SOME FREQUENCY DOMAIN CONSIDERATIONS UPON HUMAN RESPIRATORY MECHANICS

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Abstract: The aim of this paper is to present a brief analysis of recent results considering human respiratory mechanics. The final purpose of the investigation is to provide a fast method for identification of airway mechanics, in order to assist the medical staff in obtaining a diagnosis of the patient within the context of performing routine evaluation of the respiratory function. Considerations are made with respect to the future potential of the method as a screening technique on a large number of populations.

Keywords: signal processing, spectral analysis, amplitude modulation, demodulation, filter design, respiratory mechanics, forced oscillations.

1. INTRODUCTION

For about a decade in the 90s, respiratory mechanics have been intensively studied (Pride, 1996; Van Noord, 1990) with successful results. A great deal of scientists is giving special attention to signal processing, but its potential in the field of respiratory mechanics is not fully explored. Moreover, it becomes more and more necessary to focus on investigation and routine evaluation of lung functions in today’s context of air pollution (European Centre Report, 2003). Research related to respiratory mechanics tends to provide information on the interaction between other systems and the respiratory system, especially the cardiovascular system, since it involves gas exchange and perfusion phenomena (Liu, *et al.*, 1998). Another recent trend is to obtain models of the normal human lung, for analysis under different stimuli, such as exercise (Liu, *et al.*, 1998; Mañanas, *et al.*, 2002).

One of the simplest and efficient non-invasive lung function tests is the Forced Oscillation Technique (FOT). The technique is mainly used in characterization of the respiratory function, assessment of bronchial challenge, mechanical ventilation and sleep studies (Van Noord, 1990; Navajas and Farré, 1999). A parametrization of the nonlinear lung mechanics (Ionescu and De Keyser, 2003) has also been obtained using the same FOT lung function test.

In this contribution, FOT is applied on a single subject followed by signal processing (Orfanidis, 1996) focused on frequency domain analysis. A FOT-phenomenon which occurs during breathing presents special interest and a brief description of the required signal processing is given in (Ionescu and De Keyser, 2004). Another assessed aspect is the low frequency range used in the analysis: 1–9Hz, close to the breathing frequency (≈ 0.3Hz), posing interesting challenges to the signal processing (i.e. filtering, correlation with the spontaneous breathing of the subject).
The paper is organized as follows: in the 2nd Section the used apparatus and the principle of forced

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oscillation are briefly described. Signal processing of the time-signals achieved from the patient is discussed in detail in the 3rd Section. A brief discussion of the results is made in Section 4, posing future considerations and a conclusion section summarizes the main outcome of the paper.

2. THE LUNG FUNCTION TEST: FORCED OSCILLATION TECHNIQUE

The forced oscillation technique (FOT) is a non-invasive method which is generally used to measure respiratory mechanics (Van Noord, 1990). FOT employs small-amplitude pressure oscillations superimposed on the normal breathing and therefore has the advantage over conventional lung function techniques (spirometry, body plethysmography) that it does not require the performance of respiratory manoeuvres.

The conventional FOT set-up is based on superimposing a low-amplitude pressure oscillation at the mouth while the patient is breathing spontaneously. It is illustrated in Figure 1, with the following notations: MC - microcomputer; LS - loudspeaker; BT - bias-tube; BF - bias-flow; PN - pneumotachograph; MP - mouth-piece; PT - pressure transducer; Q - flow and P - pressure. The oscillation pressure is generated by a loudspeaker connected to a chamber, driven by a power amplifier fed with the oscillating signal generated by a computer. The movement of the loudspeaker cone generates a pressure oscillation inside the chamber, which is applied to the patient's respiratory system by means of a tube connecting the loudspeaker chamber and the mouthpiece. As the patient breathes spontaneously through a bias tube - ideally presenting low impedance to the breathing frequency and high impedance to the forced oscillation frequency - a constant bias flow avoids re-breathing of used air. It is advisory that during the measurements, the patient should wear a nose clip and keep the cheeks firmly supported.

