Development of a multi-frequency Focused Electrical Impedance measurement system based on synchronous peak detection method

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Abstract:

The Focused Impedance Method (FIM) provides an improved sensitivity distribution compared to the standard tetrapolar measurement technique increasing the potential for using multi-frequency electrical impedance measurements in tissue characterization studies. A microcontroller based multi-frequency system for FIM is described using synchronous demodulation and implemented using IC components readily available in developing countries. The drive current was generated from a microcontroller at 16 frequencies in the range 10 KHz to 1024 KHz. A Howland V to I converter delivers current to the tissue. The peak value of the measured voltage signal is determined by a micro-controlled analogue synchronous peak detector. Measurements on resistive and reactive phantoms give results which would allow the device to be trialled clinically.

Keywords: Electrical Impedance, Biomedical Instrumentation, Multi-frequency Bioimpedance, Peak Detection

1. Introduction:

The Focused Impedance Method (FIM) is a simple technique for impedance measurement that can localize a zone of high sensitivity beneath the centre of the electrode configuration[1, 2]. Numerical simulation together with phantom experiments have verified this sensitivity distribution for FIM[2, 3]. Single frequency FIM has been used successfully in lungs ventilation and abdominal fat thickness studies[4, 5]. More generally, multi-frequency measurements have been used successfully in a variety of research applications including lung ventilation[6], breast tumour screening EIT[7], and cervical cancer detection[8]. These applications prompted the group in Dhaka to investigate the use of multi-frequency FIM for similar applications in the context of a diagnostic measurement technique for use in developing countries. Considering the socio-economic status of developing countries like Bangladesh, a low cost and reliable system is required that can be maintained and repaired in the field by the researchers in order to investigate this. However, the limited local availability of even quite basic electronic components is a challenge. This paper presents the design and fabrication of instrumentation for a multiple frequency FIM system using low cost IC chips commonly available in Bangladesh.

2. Materials and methods:

2.1 Specification:

The specification for the multi-frequency FIM system is summarized in table-1.

Table-1: Specifications for the multi-frequency FIM

Feature	Specification
Excitation current frequency	10KHz – 1024KHz
Current level	1 mA (p-p)
Current drive output impedance	>50KΩ
Dynamic range	1:25
Impedance range	4Ω -100Ω
Frame rate	>25 fps

The most powerful microcontroller available was the ATmega8 which can be clocked at 16MHz (1 instruction per clock cycle). Therefore digital demodulation techniques [9] cannot be used and the design was based on an analogue synchronous detector. Fig-1 shows the block diagram of the multi-frequency FIM system implemented. The frame rate, the rate at which complete sets of 16 frequency measurements can be made, is the minimum required to dynamically study the heart.

2.2 Current drive section:

Microcontroller-I (ATMEGA-8) is used to generate sinusoidal waves at 16 different frequencies ranging from 10 KHz to 1024 KHz. Digital (8bit) values of samples from a full cycle of a sine wave were calculated and stored in the programme memory of the microcontroller. 25 sample points were used to for 10 KHz - 640 KHz whilst 15 points were used for 1024 KHz. These values are then cyclically clocked through 8 I/O ports of microcontroller-I to a digital to analogue converter (DAC0808) where the clocking rate determines the frequency of the output signal. The signal from the DAC is passed to a modified Howland current source[10] to maintain a high output impedance for the injected current.

