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Simple procedure for evaluation of the frequency response of flow transducers used in spirometry

Procedimento simples para avaliação da resposta em freqüência de transdutores de vazão usados em espirometria

Marcelo Alexandre Garcia
José Carlos Teixeira de Barros Moraes*
Laboratório de Engenharia Biomédica,
Escola Politécnica / USP
Av. Prof. Luciano Gualberto, trav. 3, n. 158, sl. D2-05
05508-900 São Paulo, SP
E-mail: jcmoraes@leb.usp.br

*Corresponding author

Abstract
In this research, we present a simple mechanical assembly for evaluation of frequency response of flow transducers. Also, two pneumotachometer/pressure transducer (PPT) ensembles were evaluated with this setup. The accuracy of the measurements depended mainly on the physical dimensions of a piston, without need for a closed-loop control for the generated flow, which would demand a pre-calibrated electronic pressure transducer or an optical position detection device. The gain and phase curves found for both evaluated PPTs are presented. We conclude that the presented mechanism is suitable to evaluate the dynamic response of these PPTs in the range between 1.0 and 50.0 Hz. Regarding the evaluated PPTs, we concluded that the gain curves in the whole dynamic range of both assemblies were 0 and +2.63 dB for PPT assembly 1, and 0 and +6.70 dB for PPT assembly 2.

Keywords: Respiratory flow measurement, Dynamic response evaluation, Ergospirometry, Respiratory impedance.

Resumo
Este trabalho apresenta um sistema mecânico simples para levantamento da resposta em freqüência de transdutores de vazão de gás. Dois conjuntos de pneumotacômetro/transdutor de pressão (PPT) foram avaliados com este sistema. A exatidão das medidas dependeu principalmente das dimensões de um pistão, sem a necessidade de controle com malha fechada da vazão gerada, o que demandaria o uso de um transdutor de pressão eletrônico pré-calibrado ou um dispositivo óptico para detecção de posição. As curvas de ganho e defasagem dos dois conjuntos PPT avaliados são apresentadas. É possível concluir que o mecanismo apresentado é capaz de avaliar a resposta dinâmica destes PPTs na faixa de 1,0 a 50,0 Hz. Em relação à avaliação dos PPTs, concluiu-se que as curvas de ganho em toda a faixa dinâmica avaliada em ambos PPTs ficaram entre 0 e +2,63 dB para o conjunto PPT 1 e entre 0 e +6,70 dB para o conjunto PPT 2.

Palavras-chave: *Medição de vazão respiratória, Avaliação de resposta dinâmica, Ergoespirometria, Impedância respiratória.*

Introduction

Human respiratory flow is commonly measured for pulmonary disease diagnostics and cardiopulmonary performance evaluation. Many types of transducers have been used to perform respiratory airflow measurement, such as: Pitot tube based pneumotachometer (Porszasz *et al.*, 1994), Fleisch type pneumotachometer (Strömberg and Grönkvist, 1999), mesh type pneumotachometer, hot-wire pneumotachometer (Plakk *et al.*, 1998), and ultrasonic beam pneumotachometer (Buess *et al.*, 1986). Main applications are in spirometry measurements (ATS, 1995), cardiopulmonary exercise testing (ATS/ACCP, 2003), and respiratory impedance evaluation through forced oscillation technique (FOT) (Oostveen *et al.*, 2003).

However, since the respiratory signal is variable in time domain, the dynamic response compensation for flow transducer may be considered for measurement accuracy improvement. Moreover, the frequency response uniformity in FOT measurements is a non-negligible requirement. The correction of the response frequency of the PPT used in FOT procedures introduces changes in the physical model of the lung undergoing evaluation, as described by Renzi *et al.* (1990).

Some methods for flow transducer dynamic response prediction and evaluation have been described in previous studies (Farré *et al.*, 1986; Finucane *et al.*, 1972; Francis *et al.*, 1979; Frye and Doty, 1990; Melo *et al.*, 1997; 1998; Renzi *et al.*, 1990; Turner *et al.*, 1988).

