Technical paper

Relation between different measures of feedback in hearing aids and gain measures derived from percentile analysis

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1 Abstract

Feedback management is a common feature of today's hearing aids. A huge variety of algorithms exist with the objective to control feedback effectively while achieving a high added stable gain, good sound quality and with a fast adaptation to changes in feedback paths. Because the real-life performance of a hearing aid is significantly affected by its feedback behavior, objective procedures for characterizing feedback management systems are desirable. This study investigates the possibilities of characterizing feedback management systems of commercial hearing aids by estimating the insertion gain derived from percentile analysis (IEC draft standard 60118-15) and analyzing its relation to existing direct measures of feedback. Responses of 10 hearing aids from 5 manufacturers with different signal processing and different feedback control algorithms were recorded in static conditions, using a dummy head setup and realistic test signals. Several instrumental measures of provided insertion gain and distortion related to feedback and its control were calculated from the recordings. Results show that the insertion gain is largely different across devices at the same hearing loss setting, which leads to pronounced differences in feedback susceptibility. Furthermore, the difference in estimated insertion gains for the same device operating with and without feedback control algorithm was found to be indicative of feedback-related problems. High correlations were found between feedback measures from insertion gain data and direct feedback measures, indicating that percentile analysis is applicable in principle to characterizing feedback behavior. The relation of instrumental measures with perceptual performance measures, however, remains to be established.

247 words

2 Introduction

Open fittings become increasingly popular in today’s hearing aids. They offer a higher wearing comfort, easier handling and reduced or absent occlusion effect. For an open fitting, however, the acoustic path between microphone and receiver including the tube may lead to annoying feedback problems at much lower gains compared to a closed fitting. Improved feedback control algorithms are therefore indispensible for hearing aids with open fittings. The aims of such feedback control algorithms are:

1. High added stable gain
2. Good sound quality and low susceptibility to tonal signals at all gains
3. Fast tracking of feedback path changes

A huge variety of feedback control algorithms exists in commercial hearing aids based on e.g. (adaptive) notch filtering, phase modifications or gain limitations. To characterize feedback behavior and to quantify the performance of feedback control systems, several direct measures of feedback-related artifacts have been proposed (e.g., Madhu et al., 2011). This technical study adds the perspective of identifying the fingerprint of feedback artifacts in the gain estimates from percentile analysis (IEC draft standard 60118-15) and relates the findings to the direct measures of feedback of Madhu et al. (2011).

The IEC 118 series contains several standards for hearing aids, e.g. IEC 118-7, "Measurement of the performance characteristics of hearing aids for quality inspection purposes". There are standards for measurements using hearing aids in test mode, technical signals (sine, modulated and unmodulated noise) and 2cc couplers to determine, e.g., the maximum level, maximum gain, total harmonic distortion, noise, battery voltage and others. The ISMADHA percentile analysis test method (EHIMA, 2007; Holube et al., 2010) is planned to become an additional standard (IEC 60118-15) for the measurement of (insertion) gain for speech under more realistic conditions. This method includes a test signal (the International Speech Test Signal – ISTS), standard audiograms, and a measurement procedure (analysis in 3rd octave bands, short time levels).

There are several measures with different aims for the characterization of feedback-related distortion and for the quantification of the effect of feedback control algorithms on system performance. These measures can be divided into five main classes (see Madhu et al. (2011) for a detailed overview):

Broadband energy measures consider energy ratios of broadband signals, such as the Output-to-Reference Signal Energy Ratio (Freed, 2008) or the Feedback-to-Reference Signal Energy Ratio (Spriet el al., 2008; 2009a). These measures exploit the fact that the energy of a hearing aid output signal increases if feedback occurs.

The second class of measures aims at detecting oscillations by, e.g., quantifying (changes of) the coloration of hearing aid transfer functions as a consequence of increasing gains. Examples are the Power Concentration Ratio (Freed and Soli, 2006) and the Hearing Aid Transfer Function Variation Criterion (Shin et al., 2007).

The third class of measures are signal distortion measures like the Frequency-weighted Log-Spectral Signal Distortion (Madhu et al., 2011). These measures consider differences between output and reference signals, perceptually weighted and integrated across frequencies.

An example of a perceptually motivated measure (fourth class) is described by Merks et al. (2006) and Merks (2009), modified in Madhu et al. (2011) to take into account the other non-linear processing that may be active in a hearing aid. Using models of loudness and sharpness, perceptual correlates of entrainment are estimated.

Finally, gain measures as the fifth class consider power spectral densities (PSD) of hearing aid output signals in comparison to the PSD of a reference. Based on PSDs, gain deviations introduced by feedback control algorithms are computed (Freed and Soli, 2006; Madhu et al. (2011).

