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Potential of Piezoelectric Sensors in Bio-signal Acquisition

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Abstract: The purpose of this paper is to understand the prospective of piezoelectric sensors in biomedical sciences to measure and analyze multiple human physiological parameters as most of the human vital sign information is non electrical, quasi-periodic and very low in amplitude, thus posing problems in detection and analysis. This paper presents a broad review on the theory and inherent advantages like high modulus of elasticity, very high natural frequency and linearity over a wide amplitude range, stability over temperature and almost negligible deflection on compression etc of the sensor. It also discusses the benefits of using a piezoelectric sensor in acquiring various bio-signals as they are non-invasive, rugged, versatile and cost effective. The electronics and signal processing involved are also presented. Existing appliances and methods where piezoelectric materials are used for bio-signal acquisition are researched and explained along with their block diagrams. It is found that these sensors are not sensitive to electromagnetic radiation, thus making them more suitable in biomedical applications. The paper gives a current, widespread review on the versatility of piezoelectric sensors for man machine interface to be used in biomedical sciences.

Keywords: Bio-signal acquisition, Non-invasive, Piezoelectric sensor, Health care monitoring.

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1. Introduction

The enhanced standard of living across the globe has resulted in better life expectancy, leading to an obligation of providing superior health care monitoring and attention. To realize this, research organizations have started integrated effort towards information and communication technologies and biomedical sciences to measure and analyze multiple human physiological parameters. Advancement in electronic technology particularly sensor technology, microcomputers and digital signal processing has greatly affected our day to day lives particularly the health care domain. The evolution in medical sensors has led to a trend of smart, micro, multi-parameter, remote-control and non-invasive technologies that convert the biological qualitative inputs to quantitative measurable output. Non-invasive method is significant and largely acceptable by receivers, has almost no effect on human body are easy-to-operate and sterilize. Piezoelectric sensors are one such non-invasive, versatile and cost effective sensor that can be used to acquire various bio-signals and has been discussed in this paper.

Front end of most of the medical equipment are sensors which are sophisticated components that translate one form of energy into another. Many sensors use piezoelectric materials which can produce mechanical movement in response to electrical input and vice-versa. Over the years piezoelectric sensors have evolved as a versatile non-invasive tool for the measurement of pressure, acceleration, strain or force etc and find application in various industrial processes that include medical, aerospace, nuclear instrumentation, touch pads of mobile phones and automotive industry to monitor combustion when developing internal combustion engines. This paper reviews the application of piezoelectric sensors in medical sector, for bio-signal acquisition.

As one of the submission, Sorvoja Hannu describes and tests the suitability of pressure sensor arrays based on electro-mechanical film (EMFi) pressure sensor, for long-term measurement of heart rate and blood pressure from the radial artery [14]. Texas instruments have developed an amplifier and microcontroller arrangement that processes the signal output of the pressure sensor to obtain useful information about the patient's health, for example the blood pressure [4]. G. Rigas et al have identified the emotional state of a subject from information gathered from bio-signals like ECG, facial EMG, respiration etc. For sensing the respiration in this work, a set of piezoelectric sensors were put around the subject’s thorax [11]. S. Dash et al also estimated the respiratory rate from piezoelectric pulse transducer signals [5]. Ceramic piezoelectric transducers are also used for non-invasive measurement of the blood flows in ultrasound Doppler instruments. It also finds application in blood pressure measurement or for observation of heart valves movement in phonocardiography [3]. A wireless pressure sensing bite guard system has also been developed for monitoring bruxism, which is grinding of teeth during sleep, using Piezo sensors [7]. Fleish’s pneumo-tachometer is an instrument that measures air flow rate using pressure transducer through which the patient breathes [3]. J. Alametsä et al examined the effect of posture in the sitting and supine positions on ballisto-cardiography (BCG) measurements by using EMFi pressure sensors [1]. Shantanu Sur et al developed a novel pulse wave detection system using low frequency specific piezoelectric material as pressure wave sensor that detects the periodic change in the arterial wall diameter produced [15]. T. Shino et al developed a novel non-invasive means of sensing heartbeat, respiration and body-movement of a subject in bed by using ceramic piezo devices kept under the bed [12]. J McLaughlin et al devised a fast and easy to use system for finding the peripheral arterial pulse wave velocity of a patient using two piezoelectric sensors [13]. D. Bansal et al developed a system for wireless transmission and analysis of carotid pulse waveforms in various body postures using piezoelectric ceramic sensor as the man machine interface [2]. Ramya Murthy et al devised a non contact way for measurement of breathing function [10]. Looking at the vast application of Piezo electric sensors in medical monitoring, an attempt has been made to review the theory behind its working and signal processing for bio-signal acquisition.

