A New Otological Diagnostic System Providing a Virtual Tube Model

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***Abstract*— Sonotubometry allows for the detection of the dynamic Eustachian tube function under physiological conditions, whether the eardrum is intact or perforated. Quality and reliability of state-of-the-art sonotubometry have been substantially improved by a new real-time system for otological diagnostics [1]-[4]. Moreover, this diagnostic system provides a time-variant virtual model of the Eustachian tube as a new feature, which opens up entirely new possibilities in monitoring Eustachian tube openings. In this work we investigate the correlation of the virtual model to the human anatomy.**

I. Introduction

In contrast to most clinical examinations, such as tympanometric, manometric, radiologic, and endoscopic approaches, sonotubometry studies the Eustachian tube activity in physiological conditions [5]-[7]. Applying an acoustic signal (e.g., 8 kHz sine) in the nasal cavity the reaction of the nose/ear system is recorded simultaneously by a microphone located in the ear. Changes of sound intensity in the outer ear indicate activity of the Eustachian tube provoked by, e.g., yawning or swallowing.

In previous papers [1]-[4] we introduced a novel real-time system for otological diagnostics, where the Eustachian tube is treated as a linear transmission system. Its impulse response $\mathbf{w}(k) = (w_1(k), w_2(k), \ldots, w_n(k))^T$ and the corresponding transfer function $W(e^{j\Omega})$ are obtained by a perfect sequence exitation of the nose/ear system and a subsequent system identification [8], [9].

Apart from the information at 8 kHz we now can exploit the information of the complete spectrum up to 16 kHz ($f_s = 32$ kHz). The benefits are twofold. On the one hand the fluctuations of sound level intensity can be mapped with the quadratic norm of the impulse response $\mathbf{w}(k)$

$$\Theta(k) = ||\mathbf{w}(k)||^2 = \sum_{i=0}^{N-1} w_i^2(k) \qquad (1)$$

in much better quality. Fig. 1-a illustrates the norm $\Theta(k)$ for one measurement. On the other hand the gain of information is used to extract a novel feature relevant for medical diagnostics. Based on techniques known from speech processing [10], a virtual model of the nose/ear transmission link is generated [1]. Fig. 1-b,c shows two examples at different time instants; one with a tube closed and one with a tube open.

In Sec. II we will briefly describe the setup of the real-time diagnostic system. For the verification of the virtual model it is of main interest to which extent the virtual model and the human anatomy do match. As a reference system we introduce a polyviny chloride (PVC) hardware model in Sec. III. With respect to this reference PVC model we optimize those parameters of the diagnostic system which are particularly decisive for the quality of the results and the shape of the model (Sec. IV). In Sec. V the results of measurements and comparisons between the hardware model and the optimized virtual model are summarized. Moreover, we provide a direct comparison between human anatomy and the related virtual model.

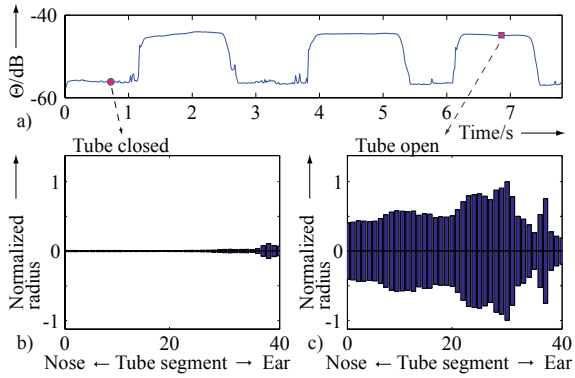

Fig. 1. Typical results of the real-time diagnostic system
a) Norm $\Theta(k)$ for 3 yawning manoeuvres of a test person
b) Virtual model for a time instant with *closed* tube
c) Virtual model for a time instant with *open* tube

II. The Real-time Diagnostic System

The setup of the new real-time system for otological diagnostics is depicted in Fig. 2. For communication with the measurement hardware the diagnostic system uses a PC based platform for multichannel real-time digital signal processing named *RT Proc*. The loudspeaker and the microphone are connected to an external multichannel sound card which in turn is connected with a laptop via USB. In this setup *RT Proc*

