Reciprocal measurement of acoustic feedback paths in hearing aids

Tobias Sankowsky-Rothe[a)] **and Matthias Blau**
Institute of Hearing Technology and Audiology, Jade Hochschule, Oldenburg, Germany
tobias.sankowsky@jade-hs.de, matthias.blau@jade-hs.de

Henning Schepker and Simon Doclo
Department of Medical Physics and Acoustics and Cluster of Excellence "Hearing4All," University of Oldenburg, Oldenburg, Germany
henning.schepker@uni-oldenburg.de, simon.doclo@uni-oldenburg.de

Abstract: A reciprocal measurement procedure to measure the acoustic feedback path in hearing aids is investigated. The advantage of the reciprocal measurement compared to the direct measurement is a significantly reduced sound pressure in the ear. The direct and reciprocal measurements are compared using measurements on a dummy head with adjustable ear canals, different earmolds, and variations in the outer sound field. The results show that the reciprocal measurement procedure can be used to obtain plausible feedback paths, while reducing the sound pressure in the ear canal by 30 to 40 dB.

[QJF]
Date Received: July 24, 2015 **Date Accepted:** September 28, 2015

1. Introduction

In hearing aids acoustic feedback due to the coupling between the receiver and the microphone is a problem which limits the maximum applicable gain, especially for open-fitting hearing aids. By using feedback cancellation algorithms, e.g., based on adaptive filters to estimate the acoustic feedback path, the maximum gain can be considerably increased.[1] The development and optimization of these algorithms, therefore, could benefit from a precise measurement of the acoustic feedback path. For that purpose, it is desirable to use acoustic feedback paths measured on human subjects to account for individual ear geometries and to track time-varying feedback paths, e.g., due to the subject moving in the acoustic field. In the direct measurement procedure the sound pressure is generated by the hearing aid receiver in the ear canal and recorded with the hearing aid microphone located outside of the ear. However, for reliably identifying the acoustic feedback path, this procedure requires a high sound pressure level (SPL) inside the ear canal, severely limiting its applicability for human subjects. In order to reduce the SPL in the ear canal a reciprocal measurement procedure of the acoustic feedback path is proposed, where, according to the reciprocity principle,[2,3] the positions of microphone and receiver are interchanged.

2. Method

The acoustic feedback path (FBP) for the direct measurement procedure is defined as

$$H_{\mathrm{FBP}}(f) = \frac{v_{\mathrm{mic}}^{A}(f)}{v_{\mathrm{rec}}^{B}(f)}, \qquad (1)$$

with $v_{\mathrm{mic}}^{A}(f)$ the voltage of the hearing aid microphone at location A and $v_{\mathrm{rec}}^{B}(f)$ the voltage of the hearing aid receiver at location B at frequency f. According to the reciprocity principle

$$\frac{v_{\mathrm{mic}}^{A}(f)}{i_{\mathrm{rec}}^{B}(f)} = \frac{v_{\mathrm{mic}}^{B}(f)}{i_{\mathrm{rec}}^{A}(f)}, \qquad (2)$$

with $i_{\mathrm{rec}}(f)$ the current into the receiver and the superscripts A and B denoting the locations of the transducers. Therefore, by interchanging the position of the microphone and the receiver the *reciprocity-based feedback path* is given by

$$H_{\mathrm{FBP}}^{\mathrm{recip.}}(f) = \frac{v_{\mathrm{mic}}^{B}(f)}{v_{\mathrm{rec}}^{A}(f)} \cdot \frac{Z_{\mathrm{el}}^{A}(f)}{Z_{\mathrm{el}}^{B}(f)}, \qquad (3)$$

with $Z_{\mathrm{el}}(f)$ denoting the electrical impedance of the receiver.

[a)]Author to whom correspondence should be addressed.

In this study a two-microphone behind-the-ear hearing aid (Siemens, Erlangen, Germany) was used, see Fig. 1. In order to avoid mechanical feedback in the direct measurement procedure, an external receiver (type TWFK-23991, Knowles, IL) was used and attached to a tube 84 mm in length and 1 mm inner diameter. In addition to the microphone signals, the signal applied to the receiver was recorded, such that the directly measured feedback paths could be determined.

