DEVELOPMENT OF A DIGITAL FREQUENCY METER FOR SIGNAL ANALYSIS ON A RESPIRATORY PHYSIOTHERAPY EQUIPMENT

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Abstract— This work presents preliminary results of a digital frequency meter that has been designed to measure the frequency of oscillatory vibrations in respiratory physiotherapy devices. Maintain a frequency around 13Hz is important to keep an efficient treatment. Therefore, the proposed circuits and systems are intended to give a visual feedback to the patient with a suggestion of the optimal blow strength. A Linear Hall-Effect Sensor was coupled to the physiotherapy device and the output signal is conditioned through a set of filters. The Fast Fourier Transform of the conditioned signal is used in order to extract frequency domain information to be displayed in real-time to patients.

Keywords— FFT, Filter, HFOO, Linear Hall-Effect Sensor, Physical Therapy Modalities.

Resumo— Este artigo apresenta os resultados preliminares do projeto de um frequencímetro digital que foi modelado para detectar as vibrações oscilatórias de um equipamente de fisioterapia respiratória. Portanto, os circuitos e sistemas propostos possuem o intuito de fornecer *feedback* visual para o paciente, assim como aconselhamento em relação à força desejada do sopro. Um Sensor de Efeito Hall Linear foi acoplado a um equipamento fisioterapêutico, e o sinal de saída é condicionado através de um conjunto de filtros. A Transformada Rápida de Fourier desse sinal é, então, usada para extrair informações no domínio da frequência para serem apresentadas, em tempo real, para os pacientes.

Palavras-chave— Filtro, OOAF, Sensor de Efeito Hall Linear, Técnicas de Fisioterapia Respiratória, TRF.

1 Introduction

Respiratory physiotherapy is commonly referred as one of the fields of study of Physiotherapy, focusing in the treatment of chronic and acute dysfunctions from the cardiopulmonary system. It covers many techniques to help patients improve respiratory capacity, with one in particular being the use of High Frequency Oral Oscillators (HFOO), that, combined with Positive expiatory pressure (PEP), an application of resistance when the patient expires, are a efficient methods for the treatment of respiratory illnesses. The Acapella is an equipment development for the DHD Healthcare, in Wampsville, New York, which has three main models: a blue-colored one for patients that cannot maintain a expiratory fluxes superior to 15L/min during 3 minutes; green-colored one, for patients that can maintain a flux superior to 15L/min at least 3 minutes and autoclaveable, for all patients (Mueller et al., 2013; Silveira et al., 2017).

The other appliances used for the same purpose, like the Flutter VRP1 and the Shaker, use a metallic sphere to apply gravitational resistance, so the sphere can transition from its initial position to an higher one, dependent of the air flow applied by the patient. For this purpose, the patient needs to maintain the instrument in parallel with the floor, requiring the patient to remain seated during the treatment. Unlike the previous equipments mentioned, the Acapella utilizes a magnet that has been attached to its base. When the air flow through the equipment begins, a rod inside the equipment starts to move back and forth according to it, with one of its extremities, which has a small, metallic cylinder fixed in it, rising up. This same edge is, then, pulled down by the magnet, returning the rod to its initial point, thus creating an oscillation. Because of this functionality, the Acapella can be used in any position, enabling patients that cannot stay seated during the treatment to receive it. Other advantage of the Acapella is that it is possible to adjust the frequency oscillation and the resistance of expiratory flux through a mechanism on the back of the instrument, which can change the magnet's height in relation to the base (dos Santos et al., 2013).