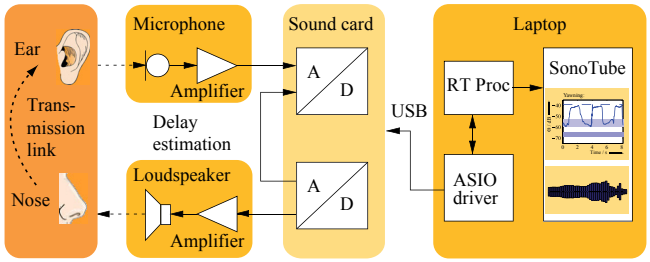

Fig. 2. A new real-time system for otological diagnostics

makes use of the sound cards ASIO driver for hardware control.

The actual application software *SonoTube*, as it is called, performs the excitation of the transmission link between nose and ear with perfect sequences [8] and records its reaction. A signal processing unit generates the two outcomes of the system according to Fig. 1. Based on the impulse responses $\mathbf{w}$, the $\Theta(k)$-curve as well as the time-variant virtual model are generated. For the model the autocorrelation coefficients φ_{ww} are calculated for each time instant and the normal equation system is set up and solved, e.g., by means of the Levinson-Durbin algorithm [10]. In analogy to the tube model used in speech processing, the resulting reflection coefficients K are transformed iteratively into cross-sectional areas A leading to the virtual model (see Fig. 3). In combination with a Graphical User Interface (GUI) *SonoTube* allows even the non-expert to operate the system in clinical routine.

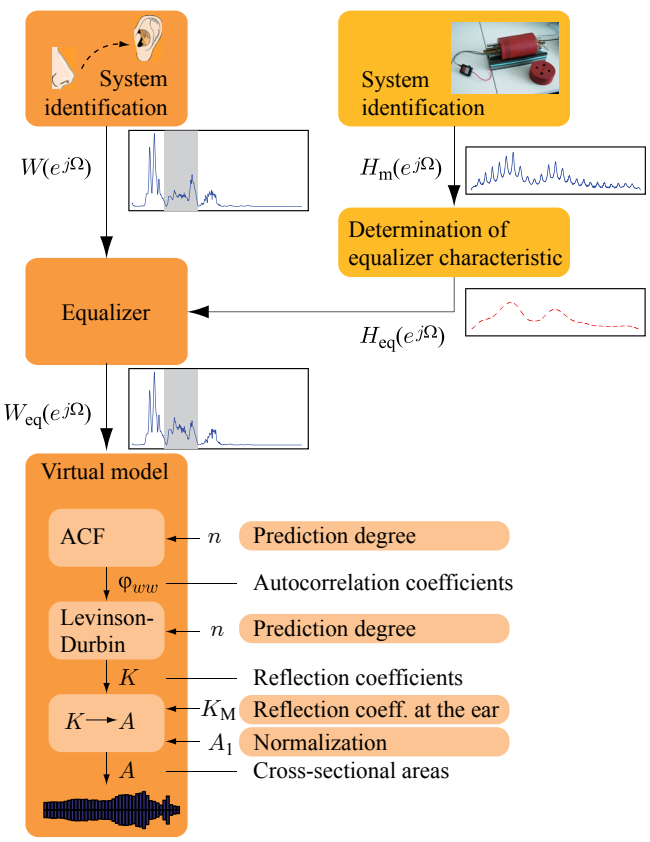

Fig. 3. Digital signal processing of the diagnostic system

III. The Reference PVC Model

For the verification and optimization of the virtual model we need a reference model as the particular contour of the human nose/ear system is not known in detail. For this reason we produced a PVC hardware model according to Fig. 4.

The PVC model consists of numerous discs. Each disc features four fixing holes and one central tube to be measured. They are fixed by guide bars. The central tubes differ in length as well as in cross section. Attaching the single discs one after another leads to a well-known tube contour. Fig. 5 illustrates the contour of one setup.

