63 dB. The calculation of frequency word (*FW*) is shown in Eq. (1), and the required frequency is set by sending 16-bit control word through serial peripheral interface (SPI) bus.

$$FW = \frac{Des.\ Freq.}{Ref.\ Freq.} \times 2^{n_1} \tag{1}$$

where n_1 is 28 for an in-built frequency register, the desired frequency (*Des. Freq.*) is the frequency of the input sinusoidal signals, and the reference frequency (*Ref. Freq.*) is 16 MHz. The phase register content is set after calculating its content as shown in Eq. (2) and sending its content as 16-bit control word.

$$Phase\ Register = \frac{\phi}{2\pi} \times 2^{n_2} \tag{2}$$

where n_2 is 12, *Phase Register* is 12 bits, and ϕ is true phase. For example, the data line value of C200 is the equivalent 16-bit control word for setting the phase of dummy bio-impedance signal as 45°. Comparators are used to convert sine waves to square waves without altering the phase information. It is essential to select a comparator integrated circuit (IC) which can sense low input voltages with favorable bandwidth and match input impedance with respect to previous stages. LT1067 from Analog Devices, Inc. is experimentally chosen from a set of comparators, as it can detect a minimum of 100 mV input sine wave and convert it into unipolar square wave. In real time applications, weak signals are magnified by subsequent amplifier stages, and hence the sensitivity of 100 mV is ample. It also functions on single supply, and this feature is essential to avoid negative signals entering the subsequent digital board. Comparator circuits generate unipolar square waves.

Noise interferences are kept away by using constant current source of 215 kΩ output impedance and 218 μV root mean square noise for excitation [3]. Symmetrical instrumentation amplifiers with common mode rejection ratio (CMRR) above 80 dB for rejection of electrode noise and motion artifacts are also used. The simulative noise analysis of comparator circuit is carried out in MULTISIM, and a considerable low value of output noise of 41 pV/Hz power is obtained. This work only focuses on the method of phase measurement, and other real time measurement challenges are considered during the development of bio-impedance devices.

The Texas board with 64 pin and 80 MHz crystal has two SPI buses, one of which is used for the communication and control of DDS chips. The reference square signal ($c1$) and test square signal ($c2$) obtained at the outputs of comparators are given to the digital pins of the board (PF2 and PF3) and then processed digitally to deduce the phase information. This simple method uses only two comparators and a digital board. The comparator works on 5 V DC single supply, and the board supplies this power. The board is universal serial bus (USB) powered.

3.2. Phase measurement using digital correlation

The phase difference of ϕ is induced between two unipolar square signals using DDS. These signals are processed by TM4C123GXL board after acquiring their samples through digital pins. The floating point unit (FPU) of the board performs digital correlation by utilizing the samples of input signals. Even though the input signal is continuous, the large sample size conserves the phase information within the board. Both auto correlation and cross correlation of waves are performed to obtain the correlation coefficient as presented in Eq. (3).

$$\gamma = \frac{\sum_{p=0}^{N}[x(p)-\overline{x}][y(p)-\overline{y}]}{\sqrt{\sum_{p=0}^{N}[x(p)-\overline{x}]^2\sum_{p=0}^{N}[y(p)-\overline{y}]^2}} \tag{3}$$

where γ is the correlation coefficient, N is the sample number of input unipolar square signals, p represents the sample number, $x(p)$ is the reference unipolar square signal, $\overline{x}$ is the mean of $x(p)$, $y(p)$ is the test unipolar square signal, and $\overline{y}$ is the mean of $y(p)$. $c1$ and $c2$ signals have an amplitude of 5 V with an offset of 2.5 V. The digital pin senses and stores 1 for 5 V and 0 for 0 V. $\overline{x}$ and $\overline{y}$ are 0.5 considering the stored inputs. The maximum value of γ occurs when ϕ is 0°, and the minimum value of γ occurs when ϕ is 180°. These values are 1 and -1 respectively, and γ is 0 at 90°. This establishes a relationship between phase difference and γ, as shown in Eq. (4).

$$\hat{\phi} = 90^{\circ} - 90^{\circ} \times \gamma \tag{4}$$

where $\hat{\phi}$ is the measured phase in degrees, and γ is the correlation coefficient. Once the correlation is performed and the correlation coefficient is obtained, the phase difference is displayed on a liquid crystal display (LCD) monitor in degrees. This value is compared with the known value set by the DDS chip. The observation is recorded for a set of phase values from 0° to 360° in a range of frequencies from 5 kHz to 1 MHz. It is necessary to analyze the errors occurred during the experimentation and resolve them to apply the method in real time applications to improve the accuracy. The *digitalRead*() command accepts the samples of unipolar signals.

