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Title: Wideband Precision Phase Detectionn for Magnetic Induction Spectroscopy

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Abstract: Magnetic induction spectroscopy (MIS) has many applications providing a contactless impedance meausrement. However, MIS applications is currently limited due to the high precision of phase detection required over a wide band of frequencies. This paper focuses on phase detection aspect of the MIS and the advantages and disadvantages of various phase detection methods and phase detection subsystem architectures are discussed. The chosen phase detection method is investigated further and prototype hardware and software is developed. The developed prototype is tested and compared to other recent MIS sysetm design. The prototype hardware is able to measure the phase difference of signals from below 200kHz to over 20MHz with milli-radian precision which will significantly enhance the MIS systems.

Dear editor for Measurement:

Please find attached our article in:

Wideband Precision Phase Detection for Magnetic Induction Spectroscopy

This is a revised version of the Paper no. MEAS-D-15-00346. As suggested by the referees and Editor we have removed all design description parts of the part making it substantially shorter as suggested.

Dr Manuch Soleimani

Dear Reviewers and Editor of Measurement. Here our responses to full revision of the article. We thank reviewer for their constructive report on the paper.

Reviewer #1: The paper presents an interesting and novel method for measuring phase-shift for MIS systems and is a welcome addition to the literature.

Answer: Thanks.

The introduction to the phase detection system "The intermediate frequency signal could also be sampled and processed digitally." is rather odd and leaves the reader questioning whether this is an option or the actual process used. This section needs re-writing to be more precise in its description of what actually is described here in this paper.

Answer: Thanks. Fixed now. The proposed method has now being clear.

I personally find Figures 2 and 3 difficult to understand, some extra explanation would be appreciated by this reader and possibly others as to the implications of what is shown in the figures.

Answer: We explain what the colormaps in figures 2, 3 are showing. In ideal scenario the reconstructed phase difference should be the same as true, but there are minor differences, which shown by these maps.

I take exception to the statement at the end of the discussion: "In this paper, it is demonstrated that by obtaining a full phase shift spectroscopy plot, the ripeness level of fruits can be established." There is a clear effect on the phase shift measurement observed on a rotting apple, which is very encouraging, but it is an overstatement to say that "the ripeness level of fruits can be established" from this one result. Much more data would be required to support the statement made.

Answer: Totally agree. We have modified this statement.

There are a significant number of errors in grammar and typography, so some editing in this respect is necessary.

Answer: The paper has been fully proofread one more time.

Reviewer #2: REVIEW REPORT
Manuscript title: Wideband Precision Phase Detectionn for Magnetic Induction Spectroscopy
Manuscript ID: MEAS-D-16-00077 The authors have presented a research study conducted on the development of a prototype system of "Wideband Precision Phase Detection for Magnetic Induction Spectroscopy". The manuscript dealt with an interesting research problem on Magnetic Induction Spectroscopy (MIS). Author also presented the experimental results obtained from their proposed research studies conducted with their prototype MIS system developed.
Though the manuscript has been written with a very good topic of interest to the research community working towards the application of the "Magnetic Induction Spectroscopy (MIS)", but the following issues must be addressed to improve the manuscript.

Answer: Thanks.

1. Author has entered the title of the manuscript in the manuscript submission system with a typo "Detectionn" which should be corrected.

Answer: Fixed.

2. The English language of the manuscript is required to be thoroughly revised. The meaning of the several sentences is not clear. A thorough English correction of the manuscript is required.

Answer: The paper has been fully proofread one more time.

3. Abstract should be rewritten with improved English language. Abstract should mention whether the prototype MIS system they developed is suitable for only biological application or it could be applied for other applications also.

Answer: Fixed.

4. Section 1: Introduction
a. Introduction section should be rewritten with a detail literature survey presenting the background and motivation by citing a sufficient number of research literatures.

b. "Magnetic Induction Spectroscopy (MIS)" has already been studied by a number of research groups and it has been applied to a number of research problems but still the authors cited only five papers in the entire manuscript.
5. The author can cite the following literatures for MIS:
a. Zakaria, Z., Sarkawi, S., Jalil, J. A., Balkhis, I., Rahim, M. A. A., Mustafa, N., ... & Rahiman, M. H. F. (2015). Simulation of Single Channel Magnetic Induction Spectroscopy for Fetal Hypoxia Detection. Jurnal Teknologi, 73(6).
b. Dávila, J. R., Gutierrez, J. C. P., & Blanco, R. P. (2012). Use of Magnetic Induction Spectroscopy in the Characterization of the Impedance of the Material with Biological Characteristics. INTECH Open Access Publisher.
c. O'Toole, M. D., Marsh, L. A., Davidson, J. L., Tan, Y. M., Armitage, D. W., & Peyton, A. J. (2015). Non-contact multi-frequency magnetic induction spectroscopy system for

industrial-scale bio-impedance measurement. Measurement Science and Technology, 26(3), 035102.
d. González, C. A., Pérez, M., Hevia, N., Arámbula, F., Flores, O., Aguilar, E., ... & Rubinsky, B. (2010). Over-hydration detection in brain by magnetic induction spectroscopy. In Journal of Physics: Conference Series (Vol. 224, No. 1, p. 012123). IOP Publishing.
e. Hevia-Montiel, N., Sanchez-Soto, E., & gonzalez, C. (2013). Early Breast Cancer Detection by Magnetic Induction Spectroscopy. 生体医工学, 51(Supplement), R-196.
f. Scharfetter, H., Casañas, R., & Rosell, J. (2003). Biological tissue characterization by magnetic induction spectroscopy (MIS): requirements and limitations. IEEE Transactions on Biomedical Engineering, 50(7), 870-880.