Feedback management is not independent of other features of the hearing aid, e.g. compression, any kind of gain limitation, directive microphone systems, noise reduction etc. Since details of such interacting features and their effect on the feedback behavior is not known in general, any procedure evaluating feedback management systems will have to consider the complete hearing aid as a black box. Only complete devices including all processing features and fitting options based on input and output signals can be tested. As the gain of a commercial hearing aid cannot be controlled directly, we propose to systematically vary hearing loss settings in order to implicitly control device gain in a systematic way. Using this technique, a variety of test signals were recorded from 10 commercial hearing aids. Insertion gain as well as direct measures of feedback according to Madhu et al. (2011) were computed from the output signals and the relation between all measures was analyzed by a correlation analysis.

The remainder of the paper is organized as follows: First, the method, including setup, test signals, test hearing aids, performance measures and evaluation procedure, is described. Results of the performed measurements are presented and discussed in the subsequent sections. Conclusions derived from the comparison of direct feedback measures and insertion gain measures are drawn in the final section. The paper by Madhu et al. (2011) provides an analysis of the different measures with respect their principal applicability to detecting feedback-related artifacts. This study uses the setup and data by Madhu et al. (2011), adds further data from several other hearing aids gathered in a different laboratory with a similar setup, adds insertion gain measures of all devices using the ISMADHA percentile analysis draft standard method and investigates the relation of the insertion gain data to the direct measures..

3 Method

3.1 Experimental setup

A detailed description of the experimental setup can be found in Madhu et al. (2011). The hearing aid device is mounted on the left ear of a dummy head. Test signals are played back by a loudspeaker in front of the artificial head, while the hearing aid output is recorded by the dummy head microphone. The acoustic gain provided by the hearing aid is set implicitly by varying the hearing loss setting systematically. The output is recorded for settings with the feedback management system switched on and off with open fittings. To generate feedback-free reference signals, which are required for computing some of the direct feedback measures of Madhu et al., outputs with closed fittings are recorded additionally.

The setup of Madhu et al. (2011) at KU Leuven, Belgium, was reproduced at a different test site (HörTech, Oldenburg, Germany). The only significant difference between the setups at the two labs is found in the usage of different dummy heads: In Oldenburg a Kemar head and torso simulator was used, in Leuven it was a Cortex II artificial head. All data of Madhu et al. (2011) and the additional data presented in this study were recorded in the framework of a joint project.

3.2 Signals

Table 1 shows signals and presentation levels that have been selected for the evaluation. For calibration, the free-field sound level was measured at the center position of the (removed) dummy head using OLNOISE: (i.e. speech-shaped noise taken from the Oldenburg Sentence Test OLSA, Wagener et al., 1999). Each signal has a length of 60 seconds and was presented with a pause time of 5 seconds.

Signal	Level(s), dB SPL	Comment
White noise band-limited to 10 kHz	65, 85	
Stationary, speech-shaped noise	65	From the HINT [23] database
Sentences by a male speaker	65	From the HINT database
ISTS	55,65, 80	International speech test signal
Impulsive sounds	peak value of 100	Opening & closing window, keys falling

Organ	65	Recording of organ music
Chamber music	65	Recording of a small chamber music ensemble
Opera	65	“Der Hölle Rache” from “Die Zauberflöte” by Mozart

Table 1: List of signals

3.3 Hearing aids

10 Hearing aids (9 behind the ear/BTE, 1 receiver in the ear canal/RITE/RITC) were provided by five manufacturers: Siemens, Phonak, GNResound, Oticon and Widex. Table 2 shows an overview of all devices with couplings and settings. The setting of each hearing aid was done as recommended by the manufacturer. Before making the recordings, a ‘sanity check’ was performed with the manufacturers to verify the settings. Open acoustic couplings were used to increase feedback susceptibility.

Device	Type	Coupling	Settings
A	BTE	Phonak fit and go	Mic. omni, noise suppression off, gain limitation off
B	r.i.t.c./BTE	open dome (on receiver)	Mic. omni, noise suppression off
C	BTE	Phonak fit and go	Mic. omni, noise suppression off, gain limitation on
D	BTE	Phonak fit and go	Mic. omni, noise suppression off, gain limitation on
E	BTE	Phonak fit and go	Mic. omni, noise suppression off, gain limitation on
F	BTE	Phonak fit and go	Mic. directive, noise suppression on, gain limitation on
G	BTE	open dome	Mic. omni, noise suppression off, gain limitation on
H	BTE	Phonak fit and go	Mic. omni, noise suppression off, gain limitation on
I	BTE	Phonak fit and go	Mic. omni, noise suppression off, gain limitation on
J	BTE	Phonak fit and go	Mic. directive, noise suppression on, gain limitation on

Table 2: List of hearing aids with couplings and settings

At test site KUL, devices A, B, E, F, H, J were used, whereas devices A, B, C, D, G, I were used at test site OL.

