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KCR PID AUTO-TUNER ALGORITHMAPPLIED TO AFOT DEVICE

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ABSTRACT

The aim of this study is to apply a PID auto-tuner to the FOT device and test whether the controller can follow a multisine reference input. The objective is that the nonlinear effects and distortions coming from the FOT device itself are corrected by the control action, such that the excitation signal of interest is delivered to the patient. In this phase, the closed loop control will be designed for a hypothetical patient: a respiratory tube and a rubber balloon. The underlying reason is because it is necessary to ensure repeatability of the experiments, in order to check the feasibility of implementing a closed loop control strategy in the lung function device. The final aim is to develop the closed loop control for the case when the patient is breathing.

Keywords: auto-tuning, closed loop control, frequency response, PID, respiratory impedance.

1. INTRODUCTION

Non-invasive lung function tests are broadly used for assessing respiratory mechanics (Northrop, 2002; Oostveen *et al.*, 2003). Contrary to the forced maneuvers from patient side and special training for the technical medical staff necessary in spirometry and in body plethysmography (Pellegrinno *et al.*, 2005; Miller *et al.*, 2005), the technique of superimposing air pressure oscillations is simple and requires minimal cooperation from the patient, during tidal breathing (Oostveen *et al.*, 2003). Among the air pressure oscillation techniques for lung function testing, the most popular one is the Forced Oscillation Technique (FOT). FOT uses a multisine signal to excite the respiratory mechanical properties over a wide range of frequencies, usually between 4-48Hz (Oostveen *et al.*, 2003).

Using measurements of air pressure and air flow, it is possible to extract information upon the human respiratory input impedance. However, this is a linear approximation of a nonlinear system; hence the output will depend on the input's amplitude and frequency (Schoukens & Pintelon, 2001). It is therefore important to ensure that the desired signal to be applied at the patient's mouth will be delivered by the lung function testing device, without introducing distortions and nonlinear effects. Hence, a closed loop control system is necessary, to continuously monitor and correct the errors between the desired input signal and the one delivered by the device at the patient's mouth.

PID controllers can incorporate auto-tuning capabilities (Åström & Hägglund, 1995). The auto-tuners are equipped with a mechanism capable of automatically computing a reasonable set of parameters when the regulator is connected to the process. Auto-tuning is a very desirable feature because it does not require a-priori identification of the system to be controlled. The auto-tuning features provide easy-to-use controller tuning and have proven to be well accepted among process engineers (Leva *et al.* 2002).

The aim of this study is to apply a PID auto-tuner to the FOT device and test whether the controller can follow a multisine reference input. The objective is that the nonlinear effects and distortions coming from the FOT device itself are corrected by the control action, such that the excitation signal of interest is delivered to the patient. In this phase, the closed loop control will be designed for a hypothetical patient: a respiratory tube and a rubber balloon. The underlying reason is because it is necessary to ensure repeatability of the experiments, in order to check the feasibility of implementing a closed loop control strategy in the lung function device. The final aim is to develop the closed loop control for the case when the patient is breathing (i.e. in presence of disturbances).

2. MATERIALS AND METHODS

2.1 Impedance measurement

The impedance was measured using a modified FOT setup, able to assess the respiratory mechanics from 4-50 Hz. The specifications of the device are: 11kg, 50x50x60 cm and 40 seconds measurement time.

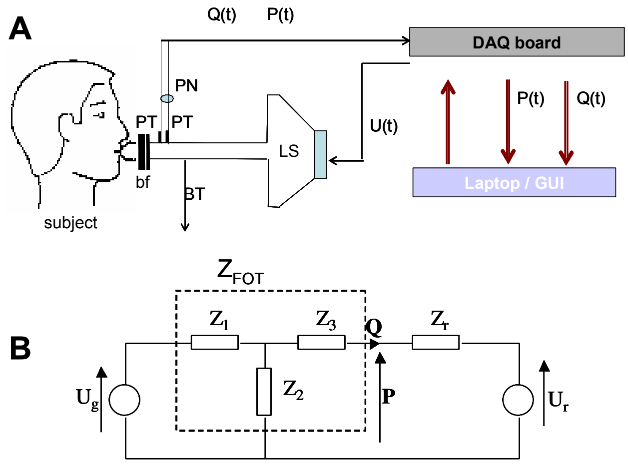

Figure-1. Schematic overview (A) and electrical analogy of the FOT setup (B).

