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application notes

Relevant loudspeaker tests
in studios
in Hi-Fi dealers' demo rooms
in the home etc.
– using 1/3 octave, pink-weighted, random noise

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Relevant loudspeaker tests in studios in Hi-Fi dealers' demo rooms in the home etc., — using 1/3 octave, pink weighted, random noise

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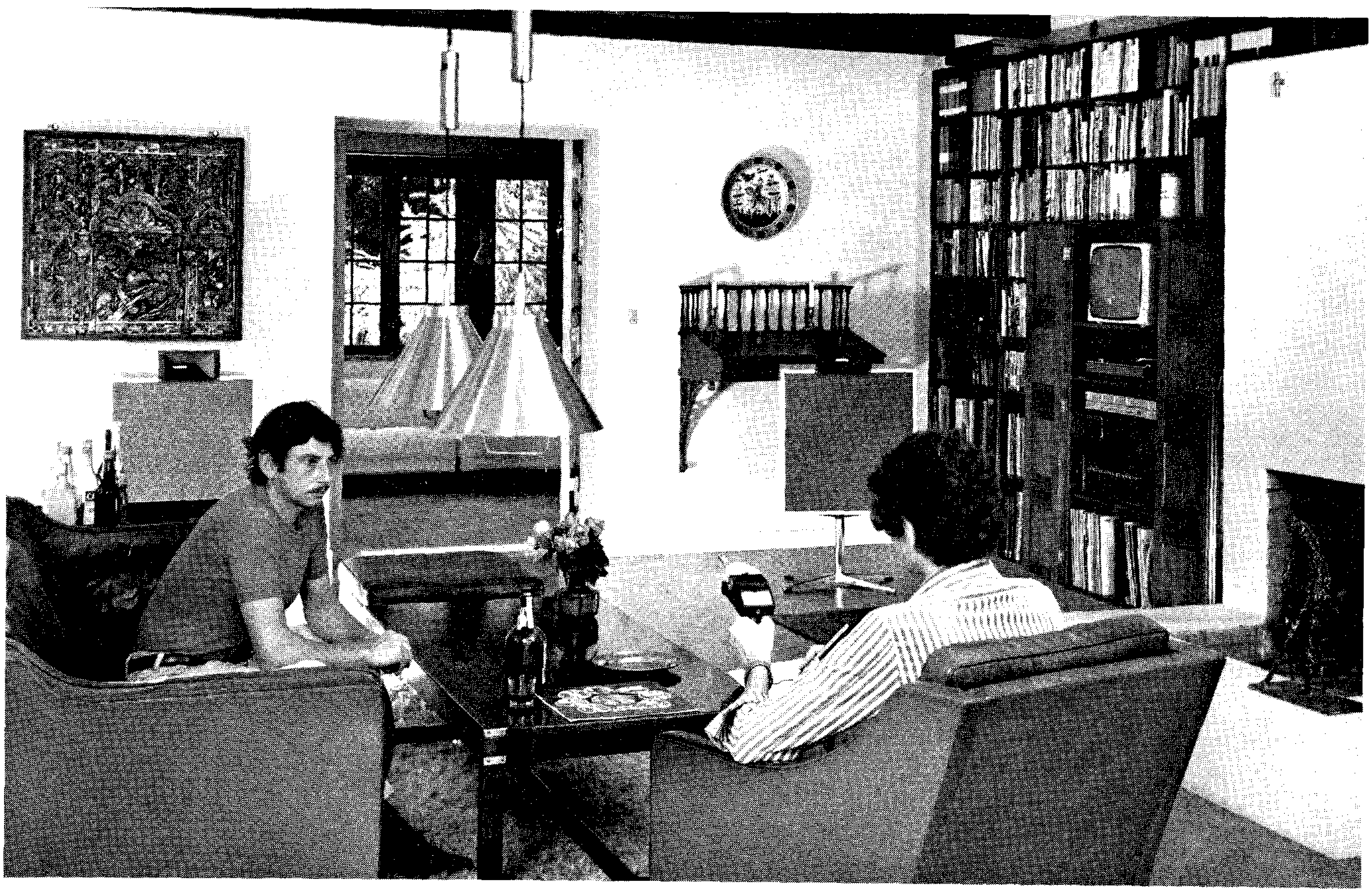

Abstract

The "sound" of a Hi-Fi set is to a great extent room dependent. Very often, the final result is determined by the room rather than by the actual equipment. Fortunately, these influences may readily be measured.

The objective test method, which seems to correspond best with subjective judgment, is the "1/3 octave, pink-weighted random noise method" carried out in the listening room. From measurements made according to this method, it is possible to say which Hi-Fi equipment will give the best result in the actual listening room. In practice, the method can be carried out in many ways.

The simplest and least expensive method, uses a pink noise test record and a precision sound level meter. The most sophisticated and accurate technique (also the most expensive), uses a pink noise generator and a real-time, third octave analyzer. The results of such measurements show the frequency response characteristics of the loudspeaker/listening room combination.

This application note will describe the measurement possibilities, and it will show some results of the methods and compare them with results obtained by listening tests. Five loudspeakers in three different rooms and a test team consisting of five critical listeners were used.

Introduction

Too often, people are disappointed when having brought home a new hi-fi set. Although it sounded good at the dealer's, and the high price paid should be some sort of guarantee of quality, the sound at home is not as good as had been hoped for. The reason is often that the influence of the listening room has not been taken into account.

It is well known that the output voltage of an electric circuit is very dependent upon the actual loading. Likewise the output of an acoustic system is dependent upon the acoustic loading — i. e. the listening room. Thus, a measurement of the complete system must be made under normal acoustic working conditions, those that exist in the actual listening room.

If a manufacturer produces loudspeakers to suit standard measurements in anechoic chambers, he can sell an ideal transducer and let the customer change his room accordingly. He can make it a little easier for the customer if he builds-in a correction network, but the optimal result can normally first be obtained after a measurement in the actual listening room. In fact, it can be very difficult, by ear alone, to decide exactly what is wrong. If, for instance, there is a resonance between 100 and 200 Hz, one could say, that there is something wrong in the bass, but not exactly where it is wrong. Normally, neither loudspeakers nor rooms are ideal, and therefore the problem is often to find a reasonable combination. Usually, this can be achieved by selecting the best suited equipment rather than by paying a higher price.

Lately, a great many investigations have been made to find suitable measuring methods in listening rooms. In Denmark, the so-called "Højttalerundersøgelse" (loudspeaker investigation, Ref. 1) has been made in order to try to find connections between objective measurements and subjective judgments. The objective measurement that seems to correspond best with results from listening tests, is as mentioned the "1/3" octave, pink-weighted random noise method" carried out in the listening room. Also, phase measurements and power characteristics seem to correspond reasonably well, although to a lesser degree. (Ref. 3 and 4).

Three Rooms and Five Loudspeakers

This Application Note deals with two types of loudspeaker tests made at Brüel & Kjær: 1) Main Listening tests and statistical treatments of the results. 2) Measurements using both expensive and inexpensive measuring equipment. The results of the subjective and objective evaluations were then compared and supplemented by additional listening tests and measurements.

As mentioned, three rooms and five loudspeakers were used.

The rooms are shown in Figs. 1, 2 and 3.

The room dimensions in meters are Room L1: 9,2 × 4,6 × 3,3, Room L2: 5,1 × 3,7 × 2,6 and Room L3: 4,3 × 3,7 × 2. The reverberation times as a function of frequency are shown in Fig. 21.

The loudspeakers used were:

H1: Richard Allan 15"
+ Lowther PM 6
+ B & O Cube 2500 (spec. filter)
H2: Quad Elektrostat.
H3: B & O Beovox 3000.
H4: Wharfedale Super Linton.
H5: Isophon HSB 30/8.

The loudspeaker positions were chosen partly because the minimum distance between the speakers is considered, and partly because the speakers should have acoustic conditions as equal as possible.

Later the dependence on loudspeaker positioning will be shown. It was also important that listening tests and measurements were made at the same position.

15 Curves

To get an immediate impression of the results, look at the 15 curves (Fig.4) which the 5 speakers, in the 3 rooms gave from measurements at the listening position, with 1/3 octave bandpass noise. Later, much more detailed information about the measurements will be given.