3.4 Performance measures

From the recorded dummy head microphone signals several performance and gain measures were computed. A detailed description of the measures can be found in Madhu et al. (2011). Measures are briefly described in the following:

The selected measures can be classified into the following five categories:

1 Broadband energy measures

Instability results in a large increase in the output signal level, which is detected by the following two measures:

- ODR: Output-to-desired energy ratio

- FSR: Feedback-to-reference signal energy ratio without and with speech-weighted frequency integration (FSR, FSRintellig)

2 Measures for detecting oscillations

Already below instability, oscillations can be perceived, which the following measures aim to detect:

- TVC: Transfer function variation criterion, measures peaks and dips in transfer function variation
- PCR: Power concentration ratio without and with normalization (ΔPCR, ΔPCRn), measures concentration of a large amount of power at a small number of frequencies

3 Signal distortion measures

- SD: Spectral signal distortion, measures deviations in short-term power spectral densities of the hearing aid output signal from the feedback-free reference signal.

4 Perceptually motivated measures

- Entrainment: an instrumental measure of distortion artifacts in the presence of tonal inputs. The entrainment factor is computed by spectral subtraction of the reference signal from the output signal, taking into account psychoacoustic masking. The overall entrainment level is computed based on the entrainment factor and the loudness and sharpness of the entrained signal.

5 Gain measures

- PSD: Power spectral density, gives information on the actual output level at all frequencies, the gain limitation by hearing aid or feedback cancellation, the presence of feedback and the effect of compression (when measured for different input levels)
- DBW: Dip bandwidth – Measures reduction in gain due to the feedback control algorithm (FBC, e.g., notch filtering or adaptive gain reduction) with respect to the reference signal; The DBW is the largest bandwidth (in octaves) where the deviation is smaller than -5 dB
- ISMADHA insertion gain: The EHIMA (*European Hearing Instrument Manufacturers Association)* Working Group ISMADHA (Chairman: M. Vlaming) has developed a measurement procedure for hearing aids, which will be standardized as IEC 60118-15: "Electroacoustics - Hearing aids - Methods for characterizing signal processing in hearing aids."

The ISMADHA procedure estimates the level- and frequency-dependent amplification of a hearing aid using the International Speech Test Signal (ISTS) which allows for reproducible measurement conditions and which features all or most relevant properties of natural speech. The procedure uses a measurement box with a speaker, a reference microphone and a coupler. Correction of the MLE (microphone location effect) and OEG (open ear gain) is done to make the measurement possible without having to use an artificial head. In this project the "original" procedure to measure the insertion gain was used: The test signal is presented to the hearing aid which is mounted on the artificial head, and the microphone signal of the artificial head is recorded. For recording the reference signal, the hearing aid is removed. Using this open ear reference ("stored equalization") any problems which could be introduced by using a reference microphone and concurrent equalization as addressed in (Lantz et al., 2007) are avoided. The insertion gain is estimated by analyzing and comparing level percentiles of these two signals in third-octave bands and 40-ms time windows. The ISTS was presented at 55, 65 and 80 dB SPL to obtain information about the behavior of the hearing aid at different levels. The procedure gives estimates of the gain, compression and any gain limitation, e.g. by maximum power output (MPO) limitation. The average gains will be presented in the results section separately for feedback cancellation enabled and disabled ("average LTASS gain"). Any

kind of feedback signal is included in the analysis, i.e., high gains will be estimated in case the hearing aid is howling. It has to be noted that differences between the different artificial heads used at KUL and OL were not compensated. Measuring the insertion gain following the proposed ISMADHA standard requires the KEMAR head and torso simulator.

Most of the measures require a feedback-free reference signal, which was estimated from the closed coupling using a model with an FIR-filter (see Madhu et al. (2011), for details).

3.5 Evaluation procedure

Completely automated measurements were done using Matlab as the main framework for Sound-I/O, controlling the linear motor and all settings of the hearing aids. SoundMexPro[1] is used to provide sample-accurate input and output and reliable access to the ASIO driver of the soundcard. AutoIt[2] is used for the automated control of manufacturers fitting modules and NOAH to set audiograms and all hearing aid settings without any user interaction.

For all hearing aids, the same hearing losses (described by audiograms) were used to fit the devices (and thus to set the gains implicitly). As the procedure has to be used for commercial hearing aids, directly setting any type of gain is not possible and the insertion gains provided by the different devices will be different due to the different fitting strategies employed by the manufacturers. Therefore, a comparison across devices by any measure of feedback is only valid when compared at the same insertion gain, as measured by the ISMADHA method. Figure 1 shows the data of the N3-ISMADHA audiogram, shifted linearly in steps of 5 dB for all frequencies. Grey lines indicate the minimum and maximum hearing loss, respectively, that the devices were fitted to.

