ISSN 0280-6819

KONGL CAROLINSKA MEDICO CHIRURGISKA INSTITUTET

TECHNICAL AUDIOLOGY

Report TA No. 118
April 1990

HEARING-AID TO EAR IMPEDANCE-MATCHING:

A LITERATURE SURVEY

Per-Eric Sanborn

TA117 1988 Perceived sound quality of reproductions with different frequency responses and sound levels.
A Gabrielsson, B Hagerman, T Bech-Kristensen and G Lundberg

TA116 1987 Influence of nonlinear distortion on speech intelligibility: Hearing impaired listeners.
A-C Lindblad

TA115 1987 Loudspeaker frequency response and perceived sound quality: Comparison between measurements in listening room, anechoic room and reverberation room.
A Gabrielsson, B Lindström and O Till

TA114 1986 Loudspeaker frequency response and perceived sound quality: Measurements in listening room.
A Gabrielsson, B Lindström and O Till

TA113 1986 Relations between speech intelligibility and psychoacoustical modulation transfer function (PMTF).
B Hagerman, Å Olofsson and A-C Lindblad

*TA112 1985 The effect of different frequency responses on sound quality judgments and speech intelligibility.
A Gabrielsson, B N Schenkman and B Hagerman

TA111 1985 Hearing aid measurements on occluded-ear simulator compared to simulated in-situ and in-situ measurements.
U Olsson

TA110 1984 Improvement of induction loop field characteristics using multi-loop systems with uncorrelated currents.
Å Olofsson

TA109 1984 Questionnaires on desirable properties of hearing aids.
B Hagerman and A Gabrielsson

TA108 1983 Audio versus audio-visual test - implications for hearing aid frequency responses.
A-C Lindblad, M P Haggard and J R Foster

TA107 1983 Clinical measurements of speech reception threshold in noise.
B Hagerman

TA106 1983 Assessment of perceived sound quality in eighteen High Fidelity loudspeakers.
A Gabrielsson, B Lindström and G Elger

TA105 1982 Detection of nonlinear distortion of speech signals by hearing impaired listeners.
A-C Lindblad.

*TA104 1982 Measurement of speech reception threshold - a comparison between two methods.
B Hagerman.

TA103 1981 Problems and methods in judgments of perceived sound quality.
A Gabrielsson.

TA102 1981 Scaling of perceptual dimensions in sound reproduction.
A Gabrielsson, B Lindström.

TA101 1981 Sentences for testing speech intelligibility in noise.
B Hagerman.

TA100 1981 Modulation transfer function and speech transmission index - a method to predict speech intelligibility in Swedish? - The Swedish contribution to the IEC 29B/WG15 multilanguage test.
B Hagerman, A-C Lindblad.

TA99 1980 En metod för subjektiv utvärdering av "kompaktanläggningar".
B Lindström.

TA98 1980 Clinical assessment of perceived sound quality in hearing aids.
A Gabrielsson, B Hagerman, C Berg, A Ovegård, L Änggård.

TA97 1980 Statistical analysis of fricative sounds.
Å Olofsson.

* indicates that the TA-report is out of stock, but is aviable at a cost of SEK 35.

KAROLINSKA INSTITUTET
TEKNISK AUDIOLOGI

Report TA118
April 1990

HEARING-AID TO EAR IMPEDANCE-MATCHING: A LITERATURE SURVEY

Per-Eric Sanborn

8

Postadress:
TEKNISK AUDIOLOGI
KTH
S-100 44 STOCKHOLM

Besöksadress:
Visiting address:
Lindstedts väg 1 o. 7
STOCKHOLM

Telefoner:
Telefon:
08-11 66 60 (sekr.)
08-20 89 23
08-791 75 15
08-791 75 16
08-791 75 17
08-791 75 18
08-791 75 19

KAROLINSKA INSTITUTET
TEKNISK AUDIOLOGI

Report TA118
April 1990

HEARING AID TO EAR IMPEDANCE-MATCHING: A LITERATURE SURVEY

Per-Eric Sanborn

ABSTRACT

The final response at the eardrum is difficult to predict while fitting hearing aids on different ears. The result is depending on the relation between hearing aid output impedance and ear input impedance. A hearing aid may produce rather varying response when used on different ears. In addition, this variation in response is different among hearing aids. Although the problem has been known for many years, no solution has reached the point of common use.

A literature survey on this subject has been carried out. Only two papers are dealing with a solution of this particular problem, but some of the work on diagnosis of the middle ear may turn out relevant to this problem too. Most of the papers found are discussing systems for impedance measurements on the human ear and theoretical models of the ear.

This work was supported by the Swedish Ministry of Health and Social Affairs.

ISSN 0280-6819

Postadress:
TEKNISK AUDIOLOGI
KTH
S-100 44 STOCKHOLM

Besöksadress:
Visiting address:
Lindstedts väg 1 o. 7
STOCKHOLM

Telefoner:
Telefon:
08-11 66 60 (sekr.)
08-20 89 23
08-791 75 15
08-791 75 16
08-791 75 17
08-791 75 18
08-791 75 19

Report TA118
April 1990

CONTENTS

INTRODUCTION

The response from a hearing aid may show great variations when used on different ears. The variations may reach 20 dB at high frequencies (Olsson, January 1985).