For the reciprocal measurement procedure, the positions of the front microphone and the receiver were interchanged with respect to the direct measurement procedure. An additional receiver tube of the same length was used with its open end positioned directly above the front hearing aid microphone, see Fig. 1. The receiver tube from the direct measurement procedure was occluded at the inner end of the earmold. The acoustic load seen by the receiver results from the receiver tube either with an open end (reciprocal measurement) or with the ear canal volume (direct measurement). Although these two cases are acoustically different, the resulting electrical impedances of the receiver are almost identical, such that $Z_{\mathrm{el}}^{A}(f)/Z_{\mathrm{el}}^{B}(f)$ was assumed to be 1 in Eq. (3). A probe microphone (type ER7c, Etymotic Research, IL) was used to sense the sound pressure, with the probe tube positioned through an additional bore with its tip at the inner face of the earmold. As the sensitivity of the microphones are part of the measured feedback path, the signal of the probe microphone (reciprocal measurement) had to be calibrated to the sensitivity of the front hearing aid microphone (direct measurement), i.e.,

$$H_{\mathrm{FBP}}^{\mathrm{recip.}}(f) = \frac{\upsilon_{\mathrm{mic,probe}}(f)}{\upsilon_{\mathrm{rec}}(f)} \frac{B_{\mathrm{mic,front}}(f)}{B_{\mathrm{mic,probe}}(f)}, \tag{4}$$

with $B_{\mathrm{mic,front}}(f)$ and $B_{\mathrm{mic,probe}}(f)$ the sensitivities of the front hearing aid microphone and the probe microphone, which were determined in a free-field measurement.

Reciprocal and direct measurements of acoustic feedback paths were performed for different ear canal geometries and ventings and for a variety of outer sound fields. A dummy head with adjustable ear canals [DADEC (Ref. 4)] was used, where the ear canal is simulated by means of tubes with different diameters, terminated by a resonator mimicking the acoustic impedance of the eardrum. By changing the position of the resonator, the length of the ear canals could be adjusted continuously. Three different ear canal diameters ($d = 6$, 7, and 8 mm) and two different ear canal lengths ($l = 15$ and 20 mm) were considered. Furthermore, custom-made earmolds with two different ventings were produced for each ear canal diameter: (1) an open earmold and (2) an earmold with a vent of 2 mm diameter. In addition, several outer sound field conditions were considered since these may significantly influence the acoustic feedback path.[5,6] More specifically, five different conditions were included in the measurements:

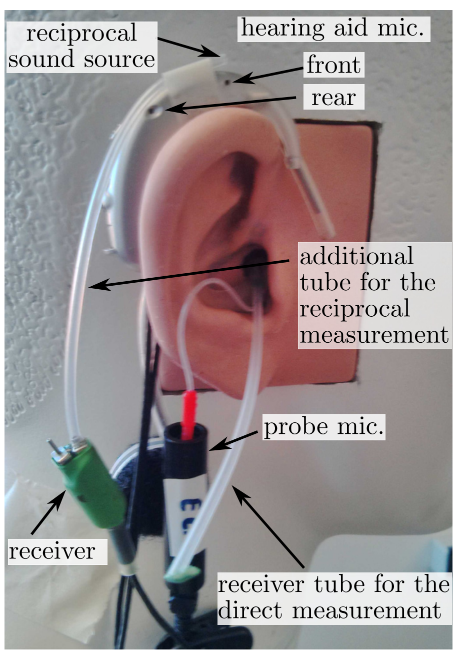

Fig. 1. (Color online) Picture of the hearing aid at the ear with the external receiver and the probe microphone connected for the reciprocal feedback path measurement.

(1) a free-field condition, meaning that there was no obstruction in a distance of at least 1.5 m to the ear, (2) a wall condition, where the dummy head was placed with its shoulder at a wall, and (3)–(5) three conditions with a telephone handset at different distances to the ear (0, 11.5, and 23 cm).

All measurements were carried out with white noise of 10 s duration, using a sampling frequency of 48 kHz. The transfer functions were computed using standard fast Fourier transform-based methods (H_1 estimate, 16 384-point Hann-window, 50% overlap).

The described measurement procedures contain potential sources of errors. First, variability was expected due to small changes of microphone and receiver positions every time the hearing aid was removed from and reattached to the ear. In order to quantify this variability, the measurements for the free-field condition were repeated ten times. In the direct measurements, the hearing aid was reattached to the ear, while in the reciprocal measurements the reciprocal source was reattached to the hearing aid between the repetitions. Second, for the reciprocal measurement procedure, microphone and receiver positions could not be exactly interchanged, i.e., the reciprocal sound source was placed above the front microphone of the hearing aid and the probe microphone was positioned at the inner face of the earmold in close distance to the receiver tube. Hence, systematic errors were expected in the comparison of both measurement procedures.

