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A SYSTEMATIC APPROACH TO MONITORING LOUD SPEAKER DESIGN

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A Systematic Approach to Monitoring Loudspeaker Design

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ABSTRACT

A general design of monitoring loudspeakers to broadcasting use is presented. Requirements are desired from practical listening conditions. Amplifier integration, crossover shapes and driver bandwidths are discussed. These integrated systems with acoustic output powers from 20 mW to 1 W are synthesized and practical results presented.

INTRODUCTION

The great variety of listening conditions and monitoring systems even within one house causes continuous troubles to normal program production because the recording, when listened in other than the original control room, sounds quite different. Several attempts have been made to standardize listening conditions but because sound quality is subjective, no international agreement of the right sound exists. In the following the monitoring loudspeaker, one vital part in the chain (fig 1.), is treated as a system having specified I/O characteristics and some process between its terminals.

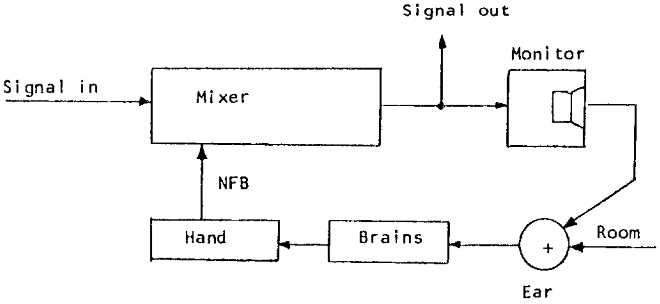


Fig 1. The Monitoring process

SPECIFICATIONS

By renewal of most production facilities of the Finnish Broadcasting Company (YLE) it came possible to realize uniform and standardized acoustical properties in control rooms. This work is presented in /1/ and the basic principles have been approved as basis for

Nordic standardization discussion /2/. In /2/ recommendations are given for listening room sizes and shapes, reverberation times, listening distances and angles, loudspeakers etc.

Monitoring loudspeakers are classified as follows:

Class A: Large control rooms, music production.
$L_{max} \geq 106$ dB at 1 m.

Class B: General use in medium-sized and small control rooms.
$L_{max} \geq 100$ dB at 1 m.

Class C: General use in small control rooms, OB-vans etc.
$L_{max} \geq 94$ dB at 1 m.

Frequency response shall be smooth (but not necessarily flat) within ± 2 dB between two 1/3 octave steps from 63 Hz to 12,5 kHz, measured in the control room. See fig 2.

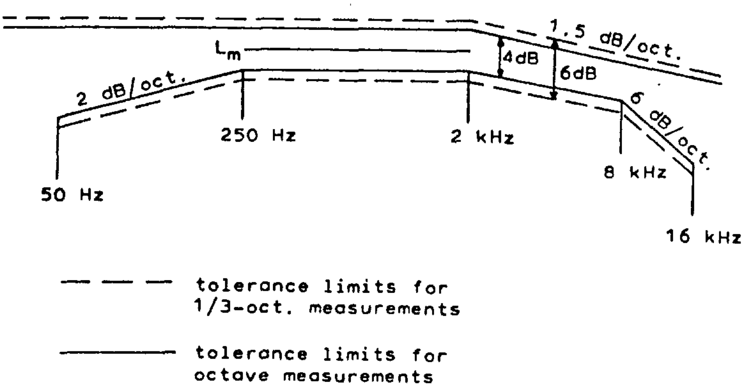


Fig 2. Loudspeaker response tolerances in control rooms.

Directivity requirements are shown in fig 3.

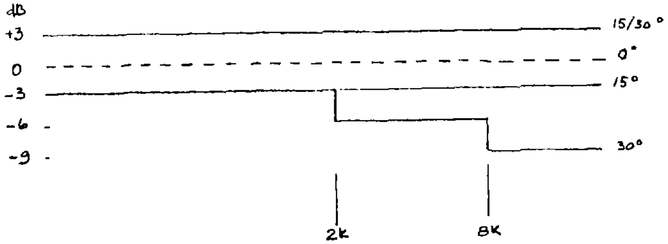


Fig 3. Directional response tolerances.

Note that the previous specifications are same for all types. Harmonic distortion at level L_{max} - 10 dB shall not exceed 3 % for f < 250 Hz and 1 % for f ≳ 250 Hz.

