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Technical note

Fan-based device for non-invasive measurement of respiratory impedance: Identification, calibration and analysis

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ABSTRACT

The paper addresses the development and performance-analysis of a lung function device for non-invasive forced oscillatory technique (FOT). The applied identification methodology allows estimating the level of noise and the level of non-linearities generated by the device and correct their influence on the patient's excitation signal. The repeatability of the system is assessed under different experiments using respiratory extensions and a calibration structure. The device allows assessing the mechanical properties of the respiratory impedance in the frequency band 0.05–5 Hz. From clinical point of view, this low-frequency band has particular interest when lung's viscoelastic properties need to be assessed, especially when airway remodeling and structural changes occur.

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1. Introduction

Forced oscillation technique (FOT) is a non-invasive lung function test based on superimposing an excitation signal over the spontaneous breathing in order to calculate the respiratory impedance [1,2].

Since its introduction in medical applications, FOT has been proven useful in the non-invasive identification of respiratory properties and widely applied in physiological studies: chronic obstructive pulmonary disease [3–5], vocal cord dysfunction evaluation [6], obstructive sleep apnea [7], respiratory mechanics in ventilated patients [8], cystic fibrosis in children [9,10], assessment of anesthetized paralyzed children [11], asthma [12], kyphoscoliosis [13]. Probably, the most attractive feature of the FOT is that the pressure-flow oscillations are measured superimposed on the normal breathing, avoiding the need of any special collaboration of the patient or specific breathing maneuvers as in standardized lung function tests: spirometry and body plethysmography or in induced apnoea [14]. The advantage of FOT is that it delivers complementary information to that extracted from standardized lung function tests.

The pressure-flow relationship is largely un-correlated from the natural pattern of individual respiratory flows, hence the estimated impedance is for the most part of the spectrum, independent of the breathing pattern [2]. Consequently, at high frequencies the impedance characterizes mainly the airway characteristics [15], while at low frequencies (<4 Hz) characterizes viscoelastic properties of the respiratory tissue [14,16,17].

In traditional estimation methods for respiratory impedance, it is assumed that the applied signal is perfectly known, but this is not the case. The designed signal and the final signal applied to the mouth of the patient differ due to noise and nonlinearities stemming from the device. The article exposes the design, assembly, identification and assessment of a FOT prototype device to estimate the respiratory impedance in the frequency range from 0.05–5 Hz. At these frequencies the measured impedance reflects important information as airway wall distensibility, parenchymal viscoelasticity, expiratory flow limitation and collateral ventilation [4,18–20]. The identification procedure is carried out using odd random phase multisine (ORPM) excitation. This kind of excitation allows separating the disturbing noise influence from the non-linear contributions and calculating the best linear approximation (BLA) of the device [21], and from here an accurate estimation of the pressure signal applied to the patient.

The article begins by illustrating the system device and its components. Subsequently, the procedure for the identification and evaluation of the system device using ORPM excitations is presented. The performance of the device is described by the BLA, the level of noise, and the presence of non-linearities. The assessment of the FOT device is carried out under calibrated measurements on a structure with known impedance, the repeatability is assessed by independent repetitions using the calibration structure and flexible

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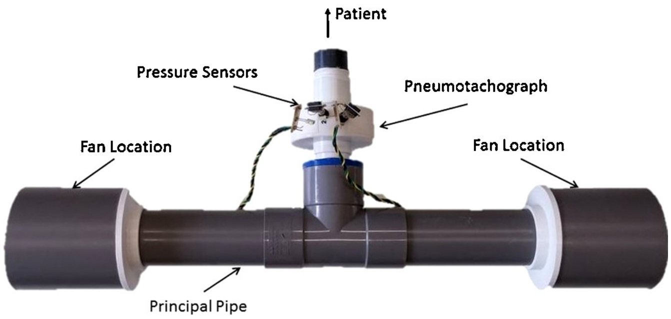

Fig. 1. Schematic overview of the second generation prototype device.

tubes used in intubation procedures. Finally a conclusion section summarizes the main outcome of the present work and points out future steps.

2. Materials and methods

2.1. Prototype device

The system developed in the present article is based on a prototype described in [22] and [23]. The system is formed by a group of fans located on each extreme of a principal pipe (see Fig. 1). One group of fans pushes the air into the tube while the second group of fans, located on the other side of the tube, extract the air. The controlled difference in speed between the two group of fans allows generating a carefully designed pressure signal to the mouth of the patient. The pipe has 2 inches diameter and has been filled with tubes with smaller diameter (5 mm) in order to preserve laminar flow. However, non-linearities given turbulence are still present. Laminar flow generally proceed in small pipes and is required to maintain a predictable relation between the speed of the fans and generated flow [24]. The end part of the device is formed by a mouthpiece, composed by a pneumotachograph and two pressure sensors to measure pressure at both sides of the pneumotachograph, located at the middle of the principal pipe as is presented in the Fig. 1.

