Transfer Function and Subjective Quality of Headphones: Part 1, Transfer Function Measurements

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Transfer functions of headphones were measured on a dummy head in order to find relations with headphones subjective quality. Depending on headphone position on the head, transfer functions may be quite different. A new technique for representative transfer function selection based on impulse response cross-correlation is presented. This technique has been applied to the measurement of twelve different headphones.

0 INTRODUCTION

Since the beginning of the electroacoustic age a number of studies have been carried out on the subjective and objective quality evaluation of transducers. Most of these studies have dealt with loudspeaker reproduction [1], [2], [3], [4], [5], and relatively few have focused on headphone listening [6], [7].
This topic seems to be of growing interest however, especially in view of increasing number of situations where headphone listening is involved, as in the case of binaural technologies [8]. Unfortunately, many difficulties arise when studying headphones. Measurements of headphones' acoustical parameters are difficult and many questions in thisconnection still remain to be clarified. For instance, although some indications exist [9], we do not know exactly what the ideal transfer function for headphones might be.
In the first part of this paper, the authors propose to show that digital signal processing techniques can be a useful means of investigating subjective headphone quality evaluation. In the second part, an experiment based on these techniques will be described. Subjective quality evaluation of headphones will be discussed in detail.

1 HEADPHONES QUALITY EVALUATION

1.1 Preliminary experiment

The main goal of this study was to look for means of linking up objective measurements with subjective quality judgements. A preliminary experiment was designed in order to obtain subjective assessments on twelve different headphones [10], using the so-called "magnitude estimation" method. Subjects listening to a piece of music through headphones were asked to attribute to each headphone a number reflecting its subjective quality. One minute was allowed for each headphone, at the end of which, the rating had to be given. Another headphone was then presented, until all twelve had been assessed.

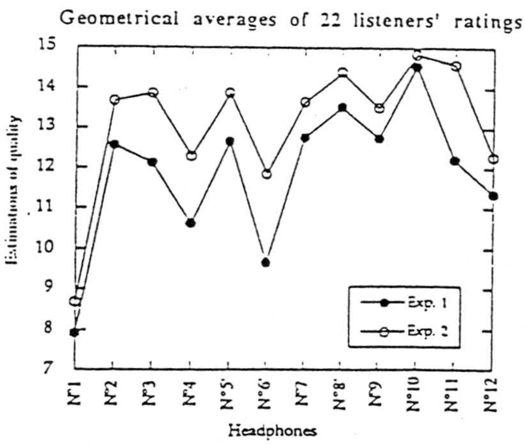

Figure 1

Fig. 1 shows the results of the preliminary experiment which was run twice. Twenty-two subjects participated in this experiment, and the results were express as the geometric mean obtained at each run. The results of the two runs had similar patterns. A slight difference can be observed between the ratings on the two runs, however, possibly due to the order of presentation, which was the same for each subject but differed between the two runs. The magnitude estimation method seems to be suitable for headphone quality estimation. Some objections can be raised however about the experiment. Irrelevant parameters such as comfort may have affected the subjects' assessments. The subjects were able to see the headphone they were listening through, and may have been influenced by what they knew about Hi-Fi equipment, which was liable to bias the results of the experiment.

1.2 Headphone Simulation

The subjective quality of headphones can be said to be a multidimensional characteristic. Some of the basic vectors depend on electroacoustic parameters and others not. Successful objective measurement/subjective evaluation correlation requires that all non-electroacoustic parameters should be eliminated as far as possible. The idea was to begin working with a single electroacoustic parameter. Among these parameters, the most decisive may be the frequency response, and it was therefore decided first to study its effects. This led us to the idea that it would be convenient to be able to perform experiments using a single headphone. The transfer functions of the set of headphones under study would then be simulated by linear filtering [11].

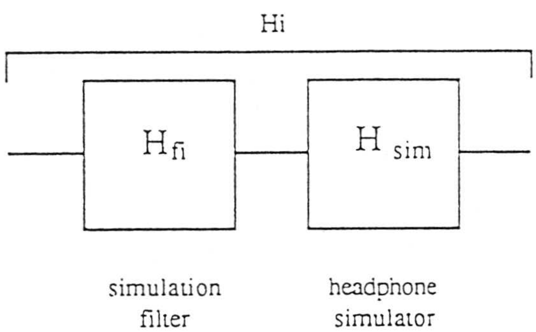

Fig. 2 . Simulation of the transfer function of a headphone Hi by mean of a simulation filter H fi and a simulator headphone H sim .