GENERAL DESIGN

A monitoring speaker is as industrial product as all other program production tools. To start right we must remember this and minimize the possible troubles and confusions on the way directly from the designer's table to normal production use, including installation and service. We start to treat this product as a system having specified input and output characteristics. What is the process inside is not so important. Output specifications we know, with input we can choose between 1) line level (+6 dBm) and AC power or 2) high-level audio from a power amplifier. It is easy to see why 1) is better:

- one interface specification can be omitted
- the user does not need to make decision, which power amplifier to choose.

We decide to integrate the amplifier and the speaker.

Now we go inside the process. The next logical step is multi-amplification. This decision will give us the following well-known benefits:

- excellent clarity /3/ due to good driver damping especially at crossover frequencies;
- less IM distortion in power amplifiers;
- crossover properties do not change with driving power, i.e. voice coil temperature (and resistance);
- subjectively high output because overload in one channel does not distort others. Less overload on HF signals riding on LF peaks.
- driver sensitivity differences are easy to compensate
- individual drivers can be easily protected against overload
- with certain precautions the channel gain controls can be used to balance the sound in the listening room.
- the integrated system is cheaper than that with separate power amplifiers and active crossovers and designed just for the drivers installed. The user cannot spoil the result.

However, nothing is without drawbacks:

- the integrated amplifier electronics is subject to vibration, which must be taken into account in the design process.
- multi-amplification means more components and more fault possibilities. Again, the designer must know

what he is doing.

- multi-channel amplifier and electronic crossover is more expensive than a single, integrated amplifier and passive network. In cost-sensitive applications this may be a problem.

CROSSOVER

Several published papers deal with crossover properties /4/.../9/. All crossovers are compromises between axial pressure response, power response, group delay response, radiation pattern etc. It depends on application, which property is found most important. In control room the listening position is usually consistent, the speakers are directed towards this point and actually, the frequency response was already specified at the listening size.

It is interesting to note that in only a few papers /7/, /9/ it has been emphasized that what is important is not the electrical filter response feeding the drivers but the acoustical output being the product of filter and driver transfer functions. Noting that the overlapping driver response should behave in a well-controlled manner down to - 20 dB of its passband response it is easily understood that first-order network requiring a driver with good response extending one decade in the system stopband cannot be very reasonable design. From this point of view a steeper cutoff is a practical necessity for driver design.

In cases where transient performance is considered to be important, the delay distortion introduced by higher-order Butterworth filters can become obvious.

For this case the Bessel filters offer an elegant solution with their flat delay characteristics. Designing the driver parameters according to the desired acoustic cutoff, fairly good results can be obtained. Another attractive solution to the flat delay/steep cutoff dilemma is delay equalizes, described principally for example in /10/.

If we want to use channel gain controls for sound balancing it is essential that in the crossover region the delays of adjacent channels are equal, otherwise changing the level in one channel results in cancellation effects. This tone control possibility is welcome because in acoustically correct control rooms no more equalization is necessary. However, from this point of view very steep cutoff is not desirable.

Where should the crossover frequency lie? In fig 4 we have the well-known equal loudness curves.

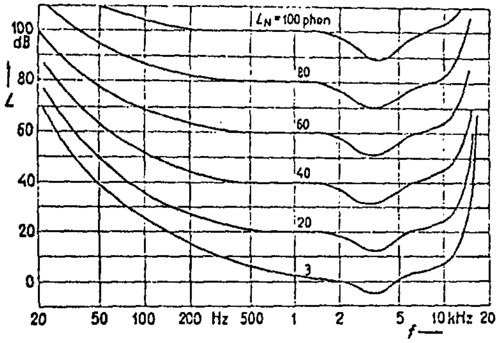


Fig 3. Equal loudness contours

The most sensitive area is wide, at average listening levels, say, from 300 Hz to 7 kHz and a single driver should cover the whole 300 Hz to 7 kHz band.
While this is certainly possible it is not common, nor necessary.