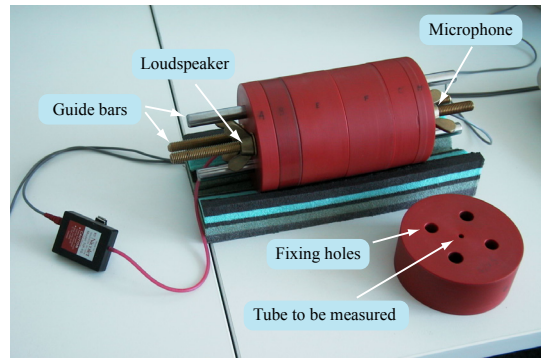

Fig. 4. Reference PVC model

For the measurement with the real-time system, the loudspeaker and the microphone are inserted at both sides of the reference PVC model. First experiments with a prototype diagnostic system provide a virtual model as presented in Fig. 5. Obviously, the degree of correlation between given tube and its virtual model has not turned out to be satisfactory and deserves further study.

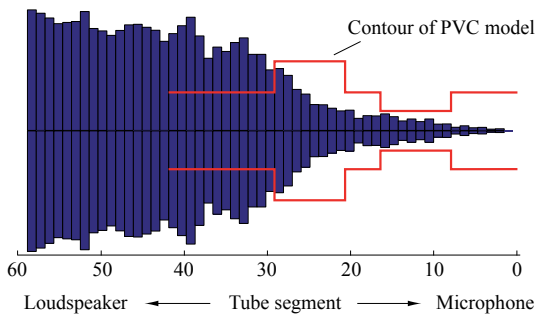

Fig. 5. Contour of PVC model and its virtual model (*first* prototype)

IV. Optimization of the Real-time System

Due to the mismatch between the known tube contour and its virtual model (Fig. 5), an optimization of the real-time system is performed. Apart from the hardware components, the diagnostic system applies different digital signal processing modules given in Fig. 3, which are decisive for the performance of the system. Within this section we will discuss their influence and optimize the different components with respect to our reference PVC model.

A. Hardware Components

For the new real-time diagnostic system mainly off-the-shelf components are used. Only the amplification of the microphone and loudspeaker signals is performed by a custom designed amplifier box.

To provide a good acoustical coupling and a comfortable fit in the nose, earphones with silicon earbuds were selected as loudspeakers. On the detection side we chose a $1/8''$ miniature microphone. Investigations have shown that the diagnostic system is especially sensitive to the absence of low frequency

components in the stimulus signal. Therefore, high-quality devices for the acoustic interface have been chosen carefully to perform well at low frequencies.

B. Equalization

For optimal results the influence of the measurement system itself, i.e., its plain transfer function measured without any tube, has to be eliminated by an equalizer. In the first prototype the exploited equalizer characteristic was measured in free field condition in an anechoic chamber.

However, for the PVC model as well as for the Eustachian tube, the measurements are generally performed inside a tube with almost closed volume. This motivates the introduction of a kind of *in-tube* equalizer characteristic.

For this reason we set up a PVC model with one uniform tube of length $L = 26\,\mathrm{cm}$ and measure the transfer function of the *complete* system ($H_\mathrm{m}(e^{j\Omega})$, Fig. 6-b), comprising both, the uniform tube *and* the real-time system. According to

$$f_n = n \cdot \frac{c}{2L}\,; \quad n = 1, 2, 3, \ldots\,; \quad c = 344\,\mathrm{m/s} \tag{2}$$

the resonance frequencies f_n of the uniform tube and thus its ideal transfer function $H(e^{j\Omega})$ can be theoretically determined. Besides the result of the measurement $H_\mathrm{m}(e^{j\Omega})$ we plot the ideal transfer function $H(e^{j\Omega})$ in Fig. 6-a. Taking $H(e^{j\Omega})$ as target, the spectral envelope of $H_\mathrm{m}(e^{j\Omega})$ can be interpreted as *in-tube* equalizer characteristic, denoted by $H_\mathrm{eq}(e^{j\Omega})$.