3. Results and discussion

3.1 Comparison of reciprocally and directly measured feedback paths for the free-field condition

Figure 2 shows, the median levels (top row) and the maximum level differences (bottom row) of the ten repeated feedback path measurements for the free-field condition for all combinations of ventings and ear canal geometries, for the reciprocal measurement procedure (left column) and the direct measurement procedure of the front microphone of the hearing aid (right column). For both measurement procedures, three general trends can be observed: (1) open earmolds lead to a higher level of the feedback path than vented earmolds; (2) a minimum in the level of the feedback path can be observed at high frequencies, which seems to be determined mainly by the ear canal length; and (3) a smaller volume (e.g., smaller diameter and length) of the ear canal leads to a higher level of the feedback path.

Furthermore, for the reciprocal measurement procedure the variability of the feedback paths (due to reattaching the reciprocal sound source) was in the range of 1 to 2 dB except at frequencies where the level of the feedback path was considered to be small. Similarly, for the direct measurement procedure the variability (due to repositioning the hearing aid) was in the range of 1 to 3 dB.

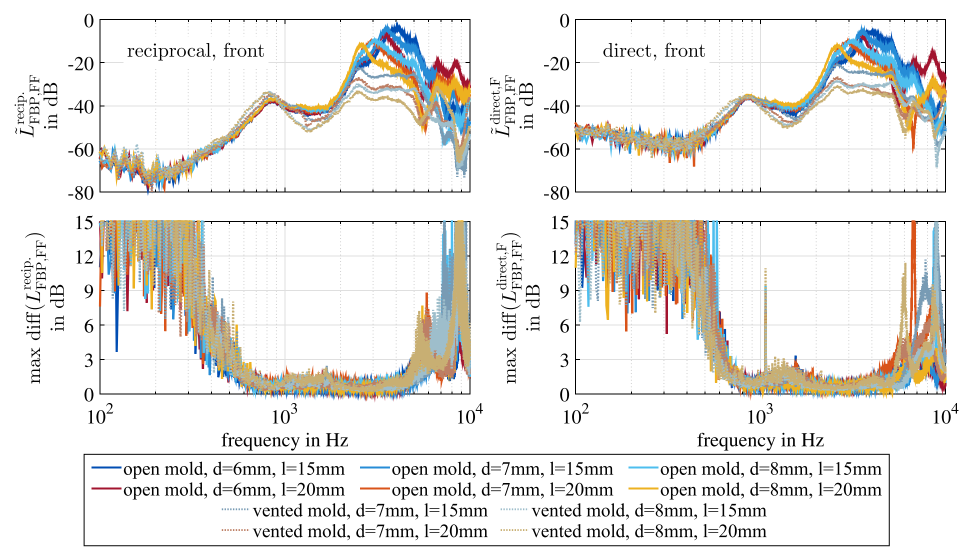

Fig. 2. (Color online) Median levels $\tilde{L}_{\text{FBP}}$ (top row) and maximum level differences (bottom row) of ten repeated feedback path measurements for the free-field condition for all combinations of ventings and ear canal geometries for the reciprocal measurement procedure (left column) and the direct measurement of the front microphone (right column).

In the left panel of Fig. 3, the level differences between the median of the reciprocally measured and the median of the directly measured feedback paths for the front hearing aid microphone are shown. Large differences are observed for frequencies below 500 Hz, where the level of the acoustic feedback path is low. For the direct measurement procedure, higher median levels were observed than for the reciprocal measurement procedure, which is due to the higher ambient noise level outside the ear canal. In the frequency range from 500 Hz to 4 kHz, level differences were in the range of −4 to 2 dB, while at higher frequencies level differences were considerably larger. Data show (in particular, for an ear canal length of 20 mm) a mismatch between the minima of the acoustic feedback paths measured using the reciprocal and the direct measurement procedure, where the minimum in the reciprocal measurement was shifted toward lower frequencies. The right panel shows median level differences between the directly measured feedback paths to the rear and the front microphone. Differences appear small below frequencies of about 500 Hz; however, since the level of the acoustic feedback path is very low, only ambient noise was measured in this frequency range. In the frequency range from 500 Hz to 4 kHz, median level differences were about −2 to −4 dB indicating a lower level at the rear microphone. At higher frequencies, larger differences could be observed at those frequencies where the level of the feedback path is low, but in contrast to the reciprocal measurements, no frequency shift of the minima can be observed. The comparison between the reciprocally and the directly measured feedback path for the rear microphone, both relative to the directly measured feedback path for the front microphone, leads to the following interpretations: (1) differences in the outer position (microphone position in the case of the direct measurement) result in a feedback path differing only by a few dB in a broad frequency range; and (2) differences in the inner position (microphone position in the case of the reciprocal measurement), which occurred only between reciprocal and direct measurement, result in a shifted minimum of the feedback path at higher frequencies.

