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Fitting the Frequency Response in Acoustic Reflectometry for an in Vitro Model of a Human Upper Airway

Ernesto R. Vazquez Ceron, Joseph H. Pierluissi, Victor R. Barrales, Ezequiel M. Rodriguez, and Raymundo Barrales Guadarrama

***Abstract*—Acoustic reflectometry has been used earlier to estimate the bore profile of a human upper airway and endotracheal tubes using thousands of acoustic pulses. The axial resolution of the profile computed depends on generating a broad frequency response, filtering undesired frequencies and compensating for wave propagation losses. The work presented here shows that acoustic reflectometry may be performed by using few Gaussian-sinusoidal acoustic waves, equally spaced along the bandwidth, and the Ware-Aki algorithm. In this way, the frequency content is controlled, the computational cost is reduced, and the axial resolution is improved. This entails fitting the frequency impulse response, compensating for propagation losses in the amplitude response, and analyzing the phase response. The methodology was validated in the laboratory with an in vitro model of a human upper airway, coupled to an acoustic reflectometer. Only one hundred acoustic waves, with a frequency step of 100 Hz, were needed to reconstruct a profile with an axial resolution within an acceptable margin of error.**

I. Introduction

The acoustic reflectometry technique has been used for years as a biomedical tool for estimating the shape of a human upper airway [1]-[3], assessing the anal sphincter function [4], evaluating the patency of endotracheal tubes in patients who require ventilatory assistance, and determining the position of endotracheal tubes placed along a human upper airway [5]-[6]. The cavity under study is coupled at the distal end of a source tube. A reflected acoustic wave is then generated when the incident wave finds a change in acoustic impedance. A microphone records both acoustic waves which are stored in a computer. A power amplifier is used to increase the level of the analog signal, such that an acoustic wave propagates into a source tube and strikes the cavity. The amplifier gain is carefully adjusted to avoid distortion of the waves. An instrumentation amplifier is used to improve the signal-to-noise ratio. The scenario defines an inverse problem that requires the use of mathematical procedures to estimate the axial resolution of a cylindrical cavity from the acoustic waves recorded. The complete instrumentation arrangement is called acoustic reflectometer, a schematic of which shown in Fig. 1.

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Ernesto R. Vazquez Ceron was with the University of Texas at El Paso, 79968. He is now with the Deparment of Electronic, Universidad Autonoma Metropolitana, Ave. San Pablo 180, Del. Azcapotzalco, Mexico City, 2200 (phone and fax: 01152- 5553189042; e-mail: ervc@correo.azc.uam.mx).

Joseph H. Pierluissi is with the Department of Electrical and Computer Engineering at the University of Texas at El Paso, El Paso, TX 79968 (e-mail: pier@utep.edu).

Victor R. Barrales, Ezequiel M. Rodriguez, and Raymundo Barrales-Guadarrama are with the Department of Electronic, Universidad Autonoma Metropolitana, Mexico City, 2200 (e-mails: vrbg@correo.azc.uam.mx; err@correo.azc.uam.mx; rbg@correo.azc.uam.mx).

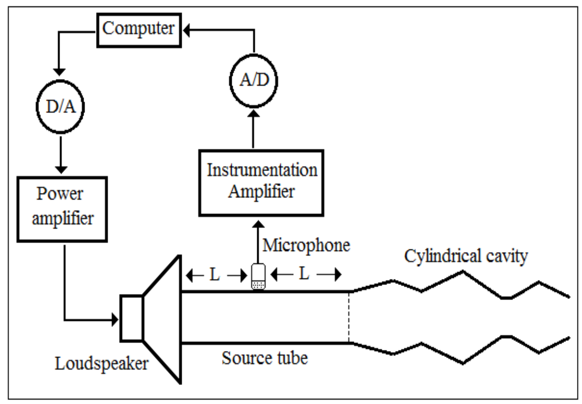

Fig. 1. Acoustic reflectometer.

The work presented here shows that a feasible solution for inverse problem may be obtained through acoustic waves with specific frequency content. Instead of using thousands of acoustic pulses, a Gaussian-sinusoidal wave packet is generated by software, and sent to the loudspeaker. Fitting techniques are used to increase the frequency content in the impulse response. The Ware-Aki algorithm is then recalled to compute the reflection coefficients [7], and estimate the axial resolution for an in vitro model of a human upper airway. A comparison between a direct measurement and a reconstructed axial resolution is presented.