Fig. 6-c depicts the transfer function

$$\hat{H}_\mathrm{i}(e^{j\Omega}) = H_\mathrm{m}(e^{j\Omega}) / H_\mathrm{eq}(e^{j\Omega}) \tag{3}$$

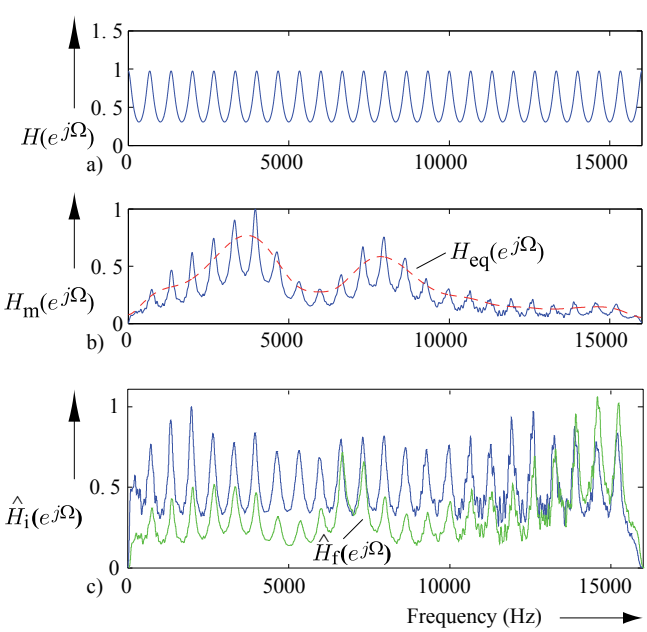

Fig. 6. Determination of the equalizer characteristic
a) Ideal transfer function of a uniform tube of length $L = 26\,\mathrm{cm}$
b) Measured transfer function $H_\mathrm{m}(e^{j\Omega})$ and resulting equalizer characteristic $H_\mathrm{eq}(e^{j\Omega})$
c) $\hat{H}_\mathrm{i}(e^{j\Omega})$ equalized with *in-tube* equalizer characteristic H_eq
$\hat{H}_\mathrm{f}(e^{j\Omega})$ equalized with *free field* equalizer characteristic

after equalization with the *in-tube* equalizer characteristic, and $\hat{H}_\mathrm{f}(e^{j\Omega})$ equalized with the *free field* equalizer characteristic.

The direct comparison demonstrates that $\hat{H}_\mathrm{i}(e^{j\Omega})$ approximates $H(e^{j\Omega})$ obviously better than $\hat{H}_\mathrm{f}(e^{j\Omega})$. The real-time system directly benefits from the new *in-tube* equalizer characteristic $H_\mathrm{eq}(e^{j\Omega})$ as we will see in Sec. V.

Despite the fact that the measures in the Eustachian tube differ from the one in the PVC model, we recommend the use of the *in-tube* equalizer characteristic as it reflects the real measurement situation in the nose/ear system significantly better than the free field condition.

C. Algorithmic Parameters

Finally, the parameters for the computation of the virtual model will be adapted to our special application. According to Fig. 3, the prediction degree n, the reflection coefficient at the ear K_M, and the normalization factor A_1 are particularly decisive for the shape of the model. The structure of the model can be basically improved by an appropriate choise of these parameters.

1) Prediction Degree: Starting at the microphone side the increase of the prediction degree n leads to more tube segments towards the loudspeaker direction. By an extension of the prediction degree from n to $n+1$, the past n cross sections stay alike, whilst one new segment is added to the left.

According to our virtual model the length of one virtual segment amounts to

$$\Delta s = \frac{c}{2 \cdot f_s} = \frac{344\,\mathrm{m/s}}{2 \cdot 32000\,\mathrm{Hz}} = 5.357\,\mathrm{mm}\,, \tag{4}$$

with sampling rate f_s and sound velocity c. In combination with length Δs the prediction degree defines the length of the complete virtual model. Consequently, for the prediction degree we recommend $n \geq L/\Delta s$.

2) Reflection Coefficient at the Ear: Within the model of speech production at the open mouth a "soft" wall reflection with $K_\mathrm{M} = 1$ is assumed. In our application, however, the tube is closed at the end by the microphone capsule. For this reason the choice of $K_\mathrm{M} = -1$, i.e., a "rigid" wall reflection, is more appropriate. Note that the change of this single parameter affects the complete virtual model.