In physiotherapy, one of the many adversities faced by its professionals is the productivity of the devices used for treatments. Due to the mechanical nature of some of these equipments used are, commonly, purely mechanical, most physiotherapists have trouble in detecting if the therapy is being efficiently applied to its patients. Some of the most noticeable examples of this situation are the applications of HFOO's in respiratory physiotherapy: due to the lack of displayable feedback from the equipment to both the patient and the professional, the physiotherapist might not consider that the HFOO isn't oscillating in it's desirable frequency and that the therapy might have been compromised. Based on the biomedical instrumentation works by (Maes et al., 2014), which utilizes linear feedback control techniques alongside hardware and software implementation via microcontrollers to obtain respiratory impedance at low frequencies; (Ionescu and De Keyser, 2009), which analyzes changes in respiratory mechanics from non-chronically and chronically ill patients through signal analysis and processing; (Pimmel et al., 1977), which utilized loudspeakers in order to simulate pressure oscillations and a special sensory unit to measure magnitude and phase angles of the pressures and the flow signals, in order to provide a modification of a respiratory treatment technique; and (de Melo and de Andrade Lemes, 2002), which proposed the development of a software fully dedicated to identify impedance on the respiratory system during sleep, as well as to evaluate its performance in different types of conditions, this paper presents the modeling of a frequency meter for the purpose of capturing information of the frequency in which the patient is blowing inside the equipment, and digitally display it to it, whose feedback and adjustment of the air flow to match said periodicity value will enable the professional to apply the adequate medical care.

The paper is divided as it follows: the HFOO's operation mechanism and purpose on respiratory physiotherapy are discussed in section 2. In section 3, a filtering project to condition the electric signal to be converted through an A/D Converter, as well to be transformed into a frequency-domain function, is detailed. Section 4 presents the simulation results and compares them to the ones obtained through experimentation. Section 5 concludes the work.

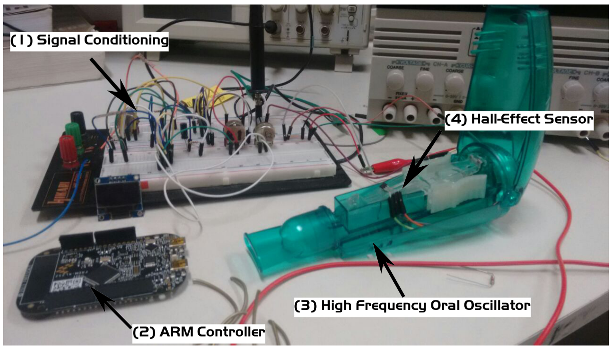

Figure 1: Experimental Setup

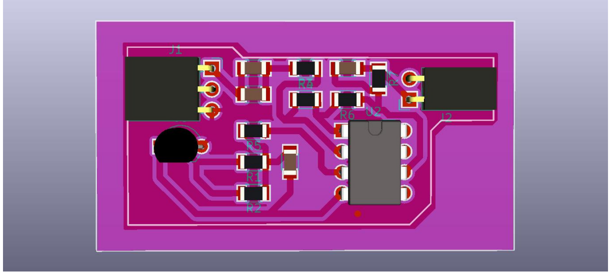

Figure 2: Layout of the Signal Conditioning's Circuit

2 Operation Analysis of the HFOO

The operation principle of Acapella is based in High Frequency Oscillation (HFO) generated by the vibration of an inner rod according to the flow of air expelled by the patient. The HFOO technique combines a oral airway frequency, generate by the instruments like the Acapella, and a Positive Expiratory Pressure (PEP) which is an application of a resistance in the expiratory phase in order to maintain positive pressure in the airway. One of the Acapella's ends has an internally magnet that causes a counterbalance so that the rod return to its initial position when the patient expelled and thus causes vibration, as it is shown in Figure 1. Carrying out experiments found that this configuration limits the range of frequencies it can obtain from 0 to, approximately, 50 Hz. The desired frequency of operation is a value between 11 and 15 Hz, as it is the natural frequency of the pulmonary alveolus. The treatment using a HFO technique is useful because the mucus, present in the lung, is sensible to high speed, causing a reduction in viscosity mucus, which makes easier to expel through the cough. Figure 2 presents, in *3D* simulation, a PCB layout for the signal conditioning circuit, while in Figure 3, a general idea on how the conditioning system works in general, beginning with the voltage generation inside the equipment up to the digital displaying of the desired frequency values to the patient.

