TECHNICAL AUDIOLOGY

Report TA No. 105
July 1982

DETECTION OF NONLINEAR DISTORTION ON SPEECH SIGNALS BY HEARING IMPAIRED LISTENERS

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ABSTRACT

Knowledge of detection thresholds for nonlinear distortion is very valuable to optimize the construction of hearing aids technically and economically.

Two Swedish sentences, with male and female speakers, were transmitted over a simulated system consisting of linear filters separated by a nonlinearity with varying degrees of quadratic or cubic distortion.
21 subjects with sensory neural hearing loss listened to presentations of a certain sentence in pairs consisting of one distorted and one undistorted reproduction. They were to decide which of the reproductions sounded worse.

The thresholds of the hearing impaired subjects were as good as those of the normal hearing subjects in a previous experiment (TA87).

Recommendations of maximum allowed distortion in hearing aids are discussed.

This work was supported by the National Swedish Board for Technical Development.
The test was performed at the Audiological Department, Danderyd Hospital.

INTRODUCTION

To be able to optimize sound reproducing systems technically and economically it is necessary to know the effects of nonlinear distortion on speech intelligibility and perceived sound quality. Recommendations for maximum allowed nonlinear distortion might be proposed from threshold values for the detection.

An experiment on detection thresholds for nonlinear distortion in a broadband system was made by Gabrielsson et al (1976). The experiment included various stimuli as music, chat, speech and sine wave. Both normal hearing and hearing impaired subjects were tested.
Another experiment with simulated telephone systems and speech stimuli was performed with normal hearing subjects (Gabrielsson et al 1978, TA87).
Both experiments gave understanding of the variability of the thresholds for different stimuli and showed the need of testing more stimuli. For hearing aid design purpose more hearing impaired subjects have to be tested. Such an experiment is described below.

METHODS

In the telephone experiment mentioned above one good system and one with bad characteristics were simulated. The good system had a rather flat frequency response with a sharp cut-off at 5 kHz. This system could be used as a somewhat idealized hearing aid, by that saving a considerable amount of work producing the test material. Consequently, part of the test material from the telephone system experiment was used with hearing impaired subjects.

Speech material

Two of the sentences that had been recorded in an anechoic chamber for the previous experiment were used. They were read by one male and one female speaker. Together with a third sentence not used here, the sentences were phonetically balanced. The two sentences were (with the numbers according to TA 87):

2) Den tomma flaskan stod överst på en bred hylla.
(=The empty bottle stood on the top of a broad shelf.)

3) Räkningen skulle betalas var fjärde månad.
(= The bill was to be paid every fourth month.)

The density functions of the levels for the sentences, read by the male speaker are shown in Figure 1. Notice in particular the differences at the highest levels.

Simulated system

A simulated system consisting of two linear filters separated by nonlinearities of the forms $x+ax^2$, quadratic distortion, or $x+ax^3$, cubic distortion, $a>0$, was used. See Figure 2. Translated into a real hearing aid, this would mean that the distortion originates before the insert receiver and is filtered by it.

The second filter included an inverse of the earphone used in the telephone test. In this experiment a different earphone was used. The frequency responses of the earphones measured in 6-cm^3 coupler are shown in Figure 2 and the responses of the total linear system in Figure 3.

Distortion

The measure of distortion used here was the same as in the previous experiment. "The total harmonic distortion is the square root of that part of the output signal variance which is uncorrelated to the input signal, $d=\sqrt{1-\rho^2}$, where d is the amount of distortion and ρ is the correlation between the input and output signals of the system."

The quadratic distortions after the nonlinearity but before the second filter were 5 %, 10 %, 20 %, 40 % and 60 % and the cubic distortions 2 %, 5 %, 10 %, 20 % and 40 %. The corresponding distortions at the output of the earphone, with the earphone used here, were calculated. The distortions at the output differed somewhat (0 - 5 %) from those in the telephone experiment because of the different frequency response of the earphone.
For details on generating stimuli see TA87.