II. Acoustic reflectometry

A. Acoustic coefficients

Reflected P_0^- and transmitted P_1^+ acoustic waves are generated when an incident P_0^+ wave finds a change in acoustic impedance along a cylindrical cavity, as it is shown in Fig. 2. Two cylindrical segments with different cross sectional area are joined at $x=0$. The transmitted acoustic wave is propagated in the same direction as the incident wave. As a consequence forward and backward reflected and transmitted acoustic waves are generated as function of space-time. This process is continued until the acoustic pressure decays as function of time. The reflection coefficient r_0 and the transmitted coefficient t_0, lead to the determination of a change in the cross sectional area [8].

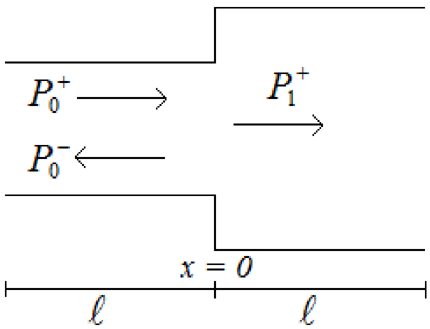

Fig. 2. A change in acoustic impedance generates both reflected and transmitted acoustic waves.

Mathematically, both acoustic coefficients are defined as

$$\begin{aligned} r_0 &= P_0^- / P_0^+ \\ t_0 &= P_1^+ / P_0^+ \end{aligned} \tag{1}$$

When an acoustic pulse is used as an incident wave, the reflected wave is named the input impulse response, which is then composed of reflected and transmitted waves. There on, the reflection coefficients are directly calculated from the impulse response.

B. Input Impulse Response

A wide frequency response is required in acoustic reflectometry. Lower frequencies are used to estimate a general axial resolution of a cylindrical cavity, and higher frequencies are used to refine the results. Several types of acoustic reflectometer have been tested to improve the frequency response. For instance, the acoustic pulse type has been constructed with the use of loudspeakers and electrical discharges. It has been adopted with either long [9] or short source tubes [10]-[12]. However, acoustic pulse reflectometry generates a limited frequency response, requiring the generation of thousands of acoustic pulses to improve the signal-to-noise ratio. They are also known for generating a small dc component in the calculation of the impulse response [13]. Any of these scenarios result the computation of abrupt changes in axial resolution. On the other hand, the mathematical procedure to compute the impulse response requires clearly identifying both acoustic waves. A long source tube is the simplest choice, as shown in Fig. 1 (L = 4 m). Therefore, the incident wave is recorded before the reflected wave is generated, although it is necessary to compensate for attenuation of the waves. The starting points for both signals recorded are chosen to generate the correct relationship of space-time, and to calculate the reflection coefficients. This procedure makes the use of acoustic pulse reflectometry a robust technique to be applied.

In this work, a Gaussian-sinusoidal wave packet, with a short time of propagation, is used to cover a bandwidth of 10 kHz and estimate the impulse response. This type of acoustic wave is simple to generate, its frequency response is under control, and neither the dc component nor the acoustic transients are recorded in the propagating wave. An example of this type of acoustic wave is shown in Fig. 3. When a long source tube is used, both acoustic waves are easily identified from each other, thus resulting computational cost reduction.

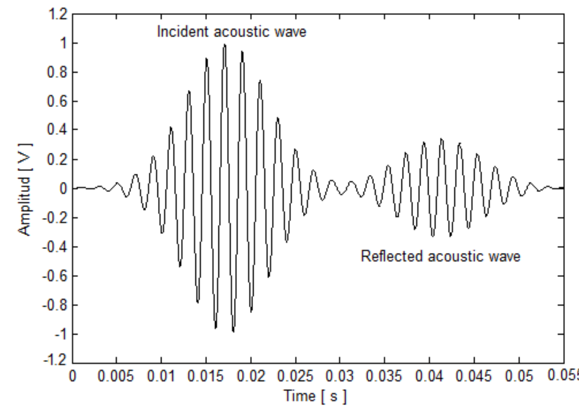

Fig. 3. A long source tube is used to identify the incident wave from the reflected wave.

The entire bandwidth is covered with a frequency step of 100 Hz. Only one hundred acoustic waves are needed in the solution of the inverse problem. Each acoustic pressure is characterized around the peak value as function of time through a least-mean-squares algorithm. Thereby, the frequency impulse response *iir(ω)* is calculated by computing the ratio of amplitudes *A(ω)*, and difference of phases *θ(ω)* between the incident and reflected waves as function of frequency step *ω*, as given by

$$iir(\omega) = A(\omega) \exp \theta(\omega) \tag{2}$$

The frequency step *ω* defines the frequency content in the impulse response. As a consequence, it improves the axial resolution in the inverse problem solution. Cubic splines are used to increase twice the frequency content by fitting the values between frequencies, such that the frequency impulse response describes a frequency step of 50 Hz. It is important to emphasize that the phase is unwrapped in order to correct for mathematical artifacts brought in by the computations. The frequency impulse response calculated for an in vitro model used in this work is shown in Fig. 4.