Answer: Many thanks. Included.

6. Authors should provide few references on the "bio-electrical impedance spectroscopy (BIS)". Author may cite the following literatures:
a. Bera, T. K., Nagaraju, J., & Lubineau, G. (2015). Electrical impedance spectroscopy (EIS)-based evaluation of biological tissue phantoms to study multifrequency electrical impedance tomography (Mf-EIT) systems. Journal of Visualization, 1-23.
b. Bera T. K., Bioelectrical Impedance Methods for Noninvasive Health Monitoring: A Review, Journal of Medical Engineering, Vol. 2014 (2014), Article ID 381251, 28 pages, http://dx.doi.org/10.1155/2014/381251
c. Jaffrin, M. Y., & Morel, H. (2008). Body fluid volumes measurements by impedance: A review of bioimpedance spectroscopy (BIS) and bioimpedance analysis (BIA) methods. Medical engineering & physics, 30(10), 1257-1269.
d. Earthman, C., Traughber, D., Dobratz, J., & Howell, W. (2007). Bioimpedance spectroscopy for clinical assessment of fluid distribution and body cell mass. Nutrition in Clinical Practice, 22(4), 389-405.

Answer: Many thanks. Included.

7. For intracellular fluid (ICF) and extracellular fluid (ECF) of the biological tissues the author should cite some literatures. Author may cite the following literatures:
a. Bera, T. K., Nagaraju, J., & Lubineau, G. (2015). Electrical impedance spectroscopy (EIS)-based evaluation of biological tissue phantoms to study multifrequency electrical impedance tomography (Mf-EIT) systems. Journal of Visualization, 1-23.
b. Bera T. K., Bioelectrical Impedance Methods for Noninvasive Health Monitoring: A Review, Journal of Medical Engineering, Vol. 2014 (2014), Article ID 381251, 28 pages, http://dx.doi.org/10.1155/2014/381251

Answer: Many thanks. Included.

8. Section 2: Phase detection method (Subsection 2.1):
a. The first paragraph started suddenly. The first sentence should be modified and presented after some introductory sentences. The first sentence "The intermediate frequency signal could also be sampled and processed digitally." of a first paragraph of this section/subsection looks like a statement made after some missing sentences.

Answer: Many thanks. Fixed.

b. The sentence "A system that could be developed to determine the phase by mixing the signals to an intermediate frequency before sampling and determining the phase using digital signal processing." is not correct. Please rewrite.
Answer: Fixed.

c. Provide some reference after "Unlike the systems that mix down to base-band [Provide Ref], …"

Answer: Ref added.

d. Please rewrite the sentence "Multiplying with a slightly o
set signal also results in any noise (y(t)) at an image frequency also being mixed down to the same lower frequency.." It is not correct.

Answer: fixed.

e. "Multiplying with a slightly offset signal…": The word "slightly" needs to be replaced by some value or range of values.

Answer: fixed.

9. Section 2: Phase detection method (Subsection 2.2):
a. Title of the sub-section could be modified.
b. The first sentence of the first paragraph of this subsection "The prototype circuit is constructed and assembled based on our design." presents very weak technical meaning.

Answer: fixed.

c. A schematic of the system must be provided to present the design details of the transmitter and receiver coils.
Answer: fixed.

d. As the transmitter and receiver coils are very important components of the MIS system, it will be better if authors provide the details of the coil materials, diameters and amplitude of the current flowing through each of the coils.
Answer: fixed.

e. Sub-subsection 2.2.1: Description of hardware operation
The sentence "The prototype consists of: Two analog multipliers (AD835) which mix both of the input signals with a locally generated signal." should be rewritten by mentioning the type of the "input signals" and "locally generated signal" i.e. whether the signals are either voltage or current.

Answer: fixed.

10. Section 2: Phase detection method (Subsection 2.3):

a. English is not good. It should be improved.

b. The sentence "Signal generating hardware available and capable of the requirements and available are: A 40MHz sample rate TTI TGA1242 dual output arbitrary waveform generator and a dual output …" is not correct. Please rewrite.

Answer: fixed.

c. The sentence "The Analog Devices DDS evaluation board is chosen due to the easy to use SPI interface, and the higher sample rate." should be modified to represent the meaning clearly.

Answer: All fixed, thanks.

11. Sometime the unit of frequency (Hz) is written in italics and sometime in normal font. It should be consistent until unless any specific reason stated in the manuscript.

Answer: Thanks. Fixed.

12. Though the working frequency band of the MIS system developed is mentioned as 200 kHz - 20 MHz, but in discussion section authors presented some results which were obtained from the studies conducted on the fruits and vegetable at 100 kHz. Please explain.

Answer: We have started test at 100 kHz but as statement says no useful information was gathered on 100kHz. So really useful data coming from 200 Hz where the system is optimally designed.