When thinking stereo image formation, we know that our hearing is sensitive to relative phase (between channels) up to 2 kHz. The lowest usable crossover will so be slightly higher. The upper crossover can be lowered so that each driver reproduces about one decade. As absolutely neutral drivers are not available in real world, it is best to let one driver determine the sound character of the whole system. This leads us to crossover frequencies of 300 - 400 Hz and 3 - 4 kHz in three-way systems, and note, independently of woofer size. The common practice to extend woofer operation to 600 - 1200 Hz in three-way systems seems to be only due to utilization of existing midrange drivers (for example small horns). When only low acoustic powers are needed a two-way system is suitable and its crossover should lie slightly above 2 kHz.

SYNTHESIS

So far we have gathered pieces to our puzzle. Let us decide what to do, fig 5.

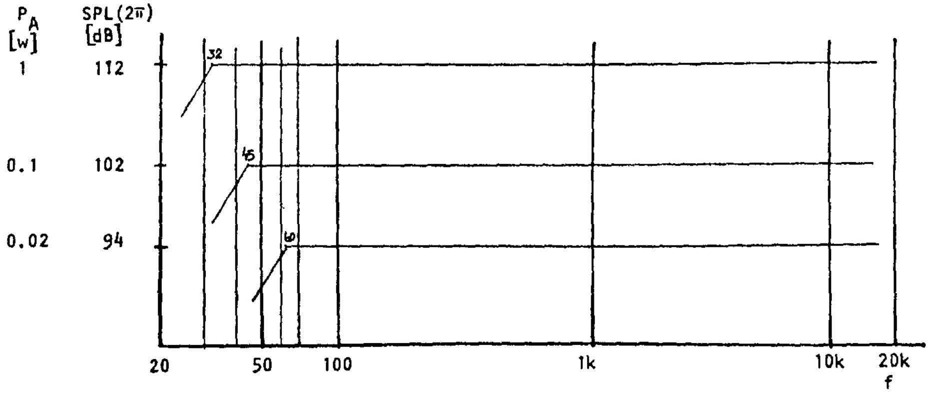


Fig 5. Propositions for class A, B and C monitoring speakers.

Because the low-end performance determines the system size and a compact structure is desired we are to look for woofer alignments which most effectively use the available volume. From Thiele /11/ we see that B6 satisfies these wishes especially when amplifiers are already available.

The necessary displacement volume will be /12/:

$$V_D = \sqrt{P_{AR}/k_p \; f_3^{\,4}} \quad \approx 380\ \text{cm}^3 \text{ for class A}$$

$$k_p = 6{,}79 \text{ for B6} \quad \approx 60\ \text{cm}^3 \text{ for class B}$$

$$\approx 14\ \text{cm}^3 \text{ for class C}$$

V_D must be divided in a practically realizable way to displacement amplitude x_{max} and cone area S_D. The resulting choice is in table 1.

Table 1.

Type	$V_D (cm^3)$	$S_D (cm^2)$	x_{max} (mm)	Dia (mm)
A	380	850	4,5	380
B	60	200	3,0	200
C	14	60	2,3	130

Two 310 mm drivers could also be used for type A, but they require more front panel area than a single 380 mm unit. Other parameters for B6 response are:

$f_3/f_s = 1$

$f_3/f_B = 1$

$V_{AS}/V_B = 2{,}73$

$Q_T = 0{,}299$

$f_{pk}/f_s = 1{,}07$

To proceed, we must decide the box size, which, in turn is related to both aesthetic and economical factors, the latter including efficiency. Class A system can be quite large, and because, for economical and maintainability reasons it would be beneficial to use same basic amplifier whenever possible, its efficiency should also be quite high.

Let our target η be 2 % and see what happens. From Small /12, eq.(26),(28),(34)/:

$$V_B = \eta_0 / (k_{\eta(Q)} \; k_{\eta(G)} \; f_3^3) \qquad (2)$$

where

$$k_{\eta(G)} = \frac{4\pi^2}{c^3} \; \frac{\alpha}{Q_T (f_3/f_S)^3} \qquad (3)$$

and $k_{\eta(Q)}$ lies around 0,85.

For B6 (Class I) response $k_{\eta(G)}$ is remarkably high, $8{,}8\mathrm{X}10^{-6}$.
Setting $f_3 = 32$ Hz,
$V_B = 82$ dm^3. When practical box losses are present, some 30 % should be added for compensation, yielding $V_B = 106$ dm^3. This is still quite compact system. If the 2 % efficiency is reached, means this 50 W electrical input rising to 200 W at 32 Hz. It must be emphasized that in room environment the real radiation space is not 2π as presumed but more likely π. As radiation resistance is essentially inversely proportional to solid angle of radiation, remarkably less electrical power is needed in practice.