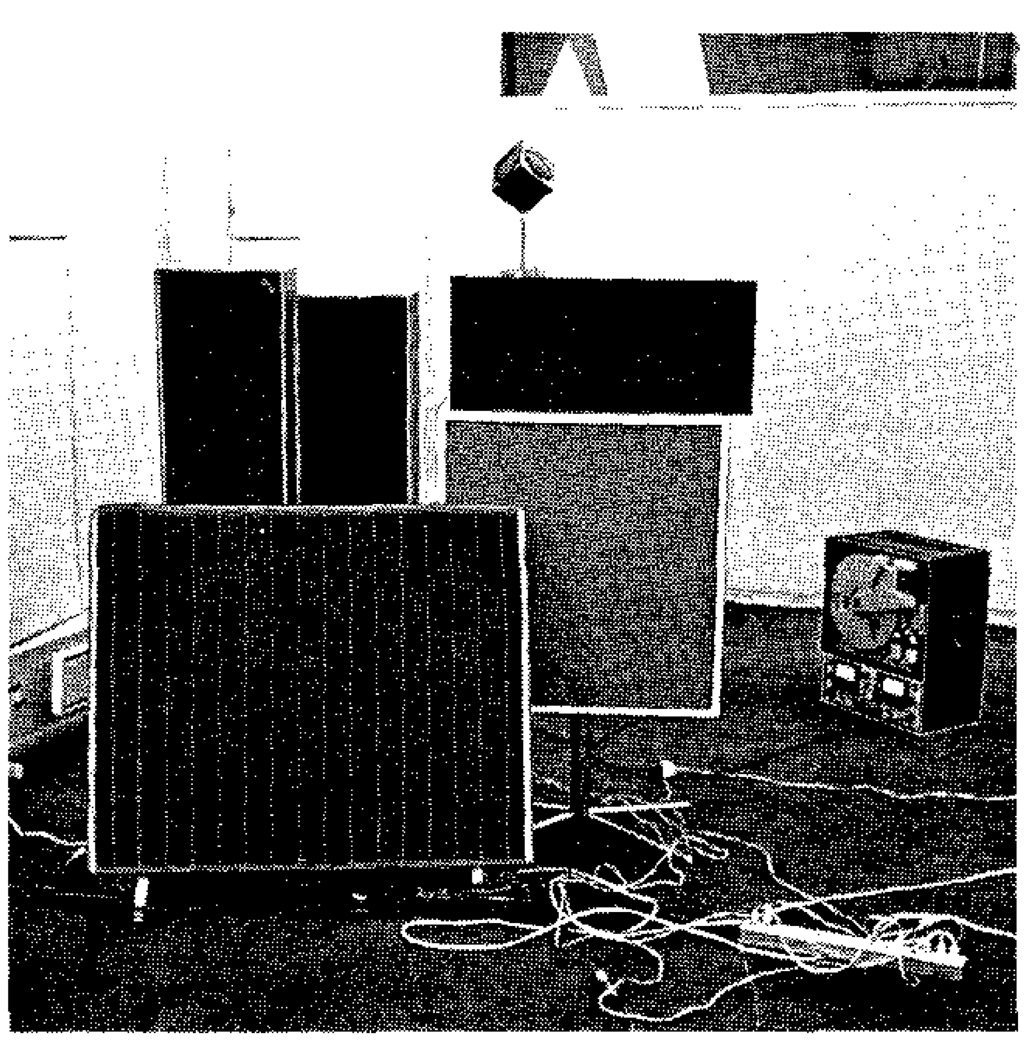

Fig.1. Room L1

Fig.2. Room L2

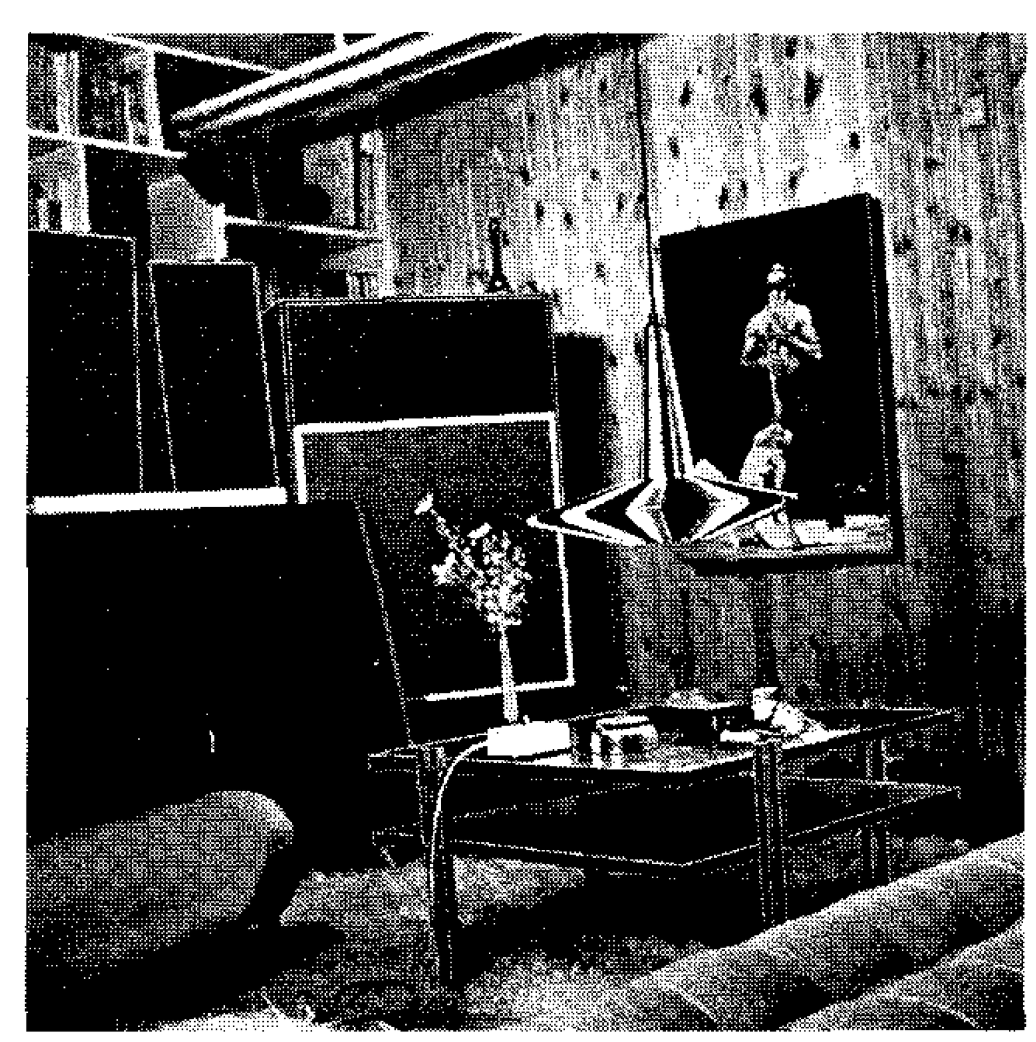

Fig.3. Room L3

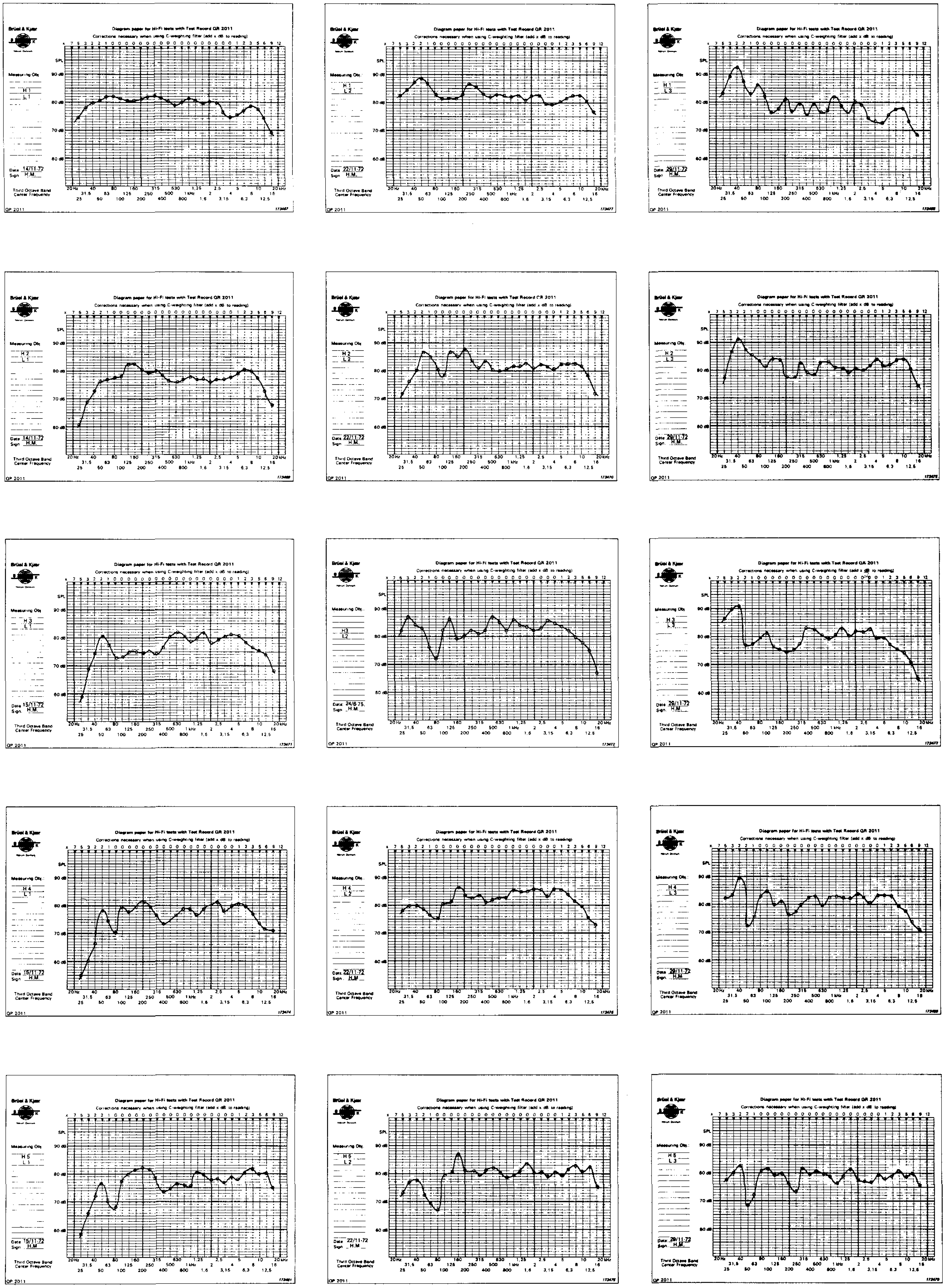

Fig.4. **These curves show how the 5 loudspeaker responses differ in the 3 rooms. The measurements were made by the portable and inexpensive method. Note that the 3 in-line curves are for the same loudspeaker tested in different rooms**

The three vertical columns represent, from the left, listening rooms L1, L2, and L3. The five horizontal rows represent the five speakers H1, H2, H3, H4, and H5. Note that the three top charts give the curves for the same speaker in three different rooms. There certainly is a big difference. In the large room, L1, the curve is fairly even, in room L2 it is somewhat worse, and in room L3 it is very uneven. Room L3 has too much bass-lift and too many resonances.

Evaluation of the Curves

Now look at the five charts in the first vertical column — that is the 5 different speakers in the same room, L1. There is no doubt that the uppermost chart is the best, No.2 is next, and the lowest chart is clearly the worst. Whether No. 3 or No. 4 is the better, is at first difficult to decide, but upon closer examination — as shown later — we will see that No. 4 is better than No. 3.

This order was later found to be the same as the order of preference indicated by listening tests.

The closer evaluation of these curves concern the following two criteria. First, the curves should be as smooth and straight as possible, indicating that all frequencies are reproduced at approximately equal level. Secondly, primary emphasis should be given to the 60 Hz to 6 kHz range.

When music is recorded under far-field conditions, it will contain a suitable mixture of direct and reflected sound, and the curve ought to be absolutely flat in that case. This is true for recordings, for instance, made with two B & K condenser microphones in the far-field.

However, since most recordings are made as a combination of near-field and far-field information, the curve should boost a little at low frequencies and roll off a little at high frequencies. A suitably shaped curve is shown in Fig.5.

The curve shows only the necessary tendencies. This curve was derived partly as a result of listening tests and partly by consideration of curves from average concert halls. According to Beranek (Ref. 2) the average concert hall has a roll off similar to that in the curve shown, but at twice the rate. Only half the rate is chosen because most recordings are equally distributed between near-field and far-field recording.

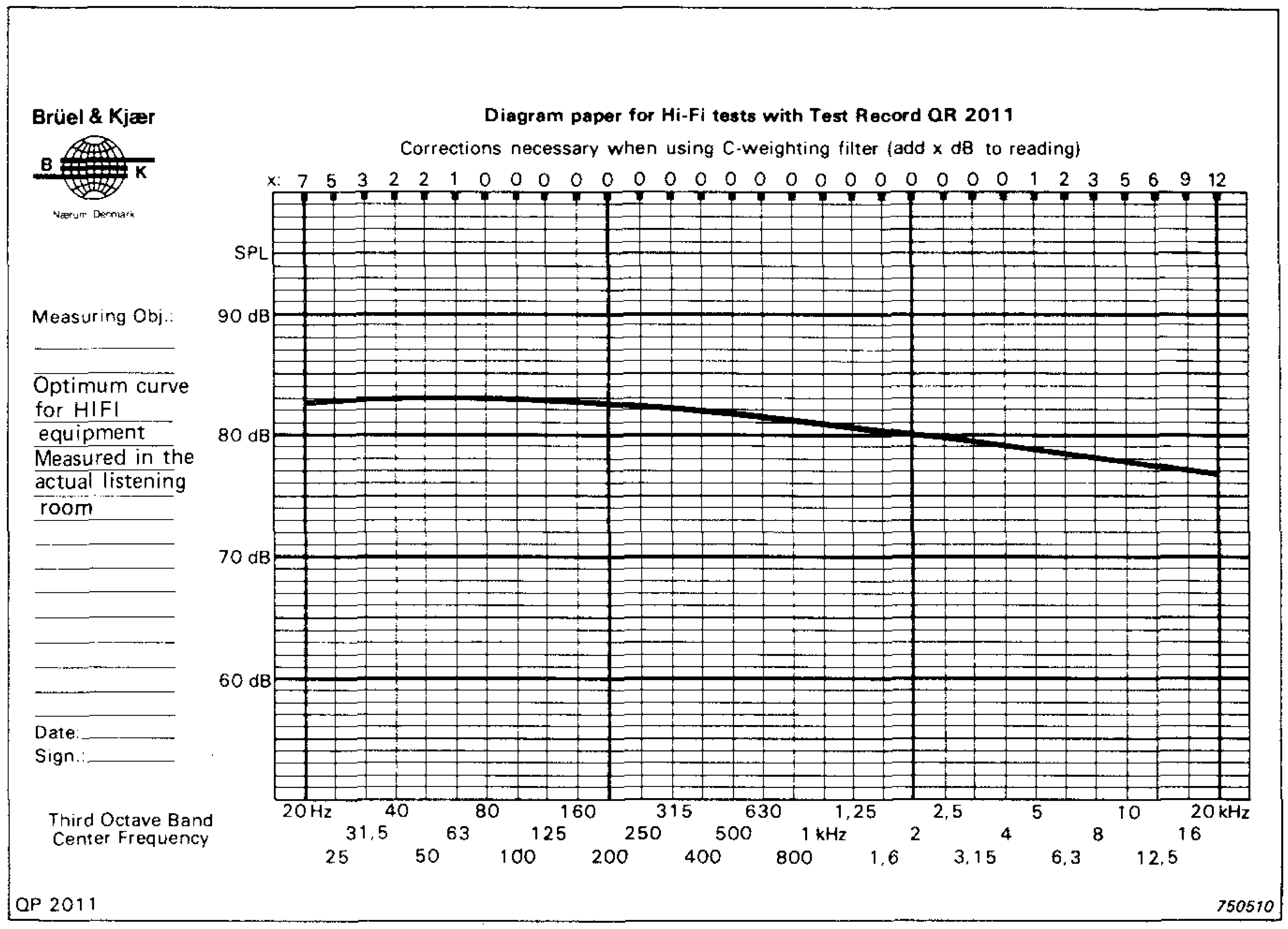

Fig.5.

Pratice has shown that this characteristic is absolutely reasonable for reproduction of most commercial recordings.

The second consideration when evaluating the curves in Fig.4 is the average frequency content in normal music recording. As we will see later (Fig.20) this is typically in the range from 60 Hz to 6 kHz, and therefore this range is given more consideration than the rest of the audible range.