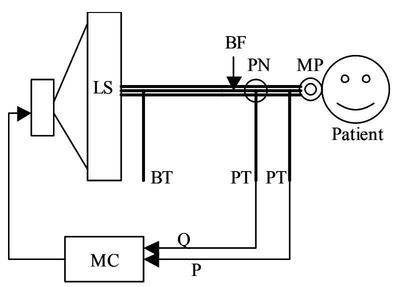

Fig.1. Conventional FOT setup.

Air-pressure and air-flow are measured at the mouthpiece, respectively by means of 1) a pressure transducer and 2) a pneumotachograph plus a differential pressure transducer. These signals are then analogically low-pass filtered, sampled and stored in a microcomputer. A detailed description with an attempt to standardization has been recently given in (Oostveen *et al.*, 2003).

3. SIGNAL PROCESSING

3.1. Measuring Data.

In a preliminary-faze experiment, a one-frequency sinusoid has been considered to be the excitation signal applied to the respiratory system. A healthy male patient in late 60s has been used to gather the respiratory pressure P(t) and flow Q(t).

The scope of the experiment lies within providing a 3, 5 and 7Hz sinusoid excitation signal to the patient (sampling frequency: 1000Hz), and obtaining the resulting respiratory air-pressure P(t) and air-flow Q(t). Signals for the experiment at 5Hz are depicted in Figure 2 below. The low frequency oscillation is the effect of the normal breathing and has to be considered as a disturbing effect ('noise'). It is straightforward to observe that the best signal-to-noise ratio is provided by the pressure measurement, and further on the signal to be analyzed and processed will thus be the trans-respiratory pressure P(t). Notice also that in Figure 2 six breathing cycles of approximately 4 seconds per cycle each, corresponding to a breathing frequency of about 0.24Hz, can be identified.

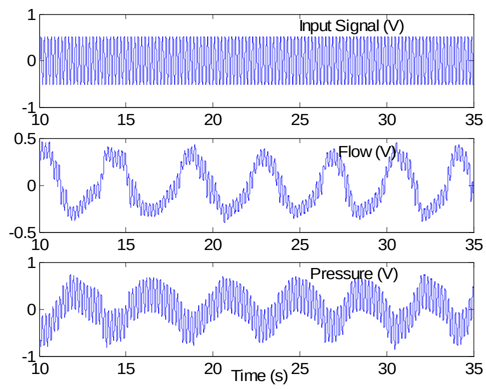

Fig.2. Input and Output Signals for 5Hz.

3.2. Filter Design.

The output signals P(t) and Q(t) are resulting from the effect of two components: the breathing signal, with a frequency around 0.24Hz, and the effect of the 5Hz test sinusoid sent from the FOT apparatus via the mouthpiece to the patient. Since the breathing and the input signals have frequencies which do not overlap (Fig. 5a) then it is possible to separate them with a 6th order low-pass Chebyshev filter, with the magnitude response characteristic depicted by Figure 3. After low-pass filtering, the breathing signal is obtained (Fig. 4b). Subtracting the breathing signal from the trans-respiratory pressure signal P(t), the signal in Figure 4a is obtained.

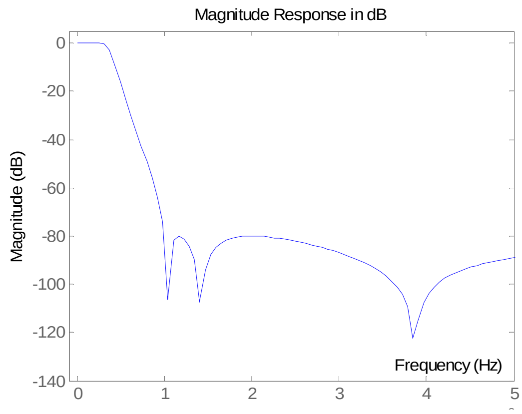

Fig.3. Chebyshev Lowpass filter characteristic.