The objectives of this research were twofold:

1. Developing a simple mechanical assembly for evaluation of frequency response of flow transducers, with no need for feedback control of its generated flow;
2. Evaluating dynamically two pneumotachometer/pressure transducer (PPT) with this setup.

Main potential application is design of dynamic response compensation filters for instrumentation using dynamic flow measurement, such as spirometry, indirect calorimetry, cardiopulmonary exercise testing and forced oscillation technique (FOT).

Materials and Methods

Setup description

The setup for evaluation of frequency response of flow transducers is shown in Figure 1. This is a mechanical device containing a sliding piston inside a fixed block (internal diameter is 28.00 mm) moved by a shaft coupled to a steering disc. The piston diameter was calibrated with a caliper (standard deviation: 0.05 mm). The internal diameter of the block matches the internal diameter of the pneumotachometer in order to avoid local turbulence. The disc is driven by a 3-phase motor (0.5 HP, 3600 RPM at 60 Hz). The speed of the motor is controlled by a programmable motor driver (Allen Bradley, model IP-20). This setup was able to generate a cosine-shaped flow with frequencies between 1.0 and 50.0 Hz, in steps of 1.0 Hz. The friction surfaces between block and piston were lubricated, avoiding heating and air leakage. The pneumotachometer under test must be strongly fixed at the output of the block with appropriate glue in order to avoid completely any vibration between the block and the pneumotachometer.

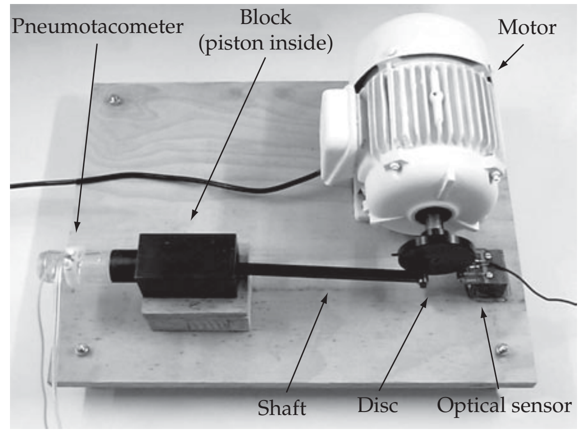


Figure 1. Setup for flow transducer dynamic response evaluation.

The disc has eccentric holes with radii of 32, 16, 8, 4 and 2 mm for fixing the pivot of the extremity of the shaft. The maximum inclination of the shaft is 7.5° (when using 32 mm radius) in order to minimize the distortion of the sine waveform. The theoretical total harmonic distortion (THD) of the generated flow waveform in this configuration is not greater than 0.41%.

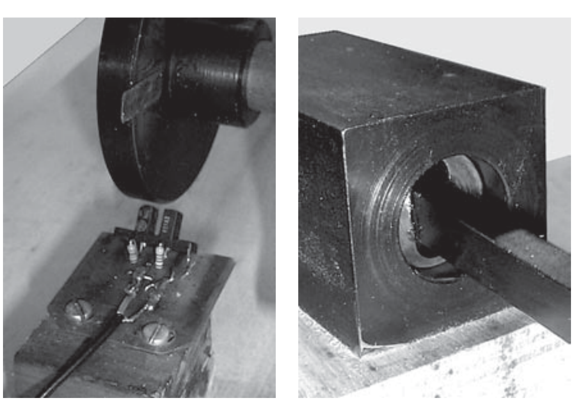
We decided to keep the flow amplitude in a restrict variation range in order to avoid the influence of possible small non-linearities from the transducers. Since flow is the derivative of volume, the lower the frequency the higher is the necessary stroke volume to keep the same flow amplitude. Therefore, lower frequencies were measured with bigger radii, and vice-versa (1-4 Hz used 32 mm; 4-8 Hz used 16 mm; 8-16 Hz used 8 mm; 16-32 Hz used 4 mm; and 32-50 Hz used 2 mm radius). Following this procedure the generated peak flow amplitude obtained remained between 123.8 ml/s and 495.2 ml/s.