Typically for lung function testing purposes, the subject is connected to the setup from Figure-1 via a mouthpiece, suitably designed to avoid flow leakage at the

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mouth and dental resistance artefact. The oscillation pressure is generated by a loudspeaker (LS) connected to a chamber. The LS is driven by a power amplifier fed with the oscillating signal generated by a computer (denoted by U in Figure-1-A and by U_g in Figure-1-B). The movement of the LS cone generates a pressure oscillation inside the chamber, which is applied to the patient's respiratory system by means of a tube connecting the LS chamber and the bacterial filter (bf). A side opening of the main tubing (BT) allows the patient to have fresh air circulation. Ideally, this pipeline will have high impedance at the excitation frequencies to avoid the loss of power from the LS pressure chamber. It is advisable that during the measurements, the patient wears a nose clip and keeps the cheeks firmly supported. Before starting the measurements, the frequency response of the transducers (PT) and of the pneumotachograph (PN) are calibrated. The measurements of air-pressure P and air-flow Q during the FOT lung function test are done at the mouth of the patient. The FOT excitation signal was kept within a range of a peak-to-peak range of 0.1-0.3 kPa, in order to ensure optimality, patient comfort and linearity (Oostveen*et al.*, 2003). From these signals, the non-parametric representation of the patient's lung impedance Z_r is obtained assuming a linear dependence between the breathing and superimposed oscillations at the mouth of the patient (Ionescu & De Keyser, 2008). The algorithm for estimating Z_r can be summarized from the electrical analogue in Figure 1-B:

$$P(s) = Z_r(s)Q(s) + U_r(s)$$

where$s$ denotes the Laplace operator. Since the excitation signal is designed such that it is not correlated with the breathing of the patient, correlation analysis can be applied to the measured signals. Therefore, one can estimate the respiratory impedance as the ratio:

$$Z_r(j\omega) = \frac{S_{PU}(j\omega)}{S_{QU}(j\omega)}$$

whereas the P corresponds to pressure (its electrical equivalent is voltage) and Q corresponds to air-flow (its electrical equivalent is current), U the excitation signal, the cross-correlation spectra between the various input-output signals, ω is the angular frequency and$j = (-1)^2$, resulting in the complex variable Z_r. From the point of view of the forced oscillatory experiment, the signal components of respiratory origin (U_r) have to be regarded as pure noise for the identification task (Ljung, 1999). In this application, the patient is replaced by a system without disturbance $U_r = 0$ (i.e. a respiratory tube with a rubber balloon attached at the end) in order to ensure repeatability and test the feasibility of implementing a closed loop control algorithm in the FOT setup.

2.2 Principles of KCR auto-tuning

The development of this auto-tuning algorithm is based on the prior art where two relay-based PID auto-tuners have been presented: the Kaiser-Chiara auto-tuner and the Kaiser-Rajka auto-tuner. Hence the proposed algorithm is an extended combination of the two: the Kaiser-Chiara-Rajka auto-tuner algorithm (KCR) (De Keyser & Ionescu, 2010). Notice that the development of the PID controller does not require a-priori knowledge of the system.