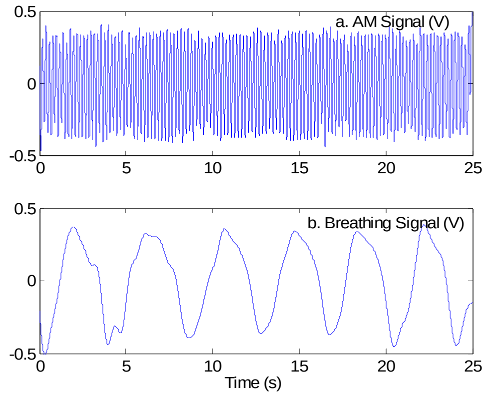

Fig.4. Time-signals after low-pass filtering.

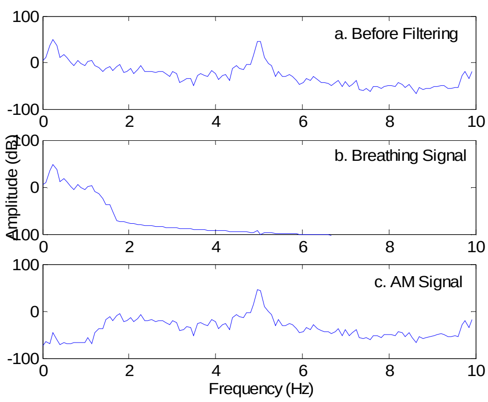

Fig.5. Spectrum for: *a.* the pressure signal P(t); *b.* the breathing signal; *c.* the remaining (AM) signal.

From the spectrum depicted in Figure 5, it is observed that harmonics of the input signal (5Hz) are introduced (10Hz). This is a property of nonlinear systems and therefore enhances assessment of the nonlinearity present in the human respiratory system. On the other hand, when separating the breathing signal from the pressure signal gathered from the subject, one would expect to remain with a sinusoidal signal of 5Hz (with different amplitude and eventually *k*-shifted in phase) similar to the *input signal* of 5Hz. The remaining signal (Fig. 4a) is indeed a 5Hz sinusoid, but it seems to be *amplitude modulated* (AM) with a signal highly correlated to the breathing frequency of the subject. Assuming that the modulating signal has the breathing frequency (ω_b) then the AM signal can be written in the form:

$$(1)\quad s_m(t) = (A + b\sin\omega_b t)\sin(\omega_{in} t + \alpha)$$

where:

- ✓ A is a positive constant (the DC component of the modulating signal);
- ✓ $\omega_{in} = 2\pi f_{in}$ with f_{in} the ‘carrier’ frequency, in this case 5Hz; and α its corresponding phase shift;
- ✓ $\omega_b = 2\pi f_b$ with f_b the breathing frequency, about 0.24Hz;

Denoting $s(t) = b\sin\omega_b t$ (a breathing-correlated signal), then we can observe from Figure 4 that $|s(t)| < A$ for all *t*, thus $[s(t) + A]$ never goes negative.

This modulation is related to existent nonlinearities in the respiratory system and poses particular interest for intersubject variability analysis.

3.3. Demodulation.

In Figure 5c it can be observed that the frequency component is not limited to the input signal frequency only (5Hz), but contains also harmonics (10Hz). Another observation is that it contains side-lobes around the 5Hz frequency and the 10Hz frequency. This is a further indication that the signal is amplitude modulated, and the respective peaks can be foreseen from (1) if trigonometric identities are applied:

$$(2)\quad s_m(t) = A\sin(\omega_{in} t + \alpha) + b\sin\omega_b t\sin(\omega_{in} t + \alpha)$$

and further processing leads to:

$$(3)\quad \begin{aligned} s_m(t) &= A\sin(\omega_{in} t + \alpha) + \\ &\frac{b}{2}\left[\cos\left((\omega_{in} - \omega_b)t + \alpha\right) - \cos\left((\omega_{in} + \omega_b)t + \alpha\right)\right] \end{aligned}$$

thus creating the side-lobes around 5Hz frequency.
One of the *classical* demodulation methods is multiplying (1) with a sine – or cosine – function at the carrier frequency (5Hz in this case):

$$(4)\quad s_m(t) = (A + b\sin\omega_b t)\sin(\omega_{in} t + \alpha)\cdot\sin(\omega_{in} t + \beta)$$

where α and β denotes the phase shift in the signal.

Introducing trigonometric identities, (4) becomes:

$$\sin(\omega_{in}t+\beta)\{A\sin(\omega_{in}t+\alpha)+ \frac{b}{2}\left[\cos\left((\omega_{in}-\omega_b)t+\alpha\right)-\cos\left((\omega_{in}+\omega_b)t+\alpha\right)\right]\} \quad (5)$$

and if brackets are omitted, then remains:

$$\begin{aligned}&A\sin(\omega_{in}t+\alpha)\sin(\omega_{in}t+\beta)+\\&+\frac{b}{2}\cos\left((\omega_{in}-\omega_b)t+\alpha\right)\sin(\omega_{in}t+\beta)-\\&-\frac{b}{2}\cos\left((\omega_{in}+\omega_b)t+\alpha\right)\sin(\omega_{in}t+\beta)\end{aligned} \quad (6)$$

Evoking trigonometric identities once again, (6) can be detailed to:

$$\begin{aligned}&\frac{A}{2}\cos\left((\omega_{in}-\omega_{in})t+\alpha-\beta\right)-\\&-\frac{A}{2}\cos\left((\omega_{in}+\omega_{in})t+\alpha+\beta\right)+\\&+\frac{b}{4}\sin\left((\omega_{in}+\omega_{in}-\omega_b)t+\alpha+\beta\right)-\\&-\frac{b}{4}\sin\left((\omega_{in}-\omega_{in}-\omega_b)t+\alpha-\beta\right)-\\&-\frac{b}{4}\sin\left((\omega_{in}+\omega_{in}+\omega_b)t+\alpha+\beta\right)+\\&+\frac{b}{4}\sin\left((\omega_{in}-\omega_{in}+\omega_b)t+\alpha-\beta\right)\end{aligned} \quad (7)$$

and if defining: $\alpha+\beta=\delta,\ \alpha-\beta=\gamma$ then (7) becomes:

$$\begin{aligned}&\frac{A}{2}\cos(\gamma)-\frac{A}{2}\cos\left(2\omega_{in}t+\delta\right)+\\&+\frac{b}{4}\sin\left((2\omega_{in}-\omega_b)t+\delta\right)-\frac{b}{4}\sin\left(-\omega_bt+\gamma\right)-\\&-\frac{b}{4}\sin\left((2\omega_{in}+\omega_b)t+\delta\right)+\frac{b}{4}\sin\left(\omega_bt+\gamma\right)\end{aligned} \quad (8)$$

Lowpass filtering leads to

$$\frac{A}{2}\cos\gamma+\frac{b}{4}\sin(\omega_bt+\gamma)-\frac{b}{4}\sin(-\omega_bt+\gamma), \quad (9)$$

which gives the modulating signal $(A+b\sin\omega_bt)$ only if $\gamma=0$. Thus the successful result is obtained only if the signals are not shifted in time. In practice, this condition is hard to achieve with this FOT application, and therefore another demodulation technique must be taken into account.
Another possibility is to investigate the effect of squaring the signal (Roden, 1991).