Subjects

21 subjects, 11 males and 10 females, age 27 - 69, with sensory neural hearing loss, including three cases of Mb Ménière, were tested. The criteria for the selection were pure sensory neural hearing loss, no tinnitus, reasonable travelling distance to the clinic, age maximum 69, speech discrimination minimum 60 % (one actually had 50 %).
Audiograms were taken, Table I and Figure 4, and tympanograms and stapedius reflexes were checked. Audiograms of the Ménière cases were taken at every session. There were no marked changes in the audiograms during the test period.
Another four persons joined the experiment but did not complete their tests.
The subjects were paid for their participation.

Test procedure

The subject was seated in a sound-insulated booth, listening monaurally at most comfortable level, MCL, through an audiometer with headphones TDH-49, MX41A/R.
The most comfortable level, for the sentences and the voices altogether, was established as the mean of four results of an up-and-down method. The MCLs varied from 50 to 95 dB SPL for different subjects.

The subject listened to pairs of sentences. Each pair consisted of two reproductions of the same sentence where distortion was added to one of them, either to the first one or to the second one, and the subject should judge which of them sounded "worst". The judgement was marked by the subject with a cross in the first or the second column on a form. The details appear from the translated instruction below.

Instruction

"As you know the sound can be different in different hearing aids. Some of them sound better - some of them worse. To be able to construct better hearing aids we want to find out how small differences in the sound you can hear.

We have recorded sentences on tape in advance. You can listen to these recordings through one of the headphones. In the experiment you will hear a certain sentence read by a male or a female speaker. The sentence is always presented twice in immediate succession. Now some demonstrations for you to listen at . . .

For each presentation you shall judge which of the reproductions you think is the worst one, the first one or the second one. You do so by making a cross in the first or the second square on the reply form.

So listen carefully to the two reproductions within each pair and try to judge which of them is the worst one. In some cases it is perhaps easy for you to decide which one is the worst one but in other cases it might be difficult. But you always have to give your answer directly after the presentation has finished. The next presentation will appear in about five seconds and then you must be prepared to listen again. You will be trained in several pretests before we start.

The worst reproduction appears equally often in the first position as in the second one in a pair. You shall trust your spontaneous impression about which reproduction is the worst one ! Notice that even if you 'guess' you usually guess much better than you think you do.

The tapes you will be listening to take about eight minutes each. Between these tapes you will get a pause. Within the tapes there are some 10 s pauses. Before the presentations continue there will be a tone sounding for you to sharpen your attention."

All subjects listened to the same test material, e.g. 2 sentences x 2 voices x 2 distortion types x 5 distortion levels x 1 system x 2 positions of the distorted stimulus x 7 replications = 560 cases to judge. The stimulus pairs were recorded in blocks of ten pairs. Each block contained only one specific voice and one type of distortion. All distortion levels were represented twice in random order in each block. Seven tapes with different random orders for stimuli and blocks were used. The time interval between the members in a stimulus pair was 1 s. The time interval between stimulus pairs was 4 s. After every block there was a longer interval of 10 s.

Before the test started and after the instruction the subject had to listen to training lists. The experimenter had a check list of the distortion levels of the separate members in the pairs presented. She could therefore judge if the subject had understood the instruction. In all, the experiment required three or four sessions of about one hour each including pauses. Every session started by reading the instruction and listening to a training list.

Data treatment

For each individual the number of correct judgements was computed for each distortion level at each listening condition. The threshold value was defined as the distortion level corresponding to 75 % correct judgements since 50 % corresponded to guessing. Only individual thresholds were calculated. The thresholds were calculated as distortion at the output, which seems most adequate for hearing aids.

Results

The 75 % thresholds, represented as distortions at the output, are presented in Table II and in Figure 5. For comparison group thresholds of the normal hearing group in TA87 are also presented in the figure. The results can be summarized as follows.

There is a difference in thresholds according to type of distortion: The thresholds for cubic distortion are noticably lower than for quadratic distortion, as expected.
There is a wider range for quadratic than for cubic distortion. The thresholds spread from 6 to 46 % for quadratic distortion, from 3 to 10 % for cubic distortion.