2. Theory of Piezoelectric Sensor

Piezoelectric sensors are based on piezoelectric effect, which is development of electric polarity in dielectric crystals like ‘quartz’ when under stress and generation of stress in them when subjected to an applied voltage, as noticed by Curie brothers. However, there are other naturally occurring ceramic, single crystal and plastic materials that exhibit piezoelectric properties. Primary quartz, Rochelle salt, ammonium dihydrogen phosphate (ADP), and ceramics with barium titanate, dipottasium tartrate, potassium dihydrogen phosphate and lithium sulphate are some materials that exhibit piezoelectricity. Piezoelectricity is based on the concept of electrical dipole and structurally a piezoelectric material is an ionic bonded crystal. At rest, the dipoles formed by the positive and negative ions cancel each other due to symmetry of the crystal structure, and so no electric field is generated. However, when subjected to a stress, the crystal deforms and loses symmetry and a net dipole moment is created causing an electric field across the crystal and vice versa. Due to internal impedance of the piezo-sensor and signal conditioning circuit, the electrical charge produced decays with time and so is not suitable for static or dc applications but can be effectively used for dynamic or ac applications. The ceramic materials have a piezoelectric constant higher than those of single crystal materials and are inexpensive to produce, but are comparatively less stable. Hence, applications that require less precision use piezoelectric ceramics. However, the single crystal materials like quartz, tourmaline and gallium phosphate exhibit long term stability and temperature resistance.

Piezoelectric ceramics are multi-crystal dielectric type with a high dielectric constant but do not exhibit the piezoelectric property till they are polarized, because the electrical dipoles inside the crystals are randomly oriented and the overall moment of the dipoles is cancelled out. So, a very high DC electric field (kV/mm) is applied to the ceramic to align the internal electrical dipoles in a single orientation. Due to strong dielectric property of the ceramic, the dipole moment remains unchanged even after the electric field is removed, and the ceramic thus exhibits a strong piezoelectric property. When compared to other piezoelectric substances, both BaTiO3 and PbTiO3×PbZrO3 ceramic piezos, have advantages like high electromechanical transformation efficiency, high machinability, high degree of freedom in characteristics design, high stability and economic mass production [9]. The basic structure of a piezoelectric ceramic diaphragm is shown in Fig. 1 and the commercially available ceramic piezo-sensors are shown in Fig. 2. The frequency response curve as a function of output voltage / force of the sensor is depicted in Fig. 3. Usable range of the piezo-sensor, as shown in Fig. 3 is the flat region of the frequency response curve that is used in various applications. To be able to detect low frequencies, the circuit should have large load and leakage resistance. The piezo sensor thus has to be signal conditioned before being used in any application and has been discussed in the subsequent section.

2.1. Signal Processing the Piezoelectric Sensor

A piezoelectric sensor may be used directly in a circuit without any additional interfacing unit. However for an optimized utilization of the sensor, an interface is needed. The electrical equivalent of a Piezo film is shown in Fig. 4. It can be used as a voltage source or as a charge generator. As a voltage source it consists of a series capacitance ‘C’ which is directly proportional to the permittivity of the film and area and inversely to its thickness. The voltage output of the Piezo film is the open circuit voltage given by $V=Q/C$ and has a wide application except in very high frequency areas. As a charge generator, it has an internal film resistance ‘R’ along with ‘C’, which can be ignored in low frequency applications. The input resistance of the interface circuit plays an important role here as it affects the signal strength at low frequencies and minimizes loading effect. Apart from the input resistance, the input capacitance of the interface circuit can also affect the signal output. The time domain response curve of a Piezo film is shown in Fig. 5(a) and the high pass filter characteristic (frequency response) is depicted if Fig. 5(b). Time constant is the time required for a signal to decay to 70.7 % (-3dB) of its original signal strength and due to this limitation it is suitable for dynamic measurements only. For longer time constant values, a high input resistance and film capacitance can be used, but they can lead to more noise. The cutoff frequency (3 dB down) in the frequency response curve is inversely proportional to the time constant and when the sensor is operated below this cut-off frequency, the output is greatly reduced [6, 8].