$$s_m^2(t)=\left[(A+b\sin\omega_bt)\sin(\omega_{in}t+\alpha)\right]^2 \quad (10)$$

$$=\left[A+b\sin\omega_bt\right]^2\sin^2(\omega_{in}t+\alpha) \quad (11)$$

$$=\left[A+b\sin\omega_bt\right]^2\frac{1-\cos(2\omega_{in}t+\varphi)}{2} \quad (12)$$

$$=\frac{\left[A+b\sin\omega_bt\right]^2}{2}-\frac{\left[A+b\sin\omega_bt\right]^2\cos(2\omega_{in}t+\varphi)}{2} \quad (13)$$

From (13) the signal $0.5\left[A+b\sin\omega_bt\right]^2$ can be extracted by low-pass filtering (6th order Butterworth filter) as frequencies do not overlap. Left-hand term contains the 0, ω_b and $2\omega_b$ frequencies, while the right-hand term contains the $2\omega_{in}$, $2\omega_{in}\pm\omega_b$ and $2\omega_{in}\pm2\omega_b$ frequencies.

It is possible to take the positive square root of the 1st term, obtained after LPF, in order to get $0.707\left|s(t)+A\right|$. Taking the magnitude |…| of a signal represents a severe form of distortion, but it was already stated that A is larger than the amplitude of *s(t)* so that $s(t)+A$ never goes negative. In that case, the magnitude $\left|s(t)+A\right|$ is equal to $s(t)+A$ and demodulation is accomplished. The results can be seen in Figure 6.

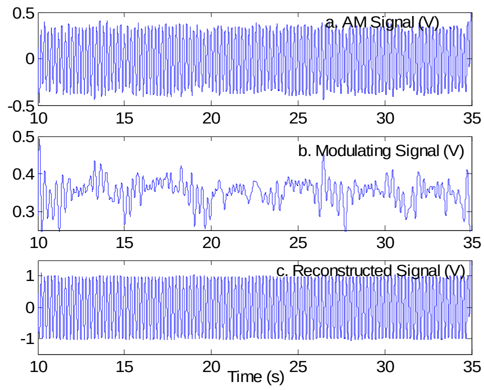

Fig.6. Time signals for: *a.* the amplitude modulated signal; *b.* the extracted modulating signal; *c.* the reconstructed signal

In Section *3.2* it has been stated that the modulation could be related to the breathing frequency of the subject. Figure 7 depicts the spectrum of the breathing signal decomposed in Figure 4b and the modulating signal from Figure 6b.

Denoting inspiration as P(t) < 0 and respectively expiration as P(t) > 0 then several max-/min- peaks are observed in the time-signal (compare Fig. 4b to Fig. 6b). The min-peak denotes the maximum pressure involved in expiration, respectively max-peak in inspiration. This could support the assumption that the 5Hz signal is AM by a signal highly correlated with the natural breathing signal of the subject.

However, a cross-correlation function is applied to the two signals and the result is depicted in Figure 8 below, leading straightforward to the conclusion that the correlation exists.

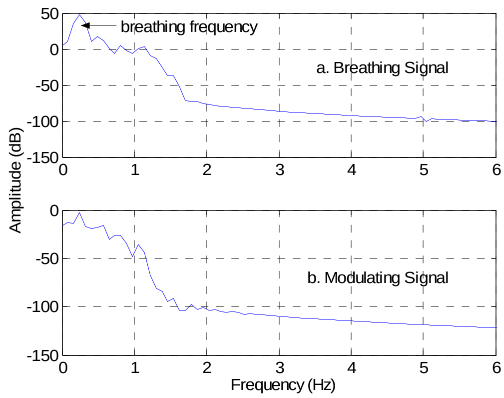

Fig.7. Spectrum for: *a.* the breathing signal; *b.* the modulating signal.