As shown in fig. 2, if we assume headphones to be linear, time invariant systems, it is possible to simulate on any headphone (the simulator) the transfer function of any other headphone by inserting a filter before the simulator headphone. The frequency response of the filterwill be the ratio between the transfer function of the headphone*i* to be simulated, and the transfer function of the simulator headphone:

$$H_{fi}(f) = \frac{H_i(f)}{H_s(f)} \qquad (1)$$

Experiments of this kind, where it is possible while listening to switch quickly from one headphone to another lend themselves readily to pair comparisons. To put this idea into practice, real-time simulation filters were required. The filter responses were calculated as shown above after measuring the transfer function of each headphone.

2 HEADPHONE TRANSFER FUNCTION MAESUREMENTS

The transfer function of a linear system is defined as the complex ratio between the output and the input spectra. In the case of headphones, the input signal is the voltage across the transducer, and the relevant output signal is the acoustic pressure at the eardrum of the listener.
It is not very easy to directly measure this output signal with subjects. Probe tips or miniature microphones have to be inserted into the ear canal, and great care must be taken to avoid injury, which can necessitate the presence of a physician. The level of the signal must not be too high for the subjects' comfort and to prevent the stapedian reflex from being elicited. This is at the expense of the signal to noise ratio. Due to anthropometric differences, the results of these measurements show considerable variability from one subject to another.
A preferable solution seems to be that using coupling devices which simulate the coupling conditions between the headphones and the subject's ears. It should be emphasized that the Headphone Transfer Function (HTF) measurements then include the coupling device's transfer function:

$$H_{mes}(f) = H_{cd}(f) \cdot H_{hph}(f) \qquad (2)$$

Substituting from Eq.(2) for $H_i(f)$ and $H_{sim}(f)$ into equation (1), it can be clearly seen that the transfer functions of simulating filters do not depend on the coupling device transfer function. In order to correlate objective measurements with subjective evaluations, fairly representative measurements require to be obtained, which means that the transfer function of the coupling device must be representative of the transfer functions measured on subjects.
On the other hand, the acoustic load fed into the earphone must match that encountered under real listening conditions. This means that a coupling device must be carefully selected. Since the authors of many papers have discussed HTF measurements [9], [12], [13], [14] , this topic will not be developed again here. Keeping in mind the above requirements, we decided to perform our measurements on a dummy head.

2.1 Methods

Fig. 3a shows an ideal linear system, where X(f) is the spectrum of the input signal and Y(f) the spectrum of the output signal.

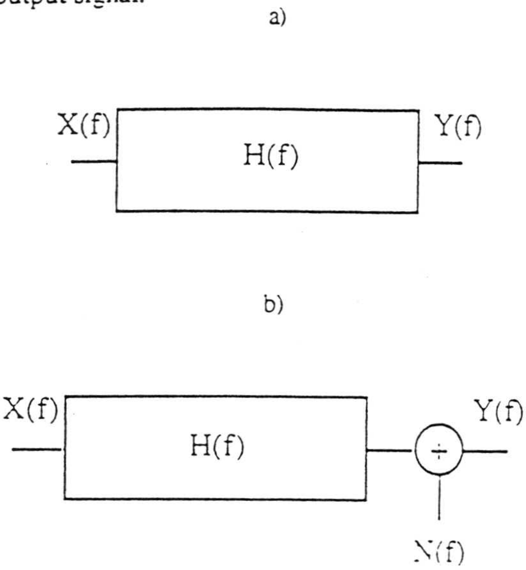

Fig. 3 . Transfer function of a linear time-invariant system: a) without noise. b) with noise N(f).

The transfer function is usually calculated as:

$H(f) = Y(f) / X(f)$ (3)

In modern two-channel spectrum analysers, quite efficient method is used to measure the transfer function of linear systems. The underlying concept is that of the cross-power spectrum between two signals:

$G_{YX} = Y(f) \cdot X^{*}(f)$ (4)

i.e. the linear spectrum of one signal multiplied by the complex conjugate of the other. Likewise, the "auto" power spectrum is defined as:

$G_{XX} = X(f) \cdot X^{*}(f)$ (5)

It can be demonstrated [15] that with systems disturbed by noise as in fig. 3b, a better estimate of the transfer function is:

$H(f) = G_{XY} / G_{XX}$

Based on this cross-power spectrum concept, the coherence function can be defined as follows:

$$\gamma^2(f) = \frac{|G_{YX}(f)|^2}{G_{XX}(f) \cdot G_{YY}(f)} \qquad (6)$$

Using developements similar to the above, coherence may be viewed as the ratio between the output power due to the input and the total output power. The coherence function is a dimensionless frequency-domain function, the values of which range between 0 and +1. Values of less than unity indicate either that at this frequency, noise was present, or that the system is nonlinear. The coherence was also checked for anomalies reflecting faulty headphone positionning on the dummy head, which can cause acoustic losses.