Which subject has the lowest or the highest threshold generally varies with listening conditions.

There is a dependence on speech stimuli: The thresholds for sentence No. 2 are lower than for No. 3 under the same conditions otherwise.

Generally the thresholds for the male voice are lower than for the female voice.
Note that the standard deviation is larger over conditions than over subjects (Table II).

The importance of the position of the distorted stimuli in the pair could not be evaluated, because some of the subjects, when they were not sure, always marked the distortion to be on the first member in the pair. They were aware they did so but could not bring themselves to guess when being uncertain.

Plotting the thresholds of distortion against speech discrimination thresholds showed no correlation.

DISCUSSION

The possibility of detecting nonlinear distortion obviously depends strongly on listener and stimulus factors. Before generalizing still more data have to be collected for more subjects and more test materials.

Compared to the results for normal hearing subjects under the same conditions, TA87, the thresholds basically show the same tendencies. The thresholds are of the same sizes, sometimes even lower, for the hearing impaired. Factors as motivation and listening to a somewhat more varied stimulus material with a possibility of better catching the character of the distortion might have been positive for the hearing impaired. On the contrary the hearing impaired complained of the difficulty of staying concentrated, which seems natural.

The normal hearing subjects listened through an earphone placed in a telephone handset, the hearing impaired through headphones. In both cases the earphones were measured in a 6-cm^3 coupler. Their performance on real ears, however, might have deviated differently from their coupler performances. Additionally the normal hearing might not have held the earphone perfectly tight to their ears, thereby changing the frequency curve and the amount of distortion.

The group of hearing impaired subjects was in some respect a "positive selection". They all agreed to make an extra visit to the hospital to participate in the experiment. Many of them had a speech discrimination between 90 and 100 %. However, there was no correlation between speech discrimination and threshold of distortion in this experiment.
Except the 21 subjects fulfilling the experiment another four subjects began the test. Two of them could not detect any differences in the stimuli. The other two did not seem to understand the instruction. Perhaps they were also too insensitive to distortion.

Comparison with the first experiment with hearing impaired subjects, TA83, is complicated due to the different definitions of distortion. Using the tables in TA87, also considering some other differing parameters, gives approximate thresholds somewhat lower than for the subjects in TA83. Noting the bandwidth up to 15 kHz in TA83 this is quite reasonable.

It is desirable that distortion should only be detected by the most sensitive listeners. Ideally, not even these persons should be aware of the distortion. A recommendation on maximum allowed nonlinear distortion might imply values around or beneath the 75 % thresholds of the most sensitive test subjects. With the definition of distortion used here this means around 6 % for quadratic distortion and around 3 % for cubic distortion measured at the acoustical output of a hearing aid.
The results show that there is no reason allowing more distortion in systems for hearing impaired than for normal hearing persons.

ACKNOWLEDGEMENTS

The author wants to express her gratitude to Lars Änggård and Anders Ovegård who made it possible to perform the tests at Danderyd hospital and to Annika Wahlström, the experimenter. Many thanks also to Åke Olofsson who recalculated the distortions and to our subjects.

REFERENCES

Gabrielsson, A., Nyberg, P.O., Sjögren, H., Svensson, L. (1976). Detection of amplitude distortion by normal hearing and hearing impaired subjects. Report TA83, Technical Audiology, Karolinska institutet.

Gabrielsson, A., Lindblad, A-C., Lindström, B., Olofsson, Å. (1978). Detection of nonlinear distortion in telephone systems. Report TA87, Technichal Audiology, Karolinska institutet.

Olofsson, Å. (1978). A generalization of the concept of total harmonic distortion. Report TA90, Technical Audiology, Karolinska institutet. (This report is also included in TA87 as an appendix.)