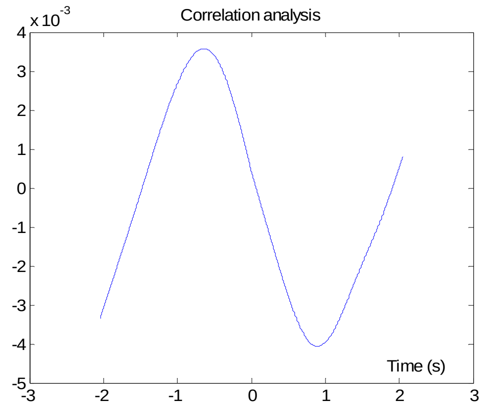

Fig.8. Correlation function between breathing signal and modulating signal.

4. DISCUSSION

There are several aspects worthwhile to be discussed in the regard of the frequency domain analysis. One of them, and perhaps the most important, is assessment of nonlinearity of respiratory system by use of forced oscillation technique. This is a novel application of the standard – well acknowledged noninvasive FOT. Another important detail is the amplitude modulation phenomena; also a characteristic of nonlinear systems.

Notice that the results presented here are based on an excitation signal (oscillatory pressure input) consisting of a single-frequency sinusoid at 5Hz. In Birch *et al.* (2001) a detailed description of results is given; results which are obtained by use of an analogue instrument using FOT and a 5Hz sinusoid oscillatory pressure. In a similar manner to the procedure in this paper, the very low (max. 0.5kPa) acoustic oscillations are imposed onto the spontaneous (and artificially-assisted) respiratory flow. The ratio of pressure to flow is used in real-time to provide a quantization of the absolute value of respiratory input impedance. The data proved to be sensitive to airway obstruction and capable of tracking mechanical events, providing useful parameters to the clinician.

In the context of the successful (but limited) results given in (Birch *et al.*, 2001), the further analysis and investigation given in this paper and the preliminary results from (Ionescu and De Keyser, 2004) could be the start of a new concept in analyzing respiratory mechanics.

The main idea is to enhance simplicity and reduce measurement variables (e.g. use only the pressure measurement) to obtain a fast but limited classification of subjects. The concept of limited classification stands in the fact that a diagnosis between different pathologies should not be the main purpose; instead, a preliminary diagnosis of healthy between pathologic cases should be provided.

In other words, a screening technique for early detection of respiratory dysfunctionalities is more appealing on a large number of populations. In nowadays context of increasing air pollution (European Center Report, 2003), this early detection becomes the key-action in prevention and early treatment of respiratory diseases. On a long-term basis, the result will consist of a diminished number of chronic pathologic cases (such as COPD – chronic obstructive disease).

However, the nonlinear effects of the human respiratory system in response to an excitation signal, i.e. introducing harmonics and amplitude modulation, are novel within respiratory mechanics investigation and present one of the main outcomes of this investigation.

FOT also presents the advantage that the frequency band may be modified depending on the patho-physiological aim of the measurement (Navajas and Farré, 1999). For instance, if the interest is focused on studying respiratory tissue properties, low frequency data would be more sensitive (since it is closer to the breathing frequency of the patient). It should be noted that measurements at 5Hz offer the considerable advantages of avoiding physiological artifacts present when studying respiratory mechanics at the fundamental respiration frequency (≈ 0.3Hz).

5. CONCLUSIONS

In this contribution, a preliminary investigation on respiratory mechanics has been described in the frequency domain. The experiments are based on the principles of the well-known Forced Oscillation Technique (FOT). The single sinusoid at 5Hz input signal offered the advantage of eliminating artifacts from the spontaneous breathing frequency of the subject. The application of a single-frequency sinusoid as a test input has also proved to be suitable for observation of novel, interesting phenomena. They provide new insights into the complexity of the human respiratory system and they are a strong basis to motivate further research and investigation.

FOT is - despite the relative simplicity considering its use by medical staff – a promising method to investigate respiratory mechanics, thus being suited for use in clinical medicine. However, it should be pointed out that FOT has so far not been standardized, although a recent attempt has been made in (Oostveen *et al.*, 2003).

A next step could be to optimize a *multi-sine* input signal, in order to provide a frequency domain analysis over a full test-range of (low) frequencies.

6. REFERENCES

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