4. Modelling for Phase Measurement Using Digital Correlation

Once the relationship between phase difference and correlation coefficient is established, it is necessary to further analyse the functionality and challenges of the digital correlation method before its real time utilisation.

4.1. Modelling by simulation

Unipolar square waves are generated in MATLAB environment using square function. The square waves are defined by amplitude (0.5 V), offset (0.5 V), phase, number of samples (200-5000), and frequency (5 kHz to 1 MHz). The phase adjustment in the degrees from 0° to 360° (ϕ) is converted to radians and is introduced to one of the signals treated as the test signal. The correlation coefficient is calculated as per Eq. (3), and the measured phase ($\hat{\phi}$) is obtained using Eq. (4). The true phase and measured phase for 2000 samples at 5 kHz are recorded, and the error is tabulated in Table 1.

A maximum error of 0.2° (the best possible accuracy) is observed at 5 kHz for true phase from 0 to 180. For the true phase greater than 180°, the value of γ repeats and hence the $\hat{\phi}$ value is also repeated. This is not an issue in phase measurement as the phase differences in all major applications are confined within 180°. Also, it is observed that as frequency increases with the fixed sample size, the error increases (addressed in section 5.1.).

Table 1 Simulative phase measurement using digital correlation

True phase, ϕ(°)	Correlation coefficient, (γ)	Measured phase, $\hat{\phi}$ (°)	Error, $\hat{\phi}$ - ϕ (°)
0.000	1.000	0	0
1.000	0.992	0.895	-0.105
10.000	0.948	9.895	-0.105
45.000	0.501	44.978	-0.022
50.000	0.449	49.835	-0.165
60.000	0.337	59.910	-0.090
90.000	0.000	89.955	-0.045
120.000	-0.107	119.820	-0.180
150.000	-0.331	149.865	-0.135
180.000	-1.000	180.000	0.000
270.000	0.000	90.000	-180.000
360.000	1.000	0.000	-360.000

4.2. Experimental modelling

The phase measurement using digital correlation method is performed by the FPU of ARM Cortex M4 based Texas board TM4C123GXL, and the experimental setup is illustrated in section 3.1. The digital pins are configured as input pins, and the unipolar signals are applied to these pins. 2000 samples of these signals are stored as arrays on which the correlation operation (repeated multiplication and cumulative addition of array elements/input samples) is performed to extract γ (Eq. (3)). The true phase set by DDS is measured using γ (Eq. (4)) as the measured phase. The result obtained at 5 kHz is tabulated in Table 2.

During the experimental modelling of the proposed method, it is seen that a maximum permissible error of 0.870°is observed at 5 kHz. The error is more in experimental modelling than in simulation due to analog elements like comparators. The measurement process is repeated for different frequencies. It is observed that as the frequency increases with the fixed sample size, the error also increases just like in the simulation of digital correlation. The reasons for this error increase are discussed in section 5.1.

Table 2 Experimental phase measurement using digital correlation

True phase, ϕ(°)	Correlation coefficient, (γ)	Measured phase, $\hat{\phi}$ (°)	Error, $\hat{\phi}$ - ϕ (°)
0.000	1.000	0	0
1.000	0.992	1.800	0.800
10.000	0.948	10.680	0.680
45.000	0.501	45.860	0.860
50.000	0.449	50.640	0.640
60.000	0.337	60.750	0.750
90.000	0.000	90.760	0.760
120.000	-0.107	121.020	0.020
150.000	-0.331	150.87	0.870
180.000	-1.000	180.000	0.000
270.000	0.000	90.660	-180.000
360.000	1.000	0.000	-360.000