As the main differences between the reciprocal and the direct measurement of the acoustic feedback path result from a minimum shifted toward lower frequencies in the reciprocal measurement, they can be attributed to the position of the probe microphone in the reciprocal measurement. The probe microphone was not placed at the exact position where the receiver tube would be in the direct measurement, but was placed next to the receiver tube. It is known that at this location in the ear canal, a plane wave cannot be assumed: in Ref. 7 it was shown that large differences of the sound pressure arise at the inner face of an earmold, especially for earmolds with large vents. The shift toward lower frequencies may be interpreted as an apparently extended ear canal length whereby the volume remains constant. This suggests that, although the reciprocal measurement did not provide the real feedback path at the minimum, it still provided a plausible feedback path.

3.2 Sound pressure in the ear canal

The main purpose of measuring the feedback path reciprocally is the reduction of the sound pressure in the ear canal. In both the reciprocal and the direct measurement procedure the receiver was driven by the same electrical voltage. In the direct measurements, the resulting SPLs in the ear canal of the dummy head were between 110 and 115 dB SPL for the different ear canal geometries and ventings which would be unacceptable for human subjects. In the reciprocal measurements, the SPLs in the ear canal were reduced by about 30 dB for the open earmolds and by more than 40 dB for the vented earmolds, thus the absolute SPLs were between 65 and 85 dB SPL.

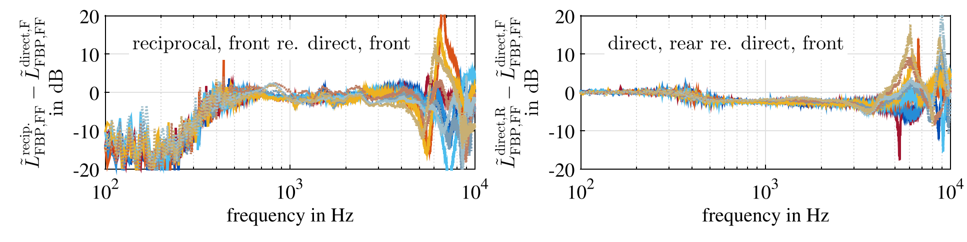

Fig. 3. (Color online) (Left) Median level differences between the reciprocally measured and the directly measured feedback paths, both referring to the front microphone. (Right) In comparison, median level differences between the directly measured feedback paths to the rear and the front microphone. The color code is the same as in Fig. 2.