13. Section 3: Testing Results

a. Title should be modified.

b. English language of the Testing Results section is required to be improved.

c. The sentence "Figure 11 shows phase shift reading of an apple in several days, showing apple the state of apple as it gets rotted." Should be modified. The word "rotted" should be replaced by the correct word "rotten".

Answer: Fixed.

14. Section 4: Discussions.

a. The MIS system developed uses 200 kHz - 20 MHz. How and why this frequency band is selected should be stated clearly in the manuscript.

Answer: Explained that the main interest in phase variation occurs in this frequency for low conductivity materials.

15. Section 5: Conclusion

a. English language of the Conclusion section is required to be improved.

b. The title of this section preferably could be "Conclusions" instead of "Conclusion".

c. The first sentence in the Conclusions section "The prototype phase detector was also proven to work in a MIS system by attaching the phase detection subsystem directly to the transmitter, detector and reference coil subsystem." should be rewritten.

Answer: a,b,c All Fixed.

16. References: The reference section should be improved as mentioned earlier.

Answer: Thanks for good list of literature, which are now built into our reference list.

Word count: 3400

Wideband Precision Phase Detection for Magnetic Induction Spectroscopy

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Abstract

Magnetic induction spectroscopy (MIS) has many potential applications in medical engineering as well as industrial and food manufacturing process applications, providing a contact-less impedance measurement. However, the applications of MIS is currently limited due to the high precision of phase detection required over a wide band of frequencies. This paper focuses on phase detection aspect of the MIS. The chosen phase detection method is investigated in depth and a prototype hardware and software is developed. The phase detection system is then tested and compared to other recent MIS system design. The prototype hardware is able to measure the phase difference of signals from 200kHz to 20MHz with milli-radian precision which will significantly enhance the MIS systems.

1 Introduction

Magnetic Induction Spectroscopy (MIS) is one of the bio-electrical impedance spectroscopy (BIS) technique that can be used to determine the electrical conductivity of materials as a function of frequency [3]. It is known that for biological tissues, the conductivity property is frequency dependent because of the cellular structure, e.g. intracellular fluid (ICF) and extracellular fluid (ECF). There is a great potential for MIS based technology for biomedical engineering applications in particular for its non-contact measurement nature. Extensive work is done in both conatct and non-contact impedadnce spectroscopy for medical and industrial applications [15, ?, 12, 13, 9, 11, 8, 7, 6, 10]. When a low frequency electric signal is passed through biological tissues, the highly resistive cell membranes act as barriers so the field can only react with the ECF phase. At radio-frequencies, the field can penetrate through both the ICF and ECF phases. By applying electrical fields using different frequencies, a complete dielectric dispersion properties of the sample can be obtained. Based on these concept, MIS can be applied into many applications including: Medical, such as tumour and stroke detection [1]. Although the main interest area for MIS is in biological field, it can also be used in industrial areas, such as detection of pipe blockages; and land mine detection. The traditional BIS techniques require a direct contact between electrodes and measuring samples, so the electric signal can be directly induced into the measuring sample. It creates a number of difficulties such as electrode positioning, intrusive contamination and electrode-sample interface consistency. In some industries like food manufacturing, direct contact is not allowed as it increase the contamination risk. To overcome these problems, an inductive spectroscopy methods were proposed so the direct contact of the samples is no longer required. MIS technique generally utilises two coils: one transmitting coil and one receiving coil. By injecting an alternative current into the transmitting coil, the primary magnetic field will be generated and induce eddy current on the testing sample. This stimulated eddy current will generate the secondary magnetic field which contains the conductivity information of the sample itself [4]. By sensing this secondary magnetic field using the receiving coil over a wide frequency range, the full BIS information can be obtained. Conductivity detection using MIS is challenging because of the small magnitudes of the induced currents, which results in a small phase shift signal on the receiving coil. Hence the performance of an MIS system is limited due to the high precision of phase detection required over a wide band of frequencies. The phase change caused by a biological variation is generally very small [1], therefore milli-radian measurement accuracy is required. Here we define a number of important parameters in performance of phase detector. Phase drift is also critical as it shows how much the measured phase changes over a long period of time [4]. Noise in the phase measurement is a measure of how much the measured phase changes over multiple measurements taken over a short period of time [4], also an important consideration. Phase skew is how much the measured phase changes when the input signal amplitude is changed was considered in [4]. The aim of this paper is to present a novel MIS electronic design and experimental validation; results from a precision phase detector suitable for MIS working in a wide range of frequencies. The conductivity, over a range of frequencies, of biological material contains information about the structure of the cells, making the MIS a potentially attractive bio-impedance device [1]. MIS has the advantage that it does not require contact with the material being tested, bio-electrical impedance spectroscopy (BIS) requires contact to be made with the material being tested. Following section shows the system implementation and experimental results.

