Design and Development of Device to measure Body Fat using Multi-frequency Bio-impedance Method

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Abstract. Obesity is the beginning of the emergence of various chronic diseases such as stroke, heart failure, diabetes, and so on. Therefore, obesity becomes one of the indicators to know the health condition. Obesity can be known from Body Mass Index (BMI). BMI only considers weight and height, while obesity is related to fat composition, so this information is less valid. One method that can calculate body fat composition is Bioelectrical Impedance Analysis (BIA). BIA works by injecting a constant current into the body and measuring its voltage. This research designs and develops device to measure the body fat content with multi-frequency bio-impedance method. The study was conducted by generating a multi-frequency sine wave from AD9850 accompanied by a DC block so that an AC sine wave was generated. It would be converted into a constant current on VCCS. The electric current is injected into the body through two electrodes and the voltage was tapped by two another electrodes. The voltage are processed by instrument amplifier (AD620). AC signal from AD620 is converted to DC signal by AD536. Analog data is processed by ADC in the microcontroller so that the body impedance is obtained. The device was tested on 7 volunteers. The calculation of body fat was compared with standard OMRON HBF 214 device. In this research we got the linearity equation $y = 0.999x + 0.161$ with $R^2 = 0.997$ as the result of correlation between the body fat from reference ($x$) and the measurement of body fat from the device was developed ($y$).

Keywords : body fat, multi frequency, bio-impedance.

1. Introduction

Data from the Indonesian Health ministry [1] shows that Indonesia is one of the countries that has complex nutritional problems due to cases of obesity. The National Health Research Data in 2016 [1] showed that people aged over 18 years who obese were 20.7%. This shows a significant increase from 2013 which was only 15.4%. This condition is categorized as alert which needs serious attention.

Obesity is a disease where extra calories are stored in the body in the form of excessive fat. Obesity is the beginning of the emergence of various chronic diseases such as stroke, heart failure, rupture of blood vessels, diabetes, and so on. These chronic diseases have a risk of disability, impaired body function, and death. According to WHO, obesity is ranked fifth cause of death.

Obesity is caused by unhealthy lifestyles, such as physical inactivity, body metabolism, genetic factors, and unhealthy food so that the distribution of body fat is uneven and accumulates. The solution is to return to a healthy lifestyle, sport, maintain nutritious food and monitor body weight.
Checking the condition of the body is very useful as an effort to detect early so that the body stays in ideal conditions.

The way to determine a health index is the Body Mass Index (BMI) which compares weight and height. BMI cannot determine whether the weight is from muscle or fat. Therefore, devices that can measure body fat levels are needed[2].

Several methods of measuring body fat levels have been developed, for example DXA (Dual-energy X-ray Absorptiometry), ADP (Air Displacement Plethysmography), and Bio-impedance [3]. Hlúbik[3] told that DXA was originally used to measure bone mineral density. But DXA can also be used to measure total body composition and fat content accurately. Disadvantage of this method is expensive and uses X-ray exposure. The ADP method is used to measure the composition of the human body by using the approach of the relationship between pressure and volume. The advantages of this method are fast, safe, comfortable and non-invasive, but this method is not practical.

Consumers demand a measuring instrument of body fat that is cheap, simple, accurate, non-invasive and safe. Several studies have been conducted using the Bio-impedance method to create these devices. Bio-impedance is defined as the ability of a biological network to inhibit electrical current. The human body's electrical resistance is closely related to fluid of the body [4].

Based on the description, it is necessary to design and develop a body fat measurement device which used the bio-impedance principle. The device is an alternative that can be used to succeed the healthy community program.

2. Materials and Methods
2.1. System Structure
The structure of the multi-frequency bio-impedance system is shown in Figure 1. The system consists of Function Generator, Block DC, VCCS, Amperemeter, Voltmeter, AC to DC converter and microcontroller. The Function Generator uses DDS[5] of IC AD9850 module which can be controlled by a microcontroller and can generate sine DC signals from 0 Hz to 40 MHz. The DC block circuit is basically a high pass filter, using a 1 kΩ resistor and a 100μF capacitor, resulting in a cut-off frequency of 1.6 Hz. This DC block circuit is to slide down a sinusoidal DC signal so that it becomes a sinusoidal AC signal. VCCS functions to produce a constant current in the measurement impedance range [6]. The VCCS module requires a sinusoidal potential input with a frequency and amplitude that can be changed as needed. The IC used to build VCCS is OPA2134. Ampere meters and volt meters are built from instrument amplifier IC620A. AC to DC Converter is built from the AD536A IC which aims to convert AC voltage into DC rms that are ready to be read by the microcontroller.