The approximation of a closed loop response by a dominant second order transfer function $T(s)$ with static gain one is given by:

$$T(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n + \omega_n^2}$$

with $\omega_n$the natural frequency and ζ the damping factor. From this equation, the relationship between the closed loop percent overshoot ($\%OS$) and the peak magnitude M_p in frequency domain can be found (Nise, 2007):

$$\%OS = 100e^{-\pi/\sqrt{1-\zeta^2}}$$

$$M_p = \frac{1}{2\zeta\sqrt{1-\zeta^2}}$$

By specifying the allowed overshoot in the closed loop, it follows that the closed loop transfer function must fulfill the condition:

$$T(j\omega) = \frac{R(\omega) + jI(\omega)}{[1 + R(\omega)] + jI(\omega)}$$

with R the real part and I the imaginary part. Taking $|T(j\omega)|^2$ results that:

$$(R + c)^2 + I^2 = r^2$$

where $c = M_p^2/(M_p^2 - 1)$ and $r = M_P/(M_p^2 - 1)$, which is nothing else than the equation of a (Hall-)circle with radius r and center in $\{-c, 0\}$ (Nise, 2007). In order to have a peak magnitude, only those circles with $M > 1$ are of interest. Intersection with the unit circle is achieved taking into account the condition: $R^2 + I^2 = 1$.Solving for R and I yields:

$$R = 0.5\frac{1 - 2M_p^2}{M_p^2}$$

$$I = -\frac{\sqrt{M_p^2 - 0.25}}{M_p^2}$$

The phase margin $PM$is given by $\tan(PM) = |I|/|R|$.Thus:

$$PM = \tan^{-1}\left(\frac{\sqrt{M_p^2 - 0.25}}{M_p^2 - 0.5}\right)$$

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In (De Keyser & Ionescu, 2010) it was stated that specifying PM does not suffice to guarantee a good closed loop performance in all situations. Therefore, the next step is to determine the cross-over frequency; i.e. the frequency where the process and controller crosses the 0 dB line (open loop).

If the settling time of the closed loop is specified, then using $T_s = 4/\zeta\omega_n$ and the previous M_p definition, the bandwidth frequencycan be obtained:

$$\omega_{BW} = \omega_n\sqrt{(1-\zeta^2) + \sqrt{4\zeta^4 - 4\zeta^2 + 2}}$$

From (De Keyser &Ionescu, 2010), it was used that $\omega_{BW} \approx 1.5\omega_c$ and the generalization to higher order systems which gives $\omega_c \le \omega_{BW} \le 2\omega_c$. By having the cross-over frequency ω_c, a sinusoid with period$T_c = \omega_c/2\pi$ can be applied to the process and obtain the output:

$$G(j\omega_c) = Me^{j\varphi} = M(\cos\varphi + j\sin\varphi)$$

using the transfer function analyzer algorithm (Ionescu*et al*, 2010). The task is now to find the controller parameters such that the specification for phase margin is fulfilled, by giving $\%OS$, T_s, M and φ.

The controller is derived in its textbook form, which for the critical frequency becomes:

$$R(j\omega_c) = K_p\left[1 + j\left(T_d\frac{2\pi}{T_c} - \frac{1}{T_i\frac{2\pi}{T_c}}\right)\right]$$

Starting from the controller frequency response, the loop frequency response is given by:

$$\begin{aligned} R(j\omega_c)G(j\omega_c) &= 1e^{j(-180°+PM)} \\ &= \cos(-180° + PM) \\ &\quad + j\sin(-180° + PM) \\ &= -a - jb \end{aligned}$$

with $a = \cos(PM)$ and $b = \sin(PM)$, schematically shown in Figure-2.

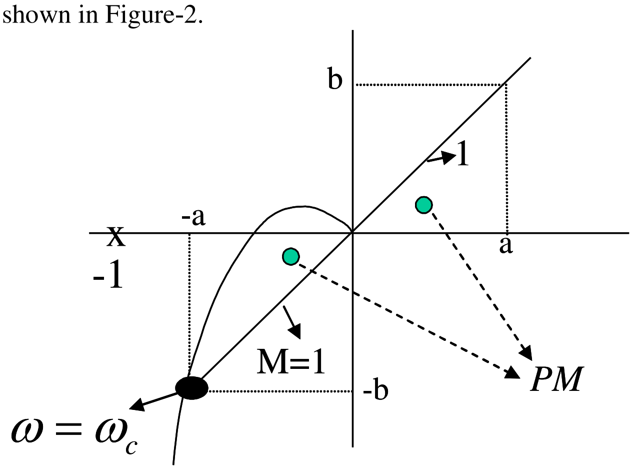

Figure-2. Schematic of the KCR tuning principle.