For Class B system our $f_3 = 45$ Hz and for compactness we decide $V_B = 20$ dm^3. The resulting efficiency is 1,3 % which will drop to 0,6...0,7 %, when the real box is made. Generating 0,1 W of acoustic power requires only 17 W with maximum of 68 W at f_3.

Class C system with its cutoff of 60 Hz becomes really small, $V_B = 6,5\ dm^3$ and η_0 around 0,5 %. The necessary electrical power is only 4 W (16 W).

Because room placement strongly affects the woofer response, usually in the form of extreme LF boost, a control possibility would be beneficial. The adopted B6 alignment offers this with its auxiliary filter. The filter Q, being normally 1,93, can be easily controlled and the resulting response reduced from +6 dB to for example -6 dB. It is clear that only one setting is then B6 and others are something else, but principally we were interested in the room response only.

Mid and treble ranges

The first breakup mode occurs in 380 mm paper cone drivers usually around 350 - 380 Hz. Usable crossover point is then at 300 Hz. Following the previously adopted line of one decade bandwidth, the upper crossover is at 3 kHz. High efficiency dictates lowish Q_T and when properly enclosed, a constant-delay second-order response is obtainded. Driven through filter an acoustical high-pass characteristics of desired order result. Depending on woofer original response and break-up dip severity, some compromising must be tolerated.

At 3 kHz both midrange and treble drivers behave usually well and final acoustical cutoff characteristics follow fourth-order Bessel response.

What is said above concerning Class A system, is valid also for Class B. The woofer break-up is now one octave higher. Crossover frequencies can be moved to 350 Hz and 4 000 Hz with third and fourth order Bessel responses, respectively.

Class C woofer operates to 2,8 kHz and according to guidelines above similar filters can be used.

REALIZATION

The specified three types were built and the validity of previous discussion tested.

Class A

A 380 mm woofer with progressive suspension /14/ was mounted in 106 dm^3 enclosure tuned to 32 Hz. The mid-range driver is an 80 mm dome with Q_T of 0,56. Acoustic high-pass is aligned to BL 4 response like the woofer low-pass. The driver can thermally withstand the amplifier's continuous output. Also at treble end an acoustic BL 4 response was obtained at 3 kHz, where a horn-loaded tweeter takes over. A power limiting protects the tweeter from thermal overload.

With Class A system time-delay compensation is used. In delay measurements it was revealed that the usually recommended way to align voice coils at same vertical line is not generally correct. The drivers' acoustical radiating origin varies greatly and in certain cases may be also in front of voice coil. Additionally, the associated filter delays must be summed to driver delay.

The enclosure was constructed according to Olson's /13/ results. Remarkable attention was paid to enclosure wall structure. This research is still going on and will be subject for a future paper.

Amplifiers are constructed on a single P.C. board which is fitted with hinges to main frame/cooling plate. Crossover passive components are on a separate plug-in board. The whole system is mounted with quick-release hinges to a recessed cavity in back of the enclosure. To ensure reliability extensive environmental tests were carried out according to IEC 68. The calculated mean time between failures is 50 000 hours.

Level controls for each frequency band are provided as well as the previously mentioned bass filter Q control.

Class B

A 200 mm woofer with progressive suspension is mounted in a 23 dm^3 enclosure tuned to 45 Hz. Crossover is similar to that used in type A, the frequency is 380 Hz and an impregnated cone type driver is used. Upper crossover lies around 4 kHz and a ribbon tweeter is used for HF reproduction. Time delay compensation is not applied.

The class A amplifier system is used with only reduced output power. This solution is valuable as it greatly simplifies service operations and also reduces manufacturing costs.

Class C

A 130 mm doped plastic cone woofer is mounted in a 7 dm^3 enclosure tuned to 60 Hz. Crossover with fourth order Bessel response is at 2,8 kHz and a 19 mm plastic dome tweeter is used. Because of small dimensions and two-way system, a different amplifier was developed, however, with the same basic principles.