![Figure 1. Block diagram of device](image)

2.2. Methods
Each component is tested so that it is obtained complete information from each component. These components consist of Function Generator, Block DC, VCCS, Amperemeter, Voltmeter, AC to DC converter.
Test of IC AD9850 module is done by activating the microcontroller to generate signals from 0 - 40 MHz. Signal output from SINE OUT1 at the output module installed on the oscilloscope. Then, it is analyzed relationship between the frequencies and Vrms.

DC block testing is done by input the DC signal from the AD9850 module and the output is observed on the oscilloscope. The test is from 1 Hz until 100 kHz, then it is observed whether the DC signal has changed to AC. The curve of the relationship between the frequencies of Vrms is analyzed.

VCCS performance is tested by giving a load from variable resistors. Tests are carried out at frequencies of 10 kHz, 100 kHz and 1 MHz. Furthermore, the relationship curve between the load and the electric current generated by VCCS is analyzed on these three frequencies.

The instrument amplifier is used as an amperemeter and voltmeter in this study. The ability of the instrument amplifier is tested by giving the AC voltage signal and ground on the two input channels. Furthermore, the output voltage channel is observed and then a curve is made for the relationship between the input signal and the output signal.

The performance of the AD536A IC is tested by providing an input AC signal. Then the output DC rms voltage is observed and compared to the rms voltage of the input signal.

BIA measures body composition by using differences an electrical conductivity in body [7]. BIA divides the human body into two compartments namely fat mass and non-fat mass. Fat Free Mass (FFM) is done by measuring the electrical characteristics and empirical data of the body. Many equations have published, Equation (1) is an empirical equation of FFM from the research conducted by E. Mylott[8]. After the FFM is obtained, Fat Mass (FM) can be obtained from equation (2). The body fat percentage can be known by equation (3).

\[
FFM = 0.36\left(\frac{H^2}{Z}\right) + 0.162H + 0.289W - 0.134A + 4.83G - 6.83 \quad \text{`(1)}
\]

\[
FM = W - FFM \quad \text{`(2)}
\]

\[
BF = \frac{FM}{Weight} \times 100 \quad \text{`(3)}
\]

where FFM is Fat Free Mass(kg), H is height (cm), W is weight (kg), G is gender (1 for man and 0 for woman), A is age (year), Z is bio-impedance (Ω), FM is Fat Mass(kg), BF is Body Fat(%).

3. Result and Discussion

The fat level device consists of hardware and software. The hardware is composed of Sine Wave Generator, DC Block, Voltage Controlled Current Source (VCCS), Instrument Amplifier, AC to DC, ADC and Microcontroller as shown in Figure 1. Furthermore, each hardware circuit is carried out characterization tests to determine its ability. After ascertaining that each component works well, then it is used to measure body fat content, the results are compared with reference.

Sine Wave Generator is a circuit that functions to generate sinusoidal signals. In this study, the DDS AD9850 was used as a controlled signal generator module. The module can produce sine signals in the frequency range of 0 Hz - 40MHz. The AD9850 circuit and the microcontroller are shown in Figure 2. The program code for controlling the DDS AD9850 is shown in Figure 3. The test results of the characteristics of the DDS AD9850 module can be displayed on the oscilloscope as shown in Figure 4.
Figure 2. AD9850 circuit and microcontroller (www.kh-gps.de)

Figure 3. Program code for DDS AD9850

```c
#define W_CLK 6
#define FQ_UD 9
#define DATA 10
#define RESET 11
#define pulseHigh(pin) (digitalWrite(pin,HIGH);digitalWrite(pin,LOW)
void tsk_byte(byte data)
    for(int i=0; i<8; i++)
        digitalWrite(DATA, data & 0x01);
    void sendFrequency(double frequency)
        int32_t freq=FREQ*4254907295/1250000000;
        for(int b=0; b<8; b++)
            tsk_byte(freq & 0xff);
    tsk_byte(0x00);
pulseHigh(FQ_UD);

int data;
void setup()
    pinMode(FQ_UD, OUTPUT);
    pinMode(W_CLK, OUTPUT);
    pinMode(DAT, OUTPUT);
    pinMode(RESET, OUTPUT);
    Serial.begin(9600);
pulseHigh(RESET);
pulseHigh(W_CLK);
pulseHigh(FQ_UD);

void loop()
    long int numeric=0;
    int i=1;
    if(Serial.available()>0)
        char datachar=Serial.read();
    while(datachar != '\n')
        if(isdigit(datachar))
            if(datachar - '0')
                (numeric=numeric * 10 + (datachar - '0'));
            datachar=Serial.read();
    long int data=numeric;
    sendFrequency(data);
    Serial.println(data);
```
Figure 4 shows that the shape of the DC sine signal generated by the DDS AD9850 module looks good, but at a frequency of more than 40 MHz the sine signal looks unstable, according to the data sheet that the DDS module works in the range of 0 to 40 MHz. DC block circuits are used to block the DC signal from entering the generator. This circuit is composed of capacitors and resistors. schematic and DC block circuit shown in Figures 5 (a) and (b). The DC block circuit converts the DC signal to AC as shown in Figure 6.

