ACOUSTIC MODELING OF NO GAS EVACUATION FROM THE MAXILLAR SINUSES

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ABSTRACT

Previous work has shown that the ventilation of nitric oxide (NO) from the maxillar sinuses is affected not only by the steady air stream through the nasal tract, but also if this air stream is modulated by vocal fold activity. In order to explain the increased ventilation during such nasal murmur two models were built; one physical model, and one computer model of this physical model. This paper describes the computer model and compares it against data from the physical model.

1. INTRODUCTION

Recent measurements have shown that the nitric oxide (NO) produced in the maxillar sinuses can be evacuated by producing nasal murmur; the NO content of the nasal airflow increases under these conditions[1]. Experiments were carried out to test the hypothesis that this effect is caused by resonance in the nasal tract and sinus cavities. In a previous study, a model was constructed where airflow from a pressure tank was modulated at different frequencies [2]. This airstream was passed through a tube with a radial hole constituting the neck of a Helmholtz resonator with a gas containing NO. The NO content of the air streaming out of the tube was measured. This NO content varied, when the location of the resonator, its air volume, or the modulation frequency of the airflow was changed.

Even though it can be assumed that the displacement of the air plug in the resonator neck has a central role for the exchange, there are rather complex mechanisms involved, including diffusion and possibly turbulence. For this reason a simplified computer model was developed. The computer model allows for easier modification of the geometry and can also provide information regarding flow and displacement, entities being difficult to measure directly in the physical model. This study examines to what extent the computer model can predict the behavior of the physical model.

2. METHOD

2.1. Physical model

A loudspeaker (Audax HM130Z12) was mounted in a 2-liter box, Figure 1. The back side of the loudspeaker element was closed and the front side was connected to a 465 mm long tube with an inner diameter of 20 mm. At 250 mm from the open end of the tube a 60 ml syringe was mounted, forming an adjustable Helmholtz resonator.

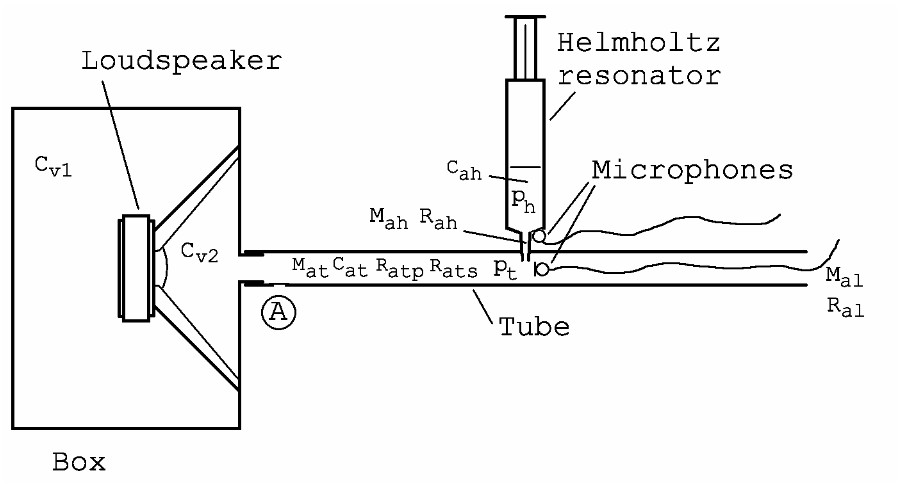

Figure 1. *The physical model. A boxed loudspeaker was connected to a tube. A syringe inserted through the tube wall formed a tunable Helmholtz resonator. Two microphones were utilized to measure the pressure exciting the resonator, p_t, and the pressure inside the resonator, p_h, respectively. In previous experiments a DC flow was inserted at point A, while in the present study no DC flow was used.*

2.2. Measurements on the physical model

To examine the excitation of the Helmholtz resonator, two omnidirectional electret microphones were used; one inside the tube near the resonator, and one inside this resonator. The first microphone measured the pressure exciting the resonator, p_t, and the second measured the pressure inside the resonator, p_h. The latter pressure is proportional to the displacement of air in the resonator neck.
The frequency responses of the model were recorded by means of the software Tombstone, written by author SG. This program generates a logarithmic sine sweep and simultaneously records the amplitude response. The sweep ranged from 20 to 20 000 Hz and lasted for 18 seconds.