Each hearing aid was measured for:

- All audiograms (hearing loss shifts between -35dB and +60dB re. N3 audiogram in 5 dB steps, cf. Figure 1)
- Three settings:
    1. feedback control on (only for the open coupling)
    2. feedback control off
    3. hearing aid muted
    4. (without hearing aid)
- Two couplings
    1. open
    2. closed

[1] http://www.soundmex.de

[2] http://www.autoitscript.com/autoit3/

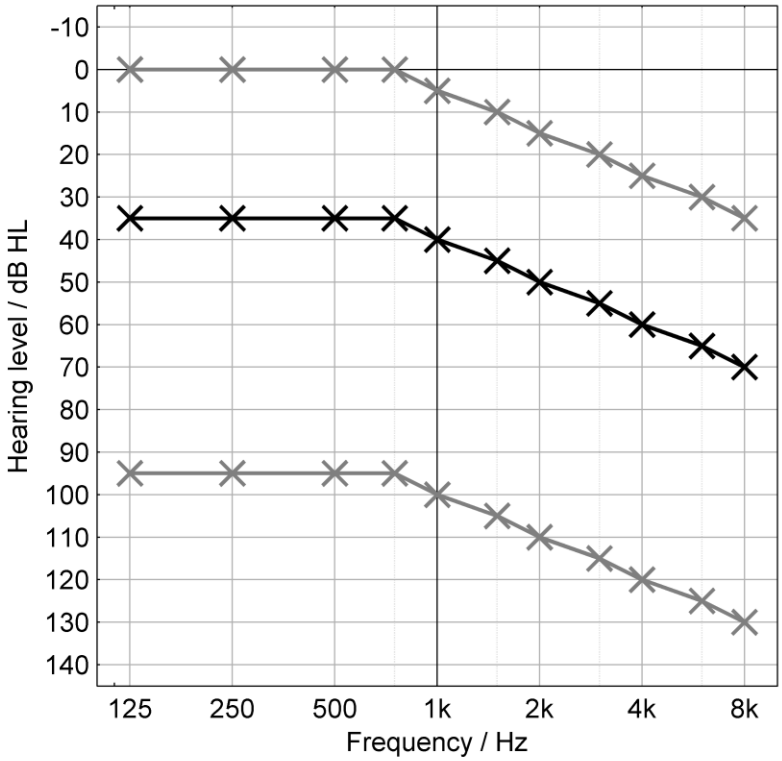


Fig 1: Shift of audiogram N3 used for the hearing aid settings (hearing loss shifts)

3.5.1 Experiments

As described in the last sections, measurements with 10 hearing aids (9 BTE, 1 RITE) and two types of fitting (open, closed for reference only) were performed. An automated fitting of the hearing aids was used with fittings prescribed by manufacturers and 20 hearing loss settings (shifted audiogram). 11 signals that were presented. The recording time per hearing aid and condition was approximately 20 hours. The total amount of data (test sites OL and KUL together) is approximately 300 GB.

The data from test site KUL presented in this paper were gathered and analyzed by Madhu et al (2011) to evaluate the properties of the different measures of feedback and to judge their significance for characterizing the feedback management system of a hearing aid. This study uses this data and adds data from the second test site and ISMADHA insertion gain data from both test sites. Adding the second test site data and the insertion gain data allows a comprehensive analysis of the influence of the different setups and of the relation of the different measures of feedback behavior with insertion gain measures.

4 Results

In the following sections, the large amount of recorded data is analyzed with respect to the following aspects:

- ISMADHA insertion gain measure: Influence of feedback on estimated insertion gain
- test-retest reliability
- Relation between insertion gain and performance measures

4.1 ISMADHA insertion gain estimates

Figure 2 shows ISMADHA insertion gain estimates for two different laboratories (two different dummy heads:KEMAR at OL, Cortex II at KUL) and the same hearing aids (devices A

and B). The data of all 20 measured hearing loss settings are plotted for feedback control on and off, also showing test and retest. Device A shows the highest difference between the laboratories in insertion gain in the 5 kHz-band. Enabling feedback management (KUL data) reduced estimated gains for the highest frequencies which is indicative of an effect of feedback suppression. More feedback is visible at OL for frequencies above 3 kHz without feedback management. The highest gain, which is expected to be due to feedback, is observed at 2 kHz with KEMAR, whereas with Cortex II this peak can be found at 2.6 kHz. Device B shows higher gains at around 1.6 kHz with Cortex II, strong feedback is visible at around 5 kHz which is suppressed by enabled feedback management. As device B is a receiver in the canal device differences between the dummy heads in the geometry of the ear canal and the acoustic coupling could have a higher impact on measures of feedback behavior and insertion gain than in device A (BTE with open fitting).

Fig. 3 shows box plots of differences in insertion gain between test and retest data. One box plot pools the data of all hearing loss settings and frequency bands for a specific device and feedback control setting (fbc). Box plots are shown for devices A (fbc off: data from OL and KUL; fbc on: data from KUL) and B (fbc off and on: data from OL and KUL). High test/retest reliability was observed. Only 1.9% of the 300 data points are categorized as outliers, i.e., data points are deviating more than 5 dB from the median values. All differences are small for stable gains, but could point to different feedback behavior in unstable conditions where larger differences were observed. Large differences in insertion gain are likely to result in differences in the instrumental measures.

Data show that the insertion gain of the devices varies systematically with the hearing loss setting and that insertion gain is largely different across devices for the same hearing loss setting, indicating that the variety of manufacturer-specific fitting rules leads to largely different gain behavior (and thus feedback susceptibility). Because the largest influence of feedback control and feedback was observed for devices A, B, C and D, further analysis of instrumental feedback measures will be restricted to these devices.