2 Phase Detection Methods

Digital phase detection by sampling signal and mixing is proposed a phase detection method. The signal is digitally sampled, once sampled, the phase difference between the received signals can be determined by using a discrete Fourier or Hilbert transform. Phase can be measured by mixing the signals to an intermediate frequency before sampling and determining the phase using digital signal processing. Unlike the systems that mix down to base-band, this system needs to be able to sample the inputs very fast, therefore the use of a micro-controller instead of an FPGA would be less suitable. Multiplying with an offset signal also results in noise ($y(t)$) at an image frequency also being mixed down to the same lower frequency. Any noise at $(2\ \omega_{LO} - \omega)$ will also be mixed down to ω_{IF}.

$$y(t) = C\ cos((2\ \omega_{LO} - \omega)\ t - \Phi_i) = C\ cos(-(2\ \omega_{LO} - \omega)\ t + \Phi_i) \tag{1}$$

$$\omega_{IF} = -(2\ \omega_{LO} - \omega) + \omega_{LO} = \omega\ \ - \omega_{LO} \tag{2}$$

Wei et al [3] found that the odd harmonics from mixing with a square wave not to be an issue, therefore the noise at the single image frequency is not likely to be a problem. If the noise at the image frequency is an issue it is possible to use the Hartley architecture to image reject. This is our chosen method in this study.

2.1 Complete System

The prototype circuit is constructed and assembled based on this design. Both hardware and software development are required for controlling the phase detector effectively. Figure 1 shows the DDS signal generator, the Arduino and the final prototype design connected for automated testing with MIS coil system. Two coils of 12 turns each with radious of 2 cm is used for transmitting and receiving coil and a current of 0.1(A) was used in transmitting coil.

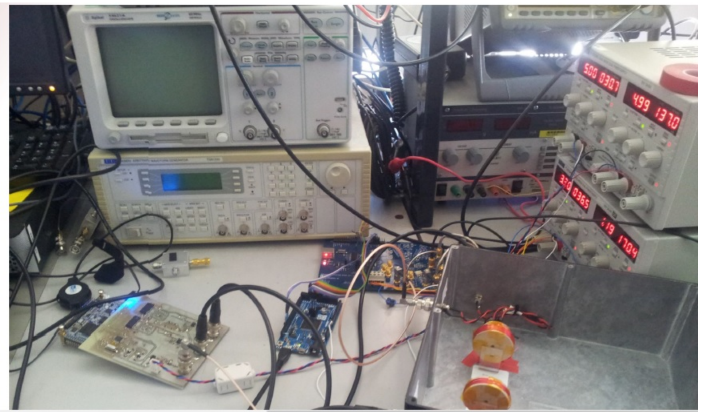

Figure 1: Test set up with the MIS coil set up.

2.1.1 Description of hardware operation

The system consists of two analog multipliers (AD835), which mix the input signals with a locally generated signal. Both of these are voltage signals. The locally generated signal is generated by a 10 *bit*, 400 MHz DDS (AD9859) which is controlled via a digital serial interface (SPI). The DDS is controlled to output a signal which has a frequency offset from the input signals by approximately a couple of hundred Hz. The output of the DDS is filtered using a third order balanced LC low pass ladder filter. The DDS control is implemented by using a FPGA to measure the frequency of the input signal, subtract a offset, and then set the local oscillator frequency by setting the frequency control register in the DDS via a SPI interface. The FPGA measures frequency of the input signal by counting the number of edges over a known period of time. Before the signal is input to the FPGA for frequency measurement, the signal is converted to a square wave by a comparator (TLV3501) with hysteresis. The signals output from the mixers contain a frequency component at the difference in frequency between the local oscillator frequency and the input signals, this is a couple of hundred Hz. Before sampling of the signals, frequency components of more than half of the sampling frequency need to be removed to prevent aliasing. It is important that the anti-aliasing filters have a very small affect on the phase of the signals because it is not possible to have exactly identical analog filters due to real component value variations. In order to achieve a small affect on phase of the wanted signal, a high cutoff frequency is chosen. A RC filter for each channel is used. Because of the high cutoff frequency, a high sampling rate is required. The signals are sampled using two 12 $bit, 10\ MHz$ ADCs (AD9220). The parallel digital outputs from the ADCs are input to the FPGA where a large amount of the redundant data resulting from the poor analog anti-aliasing filter and the oversampling is removed using a 10th order CIC filter and decimator. This decimator is implemented in the FPGA's configurable logic. The lower rate data, $(\frac{10\ MHz}{1024})$ is stored to an external SDRAM which is on the FPGA development board (Altera DE0-Nano). After a number of samples have been written to memory, they can be read and copied to a PC via a USB interface. The PC does further digital signal processing in order to determine the phase difference between the two signals.

2.2 Automated Test Implementation

It is decided that in order to characterise the performance of the prototype a automated test system to be assembled. An automated test system has the major advantage that data can be collected over many combinations of the 4 dimensions of independent variables: These are; input phase difference, input amplitude, input frequency, and time. The test system needs to be based around a signal generator that is capable of generating a wide range of signals with a known and adjustable phase, amplitude and frequency. Suitable signal generators are selected: A $40MHz$ sample rate TTI TGA1242 dual output arbitrary waveform generator, and a dual output $10 - Bit$, $500MHz$ sample rate, Analog Devices DDS (AD9958) evaluation board. The Analog Devices DDS evaluation board is chosen due to its use of SPI interface, and the higher sample rate.

