lung capacity testing prototype for covid-19 and other chronic resiratory diseases severity assessment

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Abstract. To estimate the severity of different Covid-19 infections, the current lung capabilities of patients are one of the most important inspects. This paper explores practical redesigns of a spirometer, in this way, when patients exhale, the volume and time can be recorded, using comparatively inexpensive load cells as a substitute for commercial spirometers. When exhaling into the one end of a tube, the plate at the other end will be deflected. With this plate connected to a beam and load cell, the force of a patient's respiration can be recorded over time. This data can be applied to calculate the required metrics at a small cost. Before actual prototyping the device, sample data of normal breathes will determines the geometry of the beam, primarily the length. Reasonable length is estimated which would create deflection given a range of expected forces. In order to apply the load cell in an effective way, Wheatstone bridge circuit is necessary. To make sure the output voltage reflects the force input correctly, the bridge needs to be balanced. The signal is amplified using an IC-741 op amp. The need for gain is calculated in accordance with a range of flow rates; a healthy person ought to create an output of 0-2 volts with a breath, so that it allows for high resolution output from the DAQ. Another amplifier is utilized to eliminate aliasing. To ensure accurate datum, the load cell is tuned with known weight output on the end of the beam. This configuration gauged the force and volume output from a bicycle pump.)

Keywords: spirometer; lung capacity; covid-19; wheatston bridge; digital amplifier; low pass filter; MATLAB

1. Introduction

In early December 2019, the World Health Organization first reported the current burst of the novel coronavirus SARS-CoV-2 (coronavirus disease 2019; previously 2019-nCoV) [1]. By the end of November 3rd, there are 246,303,023 confirmed cases, at the same time, 4,994,160 people have died [2]. Living in the current time when Covid-19 appear not to vanish away, for any third world country, testing will be a tremendous burden.

Chronic respiratory disease (CRD) is also a growing global health and economic burden. Two mutual CRDs, asthma and chronic obstructive pulmonary disease (COPD), influence more than 0.435 billion people universally [3]; besides, each of them has an estimated medical cost of 5000 million dollars year after year [4][5]. As a result of, a proportional cheaper way of testing the lung capacity of patients will be conductive. A new design of spirometer in less expensive cost is discussed in this paper.

An equipment is needed to make notes of different measurement of lung function, they respectively are total volumetric flow and peak flow rate. The approach introduces a prototype spirometer, using a thin beam and a load cell, manipulator measures the force of a patient's exhalation through a tube. The measured force, time, and the geometry of the apparatus itself can calculate the required measurements. A balanced Wheatstone bridge and low-pass filter ensure datum precision, meanwhile, an amplifier is used to create a 0-2V output range.

2. Methods

2.1. Experimental Setup and Main Equations

In the case of calculating peak flow and total volumetric flow, this device is designed. With a plate at one end, by exhaling into a PVC pipe, the user produces a stagnation pressure. This leads to deflection of a cantilever beam. The degree of deflection of the beam can be measured by a strain gage. Equation (1) shows how to calculate the force using the known.

$$(\varepsilon E b h^2) / 6L = F \tag{1}$$

Here, with E being Young's modulus accordance to the material of the beam, ε is strain, h is thickness of the beam, b is the width of the beam, and L represents the distance from the center of the strain gage to the applied force the center of the strain gage. From there, the stagnation pressure of the breath at the end of the beam can be calculated by dividing the force by the inner cross-sectional area of the pipe, A, which is calculated from internal diameter using (2).

$$P = F / A \tag{2}$$

Using (2), the stagnation pressure P is represented. This P here can also be derived from Bernoulli's equation as shown in (3).

$$c = 1/2\ \rho v^2 + P + \rho g z \tag{3}$$

Velocity is set to be zero pressure is measured at a stagnation point. Gravity is neglected, the constant c is equal to the calculated pressure P. The system is modeled as perfectly laminar. Therefore, c is constant along streamlines of flow. The pressure at the front of the tube only gets atmospheric pressure, so there is zero gage pressure. Using (4), the maximum breath velocity can be solved.

$$c = 1/2\ \rho v^2 \tag{4}$$

Table 1. Constants for Experimental SetupTable Type Styles

D_internal	15.2 mm
B	12.68 mm
h	0.4 mm
E	100 GPa

There is no assurance that the beam and load cell have same deflection unless the load cells are bonded to the beam strongly. Therefore, to accomplish this, the procedure from [6] is followed. The material is cleaned, dried, and cleaned again before applying multi-stage adhesive. Laying down these guidelines is designed to ensure adhesion failures are minimized.