Subject	125	250	500	1000	2000	4000	6000	Ear	MCL
	Frequency, Hz								
1	35	40	45	50	60	45	55	R	70
2	20	10	10	10	10	20	20	L	50
3	25	25	40	45	40	45	55	R	70
4	10	25	40	50	60	65	60	L	70
5	25	20	40	60	60	75	65	L	85
6	10	10	45	60	55	50	45	L	75
7	25	30	35	50	55	60	60	R	75
8	20	15	25	40	55	60	60	L	70
9	10	10	10	10	60	60	55	R	70
10	35	30	40	45	65	70	75	L	75
11	35	30	30	30	40	70	75	R	75
12	20	25	50	55	55	75	100	R	85
13	25	25	20	30	50	70	60	R	75
14	15	15	30	50	55	80	75	L	70
15	10	10	10	10	15	65	60	R	70
16	10	30	60	75	75	65	60	R	90
17	15	15	15	45	40	45	45	L	70
18	65	60	65	80	90	110	105	R	95
20	20	25	15	15	10	40	75	L	70
21	30	35	35	35	35	40	55	L	75
22	15	25	20	40	55	70	80	R	80

Table I. Hearing thresholds for 21 subjects with sensory neural hearing loss. Most comfortable levels for test stimuli. Subjects 2, 20 and 21 have Mb Ménière.

TA105

Quadratic distortion

Subject	Male voice Sentence No. 2	Male voice Sentence No. 3	Female voice Sentence No. 2	Female voice Sentence No. 3	Mean	St. dev.
1	11	39	16	34	25	14
2	10	42	14	11	19	15
3	9.6	42	8.5	29	22	16
4	7.6	37	9.6	17	18	13
5	8.8	46	16	34	26	17
6	11	23	9.6	22	16	7.1
7	6.3	14	9.3	16	11	4.2
8	11	28	16	34	22	11
9	10	43	15	33	25	15
10	11	23	16	21	18	5.6
11	9.6	23	15	21	17	5.8
12	9.3	39	9.8	29	22	15
13	11	23	14	33	20	10
14	11	25	17	36	20	14
15	8.4	32	10	31	20	13
16	5.9	23	14	19	15	7.2
17	8.8	27	15	17	17	7.4
18	9.6	12	9.8	17	12	3.5
20	11	18	12	19	15	4.5
21	11	25	15	36	21	11
22	10	23	16	23	18	6.3
Mean	9.6	29	13	25	19	9.3
St. dev.	1.5	10	2.7	7.8	4.0	

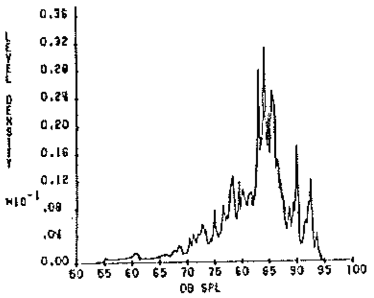
Cubic distortion

Subject	Male voice Sentence No. 2	Male voice Sentence No. 3	Female voice Sentence No. 2	Female voice Sentence No. 3	Mean	St. dev.
1	3.6	4.5	4.4	8.7	5.3	2.3
2	3.9	4.9	5.9	9.2	6.0	2.3
3	3.7	5.3	3.4	8.7	5.3	2.4
4	3.1	4.9	6.2	7.0	5.3	1.7
5	3.9	5.5	5.0	8.7	5.8	2.1
6	3.7	5.6	4.4	9.6	5.8	2.7
7	3.9	4.5	5.4	9.2	5.8	2.4
8	3.7	4.5	6.4	9.2	6.0	2.4
9	3.6	4.9	4.4	9.9	5.7	2.9
10	3.7	5.7	6.1	8.7	6.1	2.1
11	3.6	3.2	5.0	8.7	5.1	2.5
12	3.7	5.3	5.0	10	6.0	2.8
13	4.0	5.3	5.9	9.2	6.1	2.2
14	3.6	4.5	5.7	9.2	5.8	2.5
15	3.7	5.8	3.9	8.0	5.4	2.0
16	3.4	5.6	3.8	10	5.7	3.1
17	3.7	5.5	5.0	9.2	5.9	2.4
18	3.6	5.7	5.9	10	6.3	2.7
20	3.7	4.9	5.4	4.0	4.5	0.8
21	3.6	4.9	5.7	9.2	5.9	2.4
22	4.0	5.6	5.7	9.2	6.1	2.2
Mean	3.7	5.1	5.2	8.9	5.7	2.2
St. dev.	0.2	0.6	0.9	1.3	0.4	