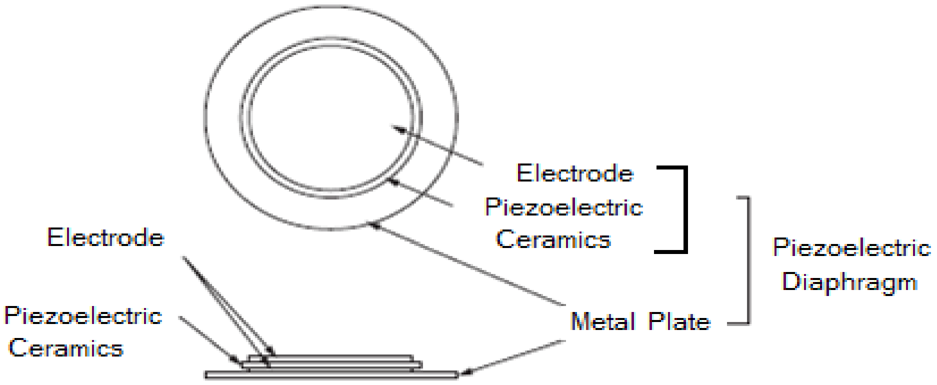

Fig. 1. Structure of piezoelectric diaphragm.

Fig. 2. Commercially available piezoelectric sensors.

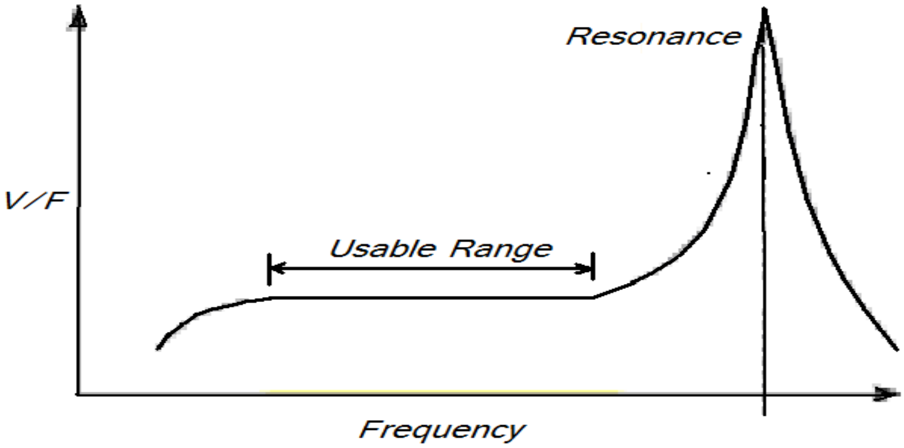

Fig. 3. Frequency response curve of a piezoelectric sensor (frequency vs. output voltage/applied force).

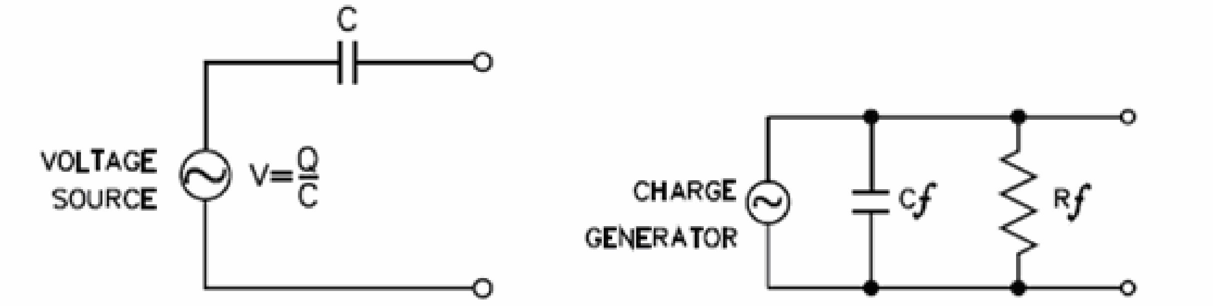

Fig. 4. Electrical equivalent circuit of a piezoelectric film.