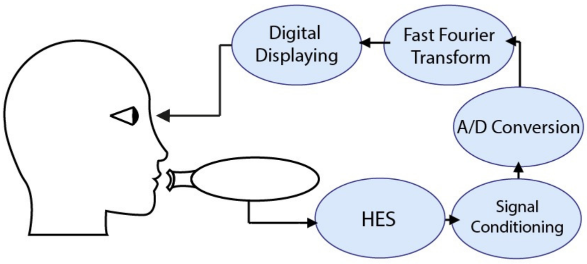

Figure 3: Diagram of the system's phases

2.1 Signal Quantification and Device's Operation Frequency

In order to quantify the frequency generated from the air stream through the oscillatory piece, it has been opted to analyze it using Hall-Effect, as its reading routine is closer to the real value of the frequency, since the variation of a magnet field is barely interfered by external factors like sound and mechanical shocks, as opposed of other sensory techniques. For that purpose, a lightweight small magnet has been attached to the internal rod, in a position that it's weight addition won't compromise the oscillation.The equipment that's been used for this project it's a SS49E Linear Hall-Effect Sensor.

2.2 Magnet's Purpose on the System

With the magnet positioned, stipulations led to the choosing of a Linear Hall-Effect over a Digital Hall-Effect Sensor as the latter, due to the discretization of the wave form, would result in the loss of information a Linear Hall-Effect Sensor was, then, connected upwards the magnet. This system gives an accurate frequency reading of the equipment: while the equipment generates an oscillatory vibration through air blows from the patient, the magnet oscillates in the same frequency, with the sensor capturing the changes of the magnetic field in real-time and translating its information in an electric signal of the same frequency. The final goal of this project is to acquire frequency-domain information and to convert this information into a digital value through an A/D Converter, which is something it can not be obtained with the current time-domain signal.

2.3 Fast Fourier Transform

The Fourier Transform (FT) is a mathematical transformation which maps time domains signals to frequency domains signals using the equation

$$F(w) = \int_{-\infty}^{\infty} f(t)e^{-j\omega t}dt \tag{1}$$

for continuous time signals and

$$X_k = \sum_{n=0}^{N-1} x_n e^{\frac{-j2\pi}{N}kn} \tag{2}$$

for discrete time signals.

FT is useful for extracting frequency related information such as sine harmonics and natural oscillation frequency of a signal. The output data from a FT is a series of impulse-shape curves which peaks at one harmonic or fundamental frequencies. As this work consists in examining a periodic signal generated from the human breath, it is crucial to quantify frequency information from the input signal.

It is known that the calculation of a Discrete FT (DFT) of a N long time signal has a computational complexity of $O(N^2)$. This may cause extremely long and unwanted computational time for long input data sets. This is specially critical for embedded systems that have limited memory and CPU clock resources. A well known alternative for computing the DFT is the Fast Fourier Transform (FFT) algorithm. The FFT algorithm uses a divide-and-conquer approach to decompose the input signal data and process the data separately while exploiting symmetric properties of the DFT. This method reduced the complexity to $O(NlogN)$.

The FFT algorithm can be implemented in embedded systems environments and are widely used in many other applications. In (Han et al., 2000), a fixed-point FFT algorithm is implemented to adjust its precision and execution time according to the design of an embedded digital signal processing (EDSP).

3 Electronic Circuit

This section presents the conditioning circuits aimed to adapt the sensor signal to the A/D conversion. The electrical signal generated has the form of an oscillatory wave with amplitude in the range of 200-500 mV and variable frequency from 0 up to, approximately, 50 Hz, that oscillates around a DC offset of 2.5 V, which is the quiescent output voltage of the sensor. This offset is unwanted, as the signal needs to be conditioned to another reference voltage, due to the 3.3-0 V range of the A/D Converter. Thus, an active filter circuit must be implemented.

3.1 Active Filters and Electronic Circuits

The first design for the active filter circuit, as it is shown in Figure 4, involves a combination of a high-pass filter, a summing amplifier and a low-pass filter, respectively, supplied by a symmetrical source of 5 V.

The oscillatory signal passes through the high-pass filter to eliminate the DC offset and center the sinusoidal around the zero reference; additionally, the inverting amplifier of the filter applies an voltage gain of 5 V/V, obtained through the formula $Gain = -(\frac{R2}{R1}$, where $R2 = 30K\Omega$ and $R1 = 6K\Omega$. For a more accurate analysis of the frequency, it has been established an operation range from 10 up to 30 Hz. To obtain the cutoff frequency of this high-pass filter, from which the frequencies below this value will be attenuated, the following equation is used to obtain it in regards to the capacitance and the input impedance (Sedra and Smith, 2004):