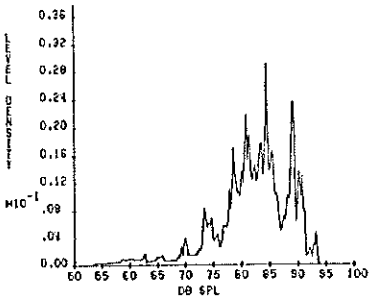
Table II. Thresholds of detection for nonlinear distortion. 21 subjects with sensory neural hearing loss.

Sentence No 2 | **Sentence No 3**

a)

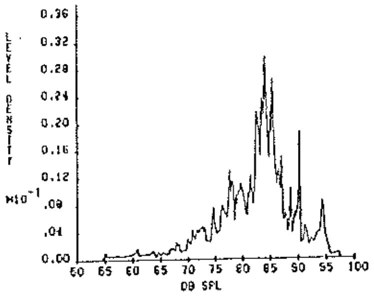


Mean = 82.0 dB
St.dev. = 7.06 dB
Max = 94.3 dB
Min = 53.2 dB



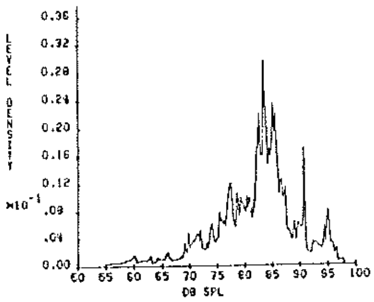
Mean = 82.0 dB
St.dev. = 6.76 dB
Max = 93.4 dB
Min = 53.0 dB

b)



Mean = 82.0 dB
St.dev. = 7.26 dB
Max = 97.5 dB
Min = 54.1 dB

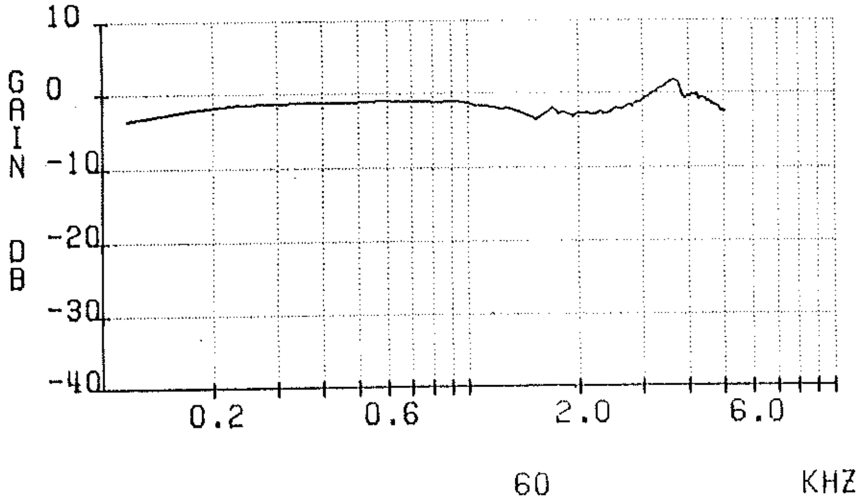
c)



Mean = 82.0 dB
St.dev. = 7.57 dB
Max = 97.8 dB
Min = 54.6 dB

Figure 1. Level density of speech material. Averaging time 20 ms. Male voice.
a) undistorted
b) with 40 % quadratic distortion
c) with 20 % cubic distortion

a)



b)