This is a major problem when fitting hearing aids. The basis for selecting hearing aids is measurements on a coupler, which does not give enough information about the final response on an individual ear.

In order to estimate the variations a study was made at three hospitals in Stockholm (Berninger, Ovegård, Svärd Oktober 1989). The result from tests in the frequency range 500 Hz to 4 kHz with one aid on 16 ears was major variations throughout the range.

The variations are due to the facts that the output impedance of hearing aids are different, and that the input impedance of the human ears are different.

The aim of the project, which this survey is part of, is to solve the acoustical problems found while fitting hearing aids. The frequency range of interest is that of speech, with some margin for further development on hearing aids.

The literature survey covered some 200 papers and reports. Out of these approximately 100 were studied in detail. This report covers the 48 most relevant to the project.

MEASUREMENT METHODS FOR THE IMPEDANCE OF THE HUMAN EAR

The "reaction-on-load" method

One of the first methods for impedance measurement of the human ear was the "reaction-on-load" method. An electro-acoustic transducer was generating a soundwave into the ear canal. The acoustic loading of the transducer caused by the ear canal was transformed to the electrical input of the transducer. In principle, the acoustic impedance of the ear can be measured as an electrical impedance. In reality the impedance was not measured directly but by comparison with the known impedance of a tube.

This method was used during the thirties and fourties. However, it had very low sensitivity except for frequencies near the membrane resonance frequency. References to measurements of this type are given in Delaney (1964) and Metz (1946).

Recently Puria and Allen (Fall 1989) presented a measurement method based on an earphone and a four-cavity calibration. For frequencies up to 15 kHz, the calibrated earphone is used to measure the impedance of the ear canal near the canal entrance. In order to transform this impedance to the eardrum impedance, the ear canal has been modelled. The following effects are accounted for by the model:

- The jump in cross-sectional area from the earphone calibration cavity to that of the ear canal.
- The distance to the eardrum.
- Variations in the ear canal cross-sectional area.
- Effects due to ear canal wall impedances.

The acoustic bridge

Some of the measurement-techniques used for ears were originally borrowed from the realm of technical acoustics, the most frequent measurement objects being porous materials. One of these techniques was the acoustic bridge. Otto Metz introduced it to clinical investigations in 1946 (Metz, 1946).

The measurement apparatus consisted of two main tubes with a symmetric loudspeaker in between, the loudspeaker providing equal but opposite phase waves to the tubes. The main tubes are connected through an indicator-tube with an outlet for stethoscope on top. One of the main tubes is connected to the ear canal, the other one to an adjustable but known impedance. When the adjustable impedance equals that of the ear, the sound pressure at the indicator-outlet is zero. Major drawbacks of this method are:

- Large size, if measurements are to be made at low frequencies.
- The variable impedance is difficult to adjust.
- The value of the variable impedance is hard to determine.
- Not able to distinguish between resistance and reactance.

Metz used four frequencies between 384 and 1145 Hz, but the range has been extended to 7500 Hz in other works (Zwislocki, 1982). One interesting modification of the instrument was made by Zwislocki. A cavity in front of the variable impedance was made equal to the volume of the ear canal. In this way the measured impedance was that of the eardrum.

The "two-tube" method

Two methods has come to a broader clinical use. One is the acoustical bridge, the other one is a "physical method" presented by Zwislocki (March 1957, 1982). Below the latter is referred to as the "two-tube" method.

An earphone is radiating sound into the ear canal through a thin tube. The source will act as a high impedance- (or velocity-) source. A microphone is measuring the sound pressure in the ear canal through another tube. Results are obtained as a difference between measurement in a cavity with known impedance and measurement in the ear.

The low frequency limit is the frequency where the source is not acting as a velocity source anymore (at approximatly 300 Hz). The upper frequency limit is given by the limited sound insulation between the tubes (at 1-3 kHz). While the acoustic bridge is considered inappropriate at low frequencies, the "two-tube" method is not recommended at high frequencies. The latter method has reached a wider use than any other method so far. In particular this is true for the variant with a third tube giving the possibility of changing the constant pressure in the ear canal. This has become known as "tympanometry".

Møller presented a variation on the same theme, and was the first one to report measurements of complex impedance of the ear (Møller, February 1960). An earphone and a microphone was connected to the same measurement tube which was in turn connected to the ear canal. The aim was to measure the impedance of the eardrum (as in the case of Zwislocki, March 1957). As the measurement was made near the entrance of the ear canal, Møller used an electrical analog model in order to calculate the eardrum impedance, thus compensating for the ear canal.

He was able to make static as well as dynamic measurements beween 200 Hz and 2 kHz. In order to achieve a high precision measurement, corrections should be made for the receiver- and microphone-impedances. As this was not made, his results are considered as indications (Pinto, Dallos January 1968).