$$Fc = \frac{1}{C \cdot 2 \cdot \pi \cdot R1}, \tag{3}$$

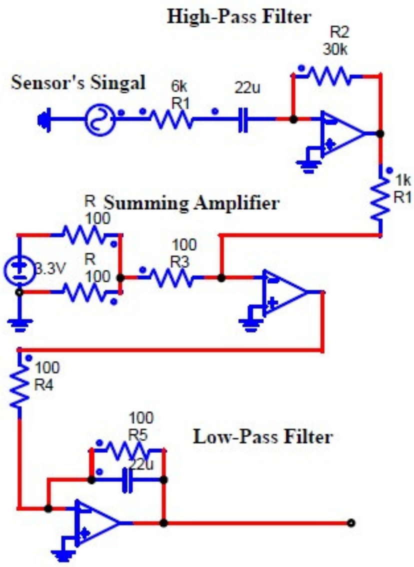

Figure 4: First Circuit's Schematic.

where Fc is the cutoff frequency. For more precise magnitude readings, the cutoff frequency is established to be a decade below the value desired. With a frenquency value of 1 Hz, the coupling capacitor used in the filter must have a capacitance of $26\mu F$, with the closest commercial value used being $22\mu F$. R1 is connected in series with the $26\mu F$ capacitor, while R2 is connected between the inverting input and the output, resulting in the formation of a negative feedback in the circuit. The signal, then, passes through a summing amplifier, which will be used to generate a new offset for the signal. For that, a reference voltage module of $2.5V$ has been connected through a voltage-divisor with equivalent resistances, resulting in an, approximately, $1.25V$ DC offset that will be applied in the non-inverting input of the op amp. Finally, the signal crosses a low-pass filter to attenuate noise remaining in the system. In addition, in order to avoid aliasing effect, this filter was set with a 50Hz cutoff frequency to limit the signal bandwidth. This is possible through an equation similar to Equation (3), however, utilizing resistors $R4 = R5 = 100\Omega$:

$$Fc = \frac{1}{C \cdot 2 \cdot \pi \cdot R5}, \tag{4}$$

resulting in a capacitance of $32\mu F$, with the closest commercial value used being $22\mu F$. Since the resistance values utilized are absolutely equal, the inverting amplifier is operating as a unity follower. Thus, the signal's conditioning method is complete and the signal itself is ready for conversion. A more profound analysis of the signal is presented in Section 4.

3.2 Portability and Simplicity

To allow room for a portable version of the circuit, the symmetrical source will be replaced by a battery, resulting in the grounding of the negative supply of the op amps. Because of that, a Virtual Ground has been set: by setting up a voltage-divider reference in the non-inverting input of the amplifiers (Baker, 2000; Carter, 2000) , not only the supply problem has been solved, as a ground reference has been enabled in the negative supply input, but it also eliminated the need of a summing amplifier, since the voltage applied to the input resulted in a new offset for the oscillation.

Thus, the second and current filtering circuit, shown in Figure 5, is composed by the connection in series of the High-Pass and the Low-Pass Filters, respectably, resulting in almost all of the same characteristics of the output signal from the previous circuit.

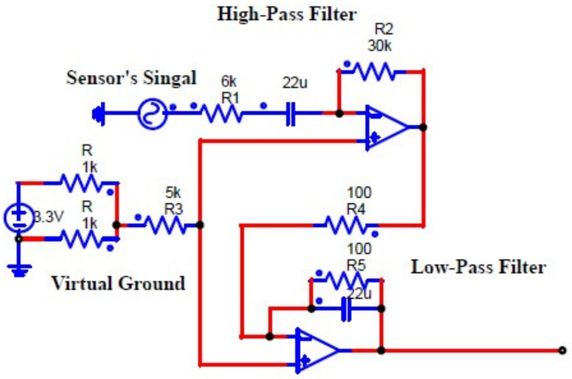

Figure 5: Second Circuit's Schematic.

By utilizing the principles of the previous circuit modeled for the project, it became possible to design the system composed by the HFFO and the Active Filters to be more portable, simple and practical: the sensor's supply pins will be directly connected to the 5 V and GND pins from NXP's FRDM KL25Z development platform (that will be discussed in Section 3.3), while the sensor's output will be linked into a printed circuit board composed of SMT components and a programmable gain amplifier (PGA), which allows for gain variations according to the necessity of the signal conversion.