C. Attenuation

The amplitude of the acoustic wave propagated along the source tube decreases as function of frequency. A low signal-to-noise ratio is recorded at higher frequencies. The solution of the inverse problem is very sensitive to acquisition of noise and round-off errors in the recursive mathematical procedure. Thereby, the error in the axial resolution is increased as function of distance. The two-microphone technique is recalled to characterize the source tube [8], and compensate the frequency impulse response. A frequency step of 100 Hz is needed to compute the attenuation factor in frequency domain. This factor is fitted through a power model to match the frequency values used for the impulse response.

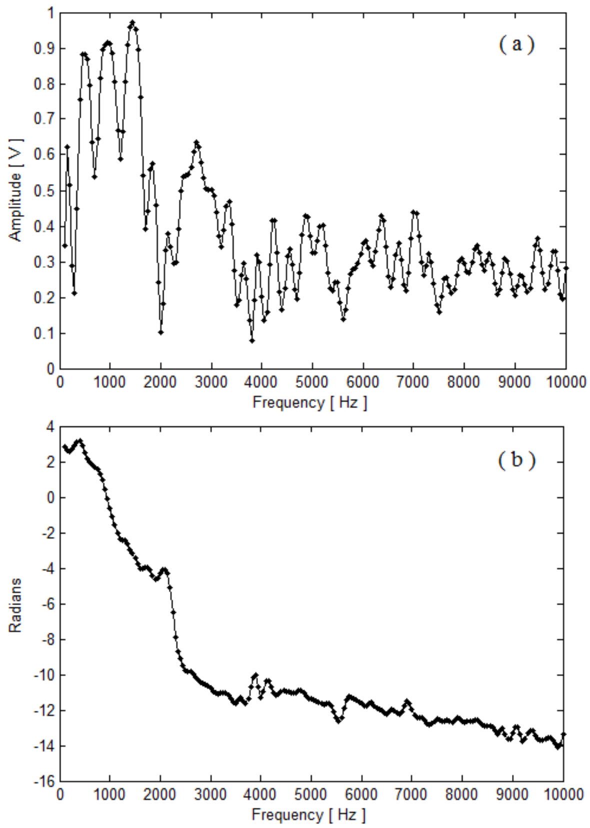

Fig. 4. Frequency impulse response computed; (a) Amplitude, and (b) Phase.

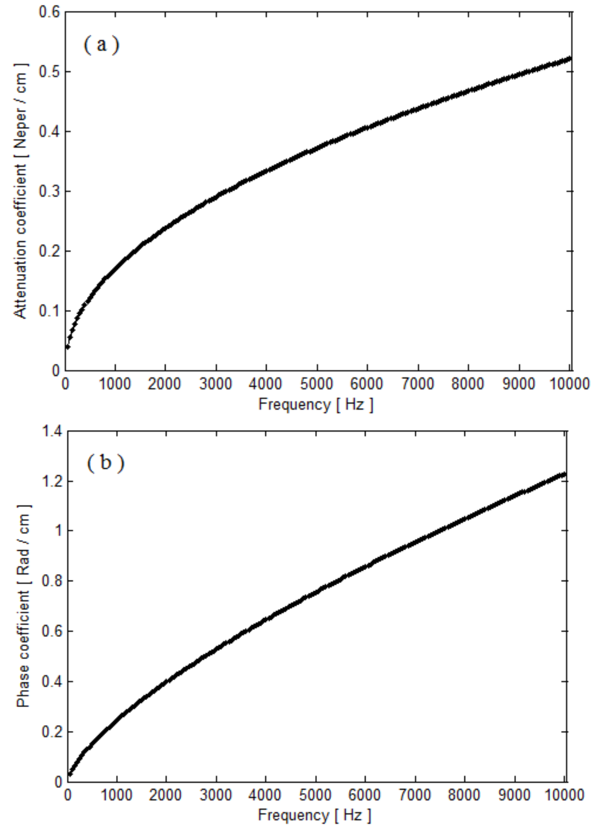

Fig. 5. Attenuation factor in frequency domain; (a) Amplitude, and (b) Phase.

The same distance covered by both acoustic waves is used in the characterization of the source tube. The attenuation factor, empirically calculated in the laboratory, is shown in Fig. 5. The amplitude response is compensated by a ratio and the phase by a difference, as function of the frequency, between the data obtained in Fig 5 and Fig. 4, respectively. When the losses are not compensated along the source tube, the reconstructed axial resolution is highly attenuated as function of distance or, in some cases; it is characterized by abrupt changes. Once the frequency impulse response is compensated, it is mapped into the time-domain by using the Inverse Discrete Fourier Transform.