It should be mentioned, that at the time of the investigation, no one was really sure about Fig.5. For instance, we could not call loudspeaker H5 in room L3 really bad, just because it did not roll off at high frequencies. If we had done, even better agreement with the listening tests would have been achieved, as will be seen later.

From the above mentioned criteria, evaluation of the measured curves in Fig.4 was as follows:

Room L 1:	H1 - H2 - H4 - H3 - H5
Room L 2:	H1 - H2 - H4 - H3 - H5
Room L 3:	H2 - H4 - H5 - H1 - H3

Preference sequence from measurements

— that is, in room L1 loudspeaker H1 was the best, H2 second, and so on.

Listening Tests

Throughout the listening tests, the loudspeakers were compared two by two. The person listening was asked to choose which of the two loudspeakers, he preferred to listen to at any given time. All the loudspeakers were equalised to the same sound pressure level, using pink noise. All the speaker cabinets were covered by a porous cloth, so that the cabinets could not be seen during the listening tests.

Throughout the tests, six different short music pieces were used (See Fig.20) Wagner Opera, Modern String Quartet, Organ Music from a church, Beat, Jazz, and Popular

Music, to ensure that the results were independent of the type of music material used.

For each of these two-by-two comparisons, the person listening had to fill out a questionnaire as shown in Fig.6.

It is seen that there are 35 characteristics and for each characteristic the listener was to select which of the two speakers, in his opinion, possessed most of that particular characteristic. The following code was used.

1 = Loudspeaker 1 has most of the characteristic
2 = Loudspeaker 2 has most of the characteristic
3 = Both speakers have the characteristic in equal degree
4 = Neither of the speakers has the characteristic

Using 5 loudspeakers, 5 listeners, 3 rooms and 35 characteristics a total of (4 + 3 + 2 + 1) × 5 × 3 × 35 = 5250 comparisons were made.

Results of Listening Tests

It would not be reasonable to go into details of the statistical treatment of this material here. Let us simply examine the main result (Fig.7).

The three curves show the number of times a given loudspeaker has been generally characterised as being the best one for each room, the higher the curve the better. It is seen, as mentioned in the introduction, that the results are highly dependent upon the room. The result for loudspeaker H1, for instance, differs 100% from room L3 to room L1, and loudspeaker H4 is much worse in L1 than in the other rooms.

This is a real problem for a customer who hears these five loudspeakers demonstrated by a dealer, with a demonstration room similar to room L1, He decides on loudspeaker H1, when price is not taken into consideration. But then he finds that his own room is similar to room L3, — he should never have selected H1, but H4 instead.

Identification
Listener No. . . . . ☐
Room No. . . . . ☐
Comparison No. . . . . ☐

Actual measurements:
1. First preference . . . . ☐

Overall impression
2. Natural . . . . ☐
3. Well defined. . . . . ☐

General sound quality
4. Detailed resolution . . . . ☐
5. Muddy . . . . ☐
6. Presence . . . . ☐
7. Distant . . . . ☐
8. Transparent . . . . ☐
9. Stained. . . . . ☐
10. Bright . . . . ☐
11. Dull . . . . ☐
12. Full . . . . ☐
13. Thin . . . . ☐

Frequency response
14. Uniform . . . . ☐
15. Strong bass . . . . ☐
16. Weak bass . . . . ☐
17. Strong mid range . . . . ☐
18. Weak mid range . . . . ☐
19. Strong treble . . . . ☐
20. Weak treble . . . . ☐

Distortion
21. Boomy . . . . ☐
22. Hollow . . . . ☐
23. Nasal . . . . ☐
24. Metallic . . . . ☐
25. Harsh . . . . ☐
26. Cutting . . . . ☐
27. Hard . . . . ☐
28. Mellow . . . . ☐

Most natural reproduction of:
29. Bass. . . . . ☐
30. Mid range. . . . . ☐
31. Treble . . . . ☐
32. Orchestra . . . . ☐
33. Chamber . . . . ☐
34. Popular . . . . ☐

35. Second preference . . . . ☐

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Fig.6. The questionnaire

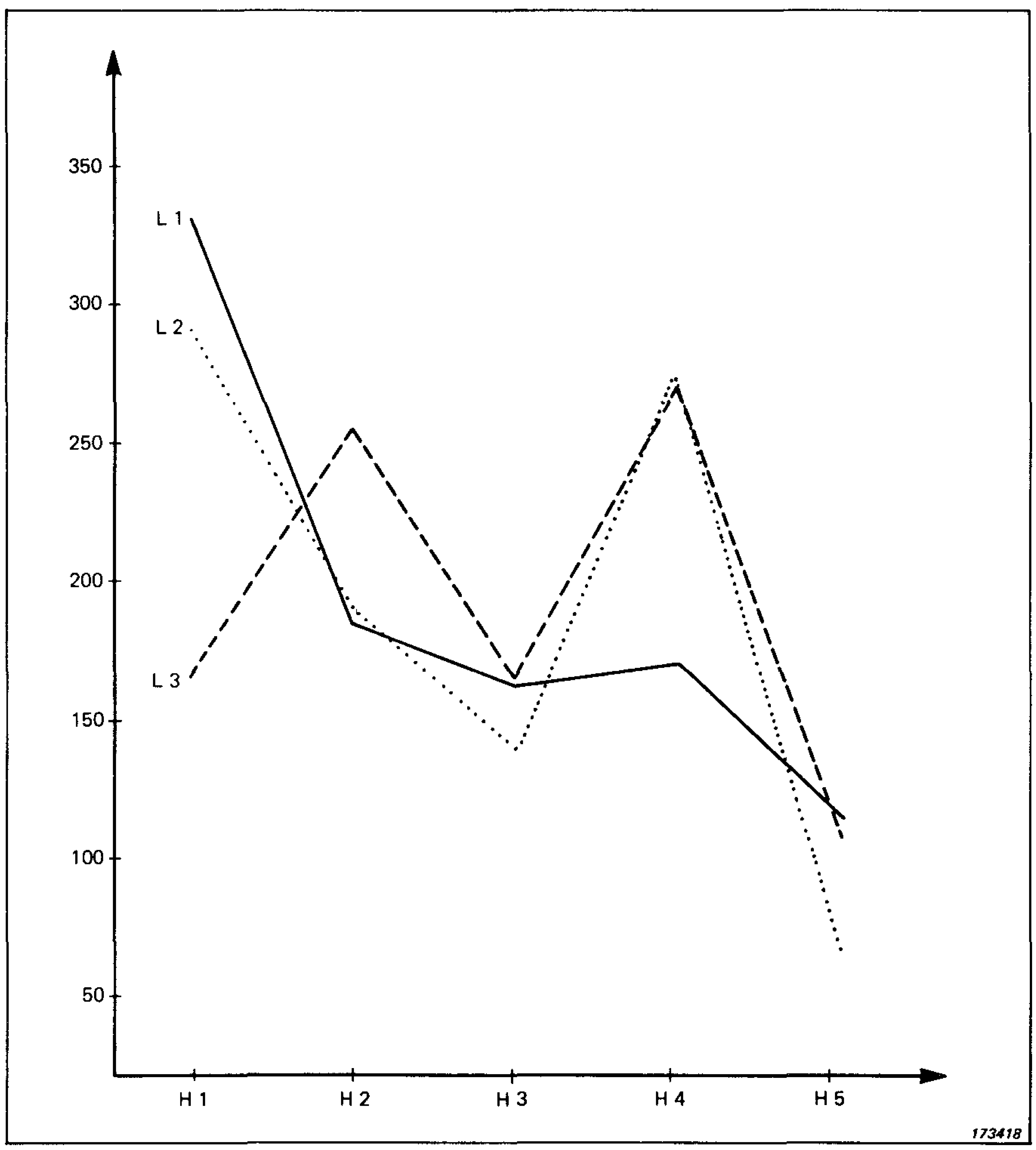


Fig.7. Curves showing how the subjective quality evaluation of a particular loudspeaker strongly depends on the actual listening room. The y-axis shows the number of times a loudspeaker was preferred. These results are based on answers to positively orientated questions

From the curves in Fig.7, we can make the following preference sequence:

Room L1: H1 – H2 – H4 – H3 – H5

Room L2: H1 – H4 – H2 – H3 – H5

Room L3: H4 – H2 – H1 – H3 – H5

Preference sequence from listening tests

Similarities Between Measured Results and Listening Results

Now compare this preference sequence from the listening tests with the one obtained from measurements. It is seen that the only essential difference in the results is that loudspeaker H5 in room L3 was placed as No. 3 from measurements, while from listening tests it was placed as No. 5. As mentioned earlier, this was based on the original evaluation. Today, Fig.5 would be considered more important and the result would be even better than shown here. The difference between loudspeakers H2 and H4 in rooms L2 and L3 is so small that it is almost impossible to state a preference, either from listening tests or from measurements.

An example of how the speakers were distributed for the different characteristics is shown in Fig.8.

The curves show the number of times the different speakers (H1,.... H5) have been characterised as better than the ones they were compared with, as a function of the positively oriented questions in the questionnaire (Fig.6).

This figure (Fig.8) is valid for room L1 but corresponding curves were also made for the other rooms, of course, as well as for the negative characteristics. The results from the positive and the negative characteristics were almost the same.

An example of how the listeners' opinions were distributed is shown in Fig.9. There is one curve for each person. It is seen that for each speaker there was one person who voted appreciably different from average. But as it was a different person each time, the listeners can be considered to be in reasonable agreement. The average voting must be considered to be consistent, they were also all experienced critical listeners.

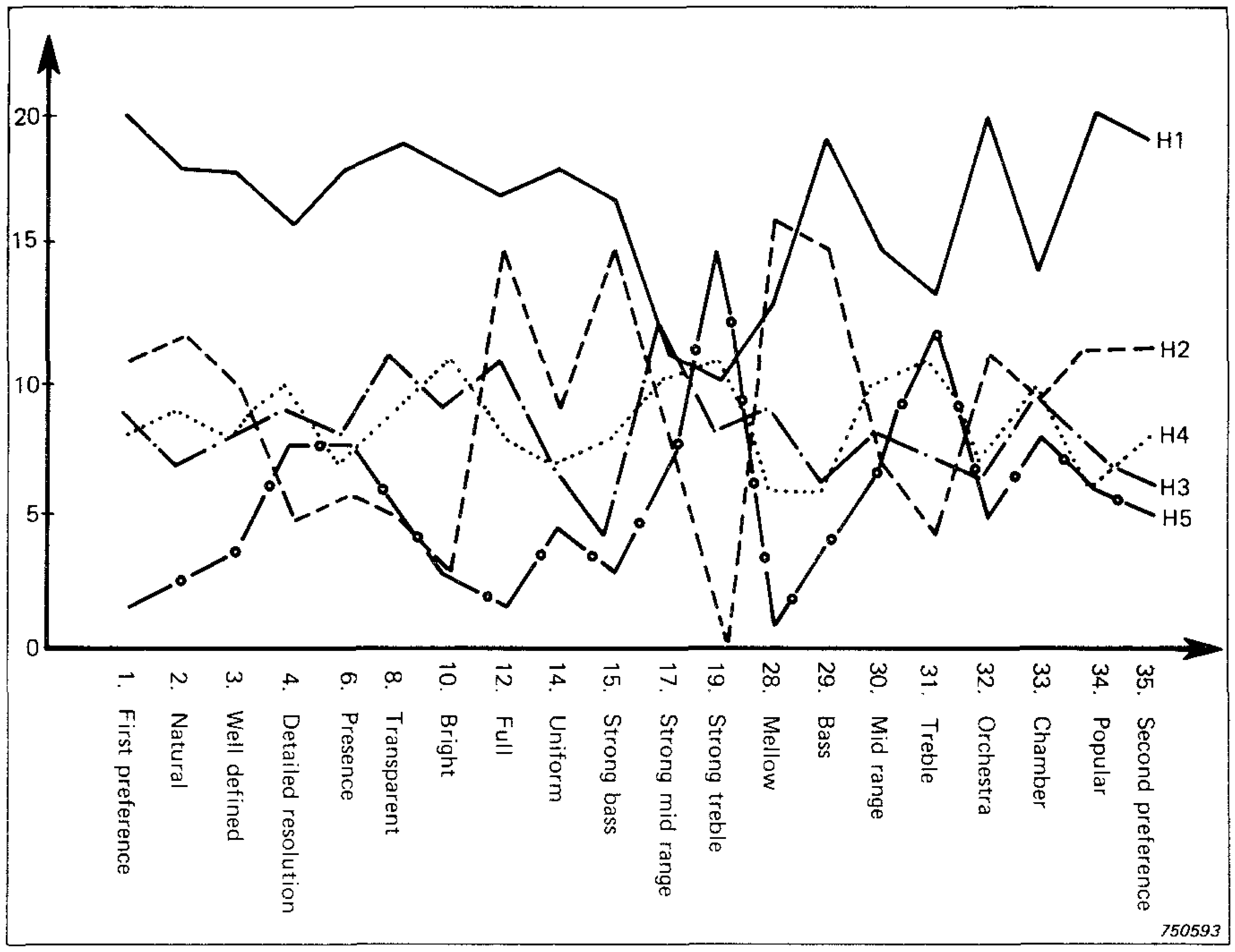


Fig.8. The number of preferences for the speakers as a function of the characteristic