2.3 Measurements set-up

Fig.4 shows the measurement set-up, where H(f) represents the headphone plus dummy head system.

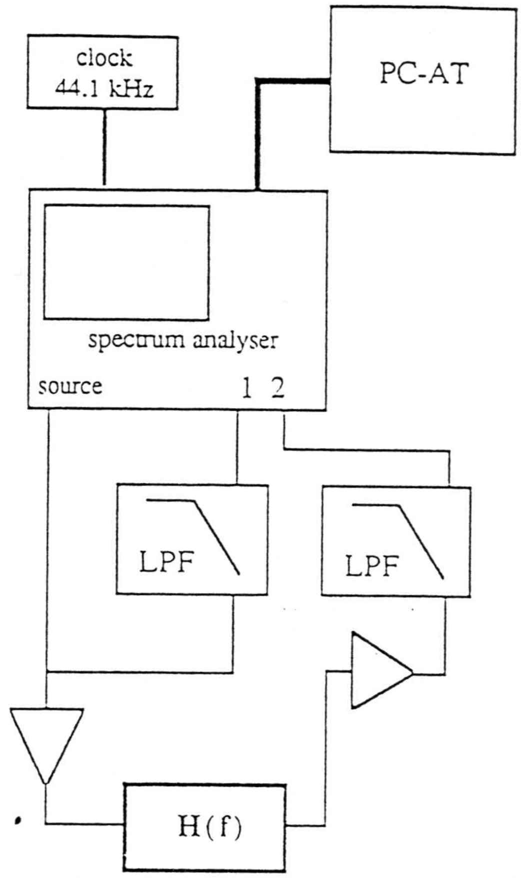

Fig. 4 . Measurement set-up. H(f) represents the system (headphone plus dummy head).

A two-channel spectrum analyser (HP 3562A) was us to perform HTF measurements as decribed abov Measurements were carried out at 44.1 kHz samplir rate. The sampling clock was picked up from a C player. Two low-pass filters (Kemo VBF 8) provid the necessary anti-aliasing. To ensure rejection beyo the Nyquist frequency, a cut-off frequency of 13.5 k was used. As the same filtering was applied to ea channel, the transfer function of the filters was of importance. This was checked by replacing the syste to be measured by a short circuit. The transfer functi was then 0 ± 0.2 dB and 0° ± 2° within a 17225 range.

Home-made amplifiers for use with dynam headphones were used. The characteristics (frequen range, distortion, etc.) were checked and found to be better than those of the headphones. A Stax electrosta headphone was purchased with its own amplifier. amplifier, including the power circuits for the dum head microphones, was constructed.

The measurements were carried out in a quiet room. The ambient noise was not measured because it varied with time. The coherence function was systematically checked and measurements disturbed by noise were rejected.

A PC-AT compatible computer was connected to the analyser via an HPIB interface. Provided the coherence function indicated that the measurements were accurate in the 100 Hz - 16 000 Hz range, the impulse responses of the headphones (2048 taps) were stored on the computer disk for further processing [16].

3 TRANSFER FUNCTION SELECTION

It is well known that the transfer function of a headphone depends on its position on the coupling device. With some headphones, the variability is quite low, but others exhibits a high variability. The problem therefore arose as to how to decide what transfer function should be taken to be representative of the headphone.

3.1 Averaging

The first idea was to average the measurements. Upon close examination however, it turned out that it is not the best method. One characteristic of HTF's is the large number of peaks and dips in the response. These peaks and dips occur at various frequencies, depending on the headphone position. Averaging HTFs would smooth out these irregularities. These might however be an important factor for determining the subjective quality, because head-related transfer functions show the same kind of peaks and dips, which are known to depend on the source location. Averaging the HTF's would result in the loss of this information.

3.2 Other Techniques

Other authors investigating head-related transfer functions have encountered the same problem. Solutions have been proposed for averaging data from many measurements in such a way that the structural features are preserved. The so-called "structural averaging" techniques have been described in detail [17], [18]. Briefly, the idea is to subject each transfer function to a nonlinear transformation of the abcissa, in order to obtain a maximum similarity among the curves before averaging. However artful these techniques may be, it seems questionable whether the result of such averaging actually correspond to any physical reality, however .

3.3 Correlation

Another approach consists of taking one of the measurements to be a representative transfer function. Cross-correlation analysis of the impulse responses was carried out to determine with each headphone which of the measurements showed the greatest degree of similarity to all the others combined.

The highly efficient principal component analysis techniques may also help to solve the problem of HTF selection. Each measurement can be expressed in this way in relation to a set of factors. One of the factors will be found to have a high weight on the axes representing the measurements. The measurement depending most strongly on this factor will then be taken to be as the most significant. These calculations are long and tedious, however. As these methods have been described in detail [19], they will not be discussed here. These method can also help to evaluate whether the two earphones of a headset are well matched.