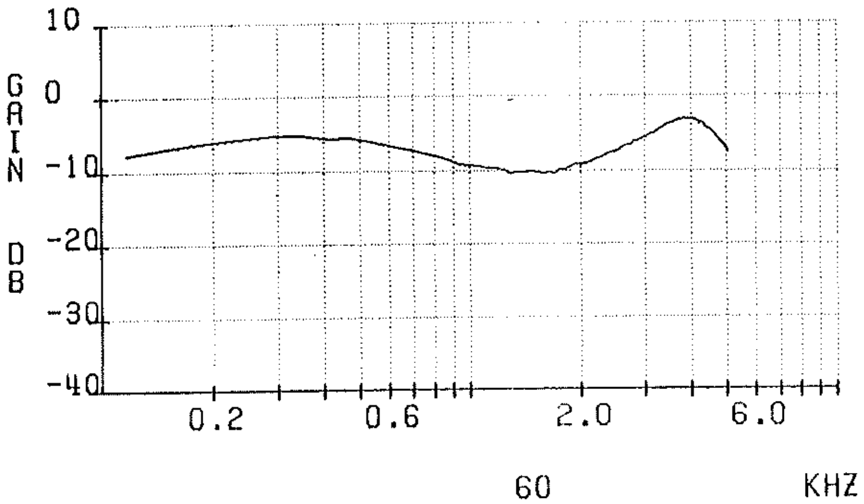


Figure 2. Frequency response of earphone.
a) current experiment
b) telephone experiment