From previous designs, [22] and [23], it has been shown that higher number of fans will not improve the related pressure. Previous works have envisaged the elimination of nonlinear effects and eliminate the effect of the breathing through complex filtering techniques. In this design, attention is focused on the analysis of non-linear distortions and identify their effect over the general dynamic characteristic of the system.

The device has been built in a configurable National Instruments CompacRIO (cRIO) platform. The cRIO is a reconfigurable embedded control and acquisition system that includes I/O modules in a reconfigurable FPGA chassis. Additionally, cRIO is programmed with NI LabVIEW graphical programming tools and can be used in a variety of embedded control and monitoring applications. Technical details are given in the appendix. The embedded platform used in this novel setup allows controlling the desired signal applied to the mouth of the patient. This is achieved by controlling the speed of the fans with a classical proportional-integral controller plus feedforward compensation, hence undesired biased effects may be eliminated from the impedance estimation.

2.2. Non-parametric identification approach

Physical systems present in general a non-linear behavior which makes difficult their interpretation and analysis, mainly due to the fact that the dynamics of the system will change depending on the spectral characteristics of the used signal excitation [25,26]. A simple way to reduce the non-linear contributions of a system response is to reduce the peak to peak amplitude assuming that the linear contribution dominates the non-linear ones. However, this approach often leads to low signal-to-noise ratios (SNR) diminishing the capacity of the system to differentiate small changes [27]. Alternatively, one may develop pseudorandom signals where interactions among the frequency components are reduced. In [25] the authors suggest to use pseudorandom signals where the harmonics are non-integer multiples of each other. Unfortunately, such a signal still can present non-linear distortions given intermodulation or crosstalk between frequencies as has been described by Bedrosian and Rice [28] and Victor and Knight [29]. Other approach suggests the development of a signal that cannot be reproduced by integer harmonics of a fundamental frequency [29]. However, such a signal, not being periodic, adds leakage problems to the identification process and from here to a biased estimate of the system.

To identify our FOT fan based system a conjugate approach is used. We identify the system around an operational point including the non-linear effects, but reducing those effects by a convenient signal excitation, while keeping the advantages of periodic signal processing. This approach is essentially different from those reported in [30–32] because our excitation signal allows controlling the even and odd frequency contributions, which allows separating the linear contributions from the nonlinear ones.

In general, the nonlinearities can be classified in even (quadratic) and odd (cubic) nonlinearities. For multi-harmonic periodic excitation signals, the quadratic non-linear effect is present at combination of $f_i \pm f_j$ frequencies; while the cubic non-linear effect is identified for the triple combination $f_i \pm f_j \pm f_k$ (with f_i, f_j and f_k frequencies present at the excitation). Consequently, exciting the system with periodic signals with only odd harmonics will prevent the appearance of even non-linear distortions at the excited frequencies (since combination $f_i \pm f_j$ of odd harmonics generates even harmonics which can be easily identified from the response of the system). This allows discriminating between even and odd non-linear contributions, while providing the best linear approximation (BLA) of the system [27].

A periodic signal that allows a careful and easy selection of the excitation harmonics and their amplitude, keeping the properties of a pseudorandom signal, is a random multisine excitation:

$$r(t) = \frac{1}{\sqrt{N}} \sum_{k=1}^{N} A_k \sin(j\omega_k t + \phi_k) \tag{1}$$

the phases ϕ_k are random uniformly distributed in the interval [0, 2π[, ω_k are the excited frequencies of the multisine ($\omega_k = 2\pi k f_o$), with f_o the frequency resolution of the signal, j the complex number $\sqrt{(-1)}$, N the number of excited harmonics and A_k the spectrum amplitude. In so far, the approach is similar to that reported in [33]. However, the further use of the signal is different, as described in the remainder of this section.

The impact of the nonlinear distortions on the frequency response function (FRF) for random multisine excitation are systematic contributions ($G_B(j\omega_k)$) and stochastic contributions ($G_S(j\omega_k)$). The systematic contributions do not depend on the actual phases of the random multisine, but they do depend on the applied power spectrum [21]. These contributions do no disappear by averaging the FRF either over several periods of one phase realization, nor over one period for several phase realizations of the multisine. The stochastic non-linear contributions ($G_S(j\omega_k)$) are not in phase with the excitation signal. Their expected value becomes zero at different phase realizations. In this sense the FRF of the system can be defined by:

$$G(j\omega_k) = G_{BLA}(j\omega_k) + G_S(j\omega_k) + N_G(j\omega_k) \tag{2}$$

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