3 Experimental Results

The results from the automated testing of the final prototype design are shown here. The difference between the measured phase difference and the input phase difference is shown against the input phase difference and the input amplitude in Figure 2. The noise in the phase measurement is calculated as the standard deviation of 32 measurements each sampled for $52ms$ and is plotted against input amplitude and input phase difference in Figure 3. The phase drift and the noise in the phase measurement is shown over 12 hours by Figure 4 and Figure 5. In ideal case the colormap should show zero difference between true phase difference and recovered phase difference, but small error in this phase detection shown in figures 2,3.

Table 1 shows the peak to peak drift and Table 2 shows the mean noise in the phase measurement. Figure 6 and Figure 7 show the prototype is very linear. The linear regression is calculated for the prototype for 16 data points between 0 $m\ rad$ and 5.75 $m\ rad$ and shown in Table 3. The measured phase is plotted against frequency for a number of input phase differences and shown in Figure 8. The noise in the phase measurement plotted against input signal amplitude is shown in Figure 9. Figure 10 shows the variation in the measured phase as the input signal amplitude is varied.

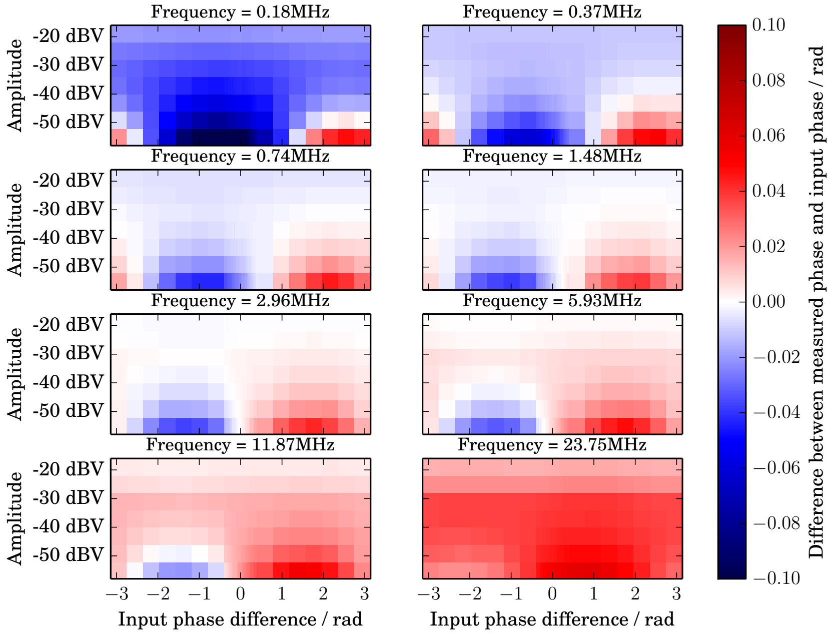

Figure 2: Measurements collected during automated test. Difference between measured phase difference and input phase difference, plotted against input signal amplitude and input signal phase difference. Gradient horizontally gives an indication of linearity, and vertical gradient gives and indication of skew.

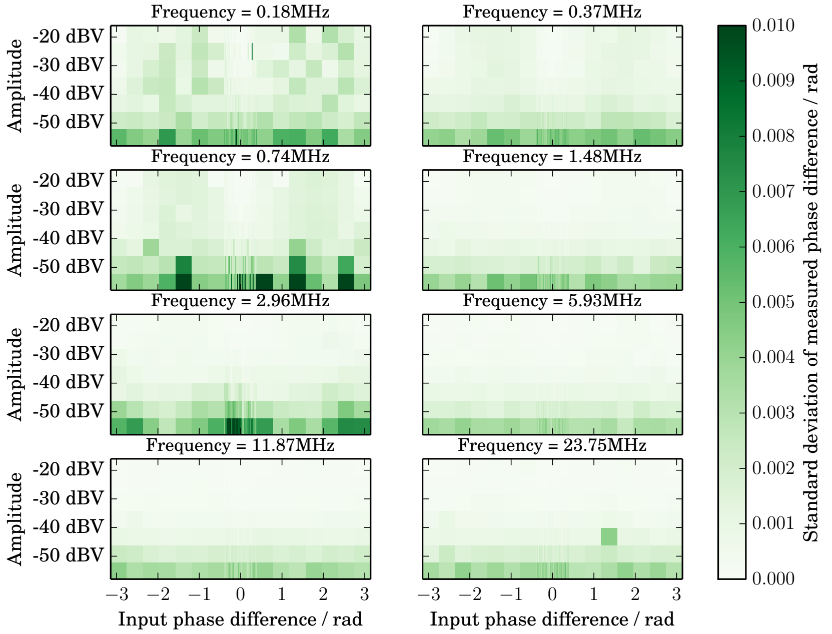

Figure 3: Measurements collected during automated test. Noise in the phase measurement, plotted against input signal amplitude and input signal phase difference.Noise in the phase measurement is higher at low input signal amplitudes and low frequencies.