D. Reconstruction Algorithm

The Ware-Aki algorithm computes all r_i reflection coefficients from the input impulse response which are used in a recursive equation to compute the axial resolution, given by

$$S_{i+1} = S_i\left(\left(1+r_i\right)/\left(1-r_i\right)\right) \tag{3}$$

Here, S_i denotes an initial condition, and S_{i+1} represents the cross sectional area of a cylindrical segment. So, the entire reconstructed axial resolution is composed by short cylindrical segments with an axial length ℓ, as seen in Fig. 2, according to the equation

$$\ell = c/\left(2F_s\right), \tag{4}$$

where c denotes the speed of sound of 343 m/s at room temperature, and F_s the sampling frequency of 100 kHz.

E. Cylindrical Cavity

The solution of the inverse problem was evaluated by estimating the axial resolution for an in vitro model of a human upper airway, as it is shown in Fig. 6.

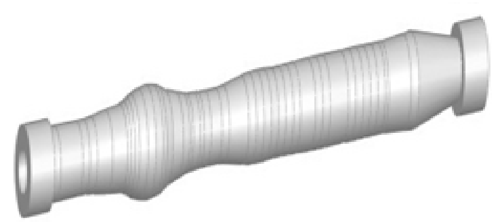

Fig. 6. The cavity of study describes a direct measurement for an in vitro model of the human upper airway.

The direct measurement represents an average resulting from the use of short cylindrical segments, measured from the pharynx down to the carina. The cavity of study is coupled to the acoustic reflectometer. A Biopac System MP150 is used to generate and record the acoustic waves which are propagated into a long source tube.

III. Results

It was found that a frequency step below 50 Hz improves the frequency content in the impulse response, although the computational cost is highly increased. On the other hand, this scenario requires the use of a much longer source tube to record a complete period for acoustic signals with a very low frequency, and avoid a noisy environment in the calculation of the frequency response. Hence, a frequency step of 100 Hz not only reduces the computational cost in the solution of inverse problem, but also provides the needed frequency content to improve the axial resolution.

Fig. 7 shows a comparison between the direct measurement and the reconstructed axial resolution. It is noticed that a reconstructed axial resolution, at a frequency step of 100 Hz, underestimates the direct measurement. However, a better reconstructed axial resolution is computed after the frequency impulse response is fitted by cubic splines to improve its frequency content such that it represents a frequency step of 50 Hz.

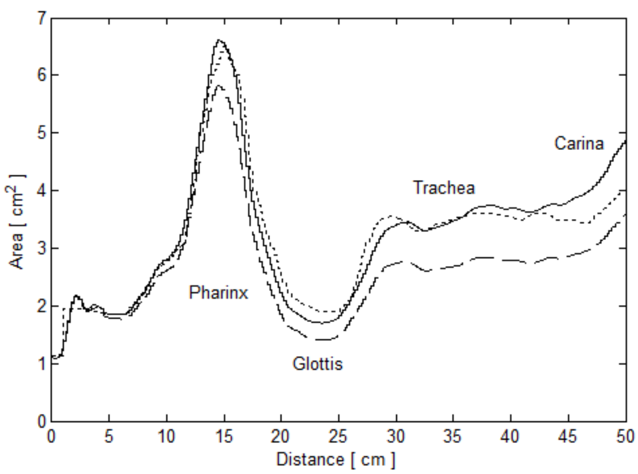

Fig. 7. Comparison among axial resolutions; - - - - - - - Direct measurement, — — Reconstructed at a frequency step of 100 Hz, and ——— Reconstructed at a frequency step of 50 Hz.

Besides the fact that the Ware-Aki algorithm does not consider losses in the solution of the inverse problem, several errors are carried out during the application of the computational method. Therefore, a drawback lies in the fact that the axial resolution for a long cylindrical cavity may be highly affected as function of distance due to losses. However, this reconstruction algorithm is an effective mathematical tool to solve the inverse problem whenever the cavity is not too long. Then, the impulse is well computed, and losses along the source tube are properly compensated.

IV. Conclusion

The computational cost for solving the inverse problem in acoustic reflectometry through Gaussian-sinusoidal waves is much lower than using acoustic pulses. Despite the mathematical procedure is very sensitive to acquisition of noise, the direct measurement is estimated within an acceptable margin of error. It is shown that Ware-Aki algorithm is not only limited in applying acoustic pulses. It is not required to identify the starting points for each acoustic wave in the mathematical procedure to compute reflection coefficients. However, it is necessary to evaluate this methodology based on several profiles and perform a comparison of results. A future development consists in using an array of loudspeakers to improve the frequency generated for each acoustic wave such that the bandwidth may be swept at different frequency steps.

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