2.3. Computer model

In order to examine the acoustic gas flow in the Helmholtz resonator neck, a computer model was developed. The model includes a classic loudspeaker model, two cavities (C_{v1} and C_{v2}), a lumped-element model of the tube, a radiation impedance (M_{al} and R_{al}) and a Helmholtz resonator. The Helmholtz resonator was modeled as a series resonator (C_{ah}, R_{ah}, M_{ah}). The tube is modeled by a number of sections (typically 26) each consisting of an acoustic mass, a compliance and two resistances (M_{at}, C_{at}, R_{atp}, R_{ats}). The analog diagram of the simulation is shown in figure 2.

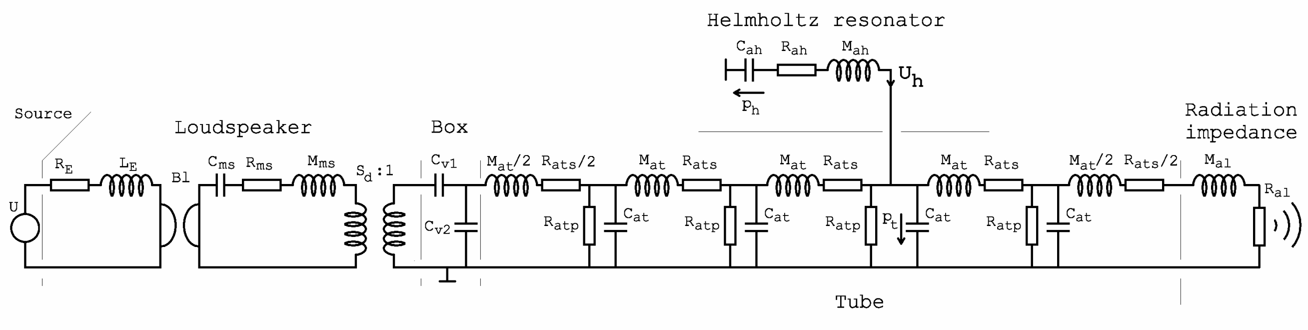

Figure 2: *The analog diagram of the acoustic model. For simplicity, only four tube sections are shown. Flow U_h is of prime interest for the ventilation of NO gas from the Helmholtz cavity.*

The inclusion of the loudspeaker and the cavities of the box in the model were essential for a good fit between data observed in the two models. The loudspeaker and the box were simulated in a classical manner, see e.g. [3] using parameters from the manufacturer's datasheet, except for the voice coil inductance, which was considered lossy according to Leach [4]. The values of the lossy inductance was obtained by matching the model against the electrical impedance curve supplied by the manufacturer.

The compliances C_{v1} and C_{v2} were calculated as

$$C_{v1} = \frac{V_1}{r_0 c^2} \tag{1}$$

$$C_{v2} = \frac{V_2}{r_0 c^2} \tag{2}$$

where V_1 and V_2 are the volumes of the cavities, ρ_0 is the density of air (1.2 kg/m^3), and c is the sound velocity in air (345 m/s). The lumped elements of the tube were calculated as

$$M_{at} = \frac{L}{n r_0 S_t} \tag{3}$$

$$C_{at} = \frac{S_t L}{n r_0 c^2} \tag{4}$$

$$R_{atp} = \sqrt{\frac{M_{at}}{C_{at}}} \cdot Q_{tubep} \cdot n \tag{5}$$

$$R_{ats} = \frac{\sqrt{\frac{M_{at}}{C_{at}}}}{n \cdot Q_{tubes}} \tag{6}$$

where S_t is the cross-sectional area of the tube, L is the total length of the tube, Q_{tubes} and Q_{tubep} are values describing the losses and n is the number of tube sections.