PERFORMANCE

Figure 6 shows frequency response of Class A system, figure 7 of Class B and figure 8 of Class C, respectively. Typical control setting responses are shown in figures 9 and 10, note the absence of cancellation effects. Finally, an example of room response achieved with Class B system is shown in figure 11.

Listening tests have shown very good clarity, most obviously due to multi-amplification. Subjectively the performance difference between Bessel and Butterworth filters was very small. The claimed positive contribution of time delay compensation to final sound quality was not clearly confirmed. It seems that identifiable sonic improvements are more easily available on driver design side.

All three types proved to have very similar sound when listening level was reasonable for Class C. The choice of midrange band seems to be correct. Increased requirements for the midrange driver relax, on the other hand, demands for the woofer, which needs only to be a piston up to fairly low frequency. Also the level controls operate well, although a control possibility around 100 Hz would be practical. The dip frequency, however, depends strongly on speaker placement and an allround compensation tends to get complicated. It is advisable to place the speakers off from the nearby reflecting walls, whenever it is possible.

REFERENCES

/1/ Draft Nordic Recommendation for Loudspeaker Listening Conditions in Sound Control Rooms, NTM79/YLE 3, 1979

/2/ Borenius, J., Korhonen, S.U., "Standardized Listening Conditions in Sound Control Rooms", AES preprint No 1332 (1978)

/3/ Smith, A.P., "Electronic Crossover Networks and Their Contribution to Improved Loudspeaker Transient Response", JAES, Vol. 19, p. 674, (1971)

/4/ Ashley, J.R. and Kaminsky, A.L., "Active and Passive Filters as Loudspeaker Crossover Networks", JAES, vol 19, p. 494 (1971)

/5/ Ashley, J.R. and Henne, L.M., "Operational Amplifier Implementation of Ideal Electronic Crossover Networks", JAES, vol. 19, p. 7 (1971)

/6/ Small, R.H., "Constant-Voltage Crossover Network Design", JAES, vol. 19, p. 12 (1971)

/7/ Augspurger, G.L. "Electrical versus Acoustical Parameters in the Design of Loudspeaker Crossover Networks", JAES, vol 19, p. 509 (1971)

/8/ Linkwitz, S.H. "Active Crossover Networks for Noncoincident Drivers", JAES vol. 24, 1976. p. 2

/9/ Linkwitz, S.H. "Loudspeaker System design", WW, vol 84, May 1978, p. 52, June 1978, p. 67, December 1978, p. 79.

/10/ Daryanani, G., "Principles of Active Network Synthesis and Design", (John Wiley and Sons, New York, 1976)

/11/ Thiele, A.N., "Loudspeakers in Vented Boxes", JAES, vol. 19, p. 382 and p. 471 (1971)

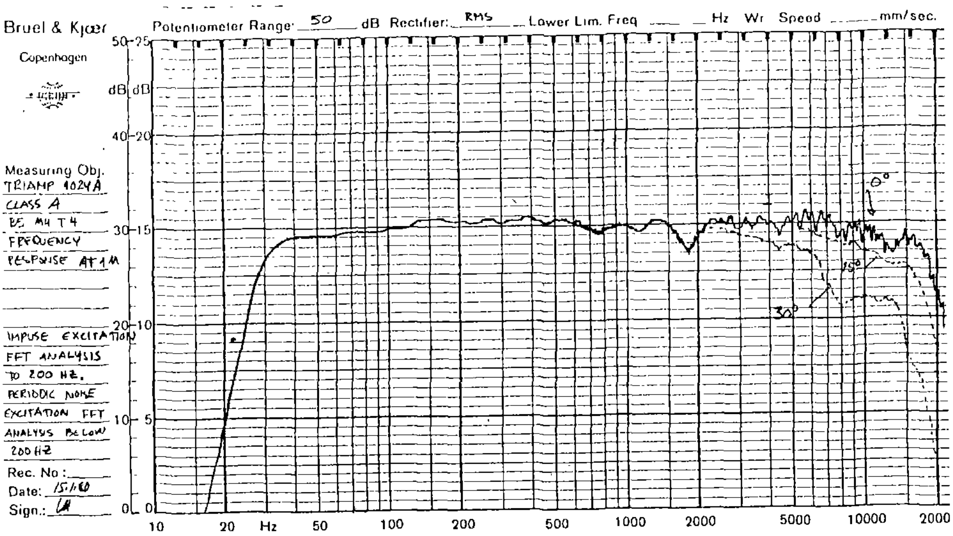
/12/ Small, R.H., "Vented-Box Loudspeaker Systems", JAES, vol. 21, p. 363, p. 438, p. 549 and p. 635 (1973)