Wheatstone bridge, differential amplifier and active low-pass filter are used in this device. The Wheatstone bridge is used to output the difference in the resistance of the strain gage. Deferential amplifier will enlarge the voltage from previous part, and the filter will screen out high frequencies and prevent aliasing. Fig. 1 shows a schematic of the entire circuitry with these three parts.

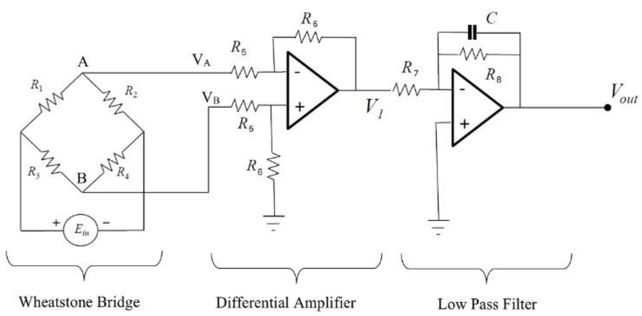

Figure 1. Schematic of a wheatstone bridge circuit.

The range of flow rates can be calculated using the known max and min breath time, max and min volume, and the air density. The max and min of air flow speed can be found by dividing the volume with the contacting area. By using (2) and (3), the max and min stagnation pressure can also be found. Using the foregone area and pressure, minimum and maximum force can be driven by (1).

Brass is chosen to be the material of the deflecting beam. Brass has 100 GPa elastic modulus, it is lower as compared with steel. It infers that a larger deflection will be experienced under same loads, so that giving a higher sensitivity to the measurements. By measuring height and base of the beam, a spreadsheet is created, whose length from 1 to 100 mm and their min strain, corresponding max strain, and range. In Table 2, the portion of spreadsheet with length from 70 to 86 is shown. Without exceeding limits, the calculated values for 82 mm length are the maximum ranges, and the chosen length in 75 mm.

Table 2. Max and Min Strain and Their Range for Different Length for Length Selection

L (mm)	Max strain (microstrain)	Min strain (microstrain)	Range
70	424.443	121.811	302.632
71	430.506	123.551	306.9554
72	436.57	125.291	311.2787
73	442.633	127.031	315.602
74	448.697	128.771	319.9253
75	454.76	130.512	324.2486
76	460.824	132.252	328.5719
77	466.887	133.992	332.8953
78	472.951	135.732	337.2186
79	479.014	137.472	341.5419
80	485.077	139.212	345.8652
81	491.141	140.952	350.1885
82	497.204	142.693	354.5118
83	503.268	144.433	358.8351
84	509.331	146.173	363.1585

The strain spectrum is between 50 to 500 microstrain. The length 82 mm represents the maximum range, which is 354. This will not exceed the ideal limits. 75 mm beam length is chosen.

Vishay Measurements Group, Inc [1] provides the adhesion guidelines, using M-Bond 200 adhesive, to attach the strain gauge to the beam element.

It is necessary that degreasing with a solvent degreaser for preparation. This step ensures that there will be not contaminations. Then, abrade the surface until it is shiny. While the surface has a thick coating of M-Prep conditioner, the above procedures are performed, afterwards, the material should be carefully wiped clean.

Host material need to be engraved with layout lines, in order to prepare for the strain gage. The layout lines function to make sure there is not misalignment due to any human error. The work area was scrubbed after the layout lines, and these steps need to be continued until the applicators are clean. In order to ensure best alkalinity, the neutralizer is also applied. Before next step, the surface is dried and cleaned.

When handling the load cell, tweezers are always used. For ease of application, single-sided tape is used to attach the gage. Spare the bonding catalyst to the surface, because excess catalyst is essential to the correctness of the process.

Between 3-5 seconds, adhesive is added to the surface, and wiped the strain gage using gauze. Pressure was applied for longer than 1 minute, and the single-sided tape was removed after 2 minutes.

The coating which is mentioned in [1] is used after the curing of gage, and this step make sure the gage is soldered to the interface.

Electrical tape is used for surrounding the soldered connections, and is also applied around the gage for safeguard.