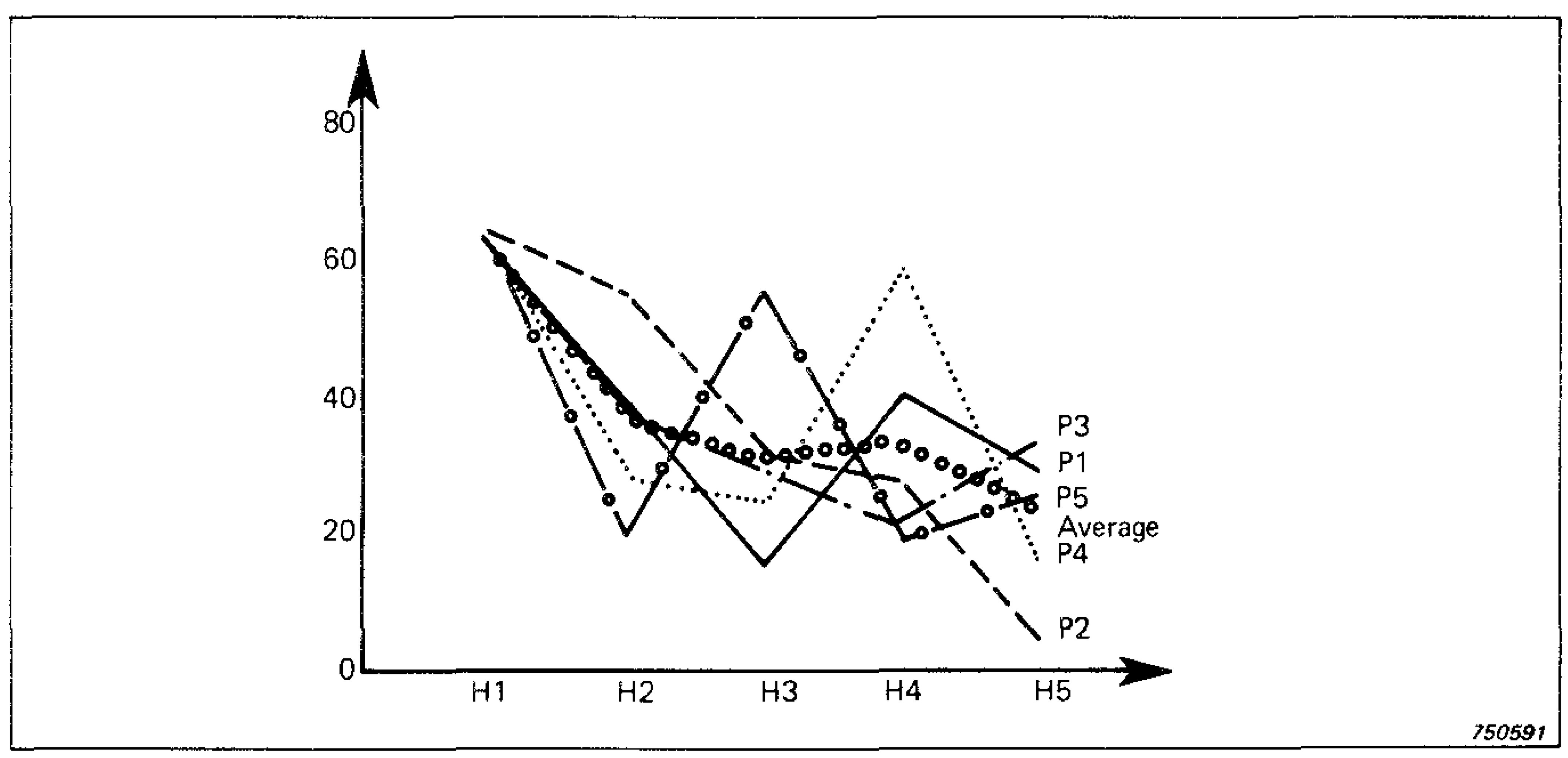


Fig.9. Example of how the listeners' opinions were distributed

Real-Time Method

Until now we have only mentioned the measuring method as "the 1/3 octave, pink-weighted, random noise method". Now let us look closer, to see how the method is used.

The professional method is shown in Fig.10. Here the Noise Generator Type 1405 sends broadband "Pink noise" through the system, and the Real-Time Analyzer is used as the measuring instrument.

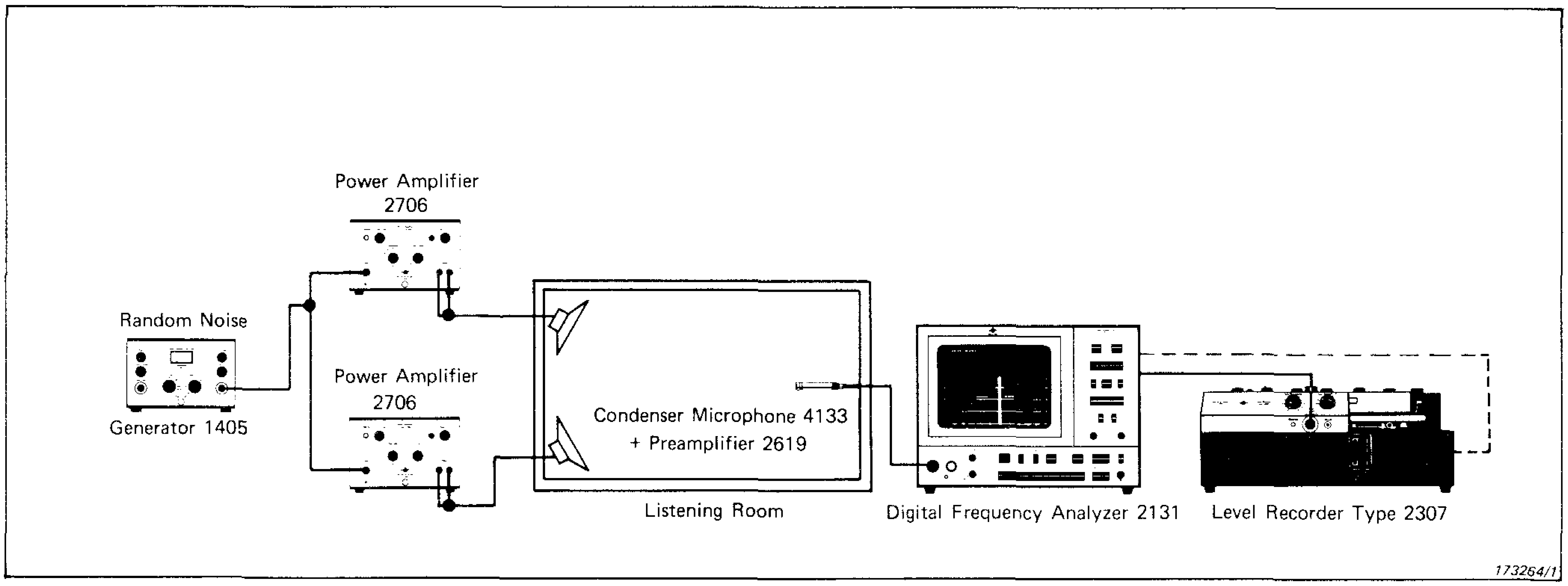


Fig.10. Measuring set-up with "pink" noise 20 Hz to 20 kHz. The result is immediately read out on the screen

"Pink Noise" looks as shown in Fig.11 when it is sent directly to the Real-Time Analyzer — each column is seen to have about the same height.

If white noise is introduced to the analyzer, it appears as shown in Fig.12. White noise contains all frequencies at the same amplitude, nevertheless a slope of + 3 dB/octave is seen. This is because a logarithmic frequency scale is used and the actual bandwidth increases proportionally with frequency, 1/3 octave at low frequencies is just a few Hz, while 1/3 octave at high frequencies covers several thousand Hz. Since the voltage for white noise is proportional to the square root of the bandwidth, the increase will be only 3 dB/octave.

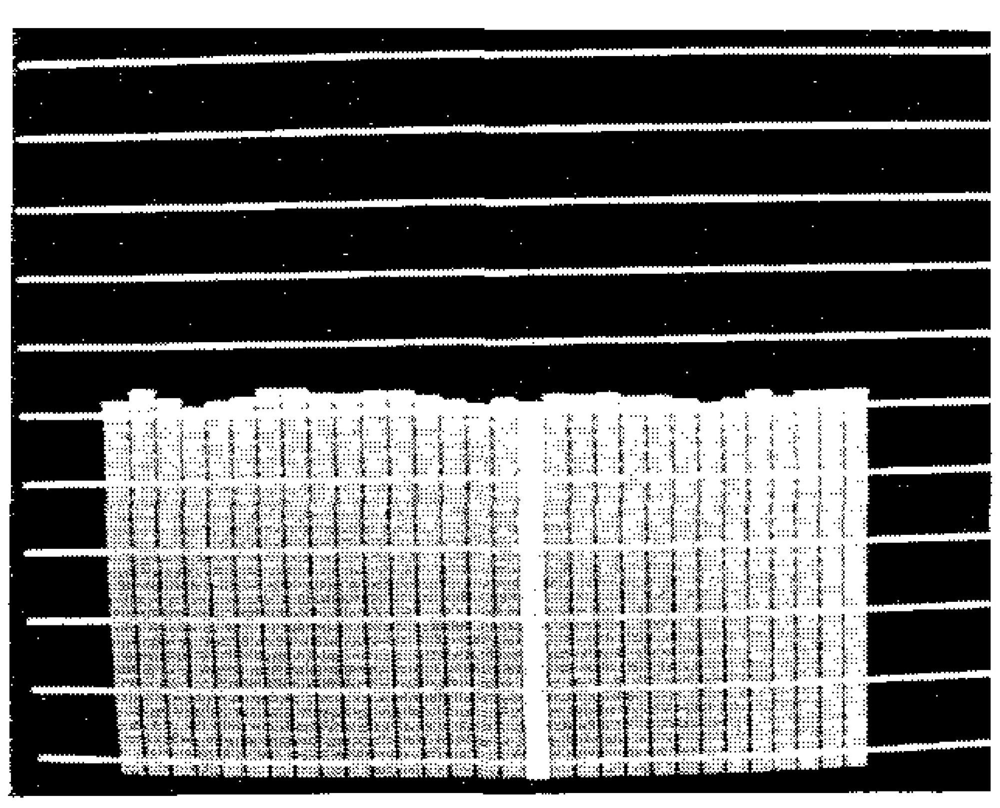


Fig.11. Spectrum for pink noise

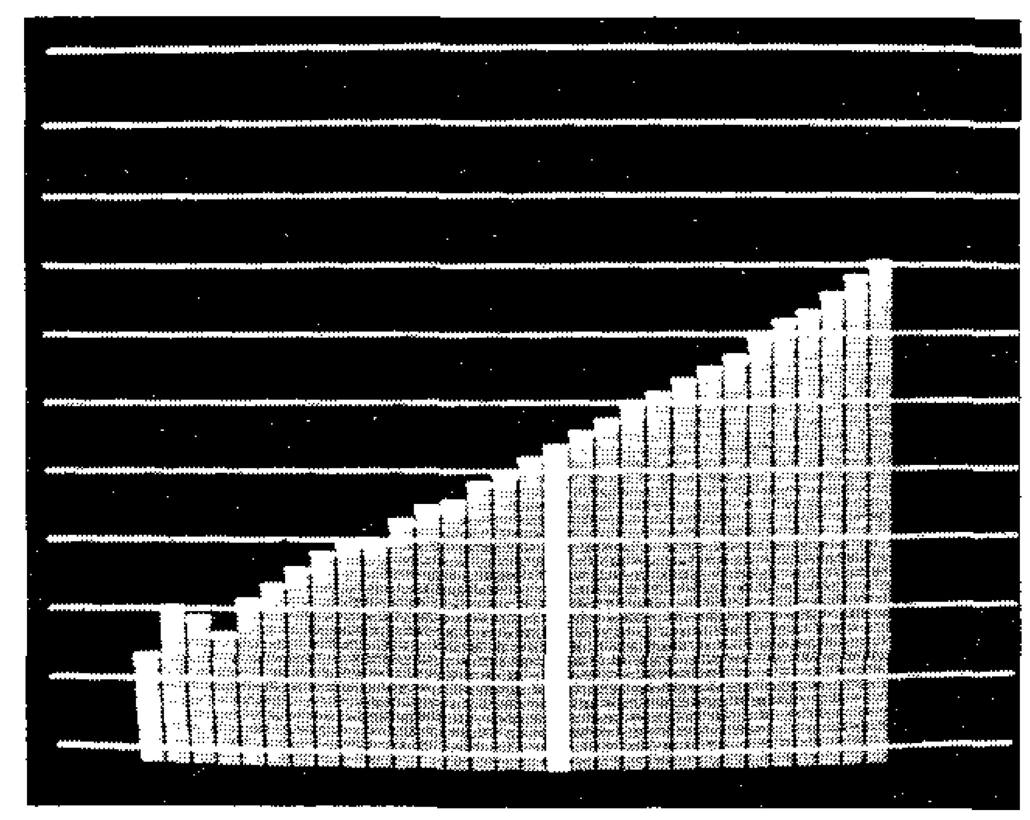


Fig.12. Spectrum for white noise

To obtain the flat curve that is wanted on the screen, we correct the white noise with a —3 dB/octave filter. This is the signal called "pink noise". Pink noise is nothing but white noise weighted —3 dB/octave, and it is usually used together with a logarithmic frequency scale and filters of constant percentage bandwidth. White noise is most often used with constant bandwidth filters.