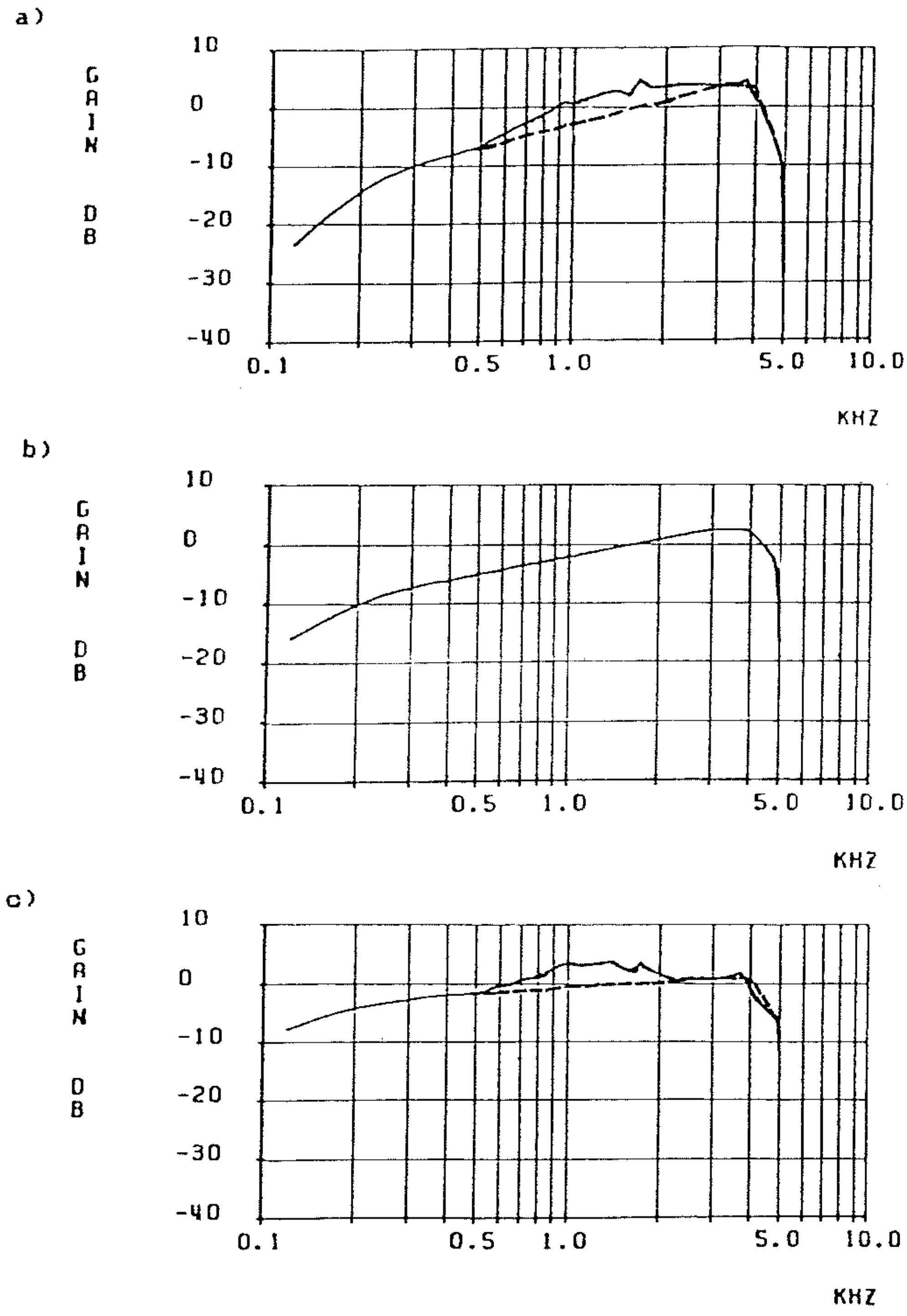


Figure 3. Frequency response of linear system.
a) total
b) first filter
c) second filter

full line - current experiment.
broken line - system A in telephone experiment (where not overlapping).

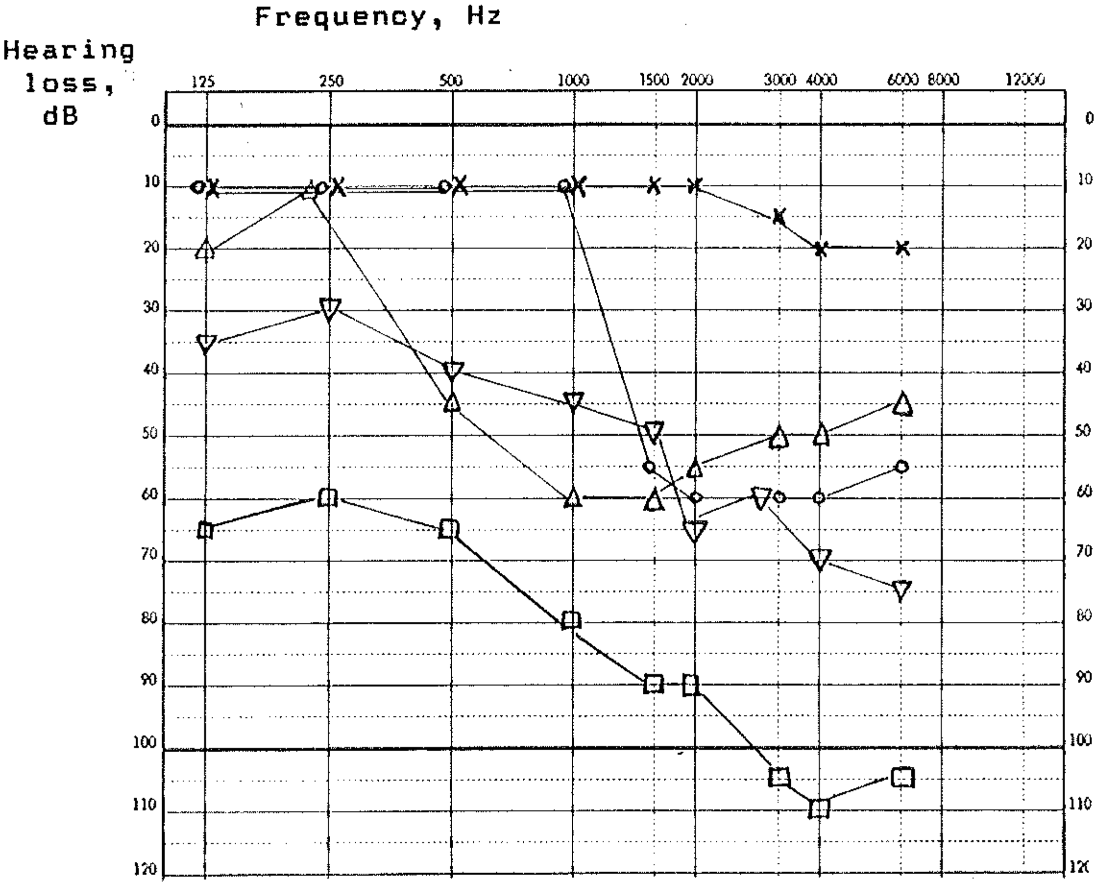
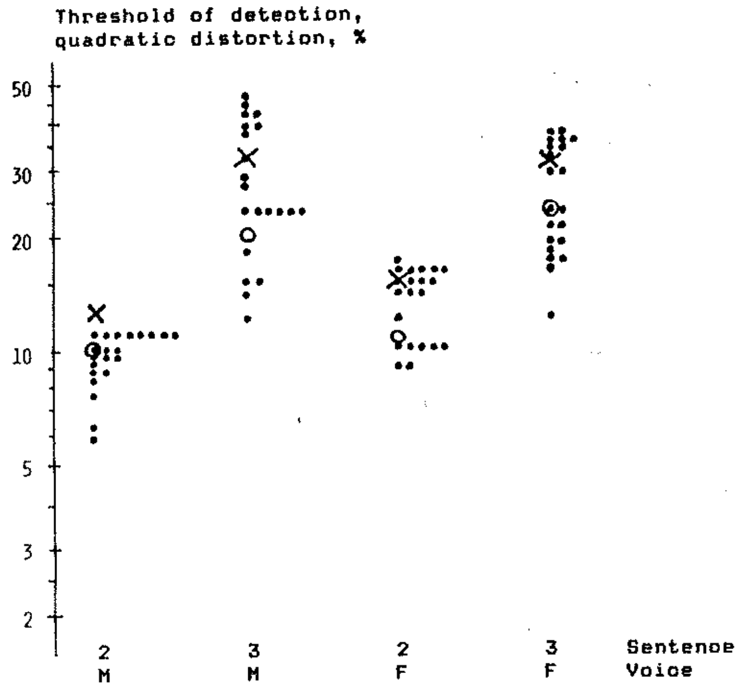