2.2. Wheatstone Bridge Theory and Procedure

In Fig. 2, the Wheatstone Bridge is utilized to precisely measure the change over the resister; this method outputs more accurate voltages compared with other methods. The design of the strain gage follows the procedures which are from Applying the Wheatstone Bridge Circuit by Hottinger Baldwin Messtechnik [7][8]. The strain gage used in this paper is where R_1 is in Fig. 2. The strain changes when the beam is bended, and provides a change in the resistance in the strain gage, and the values detected can be used to calculate the actual deformation of the beam, which will further be used to determine the air flow forces.

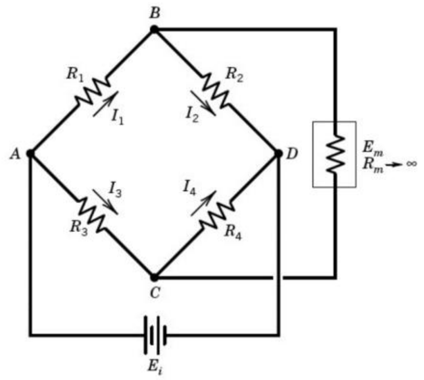

Figure 2. Wheatstone bridge circuitry.

R1 is calculated by (5).

$$R_1 / R_2 = R_3 / R_4 \tag{5}$$

For the bridge, to assure that (5) is valid, resistance is “changed” by adding a potentiometer in series or in parallel.

The voltage difference at both nodes A and B is calculated as (6)

$$V_A - V_B = E_{in} \quad \Delta R / 4R \tag{6}$$

The known parameters are 5 V for Ein, and the resistance of R where all resistors have the same value. The left part of (6) is measured, and the only variable left the change of resistance, which can be solve. After knowing the change of resistance, the stress experienced on the beam can be solved by applying (7). Here, R_nominal is measured before the deformation, it represents the unstressed strain gage resistance. R_x=ΔR, GF represents gage factor, σ represents stress, and E represents elastic modulus.

$$R_x = R_{nominal} + (\sigma \cdot GF \cdot R_{nominal}) / E \tag{7}$$

Equation (8) shows the bending equations that can be used to calculate stress. M represents bending moment; c represents the distance between the neutral axis to the strain gage; and I represents the second moment of area.

$$\sigma = Mc / I \tag{8}$$

I and c are both constant values of the beam, and the moment can be determined by the detentions of the beam. This will allow breath force at the end of the beam been determined.

The circuit is built on a breadboard. For the Wheatstone bridge, the nominal resistance of the strain gage and the three other resistors are 120 Ω. The actual resistance of each resistor is measured by a multimeter and recorded. A variable resistor is put in parallel with the resistor, its resistance is highest to balance the bridge.

Then the circuit is constructed and connected to a 5 V power source. In order to testing the bridge, the beam is deflected and the voltage error between nodes A and B is measured.

2.3. Active Low Pass Filter Theory and Procedure

Then the circuit is constructed and connected to a 5 V power source. In order to testing the bridge, the beam is deflected and the voltage error between nodes A and B is measured.

From Texas Instruments [10], the design of the active low pass filter follows the application rept. To avoid aliasing and measure data that are below the Nyquist frequency and, an active low-pass filter is utilized. The used sampling frequency is 1000 Hz; hence the f_NYQ is 500 Hz by (11).

$$f\_NYQ = f\_sampling / 2 \tag{9}$$

To accurately negate aliasing, the signal reduction is set to be bigger than 20. The tested signal decays 20 dB for every 10 unit. This indicates that 10 unit before the Nyquist frequency is when the cut-off frequency is. The cut-off is set to be less than or equal to 50 Hz.

With this cut-off frequency, (12) is followed to create a filter.

$$f\_c=1/(2\pi R\_8\ C) \tag{10}$$

For consideration of the op-amp gain, by using (10), it can be calculated.

To filter the op-amp, a gain of 1 is chosen to make the gain of the system be able to handled.

The circuit voltage will be changed by a force that creates deformation of the bean, which means strain is created. The system is calibrated before actual usage to get the relationship of the applied force to the voltage output. By using known masses to create force on the end of the beam, this can be done well; it will allow the users to create a mathematical relation between strain and output voltage. From a graph of the voltage output versus applied force, the equation can be found, as shown in Fig. 3. The slope of the plot will be the sensor's static sensitivity, meanwhile, the y-intercept will be the offset voltage of the sensor.