3) Normalization Factor: For the determinination of the cross sectional areas in the recursion

$$A_{i+1} = A_i \cdot \frac{1 - K_i}{1 + K_i}\,; \quad i = 1, \ldots, n \tag{5}$$

one cross section has to be defined, either A_1 at the ear or A_{n+1} at the nose. We opted for the normalization at the ear with $A_1 = 1$.

V. Results

Each single hardware component, software module and parameter choice has its own effect on the virtual model. The presentation of these individual effects would by far exceed the scope of this paper. Therefore, in this section we will display

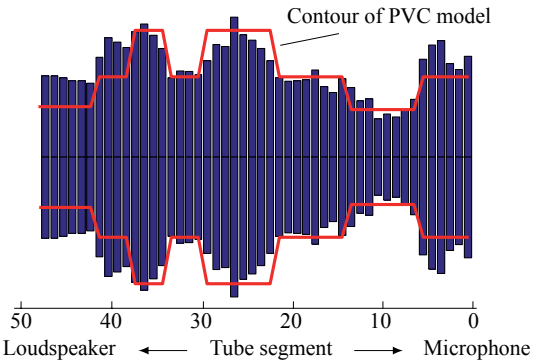

Fig. 7. Contour of PVC model and its virtual model (*optimized*)

the current virtual model combining all improvements of the optimization phase.

At first, we focus on the match between the reference PVC model and its virtual model. For one setup of discs the tube contour and its virtual representation are plotted in Fig. 7. The comparison with Fig. 5, our "starting point", indicates to which extent the virtual model benefits from the optimization. Clearly, a correlation between real and virtual model can be detected.

Alternatively, we measured a nose/ear transfer function of a test person and determined the related virtual model (Fig. 8). Based on anatomical data an artificial curve of the nose/ear system is generated and introduced in Fig. 8 as a kind of anatomic reference. Note that the lengths of the anatomic reference are precise, whilst the corresponding volumes are only estimates.

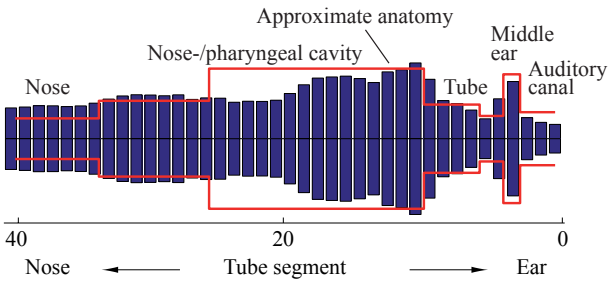

Fig. 8. Contour of human anatomy and its virtual model (*optimized*)

The inspection of the two examples provides an idea of the degree of correlation achieved so far, which is not perfect, but reasonable. Future work will aim at a further improvement of the correlation. One approach, e.g., is the consideration of loss effects in the model.

VI. Conclusions

Within the framework of an interdisciplinary cooperation a new real-time acoustic measurement prototype for otological diagnostics was developed. One novelty of the system is that a completely new feature can be attained in terms of a virtual model, which visualizes artificially the Eustachian tube activity as a kind of "acoustic tube endoscopy".

For a precise evaluation of the diagnostic system a PVC hardware model was introduced as a reference tube. In the first experiments the degree of correlation between the reference tube and its related virtual model was deemed inadequate.

Enabled by the reference tube we performed further studies at the diagnostic system and optimized the applied hardware components, the equalizer, as well as decisive software parameters.

One main result is that the system reacts especially sensitive to the absence of low frequency components leading to the choice of high-quality devices for the acoustic interface. Furthermore, the reflection coefficient at the ear turned out to be especially decisive for the shape of the model. This parameter was adopted to our application and the assumption of a "soft" wall reflection was changed to a "rigid" wall reflection.

As a result of the optimization phase, the virtual model now features a clear match to the given tube of the PVC model. Furthermore, experiments with the Eustachian tube of test persons reflect a reasonable correlation between the virtual model and the expected anatomy of the nose/ear system.

Future work will focus on a further improvement of the system for "acoustic tube endoscopy", e.g., by considering loss effects in the virtual model.

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