Design and Development of Quasi Digital Sensor Based Spirometer

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Abstract: The lack of cost-effective diagnostic devices like spirometer is becoming a prevalent challenge to the diagnosis and effective management of life-threatening respiratory diseases. This paper presents the design, development, and implementation of differential pressure sensing quasi digital sensor and instrument for spirometer application. A system which fulfills the medical standard specifications has been designed and developed by exploiting the venturi tube (Bernoulli’s principle) and quasi digital sensor principles. A low power microcontroller (PIC24F) based embedded system, venturi tube based quasi digital sensor, data acquisition software, and user interface were developed. A lab made prototype device has been constructed, tested, and subsequently analyzed the recorded data from the computer. This cost effective ($150) spirometer model can be used for detection of pulmonary diseases rural area and it is going to add a new dimension to the diagnosis of many lung diseases.

Keywords: Quasi digital sensor, Spirometer, Spirometry, Venturi tube, Embedded system, Thermistor, Microcontroller.

1. INTRODUCTION

Spirometer is the medical diagnostic equipment which measures the volume of the lung, the flow of exhaled and inhaled air from and to the lungs. One can retrieve the vital information by analyzing these measurements. Spirometry systems underlie on three flow measurement principles namely pressure difference, turbines and thermal flow. Spirometers based on these principles mainly rely on mechanical parts which are difficult to sterilize. There is a chance of spreading tuberculosis (TBC) while diagnosing the patients. Moreover, the cost of the equipment is also very high. The price is in the range of $1200-$2500 for currently available spirometers in the market. For example, SDI Diagnostics Astra Spirometer price is $2056 [1], MIR Spirolab Touch Screen Portable Spirometer price is $2940 [2] and MIR Spirodoc Spirometer with Pulse Oximeter price is $1850 [3]. Researchers have proposed a variety of sensing techniques to measure essential Spirometry values such as peak expiratory flow (PEF), force expiratory volume in one second (FEV1), force vital capacity (FVC) etc [4]. One of the researchers proposed optical mouse based spirometer which is bulky and requires sophisticated signal conditioning circuitry [5]. Currently few researchers reported venturi tube based differential pressure approach for spirometer applications [6, 7, and 8]. The venturi tube based systems are handy, rugged, and robust against temperature [9]. Another researcher proposed a
thermistor based sensor for spirometer application which works with change in temperature due to applied pressure [10]. The above mentioned methods are costly, requires more signal conditioning circuitry and they are bulky with more mechanical components.

Quasi digital sensors are direct digital interface sensors with outputs such as TTL pulse frequency, period, and duty cycle. This sensing approach can overcome the limitations (complex signal conditioning, bulkiness, high power) of the conventional sensors [11-18]. Quasi digital sensors are small in size, require low power, and they can come with lower cost. These sensors are designed with an inverting logic gate and do not require conventional electronics signal conditioning like amplification, filtering and analog to digital conversion. The output from these sensors can be directly connected to the input port of the microcontroller with simple wave shaping circuit. Since the output signal is in form of TTL pulses so they provide noise immunity, and it can be transmitted to long distance.

This paper presents a simple, cost-effective, sensor and instrument for spirometer application to monitor the respiratory function of the person. The sensor is constructed using venturi tube along with thermistors, logic gate oscillator, and fixed capacitors. The instrument to monitor respiratory function is designed using PIC24F based microcontroller. This instrument is used to read the pulse frequency, to convert into the physical parameter (flow rate), to display on LCD, and to send to the computer. In this study, a prototype spirometer was manufactured, tested the performance with a lab-made experimental setup.

2. SENSING METHODOLOGY

The method applied in the current spirometer to measure the exhaled air flow from the lungs through mouth piece is based on one of fluid dynamics law (venturi effect). According to this law when air flows from a broader to a contracted section of a pipe, the pressure of the air decreases whereas the velocity of the air increases. The venturi effect equation is given in Eq.1.

\[ P_1 - P_2 = \frac{\rho}{2} (v_2^2 - v_1^2) \]

(1)

The pressures P1 and P2 are converted into electrical signal by using two thermistors RT1 and RT2 fixed on venturi tube. Figure 1 shows the schematic diagram of the spirometer transducer. Two thermistors RT1 and RT2 were fixed on high pressure and low pressure points on venture tube respectively. According to the Gay-Lussac law the pressure of a given amount of gas at constant volume is directly proportional to the temperature. The Eq.2. shows the relation between the change in exhaled pressure and temperature.

\[ \Delta P = \frac{\rho}{2} \Delta T \]

(2)

\( \Delta P \) is change in pressure in milli bar, \( \Delta T \) is change in temperature in Kelvin.

Due to change in exhaled air pressure there is a change in resistance of the thermistors according to the Eq.3.

\[ R(T) = R_0(e^{\frac{\beta}{T}} \left(\frac{1}{T} - \frac{1}{T_0}\right)) \]

(3)

\( R(T) \) is resistance of thermistor at \( T \) in

\( R_0 \) is the nominal resistance of the thermistors at \( T_0 \) in \( \Omega \), \( \Omega \), \( \beta \) is constant.

\( T \) is the temperature due to applied pressure at the time of exhalation in K, \( T_0 \) is the temperature 298.15K

These thermistors are part of the RC type logic gate oscillators. The change in resistance of thermistors cause a change in output frequency of the logic gate oscillator. The Eq.4 and 5 gives the
The logic gate oscillators along with thermistors produce the pulse frequency as output for applied exhaled air through the mouth piece. The difference in pulse frequency carries the information about the exhaled air from the person. Calibrating of the developed spirometer with standard spirometer or flow meter can give the exhaled air flow rate.