In order to determine the sensitivity of earphones, Delany measured the ear input impedance through four different earcaps (Delaney, 1964). Two 1/2" microphones were used mounted in the earcaps. Calibrating the system to a hard-walled tube, he managed to cover the range 20 Hz to 8 kHz. An electric analog network for the impedance of the human ear as viewed through the aperture of an earcap was presented.

The first work presented with both transducers in the ear canal was Brüel et al. (1975). They used a swept sinusoidal signal (chirp) between 200 Hz and 10 kHz. Two microphones were used with protection grids removed, this made them very fragile and some difficulty with cerumen (ear wax) was experienced.

Rabinowitz measured resistance and reactance of the ear input immittance (impedance or admittance). This was carried out with a modulation technique for frequencies 62 Hz to 4 kHz. The measurement signal used was a swept sinusoidal with the frequency changed step by step, at 10 frequencies per octave (Rabinowitz, October 1981). The measurements were made, as usually, near the entrance of the ear canal. In order to calculate the immittance of the eardrum, the ear canal was modelled as a tube with constant cross-section. The volume of the tube was determined through measuring reactance at low frequencies and with ambient air pressure in the canal. The same measurement was performed with constant pressure in the ear canal different from the ambient air pressure, the remaining reactance thus being due to that of the ear canal. All this was already in common use at the time, but apart from others Rabinowitz did not regard the eardrum as rigid at over-pressure, but with a finite reactance.

The electro-acoustic bridge

An electro-acoustic bridge was presented by Terkildsen and Nielsen. The sound source consisted of an earphone plus a narrow tube. The microphone consisted of the same type of earphone plus tube (Terkildsen,Nielsen, September 1960). On the electrical side of the arrangement the microphone signal was balanced out in phase and amplitude. By doing this on known cavities and on the ear, the phase and modulus of the ear impedance was determined. The volume of the ear canal was measured by filling it with alcohol. The measurement results were corrected according to this volume with a hard-wall cavity as a theoretical model. A single frequency of 220 Hz was used.

Pinto and Dallos used essentially the same method as Terkildsen and Nielsen, but with a slightly more complicated electrical equipment (Pinto, Dallos, January 1968). The range 250 Hz to 1250 Hz was covered with a maximum error of 5% in magnitude and 3 degrees in phase.

The "one microphone" method

Sondhi and Gopinath (1971) used a measurement device consisting of a tube with one microphone at one end, and the other end terminated by absorbing material. The measurement signal was impulse, and from the response the area function of the vocal tract was determined. This method requires that only plane waves are propagating. It was shown that a measurement in one point only can not provide any information about losses in the measured sample (Sondhi, Resnick, March 1983). Sondhi and Gopinath used the method on the human vocal tract.

Joswig used this technique on the ear. In this case the sound source is a high voltage spark which is not constant over long periods of time. The main problem is however the connection of the measurement tube to the ear. Errors at this point may for instance be caused by leakage or by the tube being placed at wrong angle (Joswig, Spring 1981, Hudde, 1984).

The "two microphone" method

From measurements in free field, Mehrgardt and Mellert (June 1977) was able to calculate the ear canal transfer function from 2 kHz to 15 kHz. Although the technique was not referred to as the "two microphone" method, the approach is closely related.

When developing a dummy head microphone, Hamada and Sekiya also used this method (Hamada et al., December 1980, Sekiya et al., December 1981). The tube diameter was 5 mm and the frequency range 500 Hz to 16 kHz. The energy losses in the tube were accounted for but not higher modes. Comparison was made between measured and calculated values of a copper tube, and fairly good agreement was obtained.

With three microphones in the ear canal, Hudde was able to measure both the eardrum impedance and the area function of the ear canal between 960 Hz and 19.2 kHz (Hudde, January 1983a, January 1983b, 1984). A requirement for his method to be valid is that the sound pressure in one point is possible to determine from the sound pressure in the other two points. The technique is basically the "two microphone" method, but the algorithm also gives corrections from which the quality of the measurement can be determined. Although not able to detect all errors, it did reject 13 out of 22 measurements. It is suggested that reflectance should be used instead of impedance. The reason for this is that reflectance is less sensitive to variation in probe position (Hudde, January 1983b). At 2-3 mm from the eardrum higher modes are considered negligible and are not included in the measurement algorithm or the theoretical model. It is also declared that a complete knowledge of the sound field at this point requires knowledge of the higher modes. Another conclusion is that the tube with constant section and rigid walls is not sufficient as a model of the ear canal at frequencies higher than 2 kHz.

Murphy proposed an intensity measurement technique (which is closely related to the "two microphone" method) slightly downstream from the point of sound delivery (Murphy et al., Spring 1987, Fall 1989). The measurement device plus sound delivery system is built into a two-port earmold and is measuring the reflectance of the ear canal. It requires measurement of the effective ear canal transfer function to the points of the multiple microphones (Rabbitt, December 1988).

The "two microphone" method was also used by Okabe et al. (1988) for measurements between 800 Hz and 8 kHz. From measurements near the ear canal entrance, the eardrum impedance was calculated using a matrix formulation of the ear canal. This theoretical canal model consisted of sections of tubes with constant cross-section. A cavity was used for comparison between measured and theoretical reactance. The agreement was good in the frequency range used.