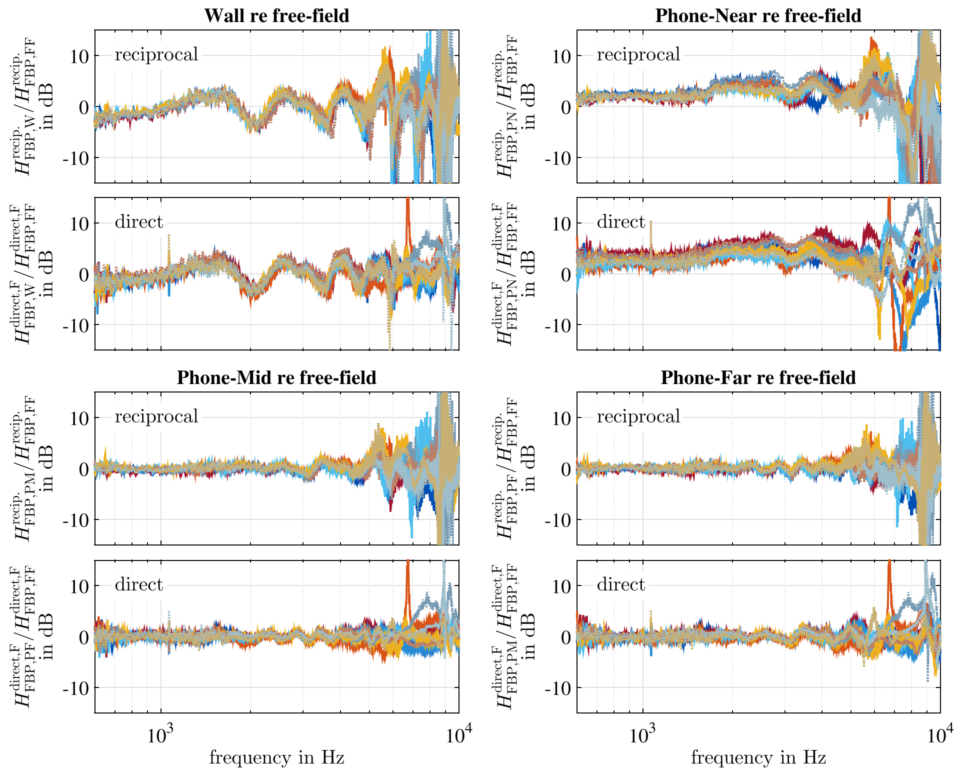

Fig. 4. (Color online) Deviations in the level of the feedback path between obstructed outer sound field and the free-field condition for reciprocally and directly measured feedback paths, for all conditions of ear canal geometries and ventings. The color code is the same as in Fig. 2.

3.3 Influence of the outer sound field

The influence of an obstruction of the outer sound field on both the directly and the reciprocally measured feedback path is shown in Fig. 4, where the deviations in level relative to the free-field condition for the four applied obstructions (a wall, and a telephone handset at three different distances) are shown. As can be observed, the reciprocal and the direct measurements yield similar results up to about 5 kHz. Furthermore, the interaction between the outer sound field and the different combinations of the ear canal geometries and ventings is quite small and in many cases negligible. For frequencies above 5 kHz, the differences between the directly and reciprocally measured feedback paths are more pronounced, although no clear trend is observed that can be attributed to the different obstructions. The differences might be explained by the shift of the minimum and the low signal-to-noise ratio at higher frequencies.

4. Conclusion

In this paper, the reciprocal measurement of acoustic feedback paths in hearing aids was investigated. To this end, direct and reciprocal measurements of acoustic feedback paths were performed on a dummy head while varying the main factors influencing the acoustic feedback path, namely, the outer sound field, the venting, and the ear canal geometries.

It was shown that the overall agreement between directly and reciprocally measured feedback paths was very good, however, errors in the position of the reciprocal microphone in the ear canal lead to a shift of the minimum in the feedback path. Nevertheless, the reciprocally measured feedback paths were plausible and thus can be used in the development of feedback cancellation algorithms. Furthermore, the data showed that the ear canal geometry has a significant influence on the feedback path, such that measurements on individual ear canals seem to be advisable for the development of feedback cancellation algorithms. It was found that the sound pressure in the ear canal was about 30 to 40 dB smaller in the reciprocal measurements compared to the direct measurements when the receiver is driven with the same electrical voltage.

As an outlook, the proposed procedure could be used to track the changes in the acoustic feedback path due to changes in the environment.

Acknowledgment

This work was supported in part by the Research Unit FOR 1732 "Individualized Hearing Acoustics" and the Cluster of Excellence 1077 "Hearing4All," funded by the German Research Foundation (DFG). All data are available at https://www.uni-oldenburg.de/en/mediphysics-acoustics/mediphysics/projects/for-1732/project-f-ear-canal-presentation/publications/.

References and links

[1]A. Spriet, S. Doclo, M. Moonen, and J. Wouters, "Feedback control in hearing aids," in *Springer Handbook of Speech Processing* (Springer, Berlin, Heidelberg, 2008), pp. 979–1000.

[2]J. W. Strutt (Lord Rayleigh), "Some general theorems relating to vibrations," Proc. London Math. Soc. **s1-4**(1), 357–368 (1873).

[3]S. Ballantine, "Reciprocity in electromagnetic, mechanical, acoustical, and interconnected systems," Proc. Inst. Radio Eng. **17**(6), 927–951 (1929).

[4]M. Hiipakka, M. Tikander, and M. Karjalainen, "Modeling the external ear acoustics for insert headphone usage," J. Audio Eng. Soc. **58**(4), 269–281 (2010).

[5]J. Hellgren, T. Lunner, and S. Arlinger, "Variations in the feedback of hearing aids," J. Acoust. Soc. Am. **106**(5), 2821–2833 (1999).

[6]J. M. Kates, "Room reverberation effects in hearing aid feedback cancellation," J. Acoust. Soc. Am. **109**(1), 367–378 (2001).

[7]M. R. Stinson and G. A. Daigle, "Transverse pressure distributions in a simple model ear canal occluded by a hearing aid test fixture," J. Acoust. Soc. Am. **121**(6), 3689–3702 (2007).