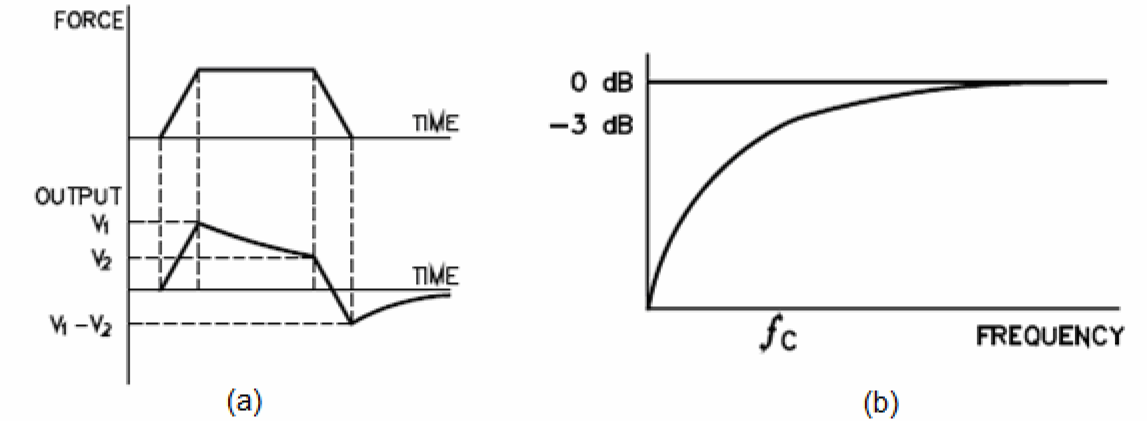

Fig. 5. Characteristic curves of a piezo film.

The output of piezoelectric sensors normally varies from microvolts to hundreds of volts and therefore the electronics required for signal conditioning may vary significantly. Signal processing mainly includes filtering, averaging and common mode rejection in these sensors. Points to consider when designing the amplifier for these sensors are the frequency of operation, signal amplitude, input impedance, mode of operation, use of proper load resistance to minimize loading effect and a buffer circuit in case of very low signal. High impedance of the piezoelectric sensor normally requires an amplifier with high-input impedance JFET or CMOS input operational amplifiers [6, 8]. Fig. 6 below gives the connection diagram for a self driven piezoelectric sensor. The piezoelectric diaphragm has a feedback electrode and is used in the closed loop of a Hartley type oscillation circuit consisting of one transistor and three resistors. When the frequency is close to the resonant frequency, the circuit satisfies oscillating conditions, and the piezoelectric sensor is driven with the oscillating frequency. Some manufactures have made signal conditioning of their piezoelectric sensors easier by integrating FET buffers into the sensor. Still, proper biasing is important and additional amplification may be desired. Like for example, for measuring low level vibrations, the signal level detector of Fig. 7 is suitable. For situations where signal to noise ratios are low and where pressure signal must be distinguished from background noise, the differential amplifier circuit consisting of two sensors is used as shown in Fig. 7.

There are applications where the electronic circuit cannot be placed near the sensor. In such conditions a unity gain buffer circuit shown in Fig. 8, designed using FET or operational amplifier is used with the sensor in general. The buffer circuit converts the high output impedance of the sensor into low output impedance and thus minimizes the signal loss and noise.

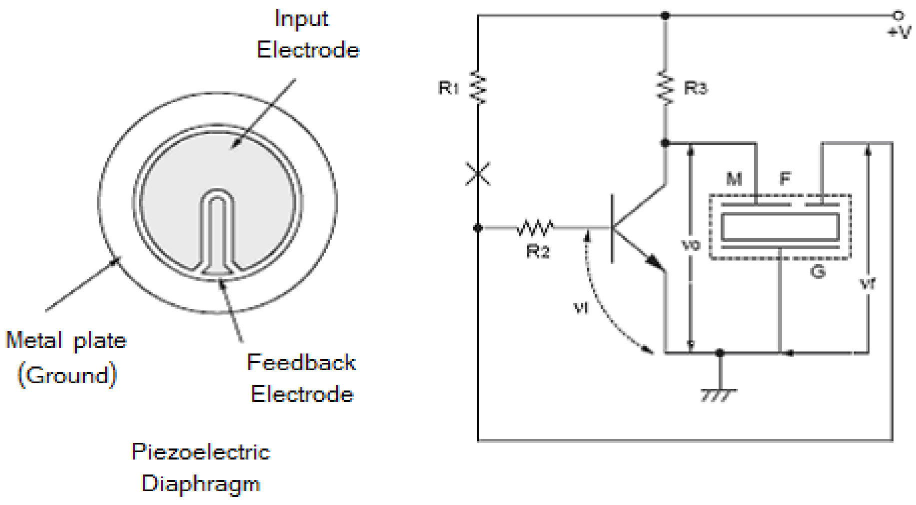

Fig. 6. The self drive circuit for piezoelectric sensor.