Automatic Method Using Successively Switched 1/3 Octave Filters

A less expensive measuring method is shown in Fig.13. In this

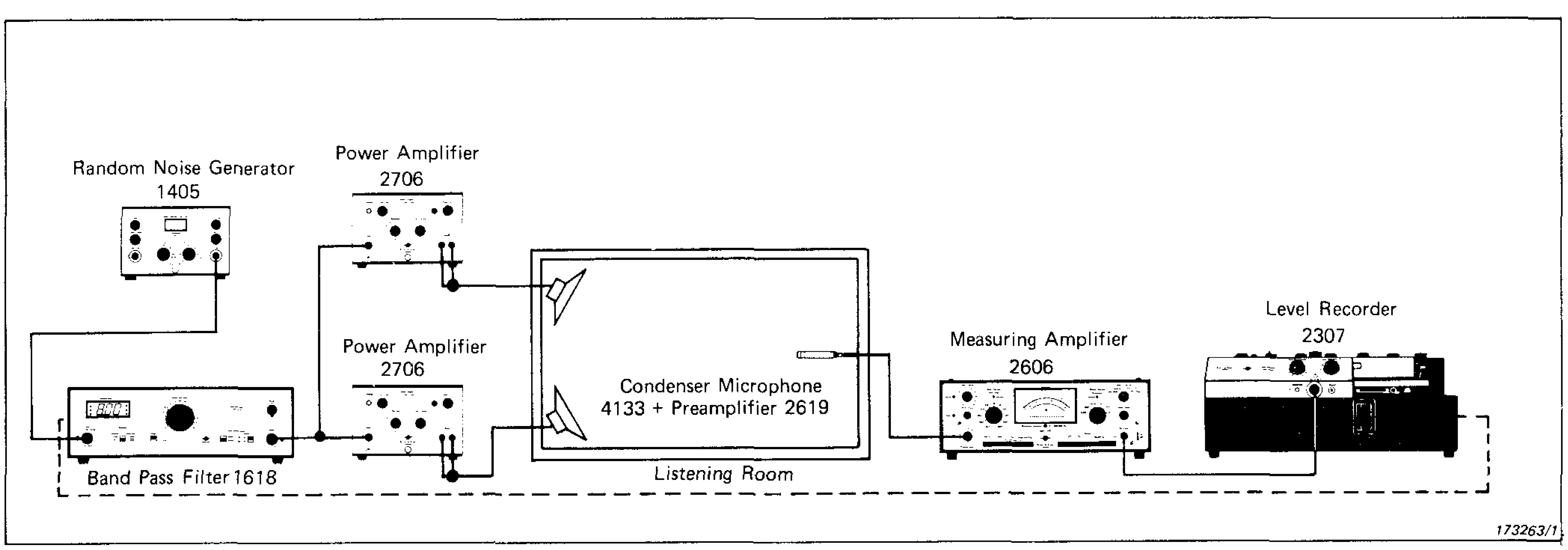


Fig.13. Set-up for "1/3 octave, pink-weighted, random noise method"

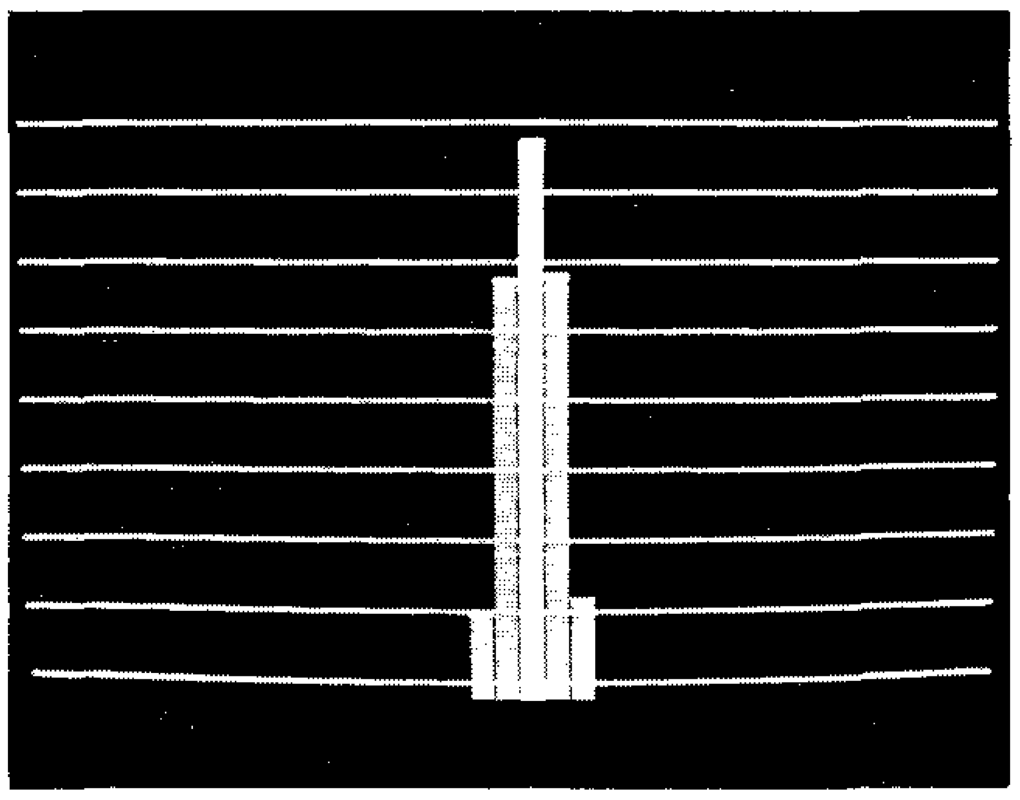


Fig.14. Spectrum for 1/3 octave

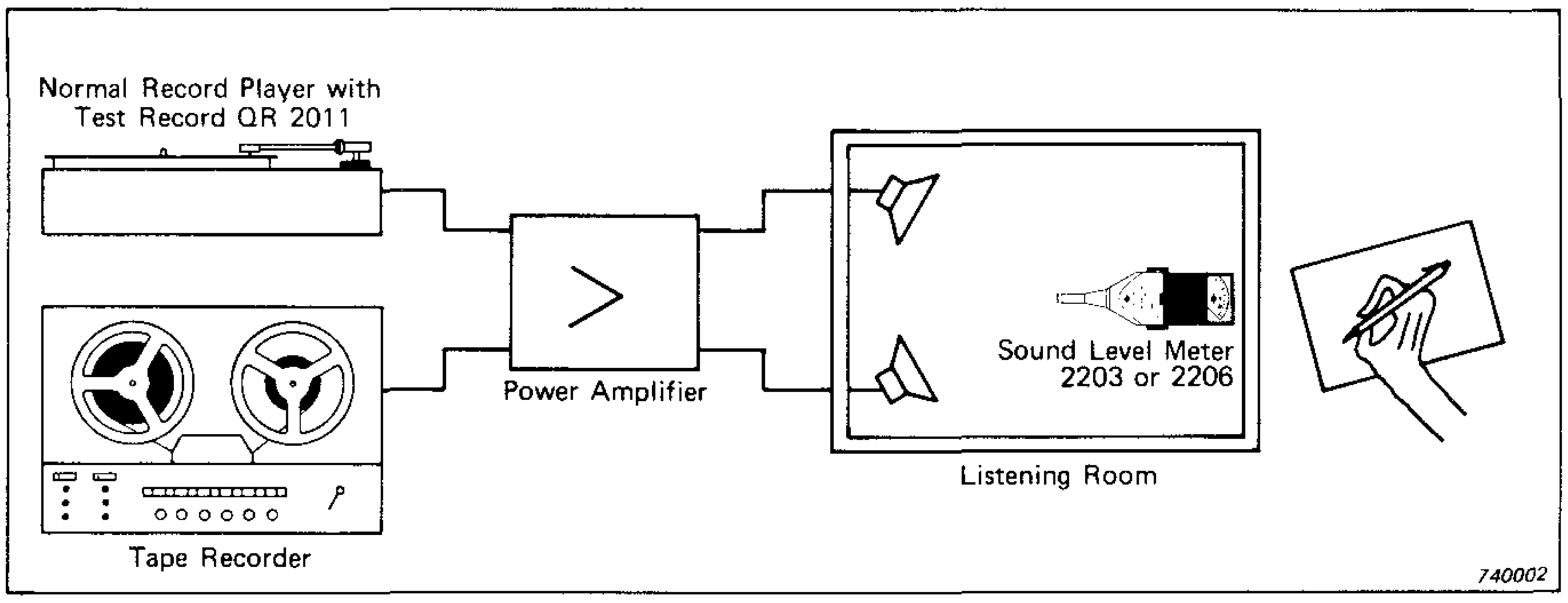


Fig.15. The portable and inexpensive method. The recording is manual with one point for each 1/3 octave

case we apply each 1/3 octave bandwidth individually and take a broad band level measurement for each 1/3 octave band. The signal looks as shown in Fig.14.

This method is slower than the Real-Time method, because we must make 30 measurements, one for each 1/3 octave, while in the Real-Time method they were all measured simultaneously.

In practice this principle can be reversed, that is, we can send out the broad-band pink noise, and measure selectively in 1/3 octaves one at a time. In this case we risk burning-out the tweeters because the full spectrum of the noise is applied to the speakers for quite a long time.

The optimum signal-to-noise ratio is obtained by both sending out and measuring in 1/3 octave bands. In practice there is no difference in the results from these different methods.

The Portable and Inexpensive Method

The same principle as used in the automatic method is used in the portable and inexpensive method.

The Test Record QR 2011 is used on the generator side, and a Sound Level Meter Type 2206 on the measuring side.

The signals recorded on the test record are the same as those which the Noise Generator and the 1/3 octave filter produced in the automatic method — that is pink noise in 1/3 octave bands.

The microphone and the measuring amplifier are replaced by the Sound Level Meter and the Level Recorder is replaced by the special chart paper QP 2011. The curve is recorded manually.

The only equipment required to make this measurement, is the Test Record QR 2011 and the Sound Level Meter Type 2206. Although this simple method is slightly less accurate than the more sophisticated methods, it is an excellent alternative because it is portable and inexpensive, it does in fact test the whole system from pick-up to loudspeaker/room combination, under the same working conditions as when playing normal music records.

The 15 curves in Fig.4 were in fact all made using the simple method. The differences between the simple method and the more sophisticated methods are typically ± 1 dB, which because of the fluctuations normally found in ordinary rooms, can be considered negligible.

Supplementary Experiments

To supplement given results, we will now look at three subjects: (1) the dependence of the measured results on the loudspeaker and microphone positions, (2) the relative frequency content of the music examples used, and (3) the reverberation time in the three rooms. Finally we shall suggest methods to improve the measured characteristic — and thereby obtain optimum performance.