The Helmholtz resonator was modeled by entering the volume of the syringe cavity V_h, the Helmholtz frequency f_h and a Q value Q_h. The software also optionally provided a possibility to lock the value of M_{ah} and recalculate f_h when V_h was changed.

$$C_{ah} = \frac{V_h}{r_0 c^2} \tag{7}$$

$$M_{ah} = \frac{1}{C_{ah}(2pf_h)^2} \tag{8}$$

$$R_{ah} = \frac{\sqrt{\frac{M_{ah}}{C_{ah}}}}{Q_h} \tag{9}$$

$$f_h = \frac{1}{2\pi\sqrt{M_{ah}C_{ah}}} \tag{10}$$

The radiation impedance was modeled as the low-frequency behavior of a baffled piston:

$$R_{al} = \frac{\rho_0}{2\pi c}\omega^2 \tag{11}$$

$$M_{at} = \frac{8\rho_0}{3\pi r_t} \tag{12}$$

where ω is the angular frequency and r_t is the radius of the tube. The use of the baffled piston impedance is an approximation; the real tube end was not baffled. However, the error caused by this approximation can be assumed to be small, since the radiation impedance is small compared to that of the tube.

3. RESULTS

Figure 3 shows the agreement between the two models with respect to the pressure driving the resonator, and the pressure inside the resonator cavity. The testing was performed for resonator volumes V_h of 5, 10, 20, 40, and 60 ml. The results show that the computer model was capable of predicting the behavior of the physical model up to about 2 kHz. Some of the parameters had to be manually adjusted in order to make the curves fit. This was particularly true for the resistive losses, which are hard to estimate from the geometry of the model. However, once a good match was achieved, all parameters were kept constant, except for the V_h parameter which was set to the values listed above.

The displacement of air in the resonator neck is proportional to the pressure inside the cavity. Thus, from the pressure inside the cavity it can be seen that this displacement varies with the frequency. Furthermore, the maximum displacement amplitude in the neck does *not* occur at the Helmholtz resonance frequency f_h. The reason for this difference can be seen in the curve representing the driving pressure, which shows a minimum at f_h. This indicates that the frequency for maximum exchange of NO gas in the maxillar sinuses probably cannot be calculated from dimensions of the sinuses and the channel to the nasal cavities alone. Also the rest of the nasal cavity would probably have to be taken into account.