Keefe et al.(Spring 1987) used this technique for a narrow impedance tube. In this system, a calibrated tube with known geometry is sealed to the ear canal. The viscous and thermal losses in the tube were accounted for, and measurements were made between 200 Hz and 6 kHz. One advantage of this method is that no constant velocity source is required.

Measurements in physical models

Stinson presented a theory (Khanna,Stinson, February 1985) together with measurements in scaled replicas of the ear canal. The canal was enlarged by a factor 2.56, and the model was provided with holes for probe microphones along the canal and along the eardrum surface (Stinson, November 1985). The cross-sectional area function was determined in the following manner: With the canal in a vertical position, the model was filled with water up to the level of measurement. By dropping a chrome steel ball with known volume into the water, the cross-section area at this coordinate was determined from the change of the water surface location. Comparison was made with the above mentioned theory and the results are quite good with the eardrum modelled as a single point impedance.

Stinson also reports measurements of the shape of 15 ear canals. The measurements are made in 1000 coordinate points (each one in three dimensions) on molds of original size (Stinson, Lawton, June 1989). The measurements are summarized as individual ear canal area functions. It is shown that accurate specification of the canal geometry leads to improved predictions of the sound pressure distribution along the canal at frequencies higher than 8 kHz.

In order to investigate what effect a spatially distributed eardrum impedance has on the sound pressure distribution, Stinson and Khanna (June 1989) made measurements in a tube with square cross-section. The eardrum was modelled as a flat surface along one side of the canal. It consisted of a piston with shaker in one experiment and a locally reacting absorber in another. Along the canal three probe microphones were moved in order to detect higher order modes. The results are compared with the theory of Rabbitt and Holmes (March 1988). The agreement is good up to a frequency that corresponds to 15 kHz in a human ear canal.

Higher order modes

Most of the papers in this survey deal with low frequency methods. This means that only plane waves are considered. No propagating higher modes are to be expected below 18 kHz (Rabbitt, December 1988). But higher modes in the sense of nearfield modes (primarily near the ear canal entrance and the eardrum) may be found above 2.5 kHz (Rabinowitz, October 1981). According to Hudde (June 1989), these nearfield modes may exist as low as 1/10 of the cutoff frequency of the first nonplane mode, but there is no distinct limit. When including higher order modes the reflectance as a scalar is not adequate. The modes may interact and the reflectance is therefore specified as a matrix.

Hudde (1989) presents two measurement methods for the reflectance matrixes. As higher modes are considered, the frequency range is increased compared to other methods. The measurement arrangement consists of a measuring pipe, an extendable adapter and a test pipe in which the object being tested is placed.

MEASUREMENT METHOD FOR OUTPUT IMPEDANCE OF THE HEARING AID

The "two-load" method

Little attention has been paid to the sound source in question, i.e. the hearing aid. Concerning the output impedance of the receiver (or receiver plus tygon tube and mold), David Egolf et al. (October 1977, January 1978, 1988) published results from a measurement technique using four-pole theory.

In Egolf et al.(October 1977), the "two-load" method is presented. This implies loading the object with two different acoustic loads (coupler and coupler plus tube) and calculating the four-pole parameters from measurements on the electrical input and acoustical output. The limitations in terms of impedance is given as (Zs: source impedance, Z1,Z2 : load impedances):

- Z1 approx. equal to Z2
- Z1 << Zs and Z2 << Zs , or Z1 >> Zs and Z2 >> Zs

Direct experimental verification is possible only for one of the four parameters, the other three require zero output velocity which is not possible to achieve. Hence the other verifications are carried out in an indirect way. Comparing experimental and computer generated results showed a maximum difference of 5 dB in the range 250 Hz to 6.5 kHz.

THEORETICAL MODELS OF THE HUMAN EAR CANAL WITH EARDRUM

The ear canal geometry must be properly described before quantitative predictions of sound pressure distributions in the canal can be made. Reflections at the eardrum result in standing waves in the ear canal in case of a stationary sound field (Khanna, Stinson, February 1985). The tapered shape of the canal results in higher sound pressure near the eardrum and a different standing wave field from that of a homogeneous tube. The eardrum is terminating the canal at a sharp angel and causes the sound pressure to vary over it for high frequencies. Therefore, the sound pressure level at the eardrum is not a direct measure of the input to the ear.

Below 18 kHz, the plane wave is the only mode that propagates along the length of the canal (Rabbitt, December 1988). It has been shown (Rabbitt,Holmes March 1988) that multidimensional higher modes, although not transporting energy, affect the behavior of the eardrum. Mainly low-frequency models are used and the degree of sophistication required in representing the human ear depends primarily on the highest frequency of interest.

The cavity

The cavity model implies that all dimensions of the ear canal (the canal length is about 25 mm) are considerably less than a quarter of a wavelength of sound. In this model wave propagation is not taken into account. All parts of the cavity are affected equally and at the same instant. In a lumped model the ear canal may therefore be treated as a compliant volume of air, and the model may work up to 1 kHz (Stinson, Lawton June 1989).