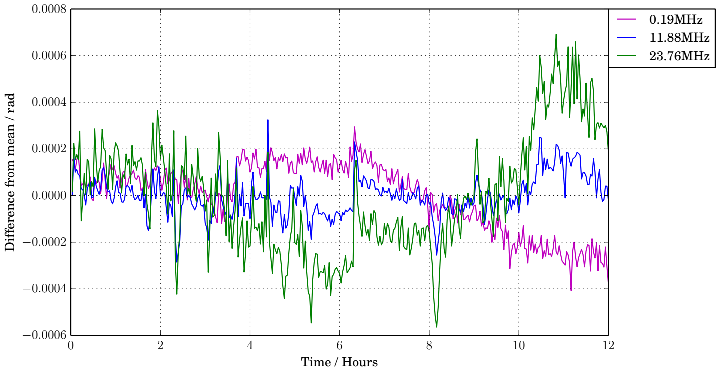

Figure 4: Drift in the phase measurement over 12 hours with the input phase difference set to 0.0245 rad.

Table 1: Peak to peak drift over 12 hours.

Frequency	Peak to peak drift (m Radians)
$0.19MHz$	0.7019
$11.88MHz$	0.6106
$23.76MHz$	1.2556

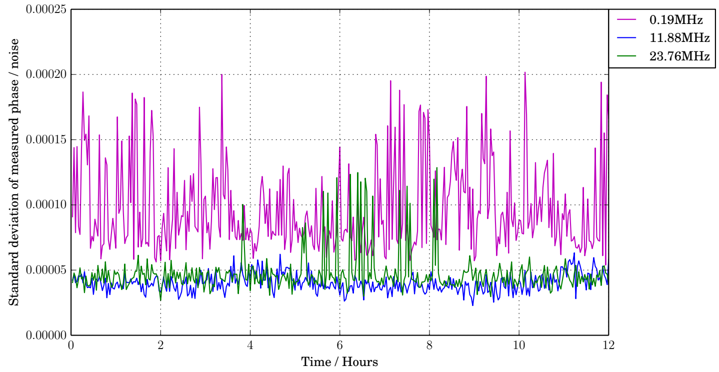

Figure 5: Noise the phase measurement over 12 hours with the input phase difference set to 0.0245 rad.

Table 2: Mean noise over 12 hours.

Frequency	Mean of standard deviation of 32 measurements(μ Radians)
$0.19MHz$	96.949
$11.88MHz$	40.225
$23.76MHz$	47.222

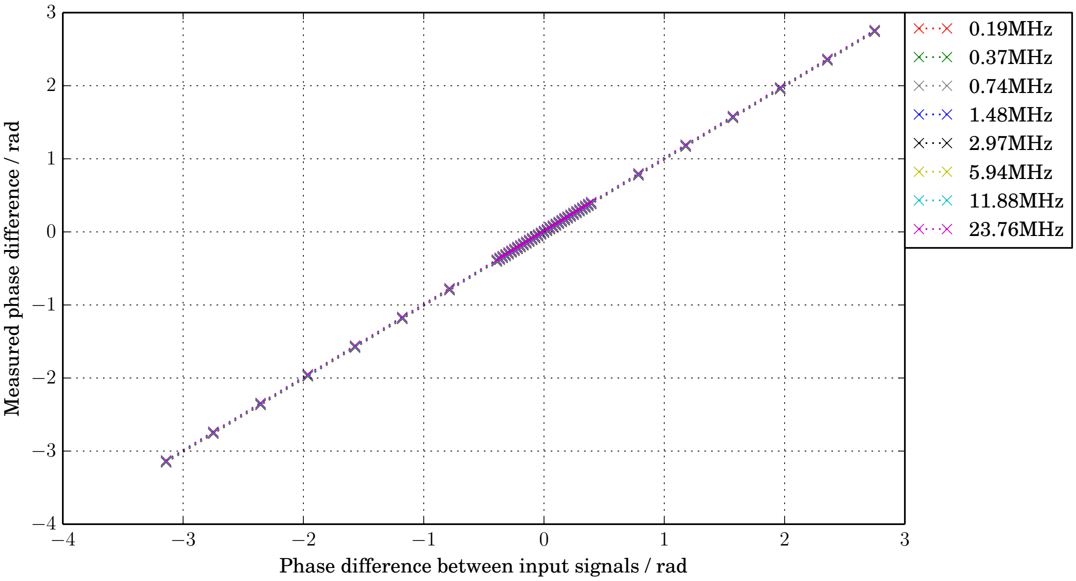

Figure 6: Linearity over full range.

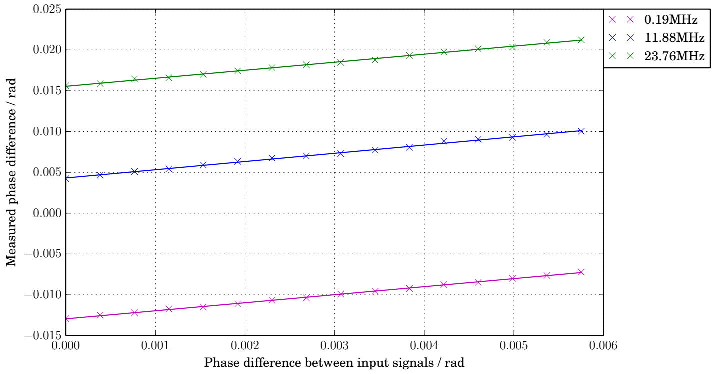

Figure 7: Linearity over small range.

Table 3: The linear regression is calculated for the prototype for 16 data points between 0 $m\ rad$ and 5.75 $m\ rad$.