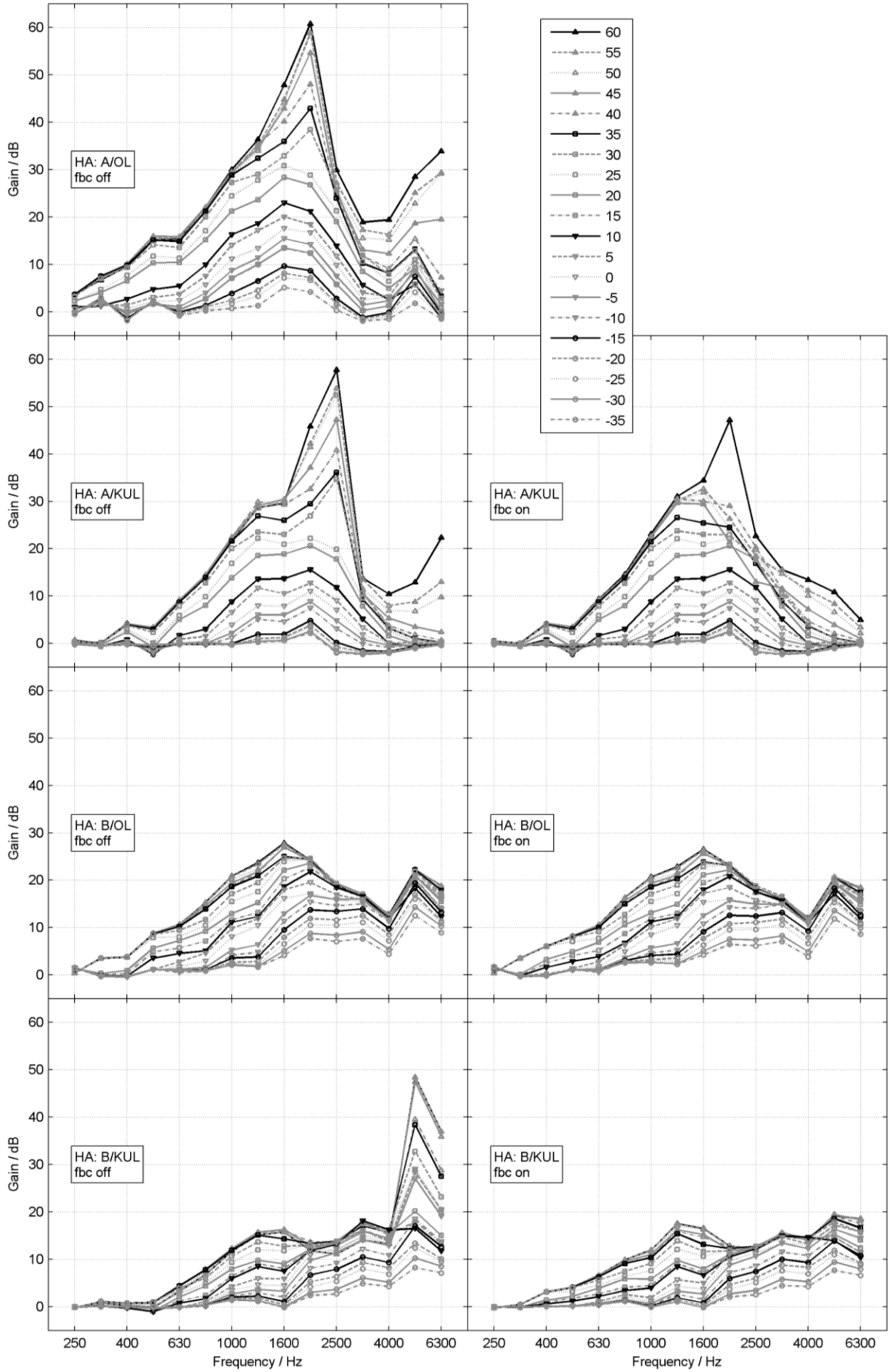


Fig. 2: ISMADHA insertion gain estimates in third-octave bands for two hearing aids (A, B) at two test sites (KUL, OL). Data are shown for feedback control on and off (fbc on/off; except for device A/OL), test and retest (solid and dashed lines) and for all audiogram settings (hearing loss shifts with respect to N3 audiogram, in dB; linestyles shown in legend). Data for device A/OL with fbc on is missing.