The tube

At frequencies higher than 1 kHz, the cavity model breaks down. In many cases the ear canal can then be modelled simply as a straight tube of uniform cross-section, and with the eardrum terminating the tube per-pendicularly. This may be sufficient up to 4 kHz (or 8-10 kHz if the ends of the canal are left out), (Blauert, Platte March 1976, Khanna, Stinson February, 1985, Stinson, Lawton June 1989). In Rabinowitz (October 1981), the upper frequency limit is said to be 2.5 kHz.

Electrical analogs

Lumped models have been used to describe the behavior of the middle ear and the ear canal. The most frequent type being electrical analogs.

The Zwislocki model from 1962 has been subject to changes a few times as results of new observations, and the latest revision is that of Shaw in 1981 (Shaw, Stinson, May 1981, Stinson, Spring 1989). It is the middle ear low-frequency model most frequent in use. The different physical parts of the middle ear are modelled with a combination of resistors, capacitors and inductors. The eardrum of a human ear is moving in a complex way at high frequencies. It may be described as two areas, one stiffly coupled to the hammer, and the other one with a loose coupling. The network values are based on available reliable anatomic data. Where such data were not available, the values were adjusted to obtain maximum compatibility between the properties of the network and the acoustical data for normal and pathological ears.

An electrical analog for the ear canal is presented by Gardner and Hawley (1972). It consists of tee-sections to a number that is depending on the highest frequency of interest and whether the cross-sectional area of the canal is assumed to be uniform or not.

Websters horn equation

The one-dimensional horn equation published 1919 by Webster, is a 2nd order differential equation giving the relation between sound pressure and cross-sectional area function of a horn (Webster, 1919). It is valid under the following circumstances:

- Only plane waves propagating.
- Rigid walls in the tube.
- Tube radius substantially less than a wavelength.
- Tube radius substantially less than radius of curvature of the tube center axis.

The horn equation gives analytical solutions only for certain shapes of the canal. By approximating the canal with a number of constant cross-section tubes, numerical calculations are possible (Hudde, June 1989) as well as four-pole calculations.

A high-frequency asymptotic theory, based on a multi-scale solution of the one-dimensional horn equation is given in Friedrich, Rabbitt (Spring 1989), Rabbitt (December 1988) and Rabbitt, Holmes (March 1988). From this theory, two methods are derived that are used together. The first method uses standing wave amplitude measurements in the ear canal and requires pressure measurements at many locations along the canal. The second method uses phase measurements in the ear canal. The phase method is simpler to apply, but is not capable of determining the cross-sectional area function without amplitude data. In combination, these two methods are used to determine the energy reflection coefficient at the eardrum, the standing wave patterns along the length of the canal and the cross-sectional area function. These are high frequency methods and not useful at low frequencies. It is possible to add higher order terms in the asymptotic series in an effort to extend its validity to lower frequencies. Another possible way is to use the resulting area function in the horn equation.

The original horn equation has been extended to account for distributions in three dimensions (Khanna, Stinson, February 1985). This theory applies to three-dimensional, rigid-walled tubes that have both variable cross-section and curvature along the length. Khanna and Stinson made measurements (100 Hz to 33 kHz) in the ear canal of a cat. The aim of the study was to compare the measured standing wave pattern with the extension of the one-dimensional horn equation. This comparison showed a good result above 12 kHz (9.3 kHz for a human ear).

The scattering matrix approach

Herbert Hudde presents a scattering matrix approach to higher order modes (Hudde, June 1989). The ear canal is modelled with a number of constant cross-sectional tubes. The main limitation is the fact that only radial modes are considered, although including azimuthal modes is not an essential problem. A limit is given by the increase of computing effort.

The finite-element approach

The finite-element method (FEM) has been used to model the behavior of the eardrum and the middle ear (Funnell, Funnell Spring 1989). It implies a numerical method with huge geometrical possibilities. The limitations of the method is most often the determination of boundary conditions.

Åbom (January 1989) points out the possibility of combining FEM with a four-pole model. Eigenfunctions and eigenvalues from the FEM-model may be used in the four-pole model. The advantage of this approach is that the latter model in this way is able to include higher order modes, which it ordinarily cannot do.

THEORETICAL MODELS FOR THE HEARING AID

The measurement and modelling of the acoustical properties of the hearing aid has not been given much attention. In the case of hearing aid to ear impedance matching, this is just as vital as measurement and modelling of the ear. Only two papers have been found that is really considering acoustical properties of hearing aids for the purpose of matching to the ear (Egolf, Leonard, October 1977, Egolf et al., January 1978).

The measurement part of these papers are discussed in the section "two-load method" above. Egolf's approach is based on the four-pole (two-port) theory, that requires plane waves. Its prime feature is the simple connection between devices described with four-poles (Iberall, July 1950).