2.3 Measurement section:

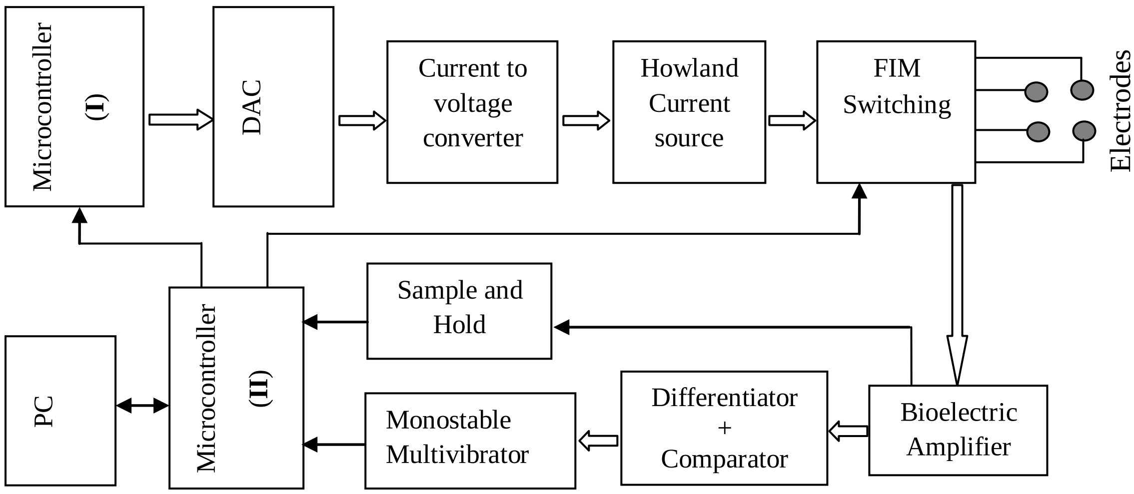

Fig-1: Block diagram of the designed multi-frequency FIM.

The synchronous peak detection is illustrated in fig-2. A bioelectric amplifier (bioamp) with a high CMRR is used to amplify the voltage signals from the body. The signal from this bioamp is differentiated by passing it through an analogue differentiator. There is a phase difference of 90 degree between the input amplifier output and the differentiator output (fig.2a and fig.2b). The differentiated signal is then passed through a comparator to produce a square wave (fig.2c) where the falling edge corresponds to the positive peak value of the input signal. A monostable multivibrator generates pulses on this falling edge which activates a circuit to sample and hold the peak value of the bioamp signal (fig.2d). The monostable multivibrator pulse also triggers the external interrupt of the microcontroller-II to start analogue to digital conversion (ADC). The ADC requires a minimum of 13.5μs for each conversion. No delay is necessary between the sample and hold acquiring data and the ADC commencing conversion because there is a 2 clock pulse delay

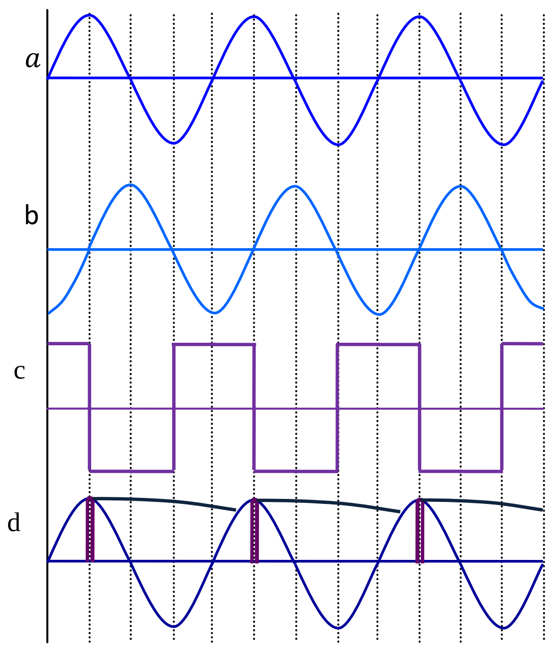

Fig-2: Peak detection method used in the measurement circuit.

between ADC initiation and conversion start while the ADC is initialized. For signals having frequencies greater than 40 KHz, a trigger pulse is generated from the monostable before the ADC conversion of the previous sample is complete. Therefore the monostable multivibrator output is gated by the microcontroller so that it cannot generate any further pulse to the ADC while the microcontroller is busy with an ADC conversion.