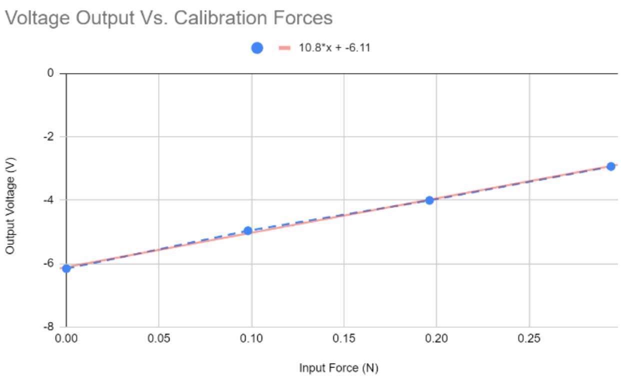

Figure 3. A sample calibration curve, created from the theoretical data.

Between voltage and force, with a known relationship, every data point from MATLAB can be transformed to a force. And then, volume flow rate can be calculated. And actual volume from each breath can be approximated by multiplying the time step.

The anticipated sampling frequency is 1000 Hz. This intends the Nyquist frequency is 500 Hz, and the cut-off should be slightly lower than 50 Hz. In the lab given the availability of capacitors, we choose to use a .33 microfarad capacitor; then by rearranging (12), the resistance required can be found to solve for R8, and the value is 965 ohms.

A 1 kΩ resistor is then selected, as the calculated R_8 serves as a lower limit. This led to an expected cutoff of 44.90 Hz, and using (12) again.

The desired gain is 1, therefore, resistors 7 and 8 should have the identical nominal value. Factually, they are different, so the theoretical gain of the filtering op-amp is 1.01 from (10).

The active low-pass filter needed a test. The goal is to find the filter's gain. This is accomplished that by using the function generator to create a voltage difference between ground and the input to the filter. The circuit is connected to a multimeter to measure the output voltage. So, the absolute gain is the quotient of the output and input voltage.

Then, the function generator is removed from the circuit, the strain gage is placed into the Wheatstone Bridge, and the low-pass filter is connected to the rest of the circuit. After the entire circuit and strain gage needed to be tested to show that they operated, any attempts at calibration could occur. The beam is held down on the desk with a finger, involving the part with the strain gage, is allowed to hang off the desk. And the free end of the beam is replaced by using a finger. After the basic test, the setup is calibrated using known masses instead of the finger to deflect the beam under gravity. Large number of 10, 20 and 30 grams are used.

Once the beam is calibrated, it is nicely attached to the L-bracket using screws. A 1.71 L pump is well attached to the end of the pipe opposite the beam. The trial is formed from air being pumped through the tube to come a breath. The datum is well acquired using the DAQ and saved as two vectors. One vector is time, the other is voltage. In these datum, volume and force can be calculated, as explained in the theory section above.

3. Results

The voltage vs. time graph shown in Figure 4 represents five breath trials from data points from MATLAB, each data point represents the reading of voltage at each millisecond. Different colors indicate the five different trials. The testing trials are conducted using bicycle pumps.

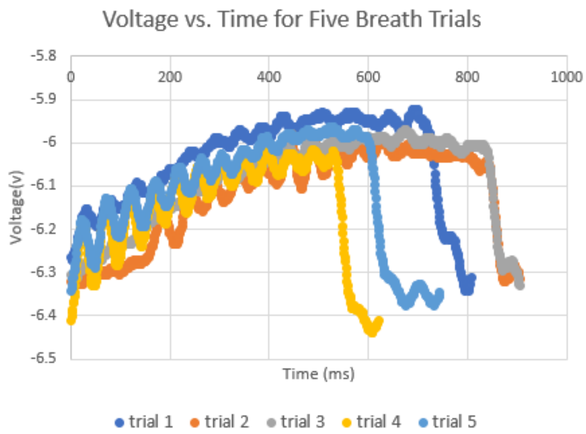

Figure 4. Time vs. voltage for five breath trials.

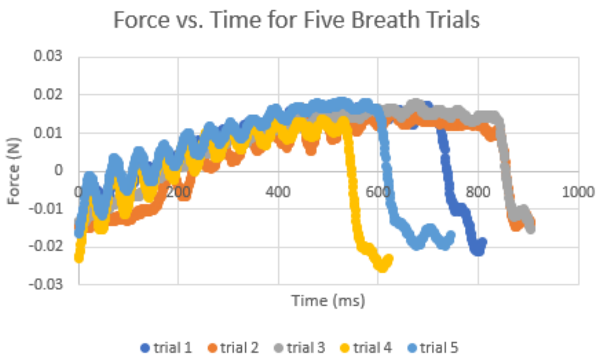

Figure 5. Time vs. forces for five breath trials.