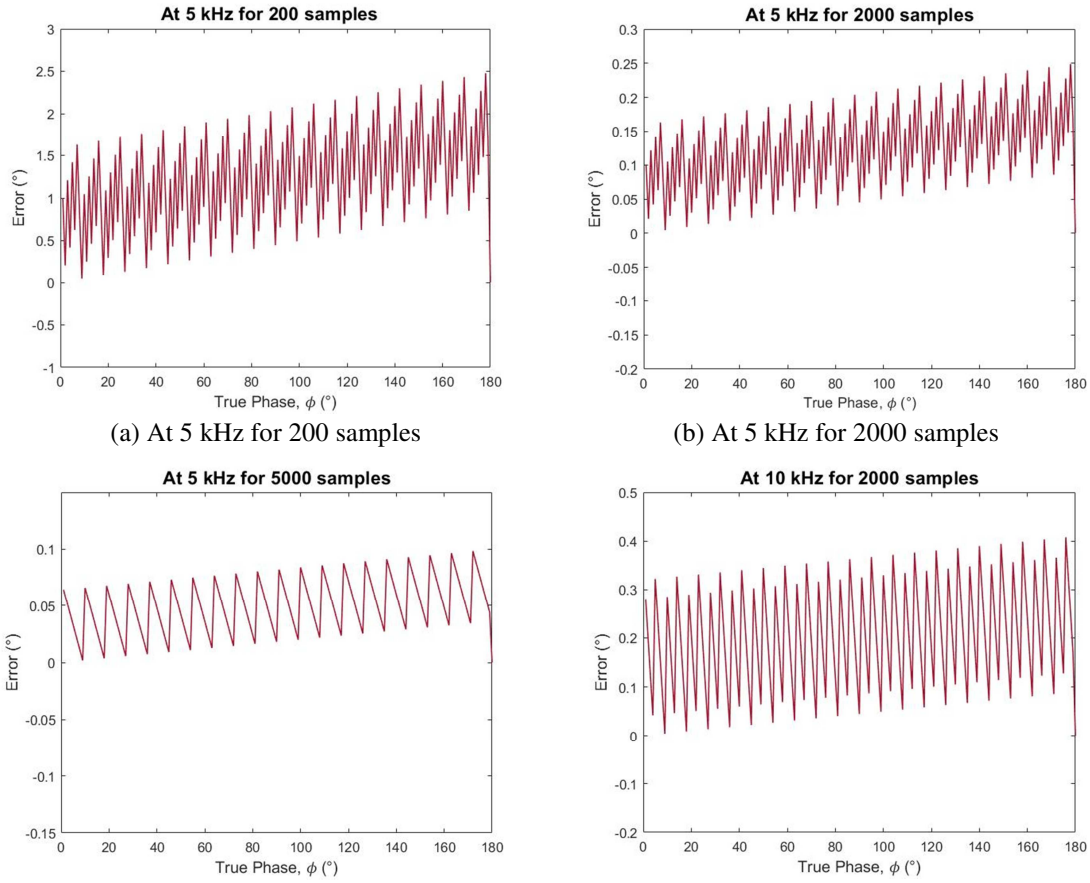
5. Results and Discussion

The characteristics of biological tissue are assessed using bio-impedance. Bio-impedance can be represented as magnitude and phase varying with respect to time. Sinusoidal carrier signals with bio-impedance information are processed to extract magnitude and phase. The proposed method uses digital correlation to measure the bio-impedance phase. Sinusoidal signals are conditioned into unipolar square signals before phase measurement. The correlation method is used to compare the

unipolar square signals and yield a correlation coefficient. The correlation coefficient represents the phase information. The phase measurement using correlation method is made viable through a series of simulative and experimental analyses. Initially, the simulation and experimentation of phase measurement is carried out at a certain frequency. Then, the frequency is varied. Other parameters like amplitude, offset, sample size, etc. are kept the same for all measurements. It is seen that the occurring error increases with respect to frequency for a fixed sample size.

5.1. Error analysis for the simulation of phase measurement using digital correlation

The frequency and sample size of signals are varied in the simulation of phase measurement using digital correlation. The error is plotted versus true phase for various frequencies and sample sizes as shown in Fig. 3. At 5 kHz, as the sample size increases from 200 to 5000, the error (2.5° to 0.1°) decreases. This is because the sample size denotes the sampling frequency. According to Nyquist criterion, the sampling frequency should be at least twice the input frequency. In the simulation, a single cycle is divided into samples. For an input frequency of 5 kHz, the number of samples should be at least 2000. Any value below that (e.g., 200) does not extract full phase information due to under-sampling whereas a large sample size (e.g., 5000) yields more information from input signals. As the frequency increases to 10 kHz, the sample size of 5000 is not enough and need to be increased to fulfill Nyquist criteria. A small error occurs even if the sample size is optimum with respect to frequency. This error is due to the harmonics of fundamental frequency of square wave and is negligible at higher frequencies.