Based on above equations, the controller is given by:

$$R(j\omega_c) = K_p\left[1 + j\left(T_d\omega_c - \frac{1}{T_i\omega_c}\right)\right] = K_p(1 + j\alpha)$$

where

$$\begin{aligned} K_pM[(\cos\varphi - \alpha\sin\varphi) + j(\sin\varphi + \alpha\cos\varphi)] \\ = -[\cos(PM) + j\sin(PM)] \end{aligned}$$

From the real and imaginary parts:

$$\alpha = \frac{\tan(PM) - \tan\varphi}{1 + \tan(PM)\tan\varphi} = \tan(PM - \varphi) = T_d\omega_c - \frac{1}{T_i\omega_c}$$

and using $T_i = 4T_d$:

$$T_d\omega_c - \frac{1}{4T_d\omega_c} = \tan(PM - \varphi)$$

$$T_i = T_c\frac{\sin(PM - \varphi) \pm 1}{\pi\cos(PM - \varphi)}$$

which gives only one positive result. Taking into account that

$$\left(K_pM\right)^2(1 - \alpha) = 1$$

with

$$1 + \alpha^2 = 1 + \tan^2(PM - \varphi) = \frac{1}{\cos^2(PM - \varphi)}$$

which gives the K_p controller parameter:

$$K_p = \pm\frac{\cos(PM - \varphi)}{M}$$

with only one positive result.

3. RESULTS AND DISCUSSIONS

3.1 Open loop identification

In order to verify the performance of the controller, the open loop frequency response of the system was identified. The Chirp-TFA (Chirp Transfer Function Analyzer) technique proposed in (Ionescu *et al.*, 2010) was used. In short, the frequency of a sinusoidal test signal varies from a minimum frequency (f_0) until a maximum frequency (f_1) in a certain time (t_1). This is known as a chirp signal. In the Chirp-TFA framework, the sampling period varies such that a fixed number of samples per period are ensured (N_s), independent of the increasing frequency.

An example of a chirp signal with fixed number of samples per period is given in Figure-3. Notice that the sampling period is adjusted at every sampling instant, because the frequency is varying continuously. After the measurement was performed, in order to process the data, the chirp signal was divided into sections, such that subsequent sections had approximately the same frequency. Each of these sections was used to obtain one point for gain and one point for the phase in the Bode diagram of the system. The schematic flowchart of the Chirp-TFA discrete-time implementation is depicted in Figure-4.

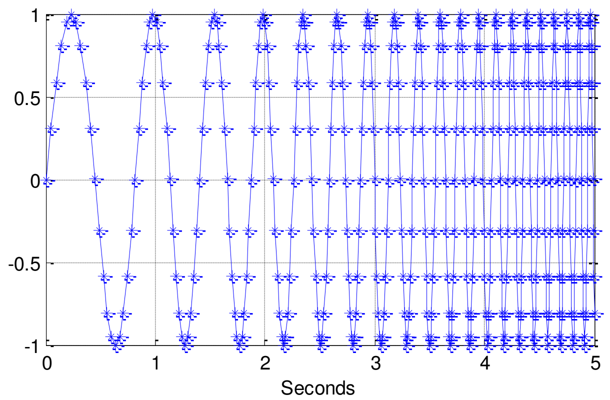

Figure-3. Chirp signal from 1 to 10 Hz in 5 seconds, 20 samples per period.

