In this paper, we report on the design, building, and testing of a Ballistocardiograph (BCG), which is a heart disease diagnostic device that monitors blood flow in the heart. The advantage of this system is that it is small in size, noninvasive, less expensive, and easy to use. More importantly, the device directly monitors blood flow through the heart chambers. The system was built and tested on a human subject before and after treatment from high blood pressure. The results show that our system can detect irregularity or abnormality in the heart function.
The classic BCG device was developed during the early decades of the 20th century [1]. This machine consists of a bed, freely suspended in air, and a strain gage for the measurement of the movement of the blood in the heart. This BCG mechanical system never really took off as a mean to measure the mechanical force of the heart. This was mainly due to the huge size of the device. A more serious problem for this early device is that the BCG signal varied from person to person, and for this reason, the reliability of the results became questionable. Fortunately, a small size, very accurate pressure sensitive sensor, based on an Electro-Mechanical Film (EMFi), has been developed lately [4]. This sensor allowed for the development of a sensor system that requires less operational area and provide very accurate, repeatable, and reliable measurements [5].

Ballistocardiogram Design

We used the EMFi pressure sensor to design and build our BCG system. This sensor is a 29 x30 cm2 mat that consists of a dielectric film for converting electrostatic energy into mechanical work [4,5]. The base material of the sensor is polyester, and the entire sensor consists of several polyester layers separated by air voids and layers of aluminum; see Figure 2. If an external pressure is exerted on the surface of the film, the thickness of the air voids changes. This change in thickness causes movement of the charges residing at the interface of the polyester layers and air voids. Thereby generating a charge on the electrodes, that is proportional to the change of the film thickness [6]. The change in voltage can be calculated as follows:

\[ \Delta V = \frac{1}{c} \cdot S_q \cdot \Delta F \] (1)

In the above equation, C is the total capacitance of the sensor measured in Farads and \( S_q \) is the sensitivity of the sensor measured in Coulombs/Newton [4]. The sensor has a capacitance \( C = 22 \text{pF} \), sensitivity \( S_q = 25 \text{pC/N} \), and size of 290 x 300 mm2. The change in the charge due to pressure on the film is applied to a two-stage charge amplifier. This circuit is shown in Figure 3. The main reason this design was chosen was due to the fact that there is a low pass filter in the first stage of the amplifier. If a non-inverting amplifier was used, the capacitance of the sensor would have to be taken into account when calculating the gain and the frequency response of the filter. In this case, any small variation of the sensor capacitance, due to change in manufacturability, would result in a drastic change in the system characteristics and would make the results unreliable. By using the inverting amplifier (charge amplifier), one can eliminate this possibility all together. The first stage of the charge amplifier of the BCG has a time constant of 2ms and a charge gain of 0.001V/pC. The gain is \( 1/C5 \), or 1/0.00\( \mu \text{F} \) which is 0.001V/pC. \( C5 \) is the feedback capacitor shown in Figure 2. Due to the feedback resistor \( R11=2\text{M}\Omega \), the gain becomes 2x106.
Between the first stage and the second stage, there is a single pole high pass filter. Its function is to eliminate any DC offset that was amplified from the first stage. \( R_{11} \) and \( C_{5} \) form a high pass filter with a cut-off low frequency \( F_L \):

\[
F_L = \frac{1}{2\pi R_{11} C_{5}} = \frac{1}{2\pi \times 1M\Omega \times 33\mu F} = 0.51Hz
\]  

(2)

The final stage has a gain and cut-off frequency as calculated below.

\[
Gain = 1 + \frac{R_{10}}{R_{12}} = 1 + \frac{150K\Omega}{1K\Omega} = 151
\]  

(3)

The second stage has a low pass filter with a cut-off high frequency, \( F_H \):

\[
F_H = \frac{1}{2\pi R_{10} C_{3}} = \frac{1}{2\pi \times 150K\Omega \times 81\mu F} = 106Hz
\]  

(4)

Since the gain of the first stage (2x106) and that of the second stage (151), the total gain becomes 302x106. The frequency range is between 0.5-106 Hz.

The BCG circuit shown in Figure 3 was simulated in Pspice [7]. The frequency chosen for the input current was 1Hz and the amplitude was 0.015µA. The output results confirmed that the above calculations are correct.

**Testing and Analysis**

The BCG was built and tested. A 28 years old male was tested, where the patient sat on the sensor mat and the system was turned on. LabviewTM [8] was used to obtain the BCG signal graphically. The signal is shown in Figure 4. When we examined the signal, the first thing noticed was that there is some abnormality compared with the standard BCG signals for healthy subjects. As shown in Figure 4, the waveform from this patient heart showed a "late M" pattern from the large L wave. (Here, the M pattern is formed from the points I, J, K, L, and M). This type of signal is indicative of hypertension. Upon diagnosis of Hypertension (high blood pressure) by a doctor, the patient started taking medication. After two months, the same patient was tested again, and the signal was found to resemble the desired "W" pattern due to the decreased L wave, as shown in Figure 5. (Here, the W pattern is formed from the points H, I, J, K, and L). This system can be very effective at tracking a patient over time to compare previous signals with current signals. If this system is placed in doctors' offices, it can provide vital cardiac information for the long-term health of the patients. However, more studies are needed to characterize this system for other heart diseases.

![Figure 4: Test results of a 28-year-old patient prior to diagnosis of Hypertension.](image)

![Figure 5: Test results of a 28-year-old patient after medication to treat Hypertension.](image)
Conclusion

We developed a BCG system that is noninvasive, easy to use, and much less costly than traditional methods that either requires a technician or is invasive. This system measures the performance of the heart directly, by tracking the flow of blood in the heart through measuring the mechanical recoiling of the body. The main advantage of our system is that the results are reliable, and the signal is almost noiseless, since forces due to repertory and body movements have been filtered out. This system can be integrated with other systems, such Electrocardiogram (ECG), phonocardiograph (PCG), and Photoplethysmograph (PPG) to build a more comprehensive diagnostic system. We have already designed, built, and tested this integrated system [9]. This system, if mass produced and used in clinics, will provide reliable and cost-effective diagnostic technique for family doctors that can have a big impact of the health of the US and the developing countries rural areas.

References

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