This system configuration presents more favorable conditions for the modeling of the filtering circuit, since PGA's rail-to-rail structure utilizes the maximum of voltage supplied to its terminals, which prevents heavy losses of energy and provides support for low voltage supplies, consequently, allowing for single-supply operations, besides presenting high optimization speeds; and SMT components small stature optimizes the board's space and processing speed, permitting smaller circuits to be modeled and simplifying the portability.

This system will later be ported to a custom PCB coupled by the side of the HFOO, alongside the FRDM KL25Z development board, which will serve as an energy supply, and a digital display from where the output information will be shown to the patient.

3.3 Micro-Controller

The micro-controller chosen for the project has been NXP's Kinetis from the KL25 sub series. This micro-controller is inserted into a FRDM-KL25Z board, an ARM Cortex based development platform, usually featured in embedded systems, automation and robotics-applied control projects, due to its high-level processing speeds, easy-to-access I/O peripherals and massive flash memory's device, among other features. The board works as a connection of the micro-controller with external peripherals, additional development features, power supply, among other peripherals. One of the many features of this board is a 16 bits A/D converter, which has an input voltage in the range of 0 to $3.3V$.

4 Signal Analysis and Results

As it was mentioned in Section 3, the electric signal generated by the HFFO is a composition of two voltage components: an AC sinusoidal wave, with frequency varying from 0 up to 50 Hz; and a DC offset originally from the quiescent output voltage of the sensor. The analysis of the signal in simulation in comparison to the one obtained through experimentation becomes necessary to validate the project.

4.1 Simulation's Results

This subsection focus on presenting the results obtained through circuits and signal simulation. Theses results are shown in Figures 4 to 8.

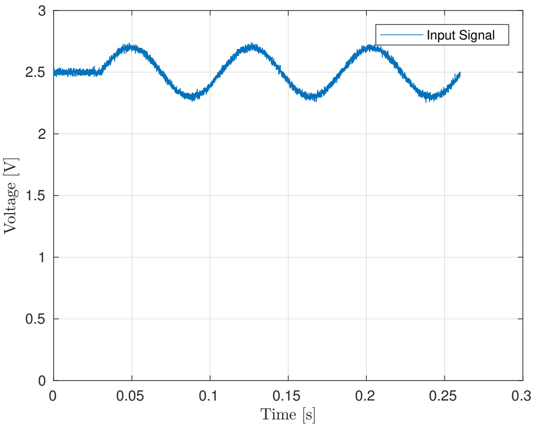

Figure 6: Input Signal from the Hall-Effect Sensor

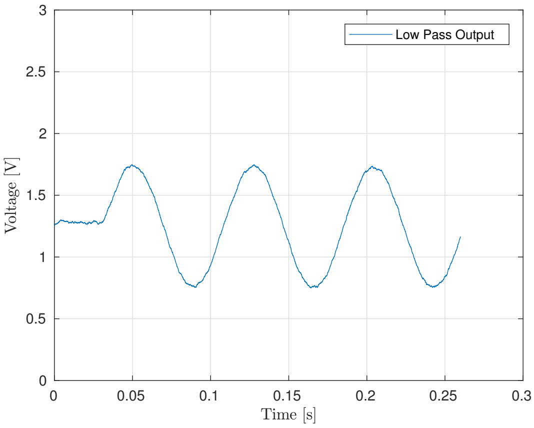

Figure 7: Conditioned signal: Post Low-Pass Signal

In Figure 6, the signal presented is the one directly sent through the sensor's output. This signal has an amplitude of, approximately, $500mV$, around an offset of $2.5V$, which is the quiescent output voltage of the sensor. The signal also contains signs of high-frequency noise, due to the raw capitation of the sensor.

In order to remove the offset the signal is processed through the high-pass filter. Then, after that the filtered signal oscillates around an desirable $1.5V$ reference voltage. The amplitude has also been amplified in a gain of 5, previously discussed in section 3, which resulted in a new range with amplitude of, approximately, 500 mV, as it was expected. This gain of amplitude has been applied to the noise interference as well. The signal lags in 180° due to the inverting configuration of the op amp.