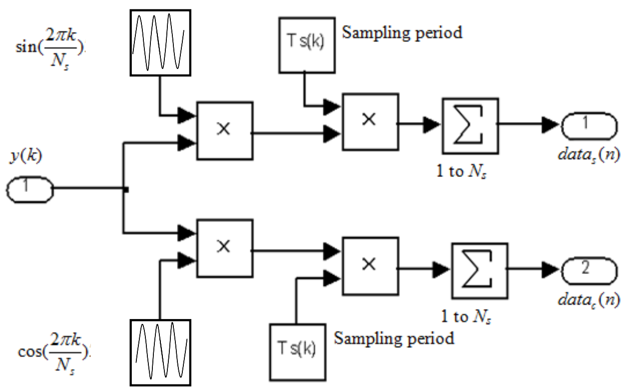

Figure-4. Scheme of the Chirp-TFA discrete implementation.

The form of the chirp signal is given by $\sin(2\pi f(t)kT_s(t))$. Hence, at every time instant t, a variable sampling period $T_s(t)$ is calculated, such that one period contains N_s samples. The relation is given by $f(t)T_s(t) = 1/N_s$. The N_s samples are then given by $\sin(2\pi k/N_s)$, with $k = 0, 1, \ldots, N_s - 1$. The sinusoidal output of a system in terms of its magnitude, phase and noise, can be written as:

$$y(k) = b\sin(2\pi k/N_s + \varphi) + n(k)$$

where n is the noise, b is the amplitude, ω is the angular frequency and φ is the phase shift. For example, at the n^{th} interval:

$$data_s(n) = \sum_{k=N_s(n-1)}^{N_s n-1} y(k)\sin\left(\frac{2\pi k}{N_s}\right)T_s(k)$$

$$data_c(n) = \sum_{k=N_s(n-1)}^{N_s n-1} y(k)\cos\left(\frac{2\pi k}{N_s}\right)T_s(k)$$

where $T_s(k)$ represents the sampling period at the k^{th} sample in the data vector and:

$$T_s(k) = \frac{1}{N_s f(k)}$$

where $f(k)$denotes the frequency at the k^{th} sample. Considering that it is obtained one point in a Bode plot for each period on which the integration was made, it makes sense to increase the frequency exponentially with time, in order to get the same resolution (points per decade) for all frequency intervals in the plot. Therefore, the frequency points are calculated from:

$$f(t) = f_0\left(\frac{f_1}{f_0}\right)^{t/t_1}$$

which is then a function of the design parameters. As the measurement time T_m increases, the above equations can be reduced to the approximations:

$$data_s(T_m) \approx \frac{b}{2}T_m \sin\varphi$$

$$data_c(T_m) \approx \frac{b}{2}T_m \cos\varphi$$

from where it follows that

$$b = \frac{2}{T_m}\sqrt{data_s^2(T_m) + data_c^2(T_m)}$$

$$\varphi = \tan^{-1}\left(\frac{data_c(T_m)}{data_s(T_m)}\right)$$

Plotting the b/a and φ values for a range of frequencies provides the Bode diagram for the observed system.

3.2 Real-time implementation

In practice, in order to send a sinusoidal signal of 50 Hz, is necessary to have a sample rate for about 500 Hz, which means about 10 samples per sinusoid period. The sampling time obtained was 0.002 seconds. In this particular example, it is not possible to work with Matlab, because the delay for calculations in the closed loop is about 14ms, much higher than the desired sample rate. A solution to overcome this limitation consists in using Real Time Windows Target (RTWT) Toolbox in Matlab. This toolbox assigns some resources of the system exclusively for this task, ensuring the desired sampling time. A

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corresponding Simulink model was developed in order to send and receive signals to/from the real FOT system. Thisis depicted in Figure-5.

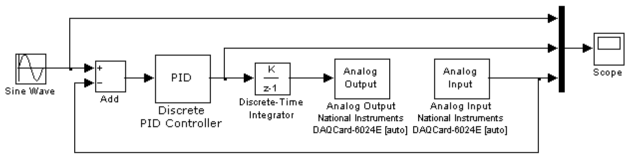

Figure-5. Real Time simulink model used in closed loop.

Next, the Simulink model is automatically compiled in C-language, making in this way a direct communication using the National Instruments DAQCard 6024E (which is recognized by Matlab and supported for real time applications).