An optical sensor was used to detect the zero-angle position of the disc. Figure 2 shows details of the setup. Figure 2a shows the optical sensor attached to a printed circuit board near the steering disc. A steel plate is fixed on the disc to excite the optical sensor. Figure 2b shows in detail the piston coupled to the shaft inside the block. The signal generated by the optical sensor was acquired simultaneously by the flow transducer signal. A low-to-high transition in the optical sensor signal denotes the peak instant of the cosine-shape generated flow. With this arrangement we could measure the time interval (Δt) between the peak in generated flow detected with the optical sensor and the peak in the signal measured with the flow transducer. The phase response θ (in degrees) of the flow transducer as function of the frequency (f) is given by (1).

$$\theta(f) = 360 \cdot \Delta t \cdot f \quad (1)$$

Evaluated transducers

Two pneumotachometers were used: a Pitot tube type pneumotachometer (MedGraphics, model PreVent) and a mesh type pneumotachometer (Hans-Rudolph, model 3813). The differential pressure generated by the pneumotachometer was injected in a differential pressure transducer (Validyne, model MP45-14-871) coupled to a carrier demodulator (Validyne, model CD19A). Therefore, the found dynamic response refers to each PPT ensemble. The connection between the PreVent and the MP45-14-871 was made with PreVent connection clip with its original tubes. The connection between the 3813 and the MP45-14-871 was made with a pair of PVC tubes with internal diameter of 3.2 mm and length of 30 cm. Since the 3813 was not supplied with tubes, we have chosen tubes with suitable internal diameter for the 3813 connections and a short length for short signal delay.



(a) (b)

Figure 2. Details of the setup: a) Optical sensor; and b) piston.

Acquisition instruments and procedures

Analog signals were registered with a 16-bit acquisition board (National Instruments, model PCI-6052E) in a PC and its NI-DAQ driver. The PCI-6052E had all channels set to a 10 kHz sampling frequency in order to preserve the wave shape of the acquired signal even at the highest signal frequency of 50 Hz. A first-order low-pass anti-aliasing filter with cutoff frequency of 5 kHz was employed. Acquisition and signal processing were made with Mathworks Matlab® 6.0 package and Data Acquisition toolbox. A thermometer probe was kept in contact with the block external surface to ensure that there was no thermal variation in the setup during all measurements. Environment conditions were kept constant at 23 ºC and 60% of relative humidity. Two analog channels were used: one for the CD19A analog output and other for optical sensor output. Each PPT had a calibration curve (output voltage *versus* input flow) previously evaluated with a flow calibrator (Timeter, model Respical). Each point of that curve was evaluated with static flow, ranging from zero to 500 ml/s. All acquired signals were compensated with the calibration curve of their respective PPT, in order to compensate the static non-linearity of the PPT gain function. For each frequency evaluated, signals were registered for 10 seconds. Averages of amplitude and phase of every entire signal period contained in the register were calculated. All experiments were repeated twice, to confirm the repeatability of measurements.

Results

The gain and phase curves found for both evaluated PPTs are shown in Figure 3. These curves were calculated in relation to the theoretical expected flow amplitude of the mechanical assembly. The PPT assembly 1 (PreVent with MP45-14-871) had a gain enhancement at higher frequencies of up to 2.63 dB in the measured dynamic range. The local peaks that took place between 17 and 20 Hz can be attributed to resonances caused by the association of the connection tubes (200 cm long) with the pressure transducer compliance, according to Melo *et al.* (1997). The same resonance effect took place at a higher frequency (around 38 Hz) for PPT assembly 2 due to the shorter used tubes (30 cm long), causing a gain enhancement of up to 6.70 dB