![DC Block Schematic](image1)

**Figure 5.** (a) Block DC schematic (b) Block DC board

![Block DC Board](image2)

**Figure 6.** AC signal after pass the block DC at 10 kHz
Figure 7 is the relationship between the Vpp voltage of the AD9850 DDS module and the frequency. Vpp voltage seems stable at frequencies 1 - 1000 kHz. But at a frequency of more than 1000 kHz, Vpp has decreased significantly.

**Figure 7.** Graph of AD9850 DDS Sinus Signal with frequency 1 kHz - 40 MHz

VCCS is an AC current source circuit that is generated from the input voltage of the oscillator circuit. Figure 8 (a) and (b) show the schematic and VCCS circuit.

**Figure 8.** (a) Schematic of VCCS (b) VCCS circuit

The current characteristics produced by VCCS are tested by giving a load to the VCCS output. The given load varies up to hundreds of kilo ohms. The test is done by using the signal input from the AD9850 with the frequency controlled by the microcontroller. The VCCS output that is connected to the resistor is then read the current with an ampere meter. Figure 9 is the current data generated by VCCS against load variations at frequencies of 1 kHz to 150 kHz.
Based on the data in Figure 9, it appears that the current is relatively constant in each load with variations in frequency. But the higher the frequency given, the resulting current will decrease. The higher the value of the load given, the current will decrease.

The Amplifier Instrument circuit is used to measure the potential leads between electrodes. Development of amplifier circuit using IC AD620 with schematic and circuit shown in Figure 10 (a) and (b).

The desired amplification of the instrumentation amplifier is 5 times so that the RG value is obtained based on equation 4,

\[
\text{Gain} = \frac{49.4 \ \text{k}\Omega}{R_G} + 1
\]

where \( R_G = \frac{49.4 \ \text{k}\Omega}{\text{Gain-1}} = \frac{49.4 \ \text{k}\Omega}{4} = 12.35 \ \text{k}\Omega \)

Amplifier Instrument Testing is done by inserting the voltage from the function generator on both AD620, positive and negative inputs, alternately. The first test of the generator signal is entered in the positive input AD620 while the negative input is connected to ground. The output pin in AD620 is connected to the oscilloscope so that the output signal can be seen on the oscilloscope display. Probe CH1 is the input signal from the function generator in sinusoidal form with several given frequencies. The signal coming out of this circuit will be seen in CH2. The same thing was done in the second test. Figure 11 and Table 4.3 are both positive and negative input outputs.
Figure 11. Output signal from instrument amplifier circuits at frequency (a) 50 kHz (b) 100 kHz (c) 150 kHz

Figure 11 shows that the output signal of the instrumentation amplifier circuit has a sinusoidal shape like the input signal from the generator. However, at a frequency of more than 150 kHz the form of the signal changes to a triangle.

In addition to observing the shape of the signal, the voltage generated by the amplifier circuit is also observed and compared to the input voltage provided. Table 1 lists the performance test data on the instrumentation amplifier circuit. The resulting gain is in accordance with the expected gain of 5.

|          | Input Positive | Input Negative |
|----------|----------------|----------------|
| Vin (V)  | Vout (V)       | Gain           | Vin (V)  | Vout (V) | Gain           |
| 1.72     | 8.59           | 4.99           | 1.69     | 8.44     | 4.99           |
| 1.69     | 8.59           | 5.08           | 1.66     | 8.48     | 5.11           |
| 1.66     | 8.52           | 5.13           | 1.63     | 8.46     | 5.19           |
| 1.63     | 8.36           | 5.13           |
| 1.59     | 8.33           | 5.24           |

AC to DC circuits are used to obtain DC voltage from AC signals. The circuit used is the IC AD536 module. The performance of the module is tested by entering the input voltage on pin 1 which is connected to the function generator module output pin. The following is the AC to DC schematic and circuit as shown in Figure 12.
The results of the AC to DC circuit performance test are shown in Figure 13. Based on the test data it can be seen that the VCD is quite stable at a frequency of 500 kHz and starts unstable at a frequency of more than 500 kHz.