3.3 Open loop versus closed loop performance

The open loop and closed loop identification using the Chirp-TFA algorithm is given by means of Bode plots in Figure-6. It can be observed that the bandwidth of the system is about 45Hz.

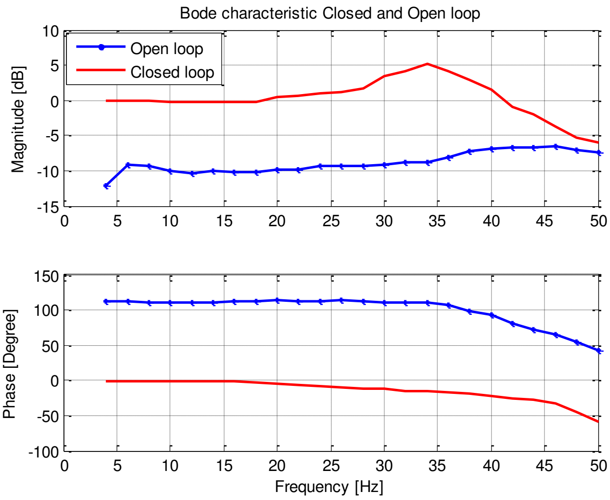

Figure-6. Bode characteristic of the open and closed loop.

For this preliminary studio,$\%OS = 20$ and $T_s = 0.041$ seconds are defined as design specifications. The KCR experiment is based on obtain the magnitude and phase of the system for ω_c (crossover frequency), or represented in time as T_c. This value is obtained from the settling time as $T_s < T_c < 2T_s$; it follows that $T_c = 0.082$ seconds, with $\omega_c = 76.62$ rad/s. A sinusoidal signal to this frequency ω_c was applied to the system, from where the magnitude (M) and phase (φ) were 10.48 dB, and 11.21° respectively.

Once the values for $\%OS$, T_s, M and φ are defined, it follows that the PID parameters are $K_p = 0.4775$,$T_i = 0.0141$ and $T_d = 0.0035$. The designed PID controller, was tested by applying a multisine setpoint with frequencies at the limits of the bandwidth of the closed loop at 3Hz and 20Hz. The response is presented in Figure-7.

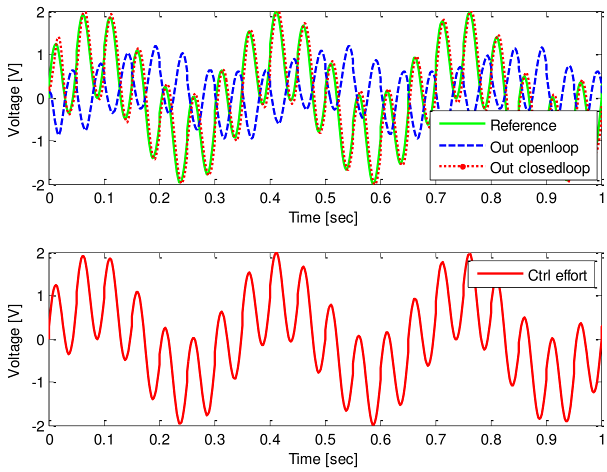

Figure-7. Comparison test between open loop and PID controller performance for a multisine setpoint at 3 Hz and 20 Hz.

In order to be able to follow a reference signal in a closed loop is necessary that the magnitude of the closed loop remains in 0dB and the phase in 0º into the frequencies of interest. From the Bode plot in Figure-6 for the closed loop, it can be observed that the results are in agreement with the expected bandwidth, and that the controller performs satisfactorily. This result is also visible when a comparison in time domain between open loop and closed loop is done. The controller avoids distortions and nonlinear effects at the output of the lung function device; the desired signal is successfully delivered at the patient's mouth as depicted in Figure-7.

In this paper, the problem of closed loop control of a medical device for lung function testing was initiated. Preliminary results show that a proposed PID auto-tuner can be applied and developed with desired closed loop performance specifications for settling time and overshoot. The next step is to develop the method in the presence of noise, i.e. interference with the breathing signal coming from the patient.

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