Frequency	R^2
$0.19MHz$	0.99905
$11.88MHz$	0.99681
$23.76MHz$	0.99783

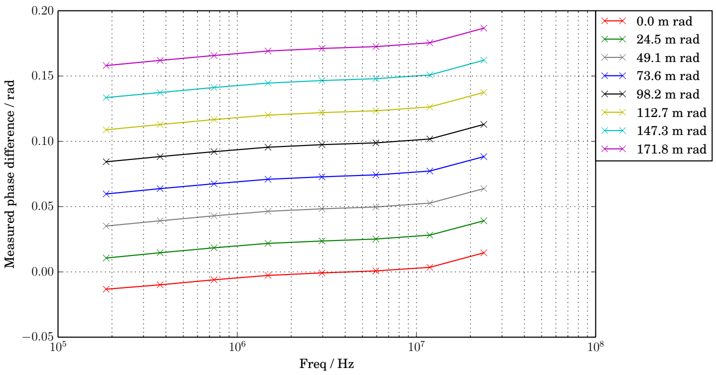

Figure 8: Measured phase against frequency for a number of input phase differences.

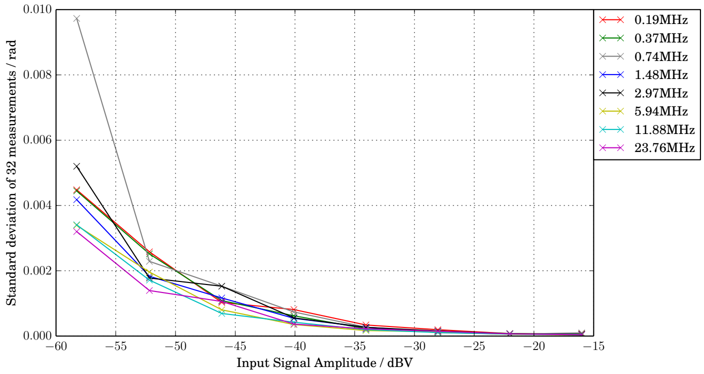

Figure 9: Noise in the phase measurement against input signal amplitude with 0.0245 rad input phase difference.

Table 4: Noise in the phase measurement.

Frequency	$-16dBV$ input / (μ rad)	$-28dBV$ input / (μ rad)	$-32dBV$ input / (μ rad)
$0.19MHz$	72.647	195.251	811.630
$11.88MHz$	41.415	108.532	424.560
$23.76MHz$	40.366	148.840	367.705

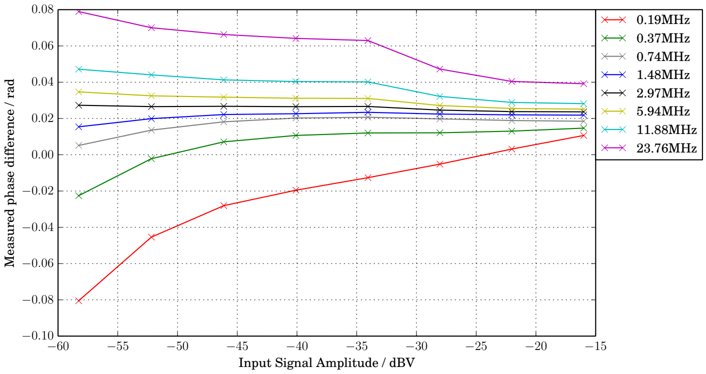

Figure 10: Phase measurement plotted against input signal amplitude with a input phase difference of 0.0245 rad.

The main focus of this paper is to show the performance of the phase detection unit. To demonstrate the work of this phase detector several tests were carried out in an MIS coil system set up. The MIS can be used to sense the magnetic fields in a novel way to determine the internal structure of biological materials through contactless methods. The MIS system here is a device that implements a planar gradiometer configuration, where the sample is placed in between the transmitter and the detection coil. The sensor will detect the sum of the primary field from the transmitter, and the field produced the induced eddy current in the sample. In order to be able to measure the phase shift this sample has created, a reference coil is placed co-axially adjacent to the transmitter, which then provides two signals that a phase demodulation unit can differentiate. The phase shift reveals information on the conductivity of the sample, which can be used to correlate to the internal structure. Figure 11 shows phase shift reading of an apple in several days, showing the state of apple as it gets rotten.

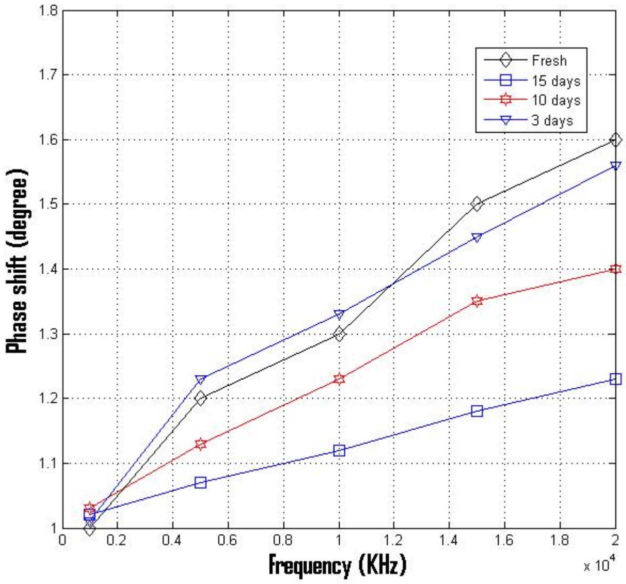

Figure 11: Experimental data from the MIS test on an apple test sample as it gets rotten over time.