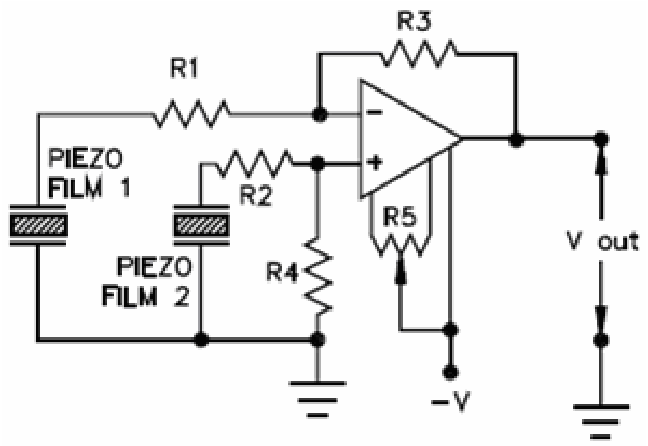

Fig. 7. Low level signal detector with differential amplifier.

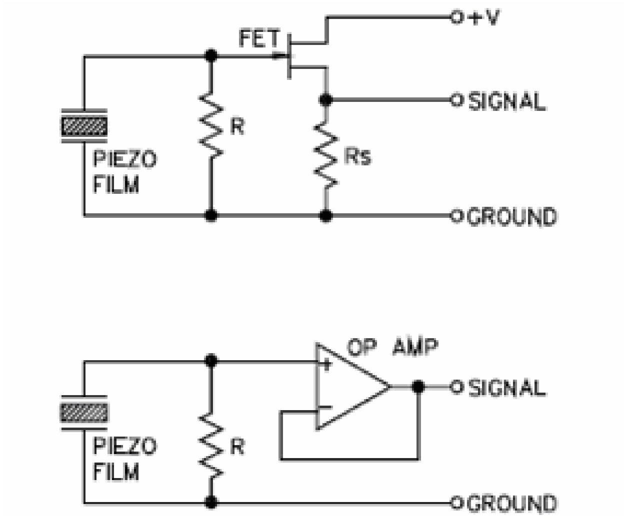

Fig. 8. Unity gain buffer circuit for piezoelectric sensor.

3. Application of Piezoelectric Sensor in Bio-signal Acquisition

Intrinsic advantages of piezoelectric sensors like immunity to electromagnetic radiation, high modulus of elasticity, very high natural frequency and linearity over a wide amplitude range, stability, temperature resistance and almost negligible deflection on compression, makes them suitable for bio-signal acquisition. Certain application areas of these sensors in biomedical engineering are discussed below.

3.1. Non-invasive Measurement of Blood Pressure and Heart Rate

Output produced by the pressure transducer used for measuring Blood pressure (BP), ranges from 0 to 40mV, so a high gain amplifier is used to boost the DC as well as AC component of the voltage to a measurable level as has been shown in Fig. 9.

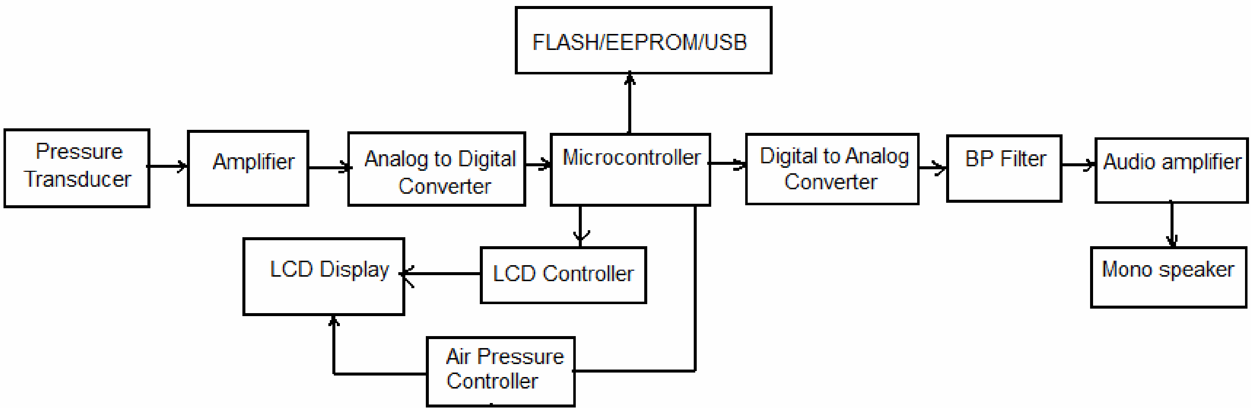

Fig. 9. Block diagram for digital measurement of BP and Heart rate [4].