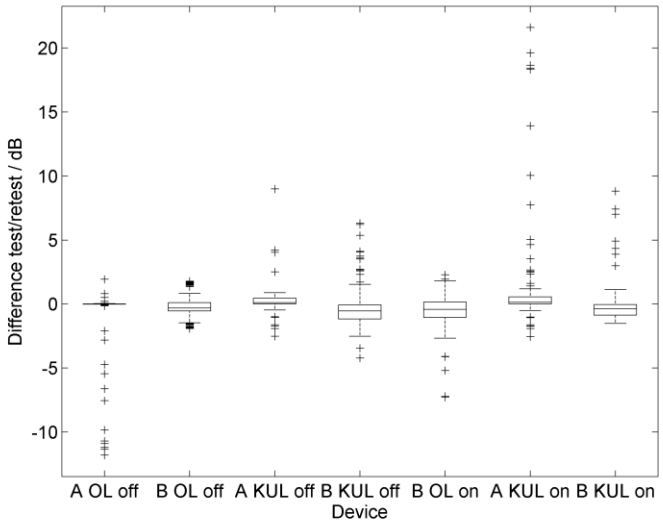


Fig 3: Box plot of test minus retest ISMADHA insertion gain data. Data points for all hearing loss settings, frequency bands, devices A and B, test sites OL and KUL and for feedback control on and off are included.

4.2 Performance measures and insertion gain

Figure 4 shows the insertion gain difference (maximum across frequencies) between the conditions of feedback control switched on and off as a function of the hearing loss setting for devices A/KUL, B/KUL, C/OL and D/OL (max delta insertion gain, solid black line). The remaining curves show corresponding differences in instrumental performance measures for the organ signal, namely, ODR, FSR, TVC, PCR, SD and DBW. For DBW, absolute measure values instead of differences were used. Note that data for FSRintellig, ΔPCRn and entrainment is not shown for a better overview. Results for FSRintellig do not give any extra information. Results of ΔPCRn and entrainment are similar to results of TVC.

All difference measures except FSR and DBW begin to increase at the same or the next hearing loss shift, indicating that the difference in insertion gain is a good indicator of feedback-related and feedback-control-related signal alteration. For device B and C FSR is an exception and starts to increase earlier, as this measure is sensitive to phase modifications introduced by the feedback control algorithm. This explains why there is a difference for the lowest hearing loss settings. Whether this represents perceptually relevant information is unclear and needs to be investigated in the future by subjective listening tests. DBW shows increasing values only for device A. This is probably caused by a notch filtering used in this device. Table 4 shows correlation coefficients between insertion gain differences and the other measures, i.e., between the curves plotted in Fig. 4. For all measures except DBW high correlations with the insertion gain difference can be found (p-values $< 10^{-4}$). The results of entrainment show similar behavior as the other measures but are not shown here.

To establish an objective criterion of feedback for each measure separately, detection thresholds for signal alteration caused by feedback were defined (see Table 3). The hearing loss shift at which the respective measure changed by an amount greater than or equal to this threshold was then used as the feedback threshold. The differences in feedback thresholds calculated from the respective measure and from delta insertion gain are given in Table 4. Of the 21 data points, 13 show a difference of 0 dB and 3 further points show a difference in the range of ±5 dB, one point shows a difference of 10 dB. For HA B feedback thresholds calculated from FSR, TVC, PCR, SD are by 15 dB or 25 dB lower than the feedback thresholds calculated from max. delta IG.