4 REAL-TIME SIMULATION

Once the HTF's have been obtained, the next step consists of calculating the simulation filter for each headphone. There exist many possible ways of calculating such filters [20]. A straightforward approach was used here. Since FIR filters do not give rise to any stability problems, it was decided to use filters of this kind. The impulse responses of the simulating filters can easily be computed as follows:

Let Hi (f) denote the transfer function of headphone i, and Hs (f) the transfer function of the simulator. The filter impulse response for simulating headphone i on headphone s is:

$$ir_i\,(t) = \mathrm{IFT}\left(\frac{H_i\,(f)}{H_s\,(f)}\right)$$

where IFT stands for Inverse Fourier Transform. Care must be taken to avoid some problems that may arise, particularly if at some frequencies Hs (f) becomes zero. In this case, the result is indeterminate.

4.1 Hardware

Implementation of real-time fir filters was achieved with boards based on Motorola 56001 DSP chips.

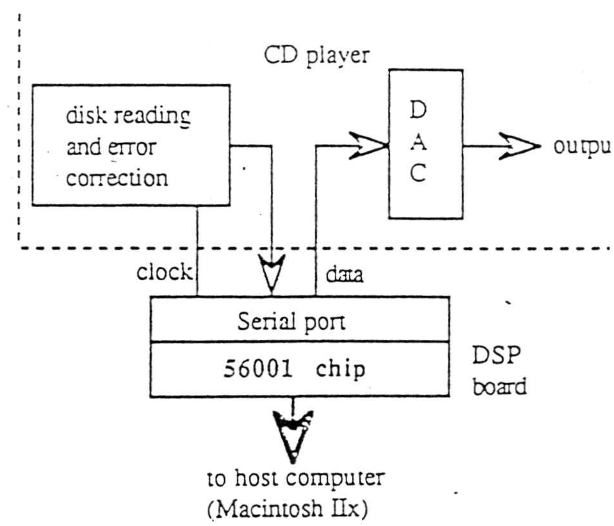

Fig. 5. Filtering set-up showing connections between CD player and DSP serial port.

At the sampling frequency used (44.1 kHz) it was possible to perform real time computation of 200 coefficients.
As depicted in fig. 5, the 56001 serial port was directly connected to a modified CD player or RDAT. The data were transferred from CD (RDAT) to DSP and back after filtering. The filter data files were stored on the host computer (Macintosh IIx) hard disk. External commands for appropriate by loading the DSP program and data memories were added to the Hypercard application for Macintosh. It was thus possible to control the whole experiment with a HyperTalk program. The details of experiments will be described in part II.

4.2 Simulation Accuracy

It is possible to calculate 2048 taps on simulation filters from the measurements. With real-time implementation, it is possible however to use only 200 taps. The calculated filters must then be truncated, which will lower the simulation accuracy. We evaluated the simulation accuracy by calculating the cross-correlation function between what we were looking for - the measured headphone impulse response, and what we obtained - the response of the simulation filter cascaded with the simulator headphone response: the higher the correlation, the better the simulation. The filter calculation program made use of this criterion to optimize the 200 taps selected among the 2048 computed. The maxima of the cross-correlation functions between the original and the simulated responses were then higher than .96.
A matter of even greater importance is the effect on listeners' ears. Measurements were performed on the dummy heads to obtain the transfer functions of the simulated headphones. Cross-correlations between the simulated and original responses were computed. The maxima of the cross-correlation functions were within the range .86 - .96 . These results were then compared with the correlations between two impulse responses measured with the same headphone at different positions on the dummy head, which was found to be typically .95 . This indicates that the accuracy was satisfactory.

5 CONCLUSIONS

Very simple digital signal processing techniques were successfully applied first to measure headphone transfer functions, and then to carry out a psychoacoustic experiment.
The coherence function was found to be a useful tool for detecting and rejecting any faulty measurements. Cross-correlation techniques were used to select a representative headphone transfer function and to estimate the accuracy of the simulation.
On the psychoacoustic side, as will be shown in part II, the simulation method was found to hold many advantages. Since it is possible to closely control the transfer functions, the bias is reduced. Full computer control of the experiment is time saving and ensures that the experimental conditions are fully reproducible. More sophisticated techniques are now being developed, with which other parameters relevant to quality estimation, such as the group-delay and distortion, can be investigated.

6 ACKNOWLEDGEMENTS

The authors are grateful to A. Freed for designing the DSP boards, and providing help for with the FIR programming. T. Angelini helped with the headphone and dummy head amplifiers design. Dr Jessica Blanc was kindly reviewed the manuscript.

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