Figure 7 presents the final signal, right after it had passed through the Low-Pass Filter to attenuate the noise. The wave form lags again in 180° and the amplitude remains the same due to the unitary gain. Note that the conditioned signal theoretically should has an offset value of 1.65 V, however the practical obtained value is 1.25 V. This difference is possibly generated due to impedance mismatching or uncertainty on the components values, but it does not represent a problem because even with this difference, the processed signal does not reach the saturation limits of the AD converter.

4.2 Experimental Results

This subsection focus on presenting the results obtained through circuits and signal practical experimentation.

In Figure 8, the raw signal from the sensor has an amplitude of, approximately, $100mV$, as expected, as well an accurate $2.52V$ offset voltage.

Figure 9 presents the High-Pass filtered signal with an amplitude of $500mV$, still in the error

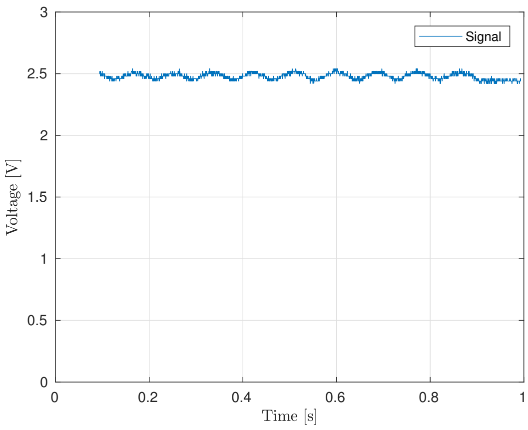

Figure 8: Input Signal

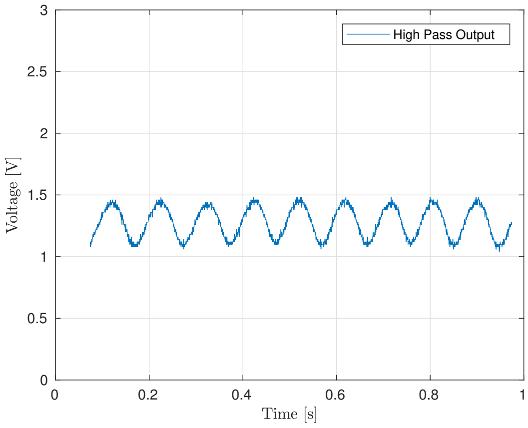

Figure 9: Post High-Pass Signal

range of the expected limit inferior $1V$, as well an offset of $1.25V$.

Figure 10 shows the post Low-Pass filter signal, with an amplitude between 400 and $500mV$ around an offset of $1.25V$. The resulting wave forms from the experiments are different from the simulated ones due to the measuring device's and the components own limitations. However, the ending results are sufficient for A/D conversion and signal analysis through FFT.

After passing through signal conditioning and A/D conversion, a FFT algorithm is then applied to transform the signal into a frequency-domain function. Figure 11 displays the FFT performed on five different patient blow strengths. The algorithm is used on the 128 samples obtained by the A/D converter connected the output of the High-Pass filter. The constructed circuit is able to detect frequencies from 10 Hz up to 25 Hz. Higher frequencies causes the signal to lose amplitude due to the limited amplifier gain, but such frequencies are not expected from normal use of the device. Table 1 displays the relation between the frequency and the amplitude of air blows, according to its strengths.