4 Discussions

The subsystem has been tested at frequencies between 200kHz and 20MHz and is able to operate over this range. This frequency range is selected as the magnetic induction phase detection for low conducitivity materials are occuring in this frequency range. The maximum drift measured over 12 hours was 1.3 $m\ rad$, this meets the drift specification. The phase skew measured is reasonably small. The maximum noise in the phase measurement is less than 1 $m\ rad$, this is within the specification. The subsystem is able to operate from positive and negative 5V rails. The current drawn from the positive 5V rail is 137 mA and the current drawn from the negative 5V rail is 31 mA. The prototype is also powered via the FPGA development board, however it is assumed that this is drawing less than 300 mA resulting in the total current drawn from the positive 5V supply being below the 500mA specification. Currently 500ms is required to make a measurement at a single frequency, however uploading the data to a PC for the phase calculation takes significantly longer than this. The upload time can be reduced to be negligible in future prototypes by moving the phase detection signal processing to the FPGA or replacing the slow JTAG_UART interface with faster USB interface. The prototype board had no restriction on size, however the technology used meets the specification of having the capability to be scaled to within 10cm by 10cm. The device was tested at room temperature for 12 hours during the test for phase drift. Although not tested over the specified temperature range, it is likely that further work is required to allow useful measurements over the whole operating temperature range. Although not tested for electromagnetic compatibility, the device operates well in the laboratory with no shielding around the board. In order to gauge the performance for the prototype against other recent research, the performance results are compared to Jin et al [5] precision phase detector. The device designed by Jin et al is able to measure the phase difference between 2 signals, however has the limitation that it can only operate at 1MHz, 11.8MHz and 21.4MHz due to the band pass under sampling method used. The prototype has the advantage over the device developed by Jin et al because it is able to operate at all frequencies between 0.1MHz and 24MHz. The drift, noise and linearity performance are compared:

Jin et al record drift over 4 hours in degrees; at 1MHz there is 9 m° drift, at 10.7MHz there is 16 m° drift and at 21.4MHz there is 30 m° drift [5]. In order to have comparable data from the prototype, the peak to peak drift over the first 4 hours is used; there is a 40 m° at 0.19MHz, 35 m° at 11.88MHz and 71 m° at 23.76 MHz. Although the device designed by Jin et al has slightly less drift than the prototype, it is expected that the prototype can be modified to significantly improve the drift.

Jin et al calculated the noise in the phase measurement by taking the standard deviation of 20 measurements [5]. It is assumed that each measurement takes $50ms$ because it is stated that 200000 samples are taken at 4MHz [5]. Noise in the phase measurement from Jin et al device with a 50 mV pk-pk signal input to one channel and 500 mV pk-pk on the other channel with the same phase, is 0.8 m° at 1MHz, 3 m° at 10.7MHz and 5 m° at 21.4MHz [5]. The phase noise for the prototype was calculated as the standard deviation of 32 measurements, each measurement taking 52ms. Noise in the phase measurement with a 38 mV pk-pk signal input to one channel and a 152 mV pk-pk signal on the other channel with the same phase, is 7 m° at 0.19MHz, 6 m° at 11.88MHz and 6 m° at 23.76MHz.

Jin et al calculate the linear regression, R^2, for 9 data points between 0 deg and 80 m°. R^2 is calculated to be 0.9990 for 1MHz signals, 0.9970 for 10.7MHz signals and 0.9960 for 21.4MHz signals. The linear regression is calculated for the prototype for 16 data points between 0 m° and 330 m° to be 0.99905 for 0.19MHz signals, 0.99681 for 11.88MHz signals and 0.99783 for 23.76MHz signals.

In Figure 11, the phase measurements of apples under different rotting conditions are plotted. It can be seen that at 100 kHz, the phase measurement cannot provide any clear difference between apple conditions. However, when the operation frequency is increased further to 20 MHz, the fresh apple tends to have a larger phase shift (1.6 milli-degrees) compared to the rotten apple (1.2 milli-degrees). This apple spectroscopy test strengthens the fact that the phase detector can be implemented into an MIS system for BIS measurements. In this paper, it is demonstrated that by obtaining a full phase shift spectroscopy plot, the ripeness level of fruits could be established, but further experiments are needed to fully evaluate and demosntrate such an application.

5 Conclusions

The prototype phase detector was shown to work in an MIS system by connecting the phase detection subsystem directly to the transmitter, detector and reference coil subsystem. This was done using the automated test setup described in this paper. In next iteration of design some improvements that can be made to the configurable logic and the software of this design such as implementing the Hilbert transform on the FPGA. Fixing the synchronization of the DDS clock and the frequency measurement clock is also expected to improve performance, this could be done by adding a buffer circuit between the DDS clock output and the FPGA input pin. Even without these improvements the current prototype operates well. The proposed wide-band phase detector is an important subsystem for further development of MIS systems with many potential applications, in particular monitoring biological samples.

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