The dependence of microphone and loudspeaker positions could be important in normal rooms. Typical variations of ±5 dB fall within the frequency range 50 to 2000 Hz. The remark one normally hears — that the bass increases whenever the speaker comes close to a corner — is not completely true. It is only the upper part of the bass range and the lower part of the mid range which increase. This phenomenon occurs when the wavelength and the room dimensions are equal.

Figs.16 and 17 show the dependence on microphone and loudspeaker positions of room L2, and Figs.18 and 19 show it for room L3.

The relative frequency content of the music examples used for the listening tests is shown in Fig.20. It is seen, for example, that the organ music, M3, has a quite wide and uniform frequency content. The beat music, M4, exhibits typical electric bass around 125 Hz and brass instruments around 1,25 kHz. On the Oscar Peterson recording, M6, we see the bass around 100 Hz, the piano around 400 Hz and the cymbal around 12,5 kHz.

Fig.16. The variations in room L2 for three different microphone positions

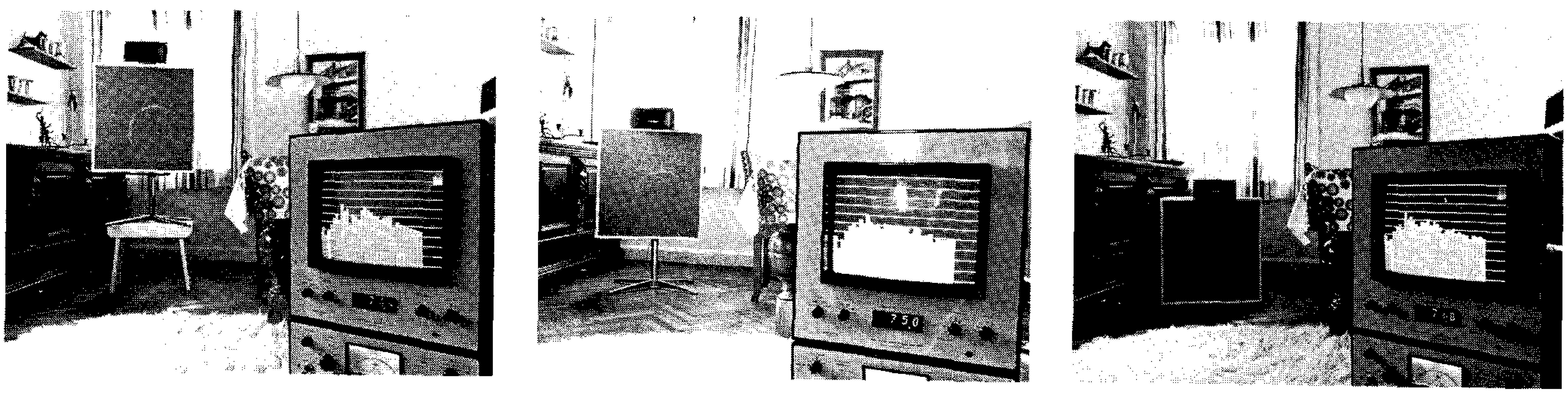


Fig.17. The variations in room L2 for three different loudspeaker positions

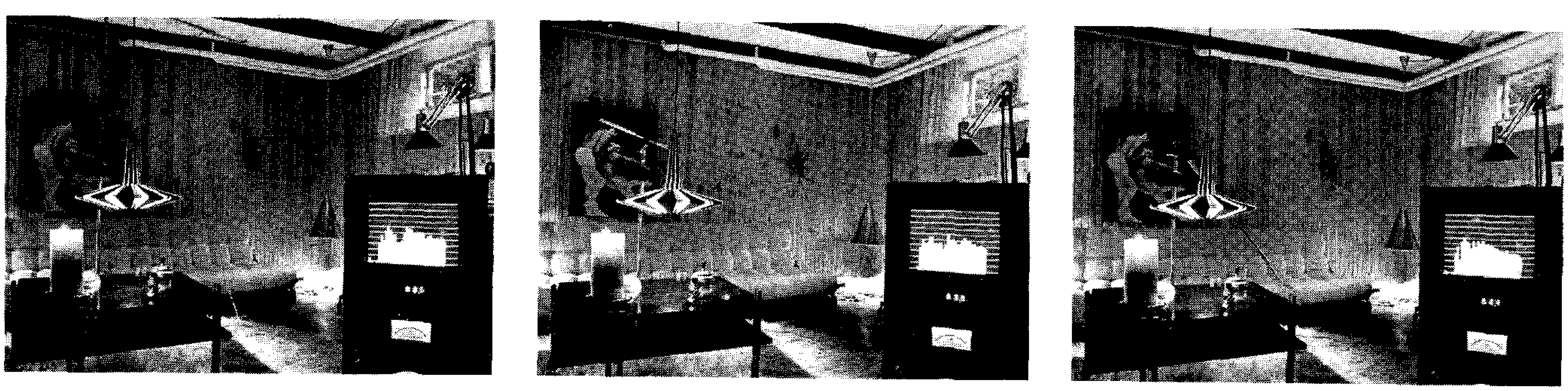
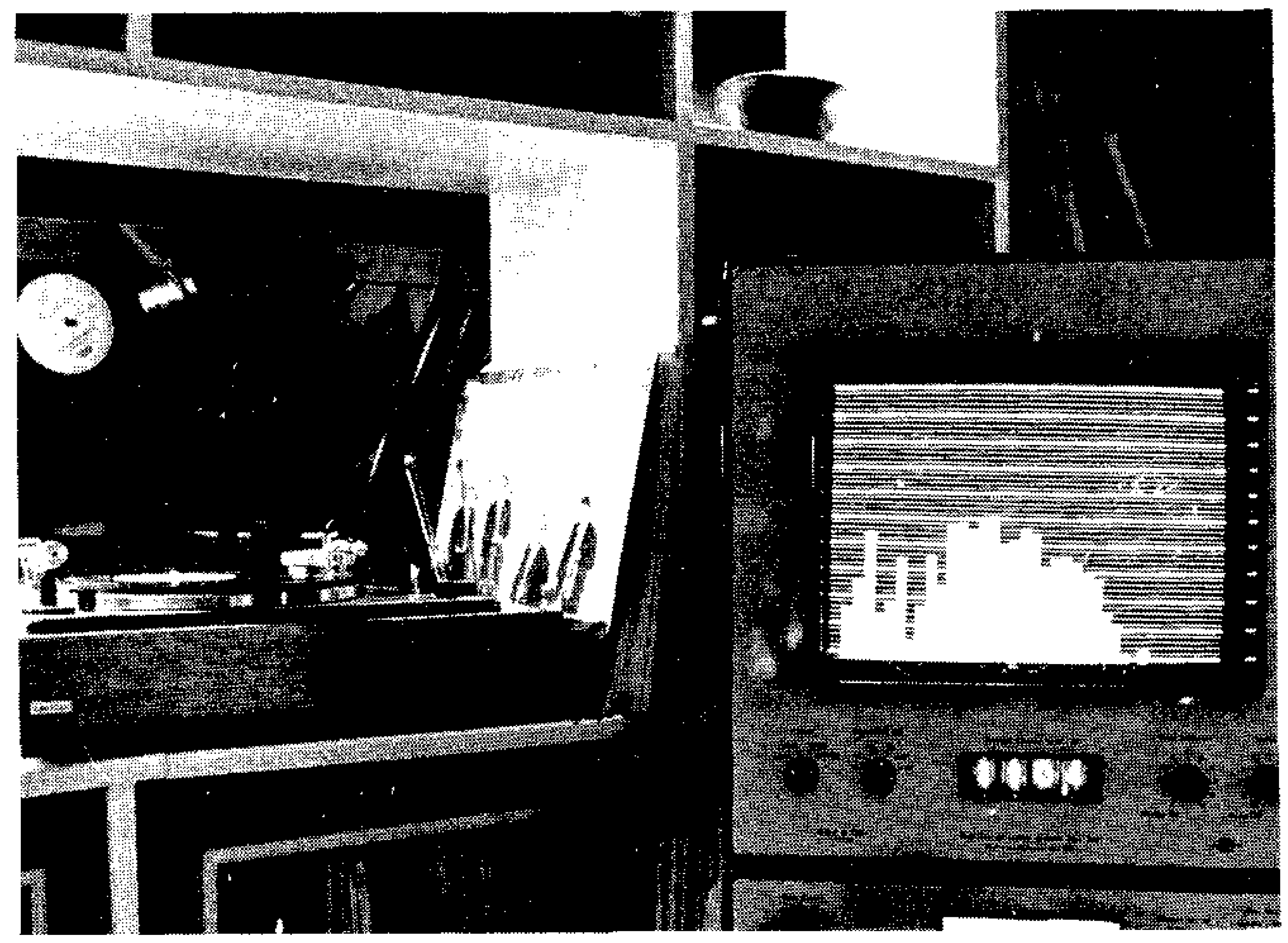


Fig.18. The variations in room L3 for three different microphone positions

Fig.19. The variations in room L3 for three different loudspeaker positions

M1 Wagner: Die Walküre, finale 3rd Act. Deutsche Grammophon 135 150

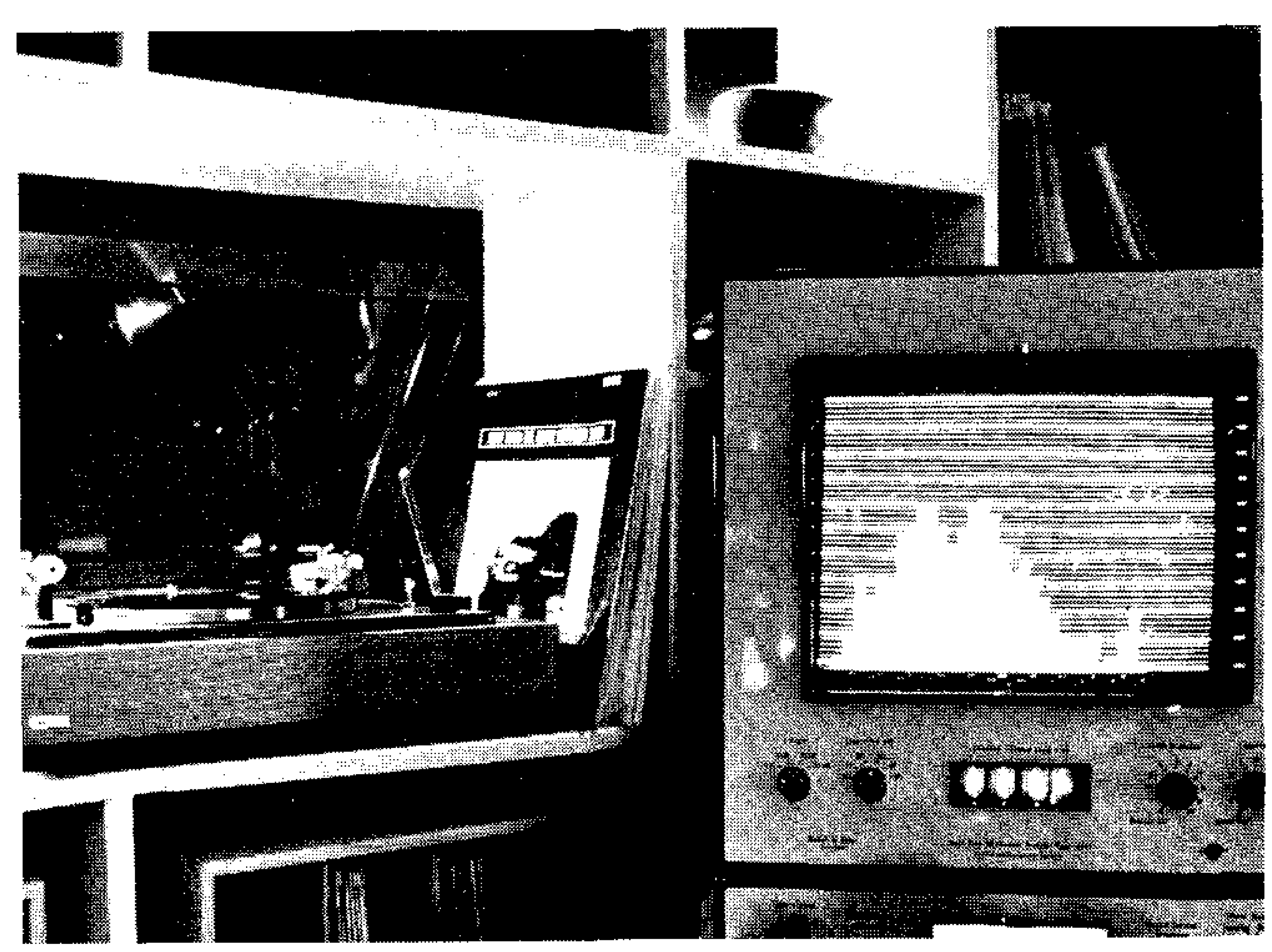


M2 Max Regor: 2nd movement from String Quartet in G-minor, Op. 54, No. 1, Deutsche Grammophon 2530 081

M3 Pipe organ from Grundtvigs church

M4 Spinning Wheel, Shirley Bassey, United Artists UAS 29100

M5 Stan Kenton: Adventure in emotions, part 6, joy. Capitol ST 2424



M6 Oscar Peterson: Things ain't what they used to be. Verve V 6-8538

Fig.20. The spectra of the music examples used for the listening tests

The reverberation time of the three rooms as a function of frequency is shown in Fig.21. In fact, it is the so-called "Early Decay Time" (EDT) which is shown, but this is almost the same as the normal reverberation time, the only difference being that consideration is placed on the beginning of the reverberation decay curve.