(a) At 5 kHz for 200 samples (b) At 5 kHz for 2000 samples

(c) At 5 kHz for 5000 samples (d) At 10 kHz for 2000 samples

Fig. 3 Simulation of phase measurement using digital correlation

5.2. Experimental error analysis for phase measurement using digital correlation

As explained in section 4.2., the phase measurement of signals with 5 kHz is carried out smoothly with a maximum error of 0.870° for 2000 samples. The input signals at the digital pins are sampled by *digitalRead*() and stored as global variables in random access memory (RAM). The digital read time for 2000 samples is found out through programming as 9.8 ms, and the

sampling frequency is hence 200 kHz. The input frequency is changed by programming DDS and is set to a higher frequency of 100 kHz. It is seen that if the sample size is kept the same, there is a drastic increase in phase error just like in simulation. The reason for the phase error is explained in section 5.1. The error is nullified by increasing the sample size, but ARM Cortex M4 board has a 32 kB RAM which restricts the sample size to 3800 (2000 is a safe value to avoid instability issues). In order to process the signals with higher frequencies, more memory in RAM is needed. The limitation of RAM affecting sample size is confirmed by trying to use an ATMega 328p Arduino board instead of TEXAS board. The sample size of input signals is limited in ATMega328p to 300 due to 2 kB RAM. External RAMs (like 23LC1024, 47LC16, etc.) can be interfaced to the board through I2C or SPI to accommodate large sized global variable arrays to solve this shortcoming. Another alternative is to use boards with microcontrollers having RAM with compatible large memories (like Arduino Due, TMS320F28335, etc.).

The BIA experimental setup using modified phase measurement technique for a biological tissue (egg) is as shown in Fig. 4. Tetrapolar bio-impedance (BI) measurement is done by inserting needle electrodes up to 1 cm into the tissue of a hard-boiled country egg. BI is measured using LCR meter, and BI phase measurement is conducted at 5 kHz, 50 kHz, and 100 kHz. LCR meter has frequency limitation up to 200 kHz and uses voltage excitation with bipolar measurement [2].The results are tabulated in Table 3.

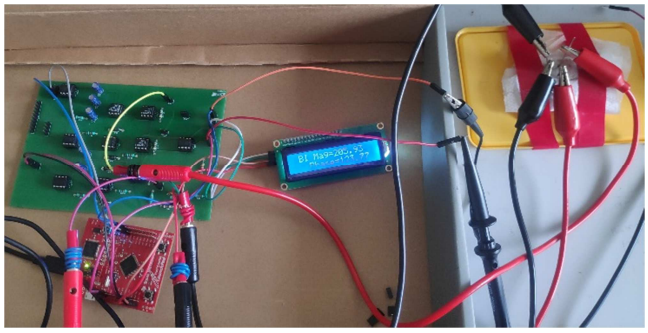


Fig. 4 Bio-impedance measurement of biological tissue (egg)

Table 3 Comparison of BI measurement with LCR meter and proposed method

Frequency (kHz)	BI using LCR meter	BI using digital correlation
	Phase (°)	Phase (°)
5	-89.65	-88.12
50	-64.56	-65.04
100	-30.19	-30.33

5.3. Comparison between the proposed method and the existing methods

The existing methods of bio-impedance measurement are compared based on signal processing type, accuracy, frequency compatibility, cost, and applications. The proposed phase measurement method is a part of the bio-impedance device which is being developed. The technique used here is the correlation method [20-23]. To analyze where the proposed method stands, a comparison between the proposed method and other traditional and contemporary techniques is made, as tabulated in Table 4.

A careful study of these methods reveals that the traditional techniques are bulky, slow, and limited by operating frequency. Other advanced techniques overcome the frequency limitation up to a certain extent and offer a better accuracy. However, they are complex. The commercially available phase detectors are expensive, sensitive to DC components, frequency limited, and offer moderate accuracy. The proposed digital correlation method is a part of bio-impedance device which is superior to all above techniques in terms of accuracy, frequency compatibility, portability (stand-alone module), speed, and cost effectiveness. The developed bio-impedance device with the present method of phase measurement costs around 140 USD. A/D quantization errors are nil in this method because there is no ADCs.