Figure 4. Examples of audiograms including the best one and the worst one. All audiograms fall within these limits at any frequency.



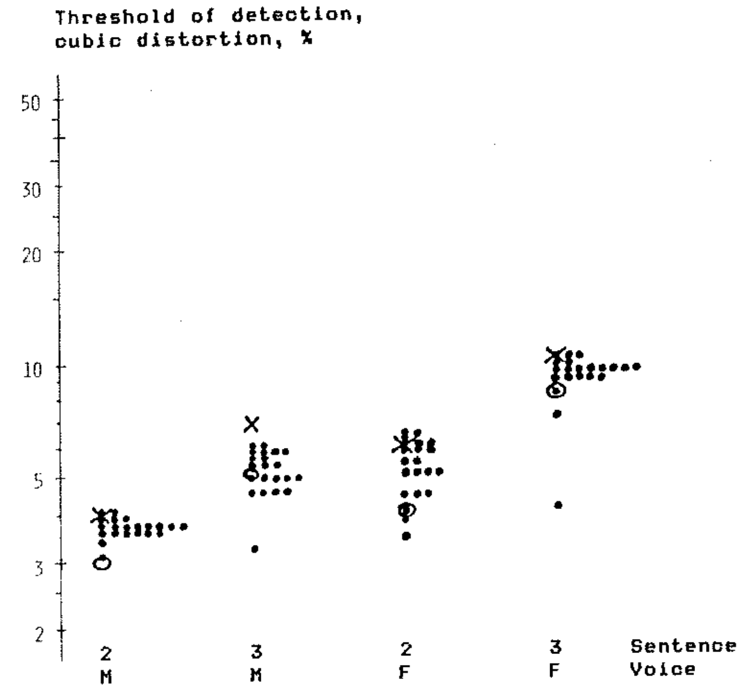


Figure 5. Thresholds of detection for nonlinear distortion.
21 subjects with sensory neural hearing loss.
Two sentences. Male and female voices.

● 75 % threshold of individual with sensory neural hearing loss, current experiment.

× 75 % group threshold of 8 normal hearing subjects, telephone experiment.

○ 60 % group threshold of 8 normal hearing subjects, telephone experiment.