![Figure 13. Performance test of AD536 for some frequency (a) 75 kHz, (b) 300 kHz, (c) 750 kHz, dan (d) 800 kHz](image1)

![Figure 14. Performance test of AD536 module](image2)
ADC is an electronic device used to convert analog signals into digital signals. Arduino has a 10-bit ADC which means it can convert analog to digital voltage from 0-1023 scale. ADC testing is done by attaching a 5 kΩ potentiometer pin to the analog pin on the Arduino at pin A0. And another potentiometer pin is connected to 5V pin and GND pin on Arduino. The load on the potentiometer is varied so that the voltage read on the ADC changes. In the ADC sampling test also requires a multimeter as a calibrator which is the reference for the measured voltage value. The tests also require the source code in the Arduino program to read the results of digital sampling. The sampling results obtained from the test are shown in Figure 15. In Figure 15 it appears that the voltage obtained is quite linear with $R^2 = 0.9986$.

$$y = 0.9982x + 0.0053$$

$$R^2 = 0.9986$$

![Figure 15. Sampling graph of ADC Microcontroller](image)

The program code used to test the sampling in the Microcontroller ADC is shown in Figure 16. Because the number of bits in the Microcontroller ADC is 10 bits, the maximum bit value is 1024. The sampling calculation starts from 0-1023 with the required reference voltage of 5 V.

![Figure 16. Program code of ADC Microcontroller](image)
Following is the arrangement of the programs used to calculate $Z$ from the hardware circuit shown in Figure 17.

![Figure 17. The complete of Program code](image-url)
Calibration was carried out by measuring 7 volunteer and calibrated with OMRON body fat levels. Volunteers are asked to stand on the scales where the right and left legs lie on the foot electrode. Volunteers do not move until the measurement on the scale is complete. The results of measurement of body fat from 7 volunteers are shown in Table 2.

In data retrieval, 4 electrodes were attached to the legs and right hand with 2 electrodes respectively. This measurement was carried out on 7 volunteers which carried out 10 data repetitions. Two electrodes on the feet and hands each have a function as an injector current in the body and another as the voltage measured in the instrument amplifier. The data is processed and the results are in the form of bio-impedance (Z) in Table 2.

Determination of bio-impedance, carried out measurements on 7 volunteers with the same age approximately 22 years. In measurement, the first thing to do before retrieving the data is to calibrate the OMRON body fat device HBF-214 as shown in Figure 18. The instrument measures body fat by inserting volunteer data which includes gender, age, and height. The volunteer is asked to stand with the right and left foot on the electrodes. From the data information, including the measured body weight, the scales can measure fat levels in the body in Table 2.

![Figure 18. Measurement of volunteer on OMRON HBF-214](image)

| Volunteer | W (kg) | H (cm) | Z of device (Ω) | Body Fat (%) | Error (%) |
|-----------|--------|--------|-----------------|--------------|----------|
|           |        |        | Omron          | Device       |          |
| 1         | 61.1   | 155.5  | 1203.697       | 32.9         | 33.8     | 2.74     |
| 2         | 45.1   | 159.0  | 1556.018       | 21.8         | 21.8     | 0.00     |
| 3         | 71.8   | 160.0  | 1060.220       | 36.5         | 36.5     | 0.00     |
| 4         | 88.2   | 156.0  | 817.970        | 41.4         | 41.4     | 0.00     |
| 5         | 67.8   | 157.0  | 1099.185       | 36.1         | 36.1     | 0.00     |
| 6         | 54.6   | 163.0  | 1417.222       | 28.3         | 28.3     | 0.00     |
| 7         | 65.5   | 158.0  | 1167.256       | 35.2         | 35.2     | 0.00     |
Bio-impedance that has been obtained is confirmed to be the percentage of fat from equation (1) to (3). From equation (1) obtained FFM from bio-impedance measurement results. Equation (1) of the experiments conducted by E. Mylott[8]. After FFM is obtained, the FM value is obtained from the difference in weight with FFM from equation (2). From the FM results, the percentage of body fat was obtained from equation (3).

4. Conclusion

1. This research designs and develops device to measure the body fat with multi-frequency bio-impedance method. The study was conducted by generating a multi-frequency sine wave from AD9850 accompanied by a DC block so that an AC sine wave was generated. It was converted into a constant current on VCCS. The electric current is injected into the body through two electrodes and the voltage was measured from two another electrodes. The voltage are processed by instrument amplifier (AD620). AC signal from AD620 is converted to DC signal by AD536. Analog data is then processed by ADC in the microcontroller so that the body impedance is obtained.

2. The device was tested on 7 volunteers. The calculation of body fat was compared with standard OMRON HBF 214 device. In this research we got the linearity equation $y = 0.999x + 0.161$ with $R^2 = 0.9972$ as the result of correlation between the body fat from reference (x) and the measurement of body fat from the device was developed (y).
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