For room L3, there seems to be good agreement between the long reverberation time at low frequencies and the appreciable bass lift that we saw from measurements with 1/3 octave noise in this room (compare with Fig.4).

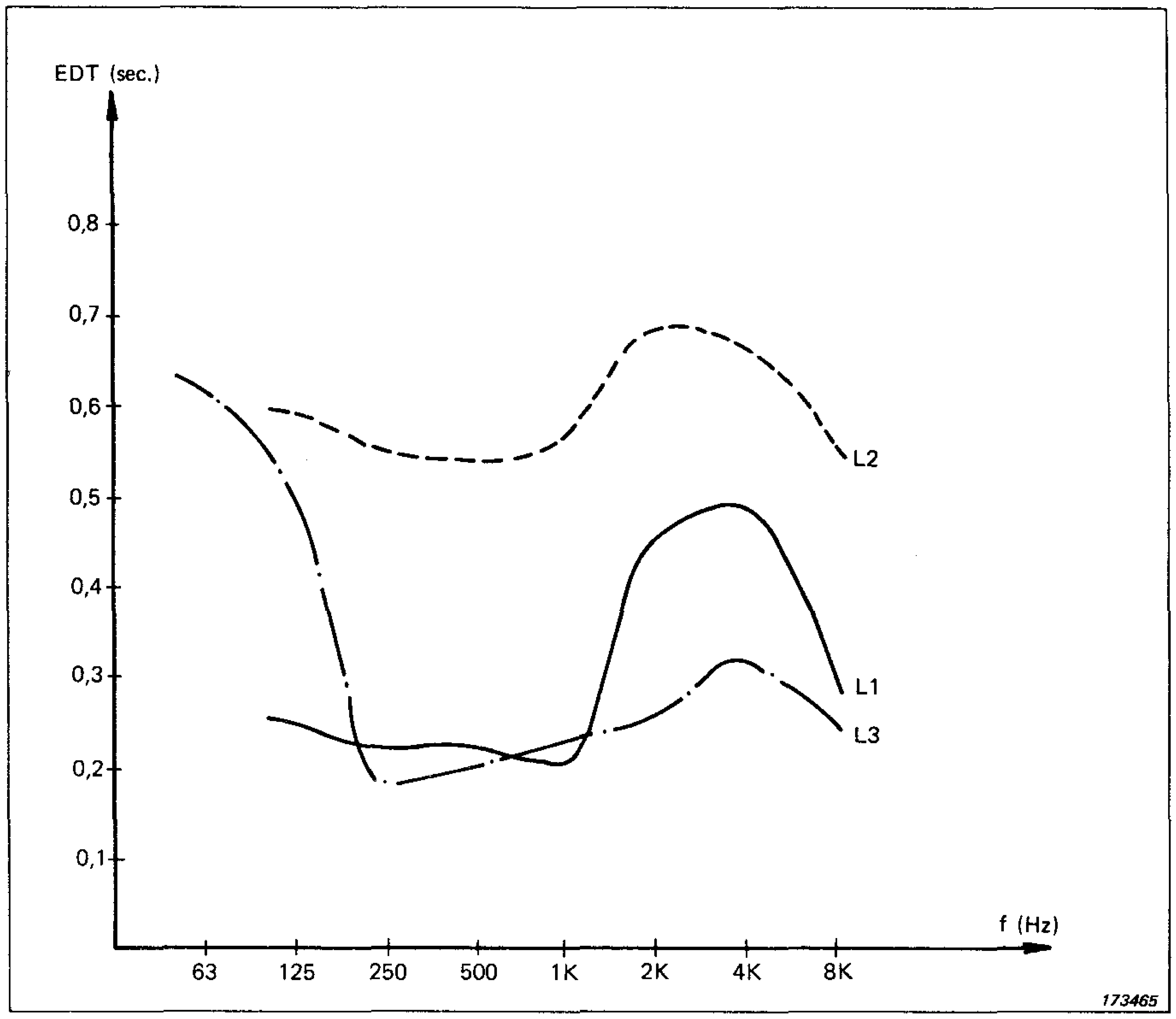


Fig.21. Reverberation Time (EDT) versus frequency in the three rooms

How can the Sound be Improved

Of course it is not enough just to be able to produce a curve from the 1/3 octave measurement indicating exactly what is wrong with a system — something should also be done to improve it. Fortunately there are many ways of correcting the measured response and thereby obtaining an improved sound.

One possibility is, of course, to select a Hi-Fi set which, as far as possible, neutralizes the acoustic deficiencies of the room. This can be done at a Hi-Fi dealer's who has in advance measured all the speakers in his demonstration room at that position where the customer listens.

It seems reasonable that the customer in the first place, simply listens and only looks at the curves when in doubt. He then selects a system, takes it home and listens again. If the sound is the same or even better than at the Hi-Fi dealer's, he is fortunate. If not, he need only make one measurement at home. He can then compare this result, with the result of the measurement on the same system made at the Hi-Fi dealer's. The difference between these two curves represents the difference between the rooms. He can now find the correct speaker for his room by adding this difference to the curves measured at the Hi-Fi dealer and then selecting the speaker which, after correction with this difference, ends up with the best curve.

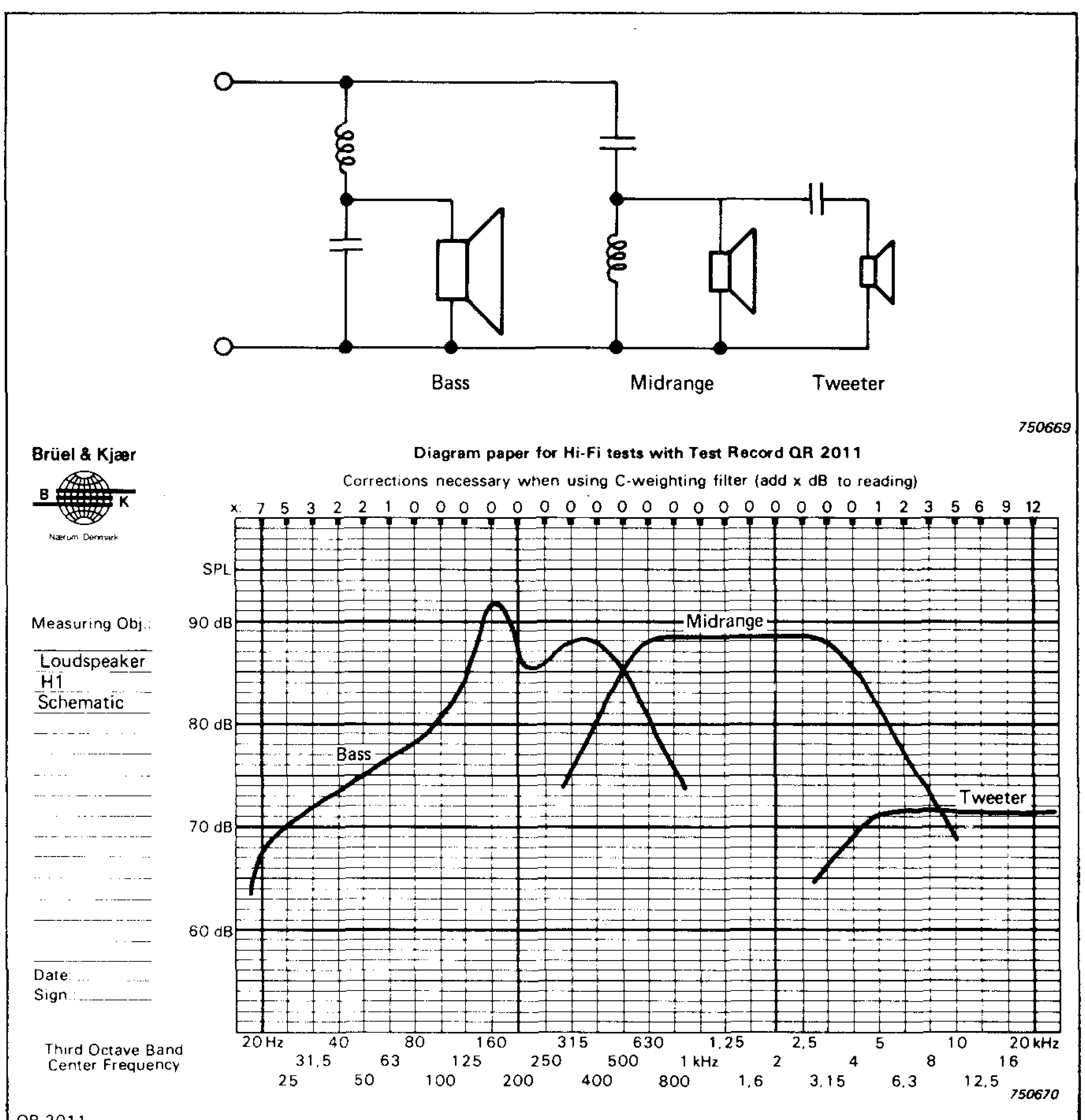


Fig.22. The original cross-over network and the corresponding curves for speaker H1

If the sound produced by a given Hi-Fi Set in a given room is considered, both acoustical and electrical corrections are possible.

The acoustical correction can be made by changing the reverberation time of the room for different frequencies, that is with furniture, carpets, curtains, wood panels and so on. Often hard ceilings need to be damped.

The position of the loudspeakers could also be changed. Normally, good results are obtained with the speakers placed in front of a damped wall, for instance in front of a book shelf, and if possible at a reasonable distance from it, the further from the wall the better.

The loudspeakers should not be parallel to the wall but should point in towards the listening position. Of course they should not be hidden behind a sofa, but be as free-standing as possible. It might also be helpful to place them on vibration dampers.

The acoustical corrections are made to avoid resonances, and standing waves which colour the sound.

The electrical correction can be made by various, commercially available spectrum shapers or by building special filters. Often, a modification to the cross-over network will be the easiest. An example of such a modification is shown in Fig.23 and is carried out on speaker HI, which is the author's own construction. The original speaker used conventional filters which together with their corresponding curves are shown in Fig.22.

The corrected filter with corresponding curves is shown in Fig.23.

The bass is corrected in two steps: first an increasing impedance for increasing frequencies is introduced by increasing the values of the original capacitor and inductor in the bass section. Then the resonance is removed by introducing a series resonant circuit directly across the bass speaker terminals. The necessary calculations for this are shown in Fig.24.