A band pass filter allows the frequency in 1-4 Hz range and rejects all other frequencies. AC component of the voltage output captures the systolic or diastolic pressures or heart rate of the patient. This signal is then fed to analog to digital converter (ADC), which is an integrated part of the microcontroller for digitization and display and the result can be stored in any memory device [14, 4]. Shantanu et al have developed a system for monitoring Arterial Blood Pressure wave which is an important parameter in assessment of cardiovascular system using low frequency piezoelectric material as pressure wave sensor. The transducer detects the periodic change in the arterial wall diameter produced by pressure wave and the amplified signal after integration represents the pressure wave and also helps to reliably detect the heart period variability (HPV). Position-specific experiments were carried out by placing the sensor array over carotid or radial artery to analyze the changes at different physiological states [15]. Likewise, T. Shino et al have used ceramic piezo devices kept under the legs of the bed to non-invasively capture heartbeat and body-movements of a subject [12].

3.2. Measurement of Blood Velocities, Air Flows and Breathing Rate

Ceramic Piezoelectric sensors working in the range 4–10 MHz, find applications in non-invasive measurement of blood velocities in ultrasound Doppler instruments. They can also be used for blood pressure measurement or for observation of heart valves movement in phonocardiography. Fig. 10 below depicts the block diagram of Fleish’s pneumotachometer that measures air flow rate when breathing, using a pressure transducer. The air passes through a fine mesh which resists the flow, and causes a pressure drop across the mesh in proportion to the flow rate. The conical ends of the tube provide laminar air flow around the pressure transducer [3].

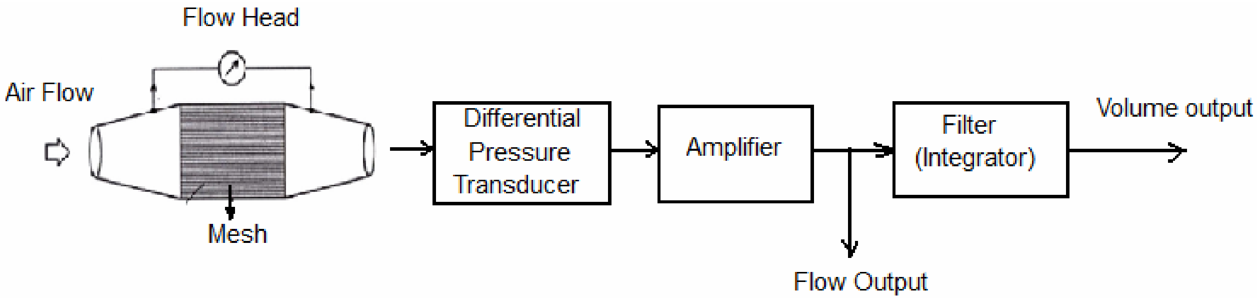

Fig. 10. Block diagram for air flow rate measurement when breathing.

Breathing function has the ability to predict various syndromes like sudden infant death, sleep apnea, heart attacks and is also used for polygraph tests. Of all the methods developed to measure breathing rate, most of them require contact with the subject making them uncomfortable and immobile and also get corrupted by artifacts. Hence, a system has been developed, that captures the profile view of the subject's face and respiratory airflow using an infra red camera system from a distance of 6–8 ft as shown in Fig. 11. A piezo-strap transducer belt is wrapped around the subject's diaphragm which measures the expiration and non-expiratory signal amplitudes and sends it to a PowerLab data acquisition system [10].

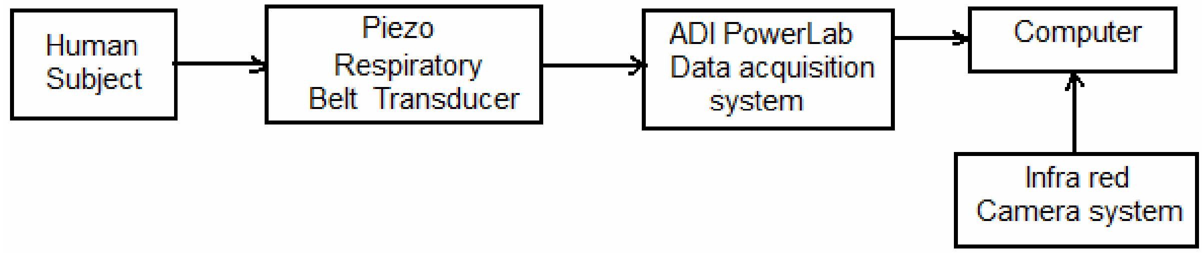

Fig. 11. Non-contact measurement of Breathing function.