Phase responses for both PPTs are shown in Figure 3. In the same figure, dashed lines represent the theoretical phase curves for a constant delay in signal as function of the signal frequency (correlation factors

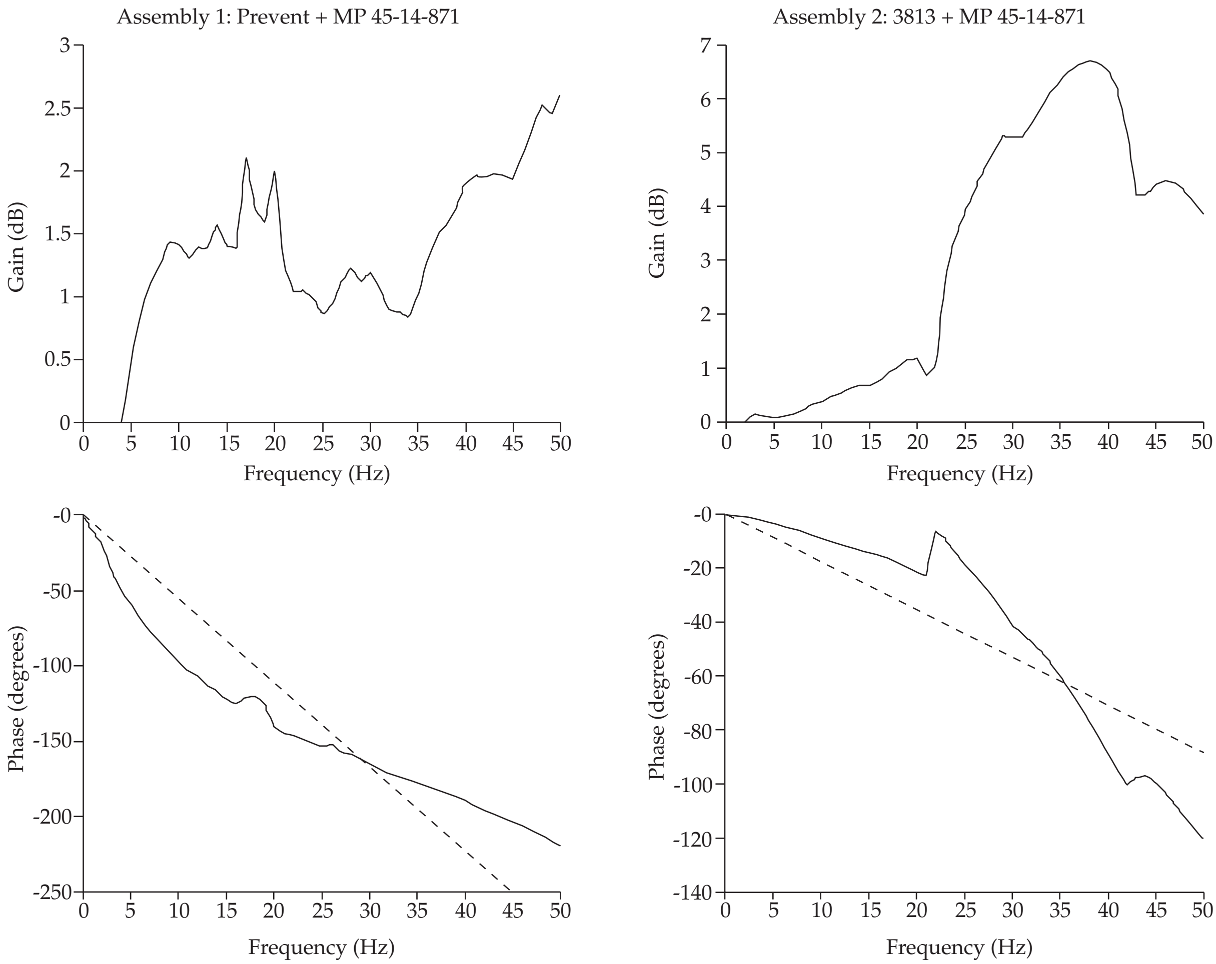


Figure 3. Solid lines: gain and phase curves for evaluated assemblies. Dashed lines: theoretical phase curves for a constant delay in PPT response (PPT assembly 1: theoretical curve for 15 ms delay; PPT assembly 2: theoretical curve for 5 ms delay).