The midrange correction is made by resistors only and the tweeter is

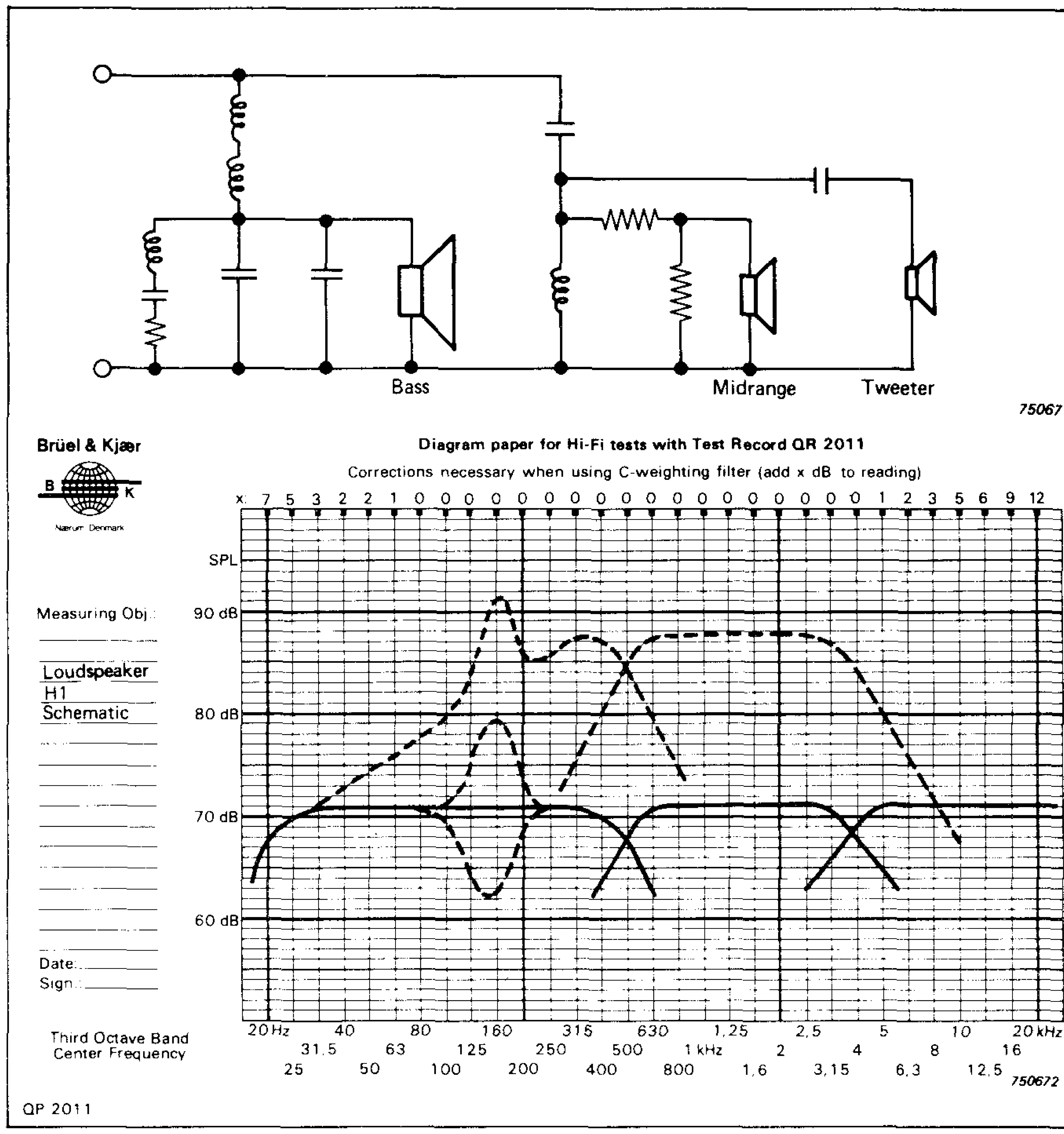


Fig.23. The corrected cross-over network and the corresponding curves

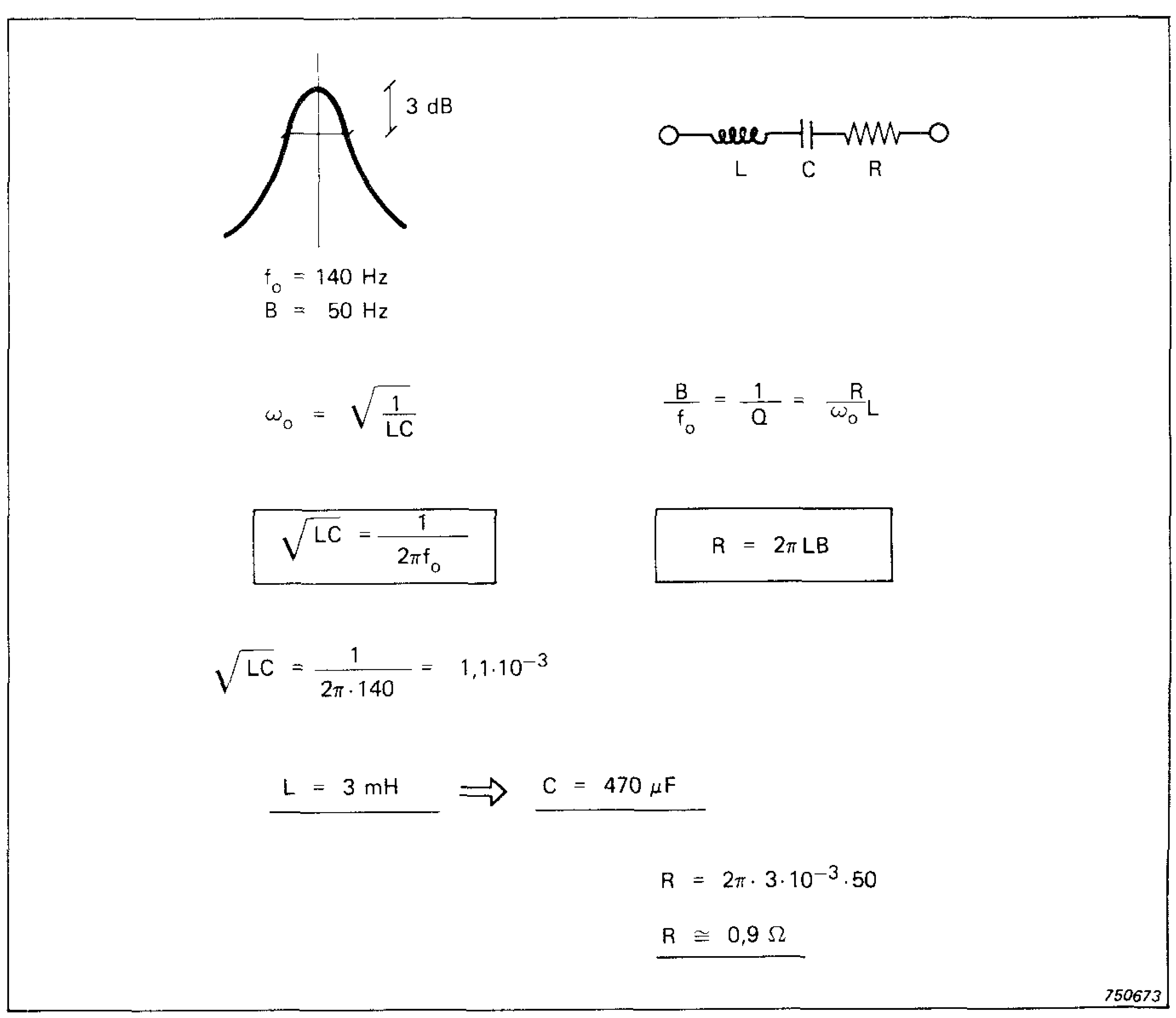


Fig.24. Calculations for determination of R, L and C in compensation series resonant circuits

actually changed from the originally used B&O 2500 to a Gamma Horn.

The differences in the system, measured in room L2, with and without the series resonant circuit is shown in Fig.25. This gives much better measurement results and much better listening results.

When these corrections were originally made, the phase response was not taken into consideration. Later this was measured and it was shown to be a minimum phase system in this range. So, improving the amplitude response also improved the phase response. (Ref.4).

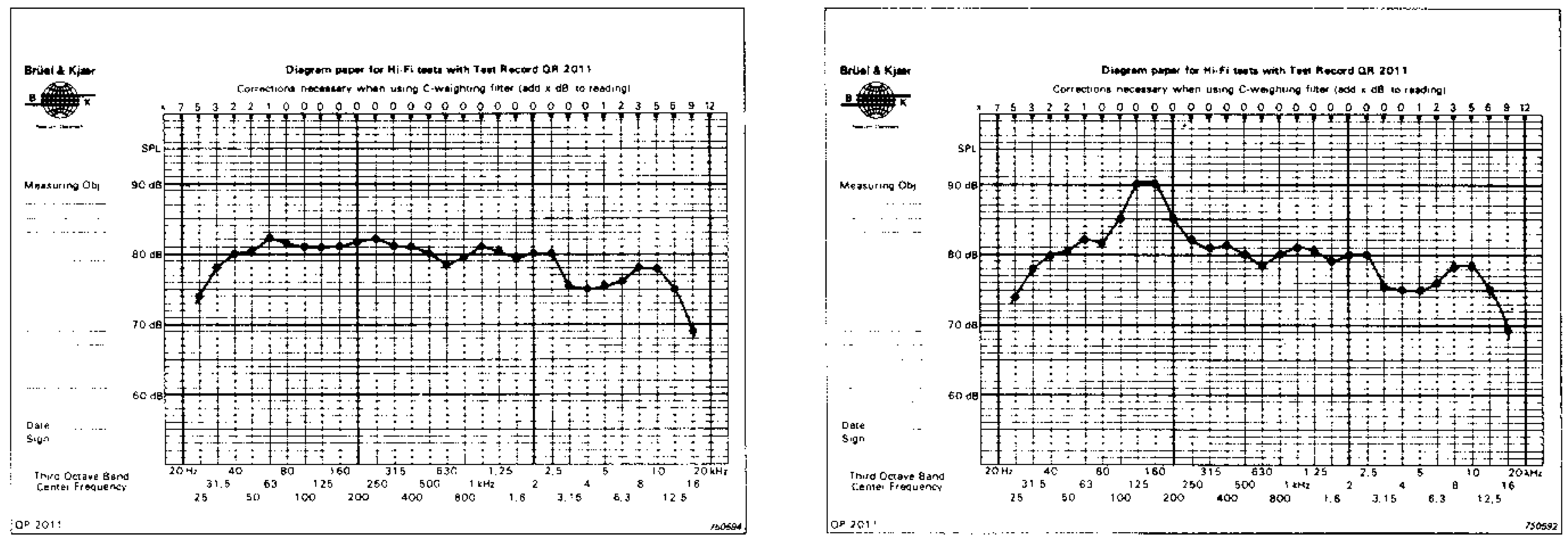


Fig.25. The amplitude response for loudspeaker H1 with and without compensation

This indicates that significant improvements are possible and often quite simple but to make the improvements it is necessary to know exactly what is wrong, which 1/3 octave measurements often reveal.

Conclusion

Since the listening room is an extremely important factor in the evaluation of loudspeaker performance, an objective test method is required that gives good correlation with subjective listening tests. It is found that pink-weighted, random noise in third octave bands, best meets this requirement.

The measurement may be implemented in several ways of various degrees of convenience and expense; (1) Real-time third octave analysis. (2) Sequential third octave analysis. (3) Pink noise test record analysis.

The more sophisticated methods are relevant in cinemas, theaters, concert halls and especially in recording- and radio studios. The Hi-Fi enthusiast and the small dealer of course require the portable and inexpensive method.

All three methods show excellent agreement with each other, and with subjective tests.
In this connection, it seems reasonable to mention that the 1/3 octave response in the listening room does not necessarily disclose everything there is to know about the system. Alone, it is not a pure scientific truth. There are many other electroacoustic measurements which also are necessary to be able to completely describe the system. Phase (Ref. 3 and 4) Efficiency, Directional Characteristics (Ref. 5), Harmonic Distortion (Ref. 6), Intermodulation Distortion (Ref. 6) Rumble, Wow and Flutter, Hum and Noise, Cross-talk (Ref. 7) etc., etc.

References

Ref.1. E. Rørbæk Madsen and H. Staffeld
Højttalerundersøgelser
Akademiet for de tekniske videnskaber
Denmark 1972.
A shortened version was presented at the 47th AES convention in Copenhagen.

Ref.2. Roy F. Allison and Robert Berkovitz
The Sound Field in Home Listening Rooms.
Journal of the Audio Engineering Society
July/August 1972, Vol. 20, No. 6.

Ref.3. Richard C. Heyser
Loudspeaker Phase Characteristics and Time Delay Distortion: Part 1 and 2.
Journal of the Audio Engineering Society
January 1969, Vol. 17. No. 1.

Ref.4. Henning Møller
Loudspeaker phase measurements, transient response and audible quality
Brüel & Kjær Application Note 15—090

Ref.5. Henning Møller
Electroacoustic free-field measurements in ordinary rooms — using gating techniques.
Brüel & Kjær Application Note 15—045

Ref.6. Carsten Thomsen and Henning Møller
Swept measurements of harmonic, difference frequency and intermodulation distortion
Brüel & Kjær Application Note 15—098

Ref.7. Henning Møller
Electro Acoustic Measurements
16—035

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