Using excel spreadsheet, the voltage values from MATLAB in Figure 4 can be processed to the actual forces experience at each millisecond. These forces are calculated using the above equations of the relation of voltages and their corresponding gains to solve for the created strains experienced by the strain gage at the end of the beam. The forces and voltages plots have similar shapes. There are forces under zero, which will be neglected because there will be not negative forces, this might be caused by the calibration part of the device. The total volume of each trial can be calculated by adding up all volume flows at each millisecond, and the results are shown in Table 3.

Table 3. Calculated Total Volume Using Area Under Curve of Five Trials

Trials	Total Volume (L)
1	1.067463
2	1.06053932
3	1.223012996
4	0.590606768
5	0.897901

Table 4. Peak & Average Forces of Five Trials and Their Means

Trials	Peak Force (N)	Average Force (N)
1	0.017286	0.006619
2	0.016985	0.003985
3	0.017929	0.006842
4	0.0136833	0.001158
5	0.018401	0.008465
Mean	0.016857	0.005414

The 9% error between the actual voltage and the theoretical data under a 10-gram load is maybe due to the small-time duration of the testing. Looking back to the calibration trials data using known weights, the voltages show a steady decreasing trend in the time period for the 10-gram weight, and the error is between 6%. For larger weights of 20 and 30 grams, the error in the regions is from negative 1 to 1.5%. This calibration results indicates that although there are small errors using known weights, the circuit itself is perfectly designed and constructed. The remaining part where it may enlarge the error is the differential amplifier and filter. When testing these parts, the observed actual gain is a bit less than the designed gain. This explains the error in the voltage being smaller than expected value. Therefore, it is concluded that the error comes from the circuit part of the device.

The pump used for testing has a volume of 1.71 litters, but the test results from Table 3 shows only 57% of the designed volume of the pump. The best tests give a volume reaches 72%. This small percentage indicates the functionality of the device is valid, because it is not reading any number greater than the testing volume. However, only partial volume is detected here might be caused by human error because the air pumped into one end of the tube is not fully transmitted. The pump tested only has 1.71 litters whereas average human breath could have 5 to 7 liters, and this device is designed for human usage. However, further tests of human breath could not be conducted because the uncertainty of each human breath will result more human error as no one can control the same volume of each breath. From Figure 4 and 5, the average time of the exhaling pump only continues for 0.7952 seconds, this is relative too short for a normal healthy human breath. The measure force on the strain gage is less than the expected force of 0.0157 N. This is due to the quadratic relationship between force and volume. From the above conclusion, the actual volume pumped into the tube is smaller than the design capacity. Therefore, this indicates the forces measured is going to be less than the expected forces, and the error would be even larger due to the calculation steps.

Fourth trial only outputs 35% of the pump volume, the trials matched up well with other results, and showing that it seems that the device works. The uncertainty of 17% of pump volume to 95% confidence displays that there is a good deal of repeatability to the system, however, it might be improved. It is commonly believed that much of the fluctuation in volume between trials is down to the way the pump is operated in time of the test being somewhat inaccurate.

In conclusion, the system designed and constructed does a fair job measuring volume and force of breath. It could be improved as the testing method does not fully mimic actual human breath. Further testing of the device could be conducted when a better testing method is found. Another point worth mentioning is that the way the end beam captures the breath from the tube. The beam covers the PVC tube's one end, however, when air flow through and the beam starts to deflect, the deformation of the beam will open gap between the beam and the PVC tube, and air would escape from this gap resulting less air being captured. One possible solution is to make the end beam a large size which could capture more air flow. Further tests could also include using more beam materials and test to see which material could capture the breath to most entirety. This device is in a reasonable size for home usages, but could also be redesigned in a smaller size for easier usage. The concept of this design is sound, and could be an acceptable prototype for future refinements.

In the Clementine software, for the user's electricity consumption, the large data prediction model is implemented.

4. Conclusions

For measuring volume and force of a breath, the system is effective.

With these fine-tuning and some findings, it is legitimate that a compacted version of this device, much cheaper alternative to commercial spirometers, which could be used in any third country for cheaper diagnoses. This would enable cheaper detection of the functionality of people's lung capacities, and a fair estimation whether they are infected by a respiratory disease like SARS-CoV-2.

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