/13/ Olson, H.F., "Direct Radiator Loudspeaker Enclosures", JAES, vol. 17, Nr 1 (1969)

/14/ Wiik, T.H. "Transient Distortion Caused by Nonlinearities in Driving Force and Suspension of a Loudspeaker", AES Preprint No. 1205 (1977)

SYMBOLS

P_{AR}	Displacement-limited acoustic power rating
Q_T	Total driver Q at f_s resulting from all driver resistances
S_D	Driver effective radiating area
V_{AS}	Air volume equivalent to driver suspension
V_B	Box volume
V_D	Peak displacement volume of driver diaphgram
c	Velocity of sound, =344 m/s
f_3	System cutoff frequency (-3 dB)
f_{pk}	Auxiliary filter peak frequency
f_s	Driver resonance frequency
k_p	Power rating constant
	System compliance ratio, V_{AS}/V_B
	Reference efficiency


Bruel & Kjær Copenhagen

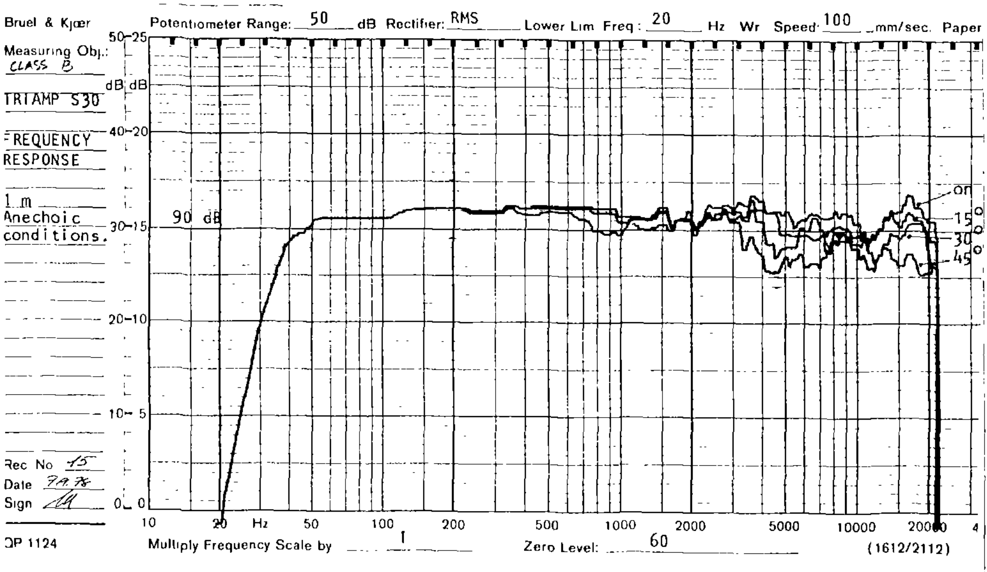
Potentiometer Range: 50 dB Rectifier: RMS Lower Lim. Freq Hz Wr Speed mm/sec.

Measuring Obj.
TRIAMP 1024A
CLASS A
BE M4 T4
FREQUENCY
RESPONSE AT 1M

IMPUSE EXCITATION
FFT ANALYSIS
TO 200 HZ.
PERIODIC NOISE
EXCITATION FFT
ANALYSIS BELOW
200 HZ

Rec. No:
Date: 15/1/80
Sign.:

Fig 6. Class A system frequency response. FFT analysis.


Bruel & Kjær

Potentiometer Range: 50 dB Rectifier: RMS Lower Lim Freq: 20 Hz Wr Speed: 100 mm/sec. Paper

Measuring Obj.:
CLASS B
TRIAMP S30
FREQUENCY
RESPONSE
1 m
Anechoic
conditions.

Rec No 15
Date 7.9.78
Sign

QP 1124

Multiply Frequency Scale by 1

Zero Level: 60

(1612/2112)

Fig 7. Class B system frequency response, anechoic conditions.