3. TRANSDUCER CONSTRUCTION

The transducer for the spirometer application was fabricated at laboratory. Figure 2 shows the photograph of fabricated and assembled transducer. Two polypropylene tubes with at side diameter of 10 mm, cone side diameter of 5 mm are joined to make venturi tube. The cone sides of the two tubes were fixed using araldite by providing the space to keep the thermistor to see the low pressure point. Thermistor 1, thermistor 2 were fixed at atter side at high pressure point and low pressure point respectively. The venturi tube is drilled and the thermistors were fixed with araldite to avoid any leak of exhaled air.

\[
F_1 = \frac{1}{2.2R_{T1}C}
\]

(4)

\[
F_2 = \frac{1}{2.2R_{T2}C}
\]

(5)

\[
\Delta F = F_1 - F_2
\]

(6)

$R_{T1}$ is the resistance of the thermistor placed at high pressure point in $RT_2$ is the resistance of the thermistor placed at low pressure point in $C$ is the capacitance of the capacitor in $\mu F$

$F_1$ is the pulse frequency of the logic gate oscillator placed at high pressure point in kHz $F_2$ is the pulse frequency of the logic gate oscillator placed at low pressure point in kHz $\Delta F$ is the difference in the output frequency of the logic gate oscillators in kHz

![Schematic of the spirometer transducer with quasi digital sensors.](image)

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4. EMBEDDED SYSTEM

An embedded system is required to read the pulse frequency from the logic gate oscillators, calculate the difference between the two frequencies (ΔF), convert the ΔF into the flow rate, display on LCD and send to the computer. Figure 3 shows the block diagram of the embedded system. PIC24F microcontroller based embedded system was designed and developed to perform above tasks. PIC24F has five timers/counters with programmable prescaler value. Our method makes use of all the five timers to measure the frequency of train of pulses. TIMER1 is given crystal frequency of 12 MHz to create a window of 1 second. TIMER1 is pre-scaled with value 256 and its Period Register is loaded with count 23,446. With this initialization of TIMER1, an Interrupt is raised by TIMER1 at the end of 1 second. For two channel frequency counter TIMER23 and TIMER45 are given external input of which frequency is to be determined. In the Interrupt Service Routine of TIMER1 commands are written such that current value of TIMER23 and TIMER45 are stored in a 32 bit variable. Now, this stored value denotes the number of pulses crossed in 1 second which equals the frequency of the input. As counters are programmed in 16-bit mode, if input frequency is more than 65,536 kHz count in the counter will exceed 65,536 and at the next falling edge counter will reset to zero. To account this overflow a new variable (overflow X) is defined in code for keeping count of the overflow and current value is stored in FXout. Final count is given by FXout = 65,536*overflow X + FXout. TIMER1 is configured in same as done in two channel frequency counter.

After reading the pulse frequency from the logic gate oscillators, the embedded system calculates the difference in the two frequencies of oscillators, exhaled flow rate as per the relation between the ΔF and flow rate. Microcontroller was interfaced with LCD to display the exhaled flow rate. In addition RS232 communication also provided to record the frequency data in computer for calibration purpose. Real time clock was interfaced with microcontroller to record the time. Figure 4 shows the flow chart of the embedded system for spirometer application.
In addition to development of the embedded system, GUI was developed using python to display the real time graph on host computer. This will plot the real time graphs between difference in frequency of LGOs and flow rate Vs time.

5. PERFORMANCE TEST

5.1. Experimental setup
An experimental setup was fabricated and assembled in laboratory to test the performance of the developed sensor and spirometer. Figure 5 shows the schematic diagram of the experimental setup.
It consists of mouth piece, flow meter, lab made spirometer transducer containing venture tube along with thermistors, logic gate oscillators, embedded system, power supply, Nokia display and host computer. Figure.6 shows the fabricated and assembled experimental setup at laboratory. The exhaled air from the person was allowed to flow through the lab made venture tube transducer and the readings of the logic gate oscillators were recorded on computer by using embedded system.

5.2. Calibration of spirometer
The lab made spirometer was calibrated using standard flow meter with 0 to 500 LPM range. The flow meter was connected between venturi tube and mouth piece. The regulated air is supplied to the mouth piece and the corresponding pulse frequency of the LGOs is recorded on computer.

A relation between the $\Delta F$ and flow rate was established and the equation was incorporated in the firmware of the microcontroller. Figure.7 shows the graph between flow rate and difference in pulse frequency ($\Delta F$).

5.3. Results
The final design of quasi digital sensor based spirometer was validated by experimental testing. A person is allowed to exhale the air from her mouth into the spirometer. The real time graph recorded in the computer is shown in Figure.8.
6. CONCLUSION

The main goal of this project was to design and develop a low cost prototype spirometer using quasi digital sensor by exploiting the venturi tube principle. Towards this a sensor and low power consuming microcontroller based embedded system with display module have been presented. An algorithm is developed to read the pulse frequency from the quasi digital sensor and convert into flow rate. The prototype instrument is constructed at laboratory and calibrated using regulated airflow. After successful calibration the prototype instrument was tested with real time inputs (exhaled air) from the mouth piece. The spirometer is interfaced with computer to communicate and store the data in personal computer to diagnose the patient. This feature provides the facility to record, print the spirometric data. Further, work will focus on the integration of the device with IOT. In future the device will be modified to test the different diseases like COPD and CRPD after several clinical trials with patients.

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