2.4 FIM Switching:

In FIM, two tetrapolar measurements for each frequency are required [2]. In the first measurement (fig3), switches ***1*** and ***4*** are closed (switches ***2*** and ***3*** are open) so that electrodes ***A*** and ***B*** are used to inject current while electrodes ***C*** and ***D*** are used to measure the resulting voltage. In the second measurement switches ***2*** and ***4*** are closed (switches ***1*** and ***4*** are open) so current is injected through electrodes ***A*** and ***C*** and the voltage measured across electrodes ***B*** and ***D***. A quad bilateral switch (CDHC4016) is used for the switching and the sequence is controlled by two I/O ports of Microcontroller-II.

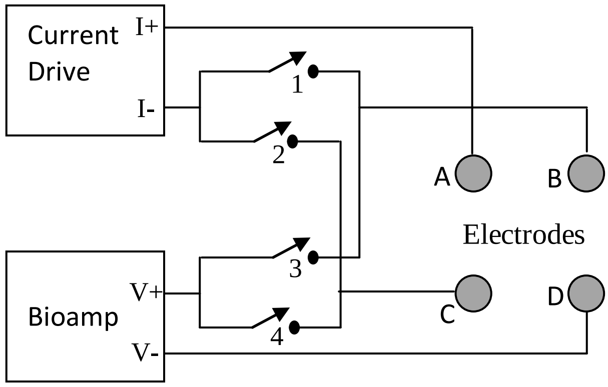

Fig-3: Switching for FIM measurements

2.5 Data acquisition:

The Universal Synchronous and Asynchronous serial Receiver and Transmitter (USART) peripheral of the ATmega8 is used to communicate with the personal computer. Microcontroller-II collects 10 consecutive peak values measurements for each frequency and then averages them before sending the resultant value to the computer. The ADC has 10 bits resolution and the most significant 8 bits of the averaged value are sent to computer for further analysis.

3. Results:

To measure the output impedance of the current drive section, a series of load resistances were used and the peak to peak currents were determined for each load resistance at each measurement frequency. The current source was designed to deliver about 1 mA(p-p) and was measured to deliver this into a load resistance of up to 3KΩ before saturation. The output impedance of the current source was measured to be 387 KΩ for 10 KHz signal and 48 KΩ for 1024 KHz.

The measurable input voltage range for the measurement section is 5mV to 100mV. So with the excitation current of 1mA the measurable range for a direct (as opposed to transfer) impedance measurement is 5Ω to 100Ω, a dynamic range of 1:20. To test the accuracy of the measurement system, current was injected through various known resistor chains and the corresponding impedance measured at each frequency. If the results at 1MHz are ignored, the maximum error was 3Ω. Fig-4 shows the error in the measured impedance values against the actual resistance value used. The circuit was also tested for capacitive loads and Fig-5 shows the measured impedance values against calculated impedance values for a Cole-Cole model phantom (74Ω in parallel with 24Ω in series with 4.7nF). Analysing the error between the measured and calculated impedance values for this phantom showed that the maximum error was 2Ω.

The software of the system is developed so that it continuously measures the FIM values at all 16 frequencies and then repeats it. Approximately 16 ms time is needed for one set of measurements which allows a monitoring frame rate of 62.5Hz.

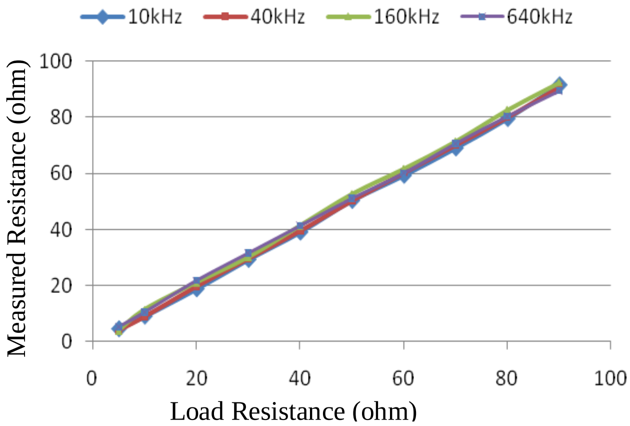

Fig-4: Measured resistances against the actual input resistances at 4 frequencies