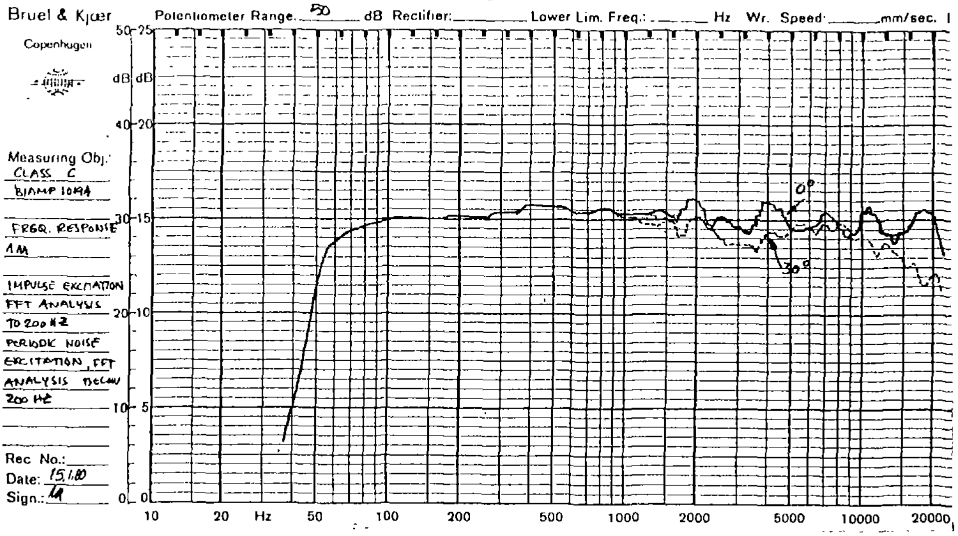


Fig 8. Class C system frequency response. FFT analysis.

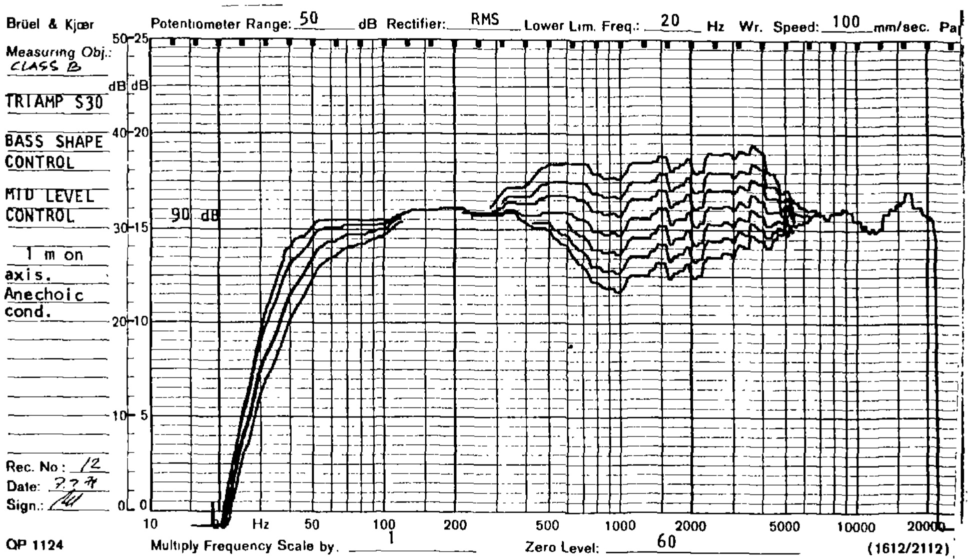


Fig 9. Effects of Mid level control and bass filter Q control.