Table 4 Comparative analysis of phase measurement methods

Ref.	Method (°)	Type of signal processing	Accuracy (°)	Max. operating frequency (kHz)	Approx. cost (USD)	Applications
[1]	Quadrature detection	Analog	0.1	100	200	Impedance measurement
[7]	Lissajious loop pattern	Analog	1	100	280	Impedance measurement
[7]	Virtual vector voltmeter	Analog	1	100	3485	Bio-impedance measurement for body mass
[8]	XOR-filter	Analog	1	10	150	Bio-impedance measurement for urolithiasis
[9]	Sine wave fitting	Simulative	0.1	1	278	Impedance measurement
[10]	Auto-balance bridge	Analog	1	10000	200	Bio-impedance of cell
[11]	Phase detector (AD8302)	Analog	0.3	100	2787	Bio-impedance measurement
[12]	LCR meter	Analog	0.1	20	2000	Bio-impedance measurement for diabetes neuropathy
[14]	FPGA method of samples	Digital	0.003	100	500	Impedance cardiography
[15]	Phase-locked loop	Digital	0.1	10000	250	Impedance measurement
[16]	Peak detection-based phase measurement	Analog	0.3	100	200	Impedance measurement
[17]	Sine phase	Software based	1	16600	6272	Impedance measurement
[18]	Eliko	Software based	0.1	349	6690	Impedance measurement
[20]	Correlation	Digital	0.15	1000	-	Range finder
[23]	Sine-tan method	Analog	0.01	1000	5000	Interferometry
[25]	FFT-inverse discrete Fourier transform	Digital	0.1	10000	-	Impedance measurement
This study	Modified digital correlation	Digital	0.002	1000	140	Bio-impedance analysis

6. Conclusions

On the basis of the studies conducted, it can be concluded that the digital correlation-based phase measurement method is a reliable means to characterize the media through which the signals pass. This characterization is done by measuring the delay/phase changes incurred by the signals. In the hardware realization, a reference wave from sources is compared with the wave at the receiving end and looked upon for phase differences by the experimental setup. The phase measurement using correlation method is not widely used in many viable applications including bio-impedance phase measurement due to the demerits such as frequency drift and phase errors. These issues are addressed in this work in a systematic manner. The best possible accuracy of 0.2° is obtained by realizing the proposed method for measuring the induced phase differences between two sine waves in a frequency range of 5 kHz to 1 MHz. This modified phase measurement technique is a part of sense module of bio-impedance device under development. This modified method can be incorporated in portable devices for any application which needs accurate phase measurement, as it uses fewer numbers of hardware components and can be operated on USB power.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] M. Sedlacek and M. Krumpholc, “Digital Measurement of Phase Difference—A Comparative Study of DSP Algorithms,” Metrology and Measurement Systems, vol. 12, no. 4, pp. 427-448, January 2005.

[2] S. Grimnes and O. Martinsen, Bioimpedance and Bioelectricity Basics, London: Academic Press, 2008.