PREDICTION METHODS FOR HEARING AID TO EAR IMPEDANCE MATCHING

A common rule-of-thumb is that a low output impedance from the hearing aid will give a sound pressure at the eardrum that is more or less independent of the ear impedance. On the other hand a high output impedance will result in a sound pressure that is proportional to the ear impedance (Brüel et al. 1975, Johansson, Sjögren August 1968). A drawback with a low output impedance is that it will cause a considerable increase in level at low frequencies (Knowles Electronics Inc. February 1975).

Two methods for predicting frequency response at the eardrum has been found: Egolf et al. (October 1977, January 1978, 1988) and Hara et al. (1988).

Egolf et al. present a method based on four-poles. It is a computer-based method for determination of the four-pole parameters of the hearing aid, described above as the "two-load" method (Egolf, Leonard October 1977). In order to create a mathematical model of an entire hearing aid system, it is necessary to model:

- The mechanism of electroacoustic transduction in the receiver.
- The mechanism of sound transmission through the various small cylindrical tubes linking the receiver with the tympanic membrane.

The narrow tubes of the hearing aid is modelled according to Iberall (July 1950).

In the first experiment, described in Egolf et al. (January 1978) the model was applied in turn, to six different receiver-earmold combinations using two receivers and three earmolds, each mounted on a calibration coupler. The result from comparison between measured and calculated frequency response is good agreement below 5 kHz.

In the second experiment a hearing aid was used on a human subject. All acoustical parts involved were modelled as in the first test. The result of comparison as above was good agreement below 1 kHz. Disagreement above this frequency was attributed to the poor signal-to-noise ratio of the measurement data.

Although the results are encouraging, the authors claim that "successful application of the mathematical scheme to other hearing aid combinations has not yet (1978) been verified".

An even simpler approach is given by Hara et al. (1988) for canal type hearing aids. Insertion gain is predicted from the two following transfer functions:

- The hearing aid transfer function from acoustical input to acoustical output when placed in the ear-canal.
- The transfer function of the outer ear canal (the part occupied by the hearing aid).

The method is verified on three subjects. Measured and predicted results agree within ±3 dB in the range 200 Hz to 5 kHz. An obvious drawback while making predictions with this method, is the fact that it takes less effort to measure the final result than to make the prediction.

REFERENCES

Berninger,B., Ovegård,A., Svärd,I. (Oktober 1989). "Hörapparatförstärkningens beroende av örats akustiska impedans", Audiologiska kliniken, Huddinge Sjukhus, Stockholm, (In Swedish).

Blauert,J., Platte,H-J. (March 1976). "Impulsmessung der menschlichen trommelfell-impedanz", Journal of Audioligical Technique, vol.15, no.2, 34-44.

Brüel,P., Frederiksen,E., Mathiasen,H., Rasmussen,G., Sigh,E., Tarnow,V. (1975). "Impedance of real and artificial ears", Brüel o.Kjaer.

Delaney,M.E. (1964). "The acoustical impedance of human ears", Journal of Sound and Vibration, vol.1, no.4, 455-467.

Egolf,D.P., Haley,B.T., Howell,H.C., Larson,V.D. (July 1988). "A technique for simulating the amplifier-to-eardrum transfer-function of an in situ hearing aid", Journal of the Acoustical Society of America, vol.84, no.1, 1-10.

Egolf,D.P., Leonard,R.G. (October 1977). "Experimental scheme for analyzing the dynamic behavior of electro-acoustic transducers", Journal of the Acoustical Society of America, vol.62, no.4, 1013-1023.

Egolf,D.P., Tree,D.R., Feth,L.L. (January 1978). "Mathematical predictions of electroacoustic frequency response of in situ hearing aids", Journal of the Acoustical Society of America, vol.63, no.1, 264-271.

Friedrich,M.T., Rabbitt,R.D. (Spring 1989). "Ear canal cross-sectional acoustic modes", Journal of the Acoustical Society of America, Suppl.1, vol.85, s67.

Funnell,S.M., Funnell,W.R.J. (Spring 1989). "An approach to finite-element modeling of the middle ear", Journal of the Acoustical Society of America, Suppl.1, vol.85, s67.

Gardner,M.B., Hawley,M.S. (1972). "Network representation of the external ear", Journal of the Acoustical Society of America, vol.52, no.6, (part2), 1620-1628.

Hamada,H., Saito,K., Ogura,Y., Miura,T. (December 1980). "The development and application of a standard dummy head microphone", Res.Rep.Fac.Eng. Tokyo Denki Univ., No.28, 23-49, (In Japanese).

Hara,M., Itami,E., Okabe,K., Hamada,H., Miura,T. (1988). "Prediction of the insertion gain on canal type hearing aid", Hearing Aid Fitting (Edited by Janne Hartvig Jensen), 13th Danavox Symposium, Odense, Denmark.

Hudde,H. (January 1983a). "Estimation of the area function of human ear canals by sound pressure measurements", Journal of the Acoustical Society of America, vol.73, no.1, 24-31.

Hudde,H. (January 1983b). "Measurement of the eardrum impedance of human ears", Journal of the Acoustical Society of America, vol.73, no.1, 242-247.

Hudde,H. (1984). "Meßmethoden für die akustische impedanz des mittelohres bei hohen frequenzen", ntzArchiv, Bd.6, H.11, 265-271.