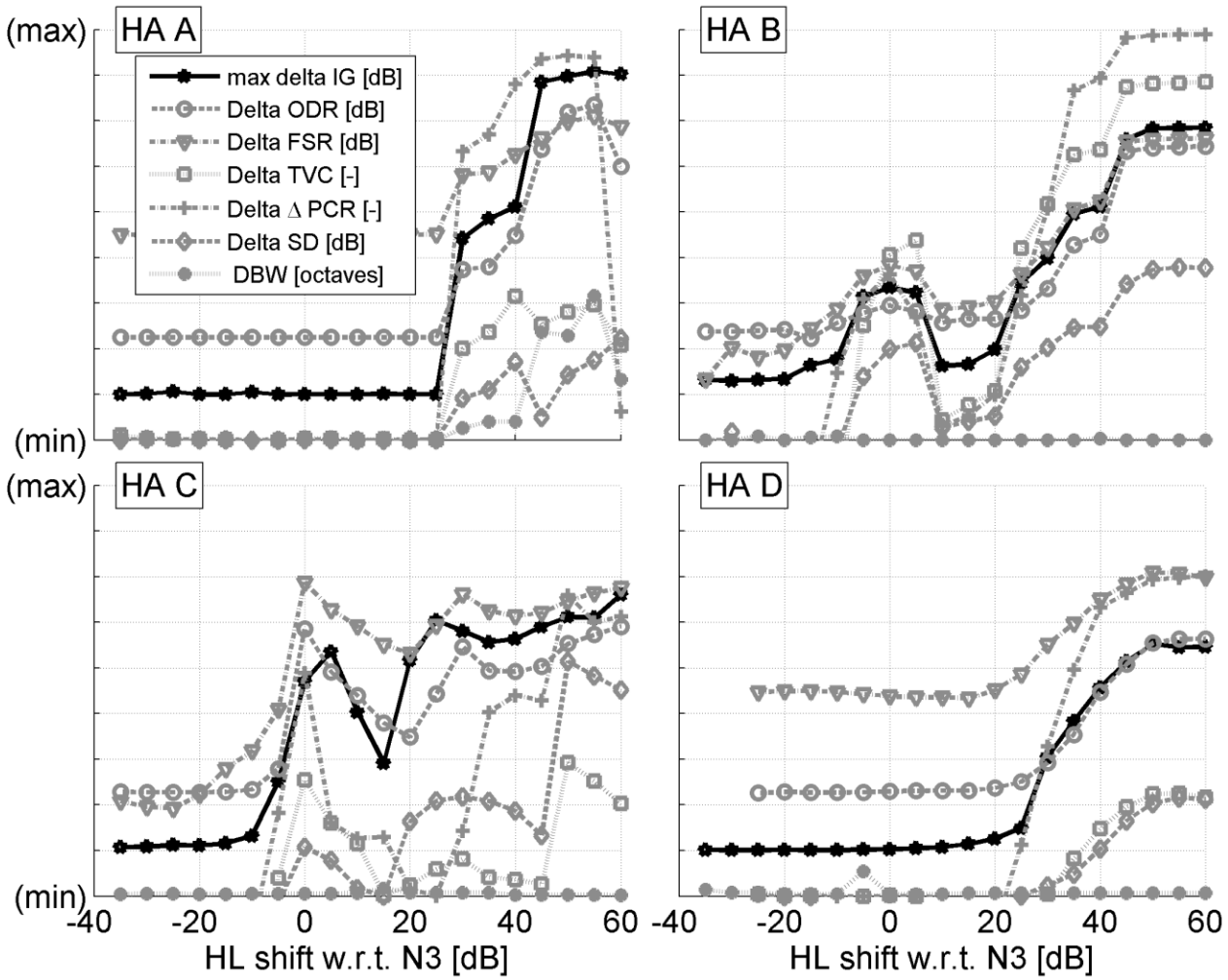


Fig 4: Insertion gain difference (maximum across frequencies) between the conditions of feedback control enabled and disabled as a function of the hearing loss setting (max delta IG, solid black line). The remaining curves show corresponding differences of the objective performance measures ODR, FSR, TVC, ΔPCR, SD, as well as the value of DBW. Different panels are for devices A/KUL, B/KUL, C/OL and D/OL. For the scaling of the y-axis for the different measures, see Table 3.

Measure	max delta IG	Delta ODR	Delta FSR	Delta TVC	Delta ΔPCR	Delta SD	DBW
Min	-5	-10	-30	0	0	0	0
Max	40	30	30	60	1	12	2
Tick	5	4.4	6.7	6.7	0.1	1.3	0.2
Threshold	3	0.7	2	5	0.1	1	0.04

Table 3: Description of the y-axis values for all measures shown in Fig. 4 and threshold defining signal alteration caused by feedback.

Hearing aids: A (KUL), B (KUL), C, D; delta = fbc off - fbc on (DBW: no delta)

Measure	ODR	FSR	TVC	ΔPCR	SD	DBW

Corr-Coeff	0.96	0.79	0.68	0.84	0.81	0.46
p-value	$< 10^{-4}$					
HA A	0	0	0	0	0	0
HA B	-5	-25	-15	-25	-15	(-)
HA C	0	-10	0	0	0	(-)
HA D	0	0	5	-5	0	(-)

Table 4: Correlation coefficients of delta insertion gain and delta measure and differences in feedback threshold calculated from the respective measure and from delta IG.

From a theoretical point of view, using the hearing aids outside the prescription range could lead to other artifacts than feedback, e.g. distortion caused by overloading the receiver, which could lead to increasing values of all feedback measures except insertion gain. Without open-loop measurements this is hard to distinguish. However, informal listening revealed no such artifacts, indicating that the hearing aids behaved basically linearly in the gain range used here.

5 Discussion

The presented measurement results obtained with the ISMADHA percentile analysis procedure show the necessity to include insertion gain measurements when characterizing the feedback management system of commercial hearing aids for several reasons: These measurements are required to compare differences between hearing aids due to a huge variety of fittings based on the same audiogram, resulting in different gains. They are also necessary for the interpretation of any feedback measure, since without taking the gain into consideration, any result of a performance measure remains unclear. For example, a strong gain limitation can avoid feedback in all scenarios and then any performance measure would not give any information. Therefore it is important to detect any type of compression and gain reduction technique. Using several input levels would give more detailed information.

Feedback management system characterization is multidimensional; a single scalar quality measure cannot characterize a feedback management system sufficiently. Instead, a small set of performance measures might be able to characterize a feedback management system in combination with an insertion gain measure. Most of the performance measures show high correlations to the insertion gain measurement. This suggests that the insertion gain measurement with the feedback control switched on and off could be sufficient to identify the gain and frequency region in which the influence of feedback or the feedback control system becomes significant. In and below this gain region, more recordings and measure calculations could be done. Existing differences between the performance measures, however, have to be compared to subjective measurements to establish the relation of objective and subjective perceptual measures.