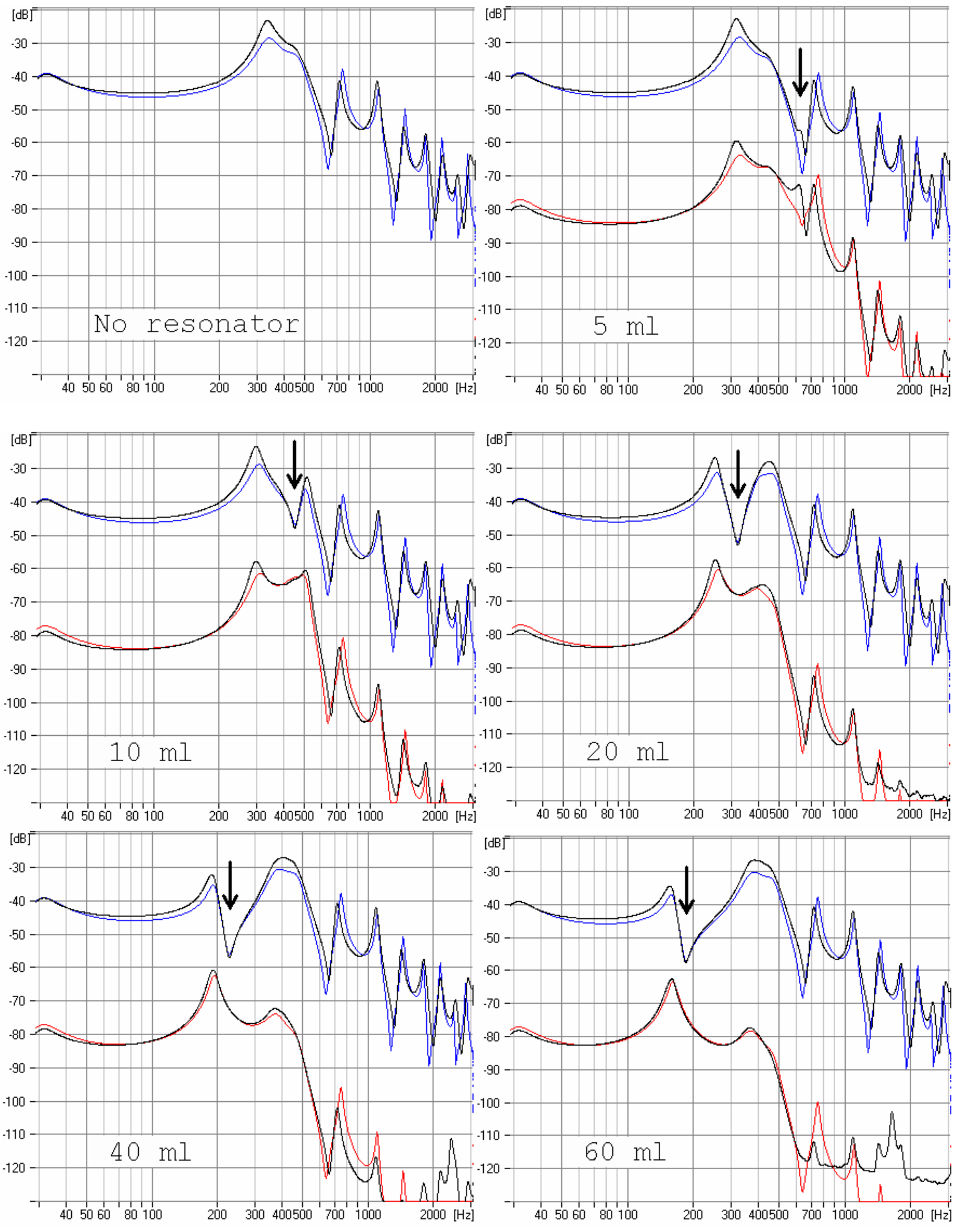

Figure 3. *Simulated and measured data. The top left panel represents the p_t pressure, when the Helmholtz resonator was removed and the hole was plugged. The other five panels represent five different resonator volumes (5, 10, 20, 40 and 60 ml respectively). In each graph the upper curves represent the driving pressure p_t, and the lower the pressure inside the Helmholtz resonator cavity p_h. The black curves were measured on the physical model and the colored curves were derived from the computer model. The arrows indicate the Helmholtz frequency*

4. DISCUSSION AND CONCLUSIONS

In a previous experiment [2], a physical model similar to the present one was used. In that case, the syringe was filled with NO gas and a DC flow was inserted near the loudspeaker end of the tube, at "A" in figure 1. It was shown that the rate of evacuation of NO gas varied depending on the frequency of the modulation induced by the loudspeaker.

In the present study, we focused on the displacement of the air in the resonator neck. It can be assumed that this air displacement is closely related to the ventilation of NO gas. As mentioned before, the displacement and flow in the physical model can be indirectly measured by measuring the pressure inside the resonator cavity. Since this pressure appears as a result of the flow through the neck into the cavity, the displacement is proportional to the pressure and the flow to its derivative.

It could be assumed that the flow U_h could be affected by several factors. One would be the relation between the Helmholtz frequency and the exciting frequency. A maximum flow could be expected if these frequencies are identical and if the exciting pressure is constant. On the other hand, the exciting pressure varies due to resonances in the tube. If the Helmholtz resonator neck is placed in a pressure node of such a resonance, a maximum could be expected to occur since the exciting pressure would then be maximized. However, the acoustic load from the resonator affects the resonances in the tube. So, if the Helmholtz resonator is placed at position where a pressure node would be expected in the unloaded tube, the node pressure drops. The simulations and measurements in this study indicate that the net effect of this is that two U_h flow maxima occur, one at each side of the original resonance/node frequency.

The matching of the computer model to the measured data was highly instructive. It turned out to be fairly easy to match the low-frequency (<500Hz) behavior of the computer model. However, in order to achieve a good match up to 2-3 kHz, the accuracy of the box and tube geometry and the resonator and microphone placement showed to be important. A second practical experience with the physical model was that it is fairly easy to overload the microphones. The sound pressure inside the tube and resonator can easily reach very high levels.

Summarizing, our computer model was surprisingly efficient in replicating data obtained from a physical model of the nasal tract and maxillar sinuses. Moreover, the model could be easily be adjusted so as to reflect realistic data obtained from e.g. MR imaging of human subjects. However, it is clear already from the present rather course modeling of the nasal resonator system that the increased NO ventilation that occurs during a nasal murmur can be explained by the acoustic flow into and out of the maxillar sinuses. The AC pressure of the modulated airstream forces the airplug in the Helmholtz resonator neck to vibrate, thus pumping NO out of the cavity.

5. REFERENCES

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