Hudde,H. (June 1989). "Acoustical higher-order mode scattering matrix of circular nonuniform lossy tubes without flow", Journal of the Acoustical Society of America, vol.85, no.6, 2316-2330.

Hudde,H. (1989). "Messung von reflektanzmatrizen absorbierender proben mit höheren schallfeldmoden im rohr", Acustica, vol.68, 77-91.

Iberall,A.S. (July 1950). "Attenuation of oscillatory pressures in instrument lines", Research Paper RP2115, vol.45, Natl.Bur.Stand., U.S.Dept.of Commerce.

Johansson,B.,Sjögren,S. (August 1968). "En jämförelse mellan allt i örat hörapparatens frekvenskurva i tryckkammare resp. i öra med ledningsfel", Report no.54, Department of Technical Audiology, Karolinska Institutet, Stockholm, (In Swedish).

Joswig,M. (Spring 1981). "Determination of the eardrum impedance of human ears with respect to the individual shape of the ear canals", Journal of the Acoustical Society of America, Suppl.1, vol.69, s14.

Keefe,D.H., Burns,E.M., Ling,R. (Spring 1987). "Auditory system impedance measurement using the two-microphone wave-tube technique", Journal of the Acoustical Society of America, Suppl.1,vol.81, s75.

Khanna,S.M., Stinson,M.R. (February 1985). "Specification of the acoustical input to the ear at high frequencies", Journal of the Acoustical Society of America, vol.77, no.2, 577-589.

Knowles Electronics Inc.(February 1975)."Effects of source impedance upon receiver response",Technical Bulletin 7.

Mehrgardt,S., Mellert,V. (June 1977). "Transformation characteristics of the external human ear", Journal of the Acoustical Society of America, vol.61, no.6, 1567-1576.

Metz,O. (1946). "The acoustic impedance measured on normal and pathological ears", Med.D. thesis, Fac.of Medical Science, Copenhagen.

Murphy,W.J., Tubis,A., Long,G.R. (Spring 1987). "Two-microphone measurement of acoustic intensity in the ear canal as a calibration of high-frequency hearing", Journal of the Acoustical Society of America, Suppl.1, vol.81, s75.

Murphy,W.J., Tubis,A., Long,G.R. (Fall 1989). "Measurement of the local power reflection coefficient in the ear canal using the two-microphone method", Journal of the Acoustical Society of America Suppl.1,vol.86, s43.

Møller,A.R. (February 1960). "Improved technique for detailed measurements of the middle ear impedance", Journal of the Acoustical Society of America, vol.32, no.2, 250-257.

Okabe,K., Tanaka,S., Hamada,H., Miura,T., Funai,H. (1988). "Acoustic impedance measurement on normal ears of children", Journal of the Acoustical Society of Japan, vol.(E)9, no.6, 287-294.

Olsson,U. (January 1985). "Hearing aid measurements on occluded-ear simulator compared to simulated in-situ and in-situ measurements", Report no 111, Department of Technical Audiology, Karolinska Institutet, Stockholm.

Pinto,L.H., Dallos,P.J. (January 1968). "An acoustic bridge for measuring the static and dynamic impedance of the eardrum", IEEE Transactions on Bio-Medical Engineering, vol.BME-15, no.1, 10-16.

Puria,S., Allen,J.B. (Fall 1989). "Impedance measurements in the ear canal", Journal of the Acoustical Society of America, Suppl.1, vol.86, s44.

Rabbitt,R.D. (December 1988). "High-frequency plane waves in the ear canal: Application of a simple asymptotic theory", Journal of the Acoustical Society of America, vol.84, no.6, 2070-2080.

Rabbitt,R.D., Holmes,M.H. (March 1988). "Three-dimensional acoustic waves in the ear canal and their interaction with the tympanic membrane", Journal of the Acoustical Society of America, vol.83, no.3, 1064-1080

Rabinowitz,W.M. (October 1981). "Measurement of the acoustic input immittance of the human ear", Journal of the Acoustical Society of America, vol.70, no.4, 1025-1035.

Sekiya,Y., Saito,K., Hamada,H., Ogura,Y., Miura,T. (December 1981). "Measurement of acoustic impedance of human ear using impedance measuring tube and digital signal processing", Res.Rep.Fac.Eng. Tokyo Denki Univ. No.29, 55-64, (In Japanese).

Shaw,E.A.G., Stinson,M.R. (May 1981). "Network concepts and energy flow in the human middle-ear", The 101st Meeting of the Acoustical Society of America, 19-22 May, Invited paper T2.

Sondhi,M.M., Gopinath,B. (1971). "Determination of vocal-tract shape from impulse response at the lips", Journal of the Acoustical Society of America, vol.49, no.6, (part2), 1867-1873.

Sondhi,M.M., Resnick,J.R. (March 1983). "The inverse problem for the vocal tract: Numerical methods, acoustical experiments, and speech synthesis", Journal of the Acoustical Society of America, vol.73, no.3, 985-1002.