S. Dash et al. compared two different time-frequency-spectrum based breathing rates for three physiological parameters, viz. ECG, photo-plethysmogram, and piezoelectric pulse (PZO) signal as earlier studies indicate the presence of amplitude due to respiration in these physiological signals. It was observed that controlled breathing affected the PPG signal, and so the rate of respiration was calculated using the wavelets. This established that breathing rate (BR) detection methods were very accurate and were better than the time-domain autoregressive modeling (AR) method, especially in the real-time for data length of 1 min. This method was further tested on the ECG and the finger PZO signal, of which only the former has been previously used with some success to derive BR [5]. G. Rigas et al have established that a subject's emotional state like happiness, disgust and fear can be obtained from his facial electromyograms (EMGs), electrocardiogram (ECG), respiration rate and electrodermal activity (EDA). For measuring the respiration in this experiment, a piezoelectric respiration sensor was placed around the subject's thorax [11].

3.3. Wireless Measurement of Bruxism

Grinding teeth during sleep is called Bruxism and can be monitored using a wireless pressure sensing bite guard system shown in Fig. 12 and Fig. 13. The pressure sensor was made from composite of carbon-polymer and was put into a bite guard system along with microcontroller-based electronics for data acquisition and transmission. A low battery requirement was designed to maximize the working life-time of the device to several months in this application [7].

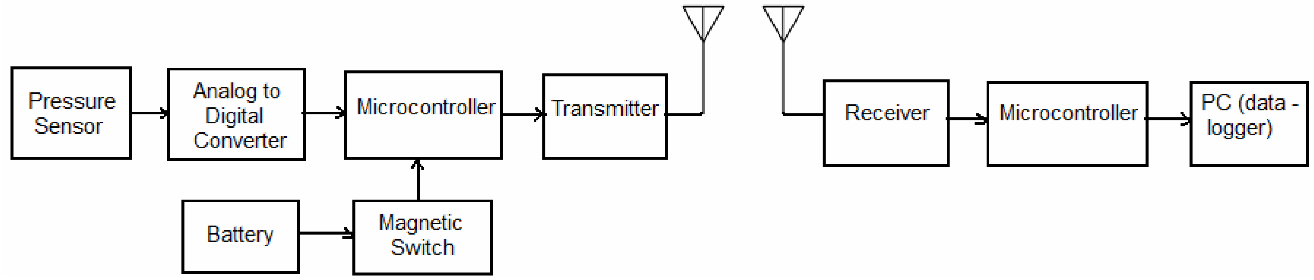

Fig. 12. Block diagram for wireless measurement of Bruxism.

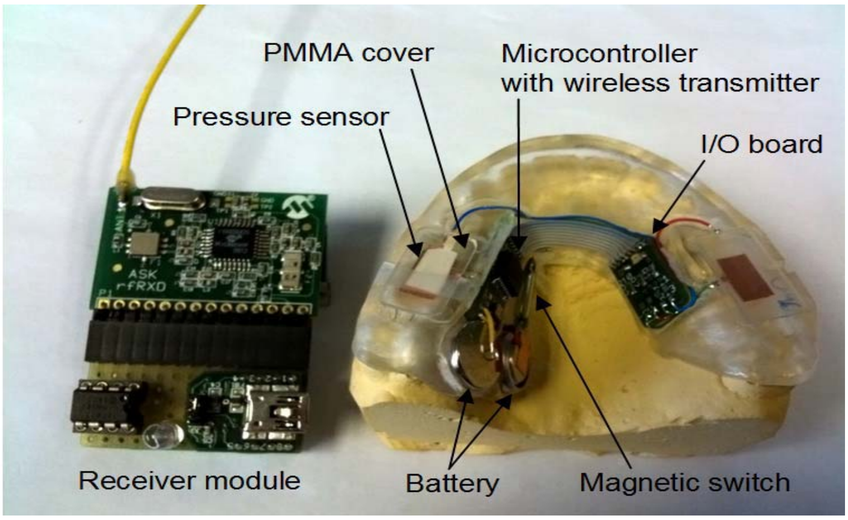

Fig. 13. Electronic module for wireless measurement of Bruxism.