[3] S. Sruthi, R. Dhavse, and J. N. Sarvaiya, "Precise, Portable and Wide Band Alternating Current Source for Extremely Low Current Values," Analog Integrated Circuits and Signal Processing, vol. 102, no. 2, pp. 273-282, February 2020.
[4] F. Simini and P. Bertemes-Filho, Bioimpedance in Biomedical Applications and Research, Cham: Springer International Publishing, 2018.
[5] H. P. F. X. Moonen, F. J. L. Zanten, L. Driessen, V. de Smet, R. Slingerland-Boot, M. Mensink, et al., "Association of Bioelectric Impedance Analysis Body Composition and Disease Severity in COVID-19 Hospital Ward and ICU Patients: The BIAC-19 Study," Clinical Nutrition, vol. 40, no. 4, pp. 2328-2336, October 2021.
[6] M. N. R. Jafari, Z. Esmaeilbeig, and M. Nemati, "Overcoming the Bottleneck in COVID-19 Detection: A Machine-Learning Approach to Improve Accuracy of Electrochemical Impedance Spectroscopy (EIS) Detection Sensitivity," Open Access Journal of Biomedical Science, vol. 3, no. 1, pp. 676-679, October 2020.
[7] J. G. Webster and H. Eren, Measurement, Instrumentation, and Sensors Handbook: Electromagnetic, Optical, Radiation, Chemical, and Biomedical Measurement, Boca Raton: CRC press, 2017.
[8] A. Silverio and J. D. Tatel, "Development of a Variable Frequency Impedance Measuring System," 14th International Symp. on Integrated Circuits, pp. 564-567, December 2014.
[9] P. M. Ramos, F. D. Silva, and A. C. Serra, "Improving Sine-Fitting Algorithms for Amplitude and Phase Measurements," 17th International Measurement Confederation World Congress, pp. 614-619, June 2003.
[10] N. Li, H. Xu, W. Wang, Z. Zhou, G. Qiao, and D. D. Li, "A High-Speed Bioelectrical Impedance Spectroscopy System Based on the Digital Auto-Balancing Bridge Method," Measurement Science and Technology, vol. 24, no. 6, 065701, May 2013.
[11] Y. Yang, J. Wang, G. Yu, F. Niu, and P. He, "Design and Preliminary Evaluation of a Portable Device for the Measurement of Bioimpedance Spectroscopy," Physiological Measurement, vol. 27, no. 12, 1293, 2006.
[12] J. P. Olivarez, F. A. Olivares, A. P. Medina, J. D. Carmona, A. R. Agundis, A. E. Calderon, et al., "Bioimpedance Phase Angle Analysis of Foot Skin in Diabetic Patients: An Experimental Case Study," Innovation and Research in Biomedical Engineering, vol. 36, no. 4, pp. 233-239, 2015.
[13] G. Hu, J. Xu, G. W. Auner, J. Smolinski, and H. Ying, "Digital Phase Detection Approach and Its Application for AlN Dual-Mode Differential Surface Acoustic Wave Sensing," Sensors and Actuators B: Chemical, vol. 132, no. 1, pp. 272-279, January 2008.
[14] D. K. Kamat, S. Nimkar, and P. M. Patil, "Bio-Impedance Computation Based on Hardware Implementation Using FPGA," International Journal of Electrical Engineering, vol. 6, no. 1, pp. 12-19, January-June 2014.
[15] "What is Direct Digital Synthesiser DDS," https://www.electronics-notes.com/articles/radio/frequency-synthesizer/dds-direct-digital-synthesis-synthesizer-what-is-basics.php, 2012.
[16] F. L. Bertotti, M. S. Hara, and P. J. Abatti, "A Simple Method to Measure Phase Difference between Sinusoidal Signals," Review of Scientific Instruments, vol. 81, no. 11, 115106, 2010.
[17] "SinePhase Impedance Analyzer," https://sinephase.com/impedance-analyzer-model-16777k-lcr-meter/, August 2016.
[18] "Impedance Spectroscopy," https://eliko.ee/quadra-impedance-spectroscopy/, December 2017.
[19] C. Knapp and G. Carter, "The Generalized Correlation Method for Estimation of Time Delay," IEEE Transactions on Acoustics, Speech, and Signal Processing, vol. 24, no. 4, pp. 320-327, August 1976.
[20] Y. Z. Liu and B. Zhao, "Phase-Shift Correlation Method for Accurate Phase Difference Estimation in Range Finder," Applied Optics, vol. 54, no. 11, pp. 3470-3477, April 2015.
[21] J. Luo and E. E. Konofagou, "A Fast Normalized Cross-Correlation Calculation Method for Motion Estimation," IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 57, no. 6, pp. 1347-1357, June 2010.
[22] Y. L. Shen and Y. Q. Tu, "Correlation Theory-Based Signal Processing Method for CMF Signals," Measurement Science and Technology, vol. 27, no. 6, 065006, May 2016.
[23] Y. R. Liang, H. Z. Duan, H. C. Yeh, and J. Luo, "Fundamental Limits on the Digital Phase Measurement Method Based on Cross-Correlation Analysis," Review of Scientific Instruments, vol. 83, no. 9, 095110, September 2012.
[24] Texas Instruments, "Tiva™ TM4C123GH6PM Microcontroller Data Sheet," https://www.ti.com/lit/ds/symlink/tm4c123gh6pm.pdf, 2014.
[25] W. Wang, Y. Tang, X. Zhang, and K. Wang, "Design of a Recursive Single-Bin DFT Algorithm for Sparse Spectrum Analysis," Cluster Computing, vol. 20, no. 2, pp. 1483-1492, April 2017.