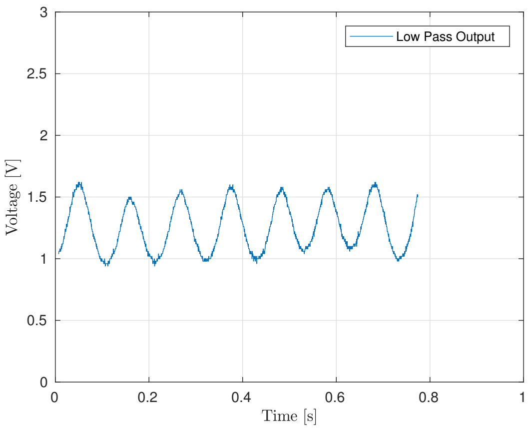

Figure 10: Post Low-Pass Signal

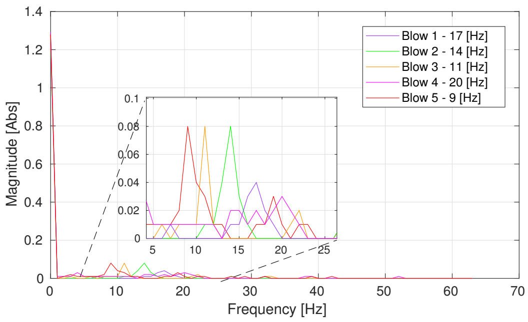

Figure 11: Fourier Transform of captured signals

5 Conclusions

This paper has shown the practicability of a digital frequency meter in aiding respiratory physiotherapy. The results obtained through experimentation in the prototype have successfully obtained accurate sensor readings displayed through software analysis. The use of analogical filter circuits has also presented successful results by presenting conditioned signals, free from static interference, with values of amplitude and offset voltage ideal to the A/D conversion and close to those of simulation. The project's team is working to successfully implement a digital display which will act as a guide for the patient by informing it which frequency is currently being obtained. Through an easy interpretation of the information via the use of color signals, this representation will inform if the patient is currently blowing the equipment in the desired frequency and if a stronger or weaker blow is needed to reach optimal frequency.

6 Acknowledgment

The authors acknowledge the support from CNPQ, CAPES, and FUNCAP, project grant number 88887.114030/2015-01.

Table 1: Relations

Blow's Strengths	Frequency (Hz)	Amplitude
Weak Blows	9 (Blow 5)	0.08
Medium Blows	11 (Blow 3)/14 (Blow 2)	0.08/0.08
Strong Blows	17 (Blow 1)/20 (Blow 3)	0.05/0.03

References

Baker, B. (2000). Using operational amplifiers for analog gain in embedded system design, *AN682, Microchip Technologies, Inc* .

Carter, B. (2000). A single-supply op-amp circuit collection, *Texas Instruments, Application Report SLOA058* .

de Melo, P. L. and de Andrade Lemes, L. N. (2002). Instrumentation for the analysis of respiratory system disorders during sleep: design and application, *Review of scientific instruments* **73**(11): 3926–3932.

dos Santos, A. P., Guimarães, R. C., de Carvalho, E. M. and Gastaldi, A. C. (2013). Mechanical behaviors of flutter vrp1, shaker, and acapella devices, *Respiratory care* **58**(2): 298–304.

Han, J., Ren, G. and Han, C. (2000). A novel fixed-point fft algorithm on embedded digital signal processing systems, *Signal Processing Proceedings, 2000. WCCC-ICSP 2000. 5th International Conference on*, Vol. 1, IEEE, pp. 48–53.

Ionescu, C. M. and De Keyser, R. (2009). Relations between fractional-order model parameters and lung pathology in chronic obstructive pulmonary disease, *IEEE Transactions on Biomedical Engineering* **56**(4): 978–987.

Maes, H., Vandersteen, G., Muehlebach, M. and Ionescu, C. (2014). A fan-based, low-frequent, forced oscillation technique apparatus, *IEEE Transactions on Instrumentation and Measurement* **63**(3): 603–611.

Mueller, G., Bersch-Porada, I., Koch-Borner, S., Raab, A. M., Jonker, M., Baumberger, M. and Michel, F. (2013). Laboratory evaluation of four different devices for secretion mobilisation: Acapella® choice, green and blue versus water bottle, *Respiratory care* pp. respcare–02654.

Pimmel, R. L., Sunderland, R. A., Robinson, D., Williams, H., Hamlin, R. and Bromberg, P. (1977). Instrumentation for measuring respiratory impedance by forced oscillations, *IEEE Transactions on Biomedical Engineering* (2): 89–93.

Sedra, A. S. and Smith, K. C. (2004). *Microelectronic Circuits*, fifth edn, Oxford University Press.

Silveira, A. C. T., Cunha, C. S., Pacheco, D. B. and de Azevedo Silva, N. M. (2017). Uso da oscilação oral de alta freqüência em pacientes ventilados mecanicamente, um estudo prospectivo e revisão de literatura the use of the oral high frequency oscillation in mechanically ventilated patients, a study prospective and literature revision, *Cadernos UniFOA* **2**(4): 104–110.