3.4. Measurement of Ballistocardiography and Carotid Pulse Signal

Alametsä J et al analyzed the effect of posture on ballistocardiography (BCG) measurements using EMFi (electromechanical film) sensors, which are processed piezoelectric sensors. An electromechanical film is a thin porous polypropylene film with biaxially oriented flat voids. Under the effect of high electric fields, the charged voids get properly oriented quasi-dipoles, and become piezoelectric. They can be obtained in any shape, can be easily handled, are of low cost and can be used for many transducer applications. However, their stability reduces beyond 50 °C, thus limiting their application range. Amplitude and periodicity of BCG along with Carotid pulse were analyzed using Piezo sensors in sitting and supine positions. This establishes new methods for evaluating the hemodynamic changes and cardiac information at different body positions [1].

In another application, D. Bansal et al developed a simple and cost effective piezoelectric sensor arrangement that improve the system portability, sensitivity and ease of interface with the computer for acquiring the carotid pulse contour in real time, as shown in Fig. 14. Sound card of the computer is used as the interfacing unit which amplifies and converts the analog input of carotid signal into digital, so additional amplifier, analog to digital convertors (ADC) and data acquisition (DAQ) boards are not required. MATLAB is used to acquire, filter and transmit the carotid wave in real time and to quantify posture related changes in the carotid data obtained [2].

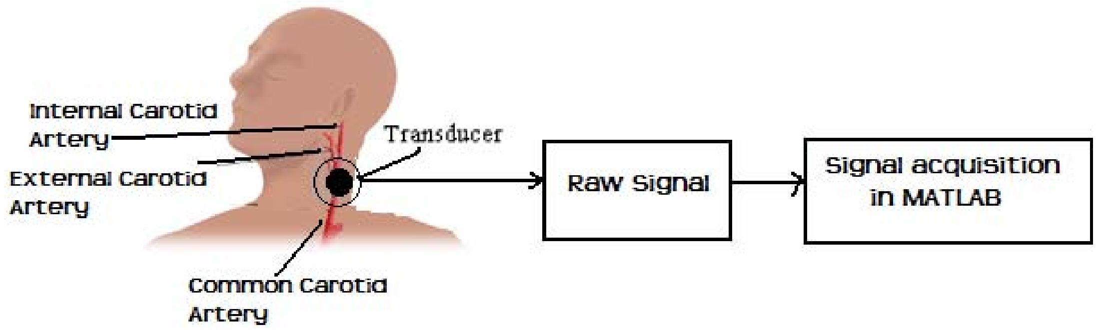

Fig. 14. Real time acquisition of Carotid pulse wave in MATLAB.

3.5. Measurement of stiffness of Arterial Blood Vessels

J. McLaughlin et al measured Arterial pulse wave velocity (APWV) which gives the elasticity / stiffness) of peripheral arterial blood vessels using a fast and easy to use system [13]. APWV is measured using two piezoelectric sensors one put at the radial artery at the wrist and the other kept at brachial artery just above the elbow for simultaneous measurement of two pulse waves. The pulse transit time between these points and the distance measured between the two locations, gives the arterial pulse wave velocity. The pulsation produced voltage in m.volts, which is amplified and filtered and then digitalized using a data acquisition card. Measurement system was optimized by carrying out tests on eight subjects ranging in age from 22 to 32 years. The APWV measured covered a range from 6 m s^{-1} to 12 m s^{-1}, with an average standard deviation of less than 2.5 m s^{-1} for individual results. Reproducible results were obtained with the simple APWV detection and analysis system discussed.

4. Conclusions

Better health care monitoring and awareness at affordable cost has become the need of the day in developing countries as well. To implement this, a lot of effort has been made in the field of electronics and biomedical engineering towards detecting and analyzing the vital human physiological signals. Most of the human body information being very low in strength and being corrupted by surrounding artifacts needs to be processed during acquisition. The primary electronics required thus becomes the design and signal processing of a cost effective transducer which is primarily non-contact type, is rugged, reliable and is easily available. One such transducer frequently used in biomedical applications is the piezoelectric sensor due to enormous advantages that they exhibit. Hence, an attempt has been made in this paper to review the theory behind the functioning of these sensors and the electronics required to interface them with the human subject, along with the various application areas where they been used and tested.

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- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
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