Extensions and combinations of performance and gain measures seem possible and reasonable. For example, the ISMADHA method could be extended and adapted for detecting feedback by distinguishing uncorrelated and correlated energy in the recorded hearing aid signal and reference signal. Another possibility could be the combination of the ISMADHA method with a perceptual measure like PEMO-Q (Huber et al., 2006). As ISMADHA seeks to become an industry standard, it is conceivable that an extension which makes an automated data analysis for feedback characterization possible would be applicable. According to our data, all regions of interest are registered by this measurement.

Differences between current measures concern, amongst others, the test signals used (e.g., white noise, ISTS) and the frequency-resolution. A higher frequency-resolution allows for detecting narrow band oscillation frequencies and notch filtering. However, the perceptual relevance of such effects and of instrumental measures in general has yet to be evaluated. To this end, formal listening tests should be carried out.

All devices were fitted with hearing losses well above the upper limit of their respective prescription range. In practice, closed fittings or otoplastics with small vents would be used for such hearing losses, whereas open fittings were used in this study. Furthermore, an integrated feedback test provided by several of the devices, which would have caused stronger gain limitations and less feedback problems, was deactivated. Thus, the susceptibility to feedback was maximized for the purpose of this study. When using the devices in their standard configuration and with hearing losses in their prescription range, susceptibility to feedback should be much smaller than observed in this study. It is therefore likely that, under standard conditions, feedback should only occur when introducing an object close to the ear.

6 Summary and conclusions

A setup for characterizing feedback management systems of commercial hearing aids using a dummy head was used to record the response of ten commercial hearing aids to several test signals for different hearing-loss settings, two acoustic couplings (open and closed) and with the feedback control system switched on and off. Several instrumental measures were computed from the recordings. It was found that gain measures are required in combination with distortion measures to characterize feedback management systems, in particular because the gain behavior of the hearing aids of different manufacturers is largely different at the same hearing-loss setting. A high correlation between direct measures of feedback and the insertion gain measure showed the informative value of the insertion gain measurements derived from percentile analysis. Extending a gain measure (e.g., ISMADHA percentile analysis measurement standard or power spectral density (PSD)) and combining it with instrumental performance and quality measures thus appears to be a promising option for future enhanced feedback management characterization. However, extensive validation with subjective data from listening tests to verify the perceptual relevance of the results is necessary to establish such a method.

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8 References

IEC 60118-15 ed1.0: Electroacoustics - Hearing aids - Part 15: Methods for characterising signal processing in hearing aids with a speech-like signal, 2012

EHIMA: Background Information on the proposal for Testing hearing aids with a speech-like signal, Version 1.0 (2007)

I. Holube, S. Fredelake, M. Vlaming and B. Kollmeier. Development and analysis of an International Speech Test Signal (ISTS). International Journal of Audiology, vol. 49:12, 891 – 903, 2010

D. J. Freed and S. D. Soli. An objective procedure for evaluation of adaptive antifeedback algorithms in hearing aids. Ear and Hearing, 27(4):382–398, August 2006.

R. Huber and B. Kollmeier. PEMO-Q. A new method for objective audio assessment using a model of auditory perception. IEEE Transactions on Audio, Speech and Language Processing, vol. 14, pp. 1902-1911, 2006

J. Lantz, O. D. Jensen, A. Haastrup and S. Ø. Olsen. Real-ear measurement verification for open, non-occluding hearing instruments. International Journal of Audiology, vol. 46:1, 11 – 16, 2007

I. Merks, S. Banerjee, and T. Trine. Assessing the effectiveness of feedback cancellers in hearing aids. The Hearing Review, 13(4):53–57, April 2006.

I. Merks. Method to detect and quantify entrainment (bias) of a feedback canceller in a hearing aid. Technical report, Signal processing group, Starkey labs, 2009.

M. Shin, S. Wang, R. A. Bentler, and S. He. New feedback detection method for performance evaluation of hearing aids. Journal of sound and vibration, 302:350–360, 2007.

A. Spriet, K. Eneman, M. Moonen, and J. Wouters. Objective measures for real-time evaluation of adaptive feedback cancellation algorithms in hearing aids. In Proc. European Signal Processing Conf. (EUSIPCO), Lausanne, Switzerland, August 2008.

A. Spriet, M. Moonen, and J. Wouters. Evaluation of feedback reduction techniques in hearing aids based on objective performance measures. 2009. Technical Report ESAT-SISTA/TR 09-08.

A. Spriet, M. Moonen, and J. Wouters. Objective evaluation of feedback reduction techniques in hearing aids. In Proc. European Signal Processing Conf. (EUSIPCO), Glasgow, UK, August 2009.

N. Madhu, A. Spriet, T. Bisitz, J. Wouters, V. Hohmann, M. Moonen. Assessing the applicability of instrumental measures for black-box evaluation of feedback control in hearing aids. J. Acoust. Soc. Am. 130(2): 933-947, 2011.

K. Wagener, V. Kühnel, and Birger Kollmeier, Entwicklung und Evaluation eines Satztests für die deutsche Sprache I: Design des Oldenburger Satztests, Zeitschrift für Audiologie/Audiological Acoustics, vol. 38, pp. 4-15, 1999