were 0.968 in PPT 1 and 0.942 in PPT 2). The comparison between the measured phase response and the phase of a constant delay suggests that the phase behavior for both PPTs has a constant delay component. Such delay was greater in PPT 1 (approximately 15 ms) than the one in PPT 2 (approximately 5 ms).

A second evaluation of all gain and phase curves has shown the same results.

Discussion

The gain curve of PPT assembly 1 was near to unitary gain (less than 3 dB of variation in the whole dynamic range), while the gain curve of PPT 2 had a larger variation (almost 7 dB of variation). Such small gain variations suggest an inverse filter deconvolution for signal recovering. With this method, the background noise will be attenuated at higher frequencies, since the deconvolution filter compensates the transducer gain enhancement at these frequencies. In a respiratory signal application, where the main portion of signal power is located to lower frequencies (Garcia *et al*., 2008; Melo *et al*., 1997), the SNR would be slightly improved, assuming that the background noise typically is more uniformly distributed over the entire dynamic range.

The rising gain observed near 50 Hz in PPT 1 is due to the pressure transducer membrane resonance (above 50 Hz), as described before by Melo *et al.* (1997) and Francis *et al.* (1979). The same effect in PPT 2 was masked by the 38 Hz resonance.

The delay presented by PPT 1 was greater than PPT 2 because the original PreVent connection tubes are 2 m long, while in PPT 2 we employed shorter tubes, as described above.

Resonance peaks and delay components are influenced by tubing configuration. Therefore, the use of a different tube length or diameter requires a new frequency response evaluation for the PPT ensemble.

In most applications such as spirometry or indirect calorimetry, a sample frequency of 100 Hz can be used with good reliability for respiratory signals. Our design meets this specification, since it could measure the response frequency until 50 Hz.

High-frequency flow generators are typically based in a chamber with a loudspeaker. In that ensemble, the position of the loudspeaker cone may be measured with some optical device. In the present ensemble it is not necessary to measure the position of the piston, since it is a known function of the angular position of the motor axis. Nevertheless, more precise flow generation methods use a piston or a syringe calibrated through its physical dimensions. Our setup calibration followed the same principle. Moreover, the transducer rigidly fixed to the block minimizes vibration effects. Internal rugosity could generate turbulences, which were avoided with the choice of the internal block diameter equal to the transducer internal diameter, thus without step shapes in the connection interface.

The obtained curves agree with previous related results (Melo *et al*., 1997) refering to gain and phase shapes and resonance peaks, as described in the Results section. However, we obtained more jittery curves than the previous studies have shown. This can be explained by the small step increment (1 Hz) adopted with our setup, which is actually an improvement when compared to previous studies.

Conclusions

We successfully developed a mechanism to evaluate the frequency response of flow transducers, in which the measurement accuracy depends mainly on the physical dimensions of a piston. The main advantage of this method is that there is no need for an electronic pressure transducer or an optical position detection device to perform a feedback for flow control during evaluation procedures. Therefore, the assumption of constant gain of the control loop within the entire dynamic range under evaluation is unnecessary, since there is no control loop. We conclude that the presented mechanism is suitable to evaluate the dynamic response of flow transducers used in spirometry in the range between 1.0 and 50.0 Hz.

The two proposed PPT assemblies were successfully evaluated and the obtained gain and phase curves were presented. As shown in Figure 3, we concluded that the gain curves in the whole dynamic range of both assemblies were 0 and +2.63 dB for PPT assembly 1, and 0 and +6.70 dB for PPT assembly 2.

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