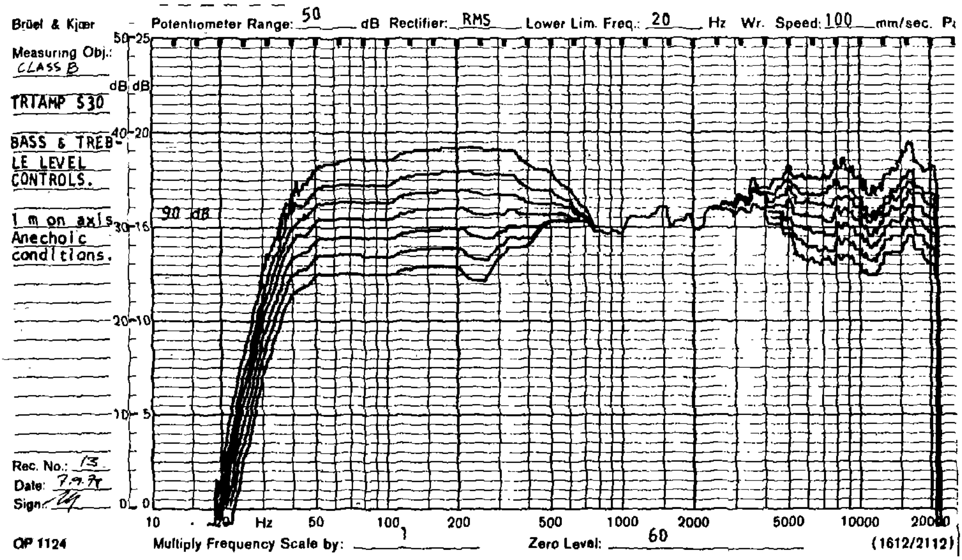


Fig 10. Effects of Bass and Treble level controls

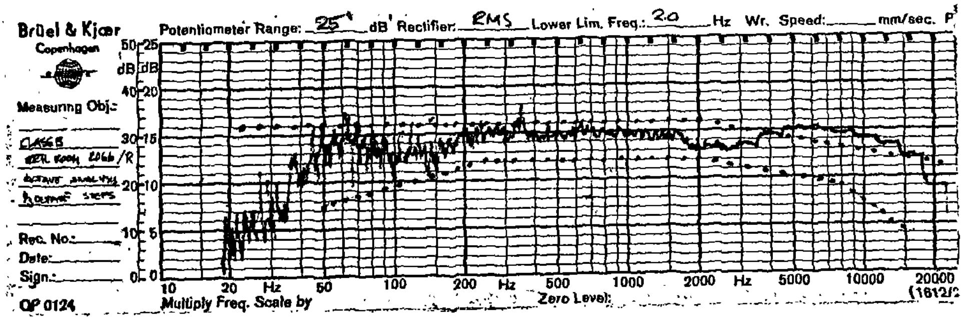


Fig 11. Room response achieved by Class system. Octave analysis with 1/3 octave steps. A 2 dB lower setting of Treble level control would result the desired response above 4 kHz.

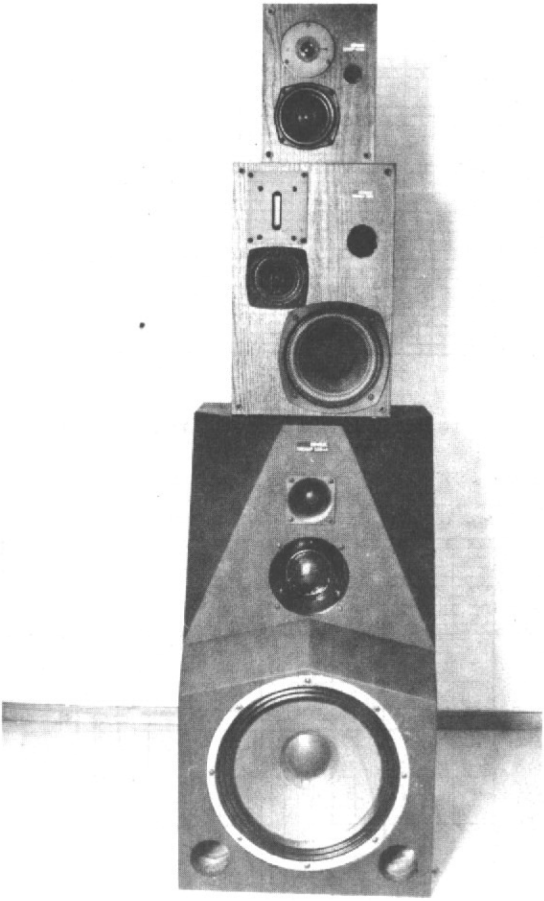


Fig. 12 The finished systems