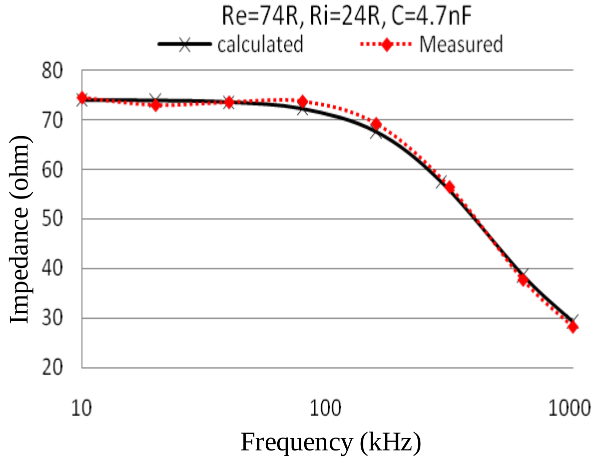

Fig-5: Comparison between measured impedance and calculated impedance of a Cole-Cole phantom

4 Discussion:

Multi-frequency instrumentation for the medical application of the Focused Electrical Impedance Method suitable for use in developing countries is described which uses locally available, inexpensive, circuit components so that researchers in the field can maintain it.

The output impedance of the current generator was just below the 50kΩ specified at 1MHz, but at this frequency the contact impedance will be very much smaller. A maximum load impedance of 3kΩ is not a problem as the contact impedance will be less than this at all measurement frequencies.

The gain of the analogue differentiator circuit used in the measurement section is frequency dependant and it was found that three differentiators with different circuit parameters were needed to cover the entire frequency range. The differentiator appropriate to a particular frequency is selected by Microcontroller-II. A dynamic range of 20:1 was achieved which is below the specified range of 25:1. This together the measurement accuracy problems at 1MHz is the result of the limited range of electronic devices, particularly high speed, low noise op-amps available. The lack of suitable op-amps was a considerable challenge in achieving the final design. It should be noted that all multi-frequency impedance measurements systems have used some form of digital demodulation (e.g. [9]) and the use of analogue demodulation is a considerable challenge within itself.

References:

1. Rabbani, K., et al., *Focused Impedance Measurement (FIM): A New Technique with Improved Zone Localization.* Annals of the New York Academy of Sciences, 1999. **873**(1): p. 408-420.
2. Rabbani, K. and M. Karal, *A new four-electrode Focused Impedance Measurement (FIM) system for physiological study.* Annals of Biomedical Engineering, 2008. **36**(6): p. 1072-1077.
3. Islam, N., K. Rabbani, and A. Wilson, *The sensitivity of focused electrical impedance measurements.* Physiological Measurement, 2010. **31**: p. S97-S109.
4. Kadir, M.A., et al. *Ventilation mapping of chest using Focused Impedance Method (FIM)*. 2010. IOP Publishing.
5. Haowlader, S., T.N. Baig, and K. Rabbani. *Abdominal fat thickness measurement using Focused Impedance Method (FIM)–phantom study*. 2010. IOP Publishing.
6. Frerichs, I., *Electrical impedance tomography (EIT) in applications related to lung and ventilation: a review of experimental and clinical activities.* Physiological measurement, 2000. **21**: p. R1.
7. Cherepenin, V., et al., *A 3D electrical impedance tomography (EIT) system for breast cancer detection.* Physiological Measurement, 2001. **22**: p. 9.
8. Brown, B.H., et al., *Relation between tissue structure and imposed electrical current flow in cervical neoplasia.* The Lancet, 2000. **355**(9207): p. 892-895.
9. Wilson A J, et. al. Mk3.5: A *modular, multi-frequency successor to the Mk3a EIT/EIS System*. Physiol. Meas. 2001 **22** 49-54
10. Horowitz, P. and W. Hill, *The Art of Electronics*. Second ed. 1989: Cambridge University Pres