Stinson,M.R. (November 1985). "The spatial distribution of sound pressure within scaled replicas of the human ear canal", Journal of the Acoustical Society of America, vol.78, no.5, 1596-1602.

Stinson,M.R., (Spring 1989)."Revision of a two-piston eardrum model to account for real ear canal geometries", Journal of the Acoustical Society of America, Suppl.1, vol.85, s67.

Stinson,M.R., Khanna,S.M. (June 1989). "Sound propagation in the ear canal and coupling to the eardrum, with measurements on model systems", Journal of the Acoustical Society of America, vol.85, no.6, 2481-2491.

Stinson,M.R., Lawton,B.W. (June 1989). "Specification of the geometry of the human ear canal for the prediction of sound-pressure level distribution", Journal of the Acoustical Society of America, vol.85, no.6, 2492-2503.

Terkildsen,K.,Nielsen,S.S. (September 1960). "An electroacoustic impedance measuring bridge for clinical use", Archives of Otolaryngology vol.72, 69/339-76/346.

Webster,A.G. (1919). "Acoustical impedance, and the theory of horns and of the phonograph", Proc.Nat.Acad.Sci.(USA), no.5, 275-282.

Zwislocki,J.J. (March 1957). "Some measurements of the impedance at the eardrum", Journal of the Acoustical Society of America, vol.29, no.3, 349-356.

Zwislocki,J.J. (1982). "Normal function of the middle ear and its measurement", Audiology 21:4-14.

Åbom,M. (January 1989). "Derivation of four-pole parameters including higher order mode effects for expansion chamber mufflers with extended inlet and outlet", paper VIII in Ph.D. thesis "Studies of sound propagation in ducts and mufflers", Report TRITA-TAK-8902, Dept.of Technical Acoustics, Royal Institute of Technology, Stockholm.

TA96 1980 A method for suppression of periodic noise signals.
S-Å Frykholm, Å Olofsson.

*TA95 1980 Hörapparaters frekvenskurvor: IEC-coupler, KEMAR, människa.
U Olsson.

TA94 1980 Some ideas in computerized acoustical impedance measurements.
S-Å Frykholm.

TA93 1979 Assessment of perceived sound quality in high fidelity sound-reproducing systems.
A Gabrielsson, S-Å Frykholm, B Lindström.

*TA92 1978 Statistical treatment of data from listening tests on sound-reproducing systems.
A Gabrielsson.

TA91 1978 Taluppfattbarhet för högtalarsystem vid Arlanda utrikesterminal.
B Hagerman, A-C Lindblad.

TA90 1978 A generalization of the concept of total harmonic distortion.
Å Olofsson.

*TA89 1978 Ett programpaket för mätning, syntes och analys av linjära tidskontinuerliga och tidsdiskreta system.
Å Olofsson.

TA88 1978 Reliability in the determination of speech reception threshold (SRT).
B Hagerman.

TA87 1978 Detection of nonlinear distortion in telephone systems.
A Gabrielsson, A-C Lindblad, B Lindström, Å Olofsson.

*TA86 1977 Adjective ratings and dimension analyses of perceived sound quality of headphones.
A Gabrielsson, S-Å Frykholm, H Sjögren.

*TA85 1977 Adjective ratings and dimension analyses of perceived sound quality of hearing aids. III.
A Gabrielsson, H Sjögren.

*TA84 1977 Automatic gain control and hearing aids. The influence of different attack and release times on speech intelligibility for hearing impaired with recruitment.
T Ahren, S Arlinger, C Holmgren, L Jerlvall, B Johansson, A-C Lindblad, H Sjögren.

*TA83 1976 Detection of amplitude distortion by normal hearing and hearing impaired subjects.
A Gabrielsson, P-O Nyberg, H Sjögren, L Svensson.

*TA82 1976 Preferred listening levels and perceived sound quality at different sound levels in "high fidelity" sound reproduction.
A Gabrielsson, H Sjögren.

*TA81 1976 Preliminärrapport slingor.
R Ingelstam.

TA80 1975 Emulator för kommunikation mellan minidator typ Honeywell 316 och stordator typ IBM 360.
Bo Jacobsson.

TA79 1975 Mätning av amplitud- och faskurvor för hörapparater med hjälp av minidator.
Å Olofsson.

TA78 1975 Styr- och registreringsenhet för psykoakustisk mätplats.
Å Olofsson, L Persson, H Sjögren.

*TA77 1975 Adjective ratings and dimension analyses of perceived sound quality of hearing aids. II.
A Gabrielsson, H Sjögren.

*TA76 1975 Similarity ratings and dimension analyses of perceived sound quality of hearing aids.
A Gabrielsson, H Sjögren.

*TA75 1974 Adjective ratings and dimension analyses of perceived sound quality of hearing aids. I.
A Gabrielsson, H Sjögren.

TA74 1974 Assessment of comfort and discomfort levels for pure tone, a methodological study.
A Gabrielsson, B Johansson, Bodil Johansson, A-C Lindblad, L Persson.

*TA73 1973 Hörapparaternas driftkostnader.
B Johansson.

* indicates that the TA-report is out of stock, but is aviable at a cost of SEK 35.