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# SYNTHESIS OF LOUDSPEAKER MECHANICAL PARAMETER BY ELECTRICAL MEANS

## A new method for controlling low-frequency loudspeaker behaviour. (ACE-bass)

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ABSTRACT

A method for extending bass response and lowering distortion in loudspeaker systems, which differs from both equalized and servo or feedback systems, is described. It can be seen as an extension of the technique to increase loudspeaker damping by giving the driving amplifier a negative output resistance. However, this method also controls the moving mass and compliance. Very good results, such as flat frequency response down to 20 Hz and excellent distortion data, have been achieved with moderately sized bass-reflex enclosures.

## 1. INTRODUCTION

High fidelity equipment has rapidly improved in the last few years, but loudspeaker systems are still a weak part of the reproduction chain, especially at the bass end. As pointed out by Small [3], [4], there is a theoretical limit of lowest cut-off frequency which cannot be passed once the box volume and efficiency are set. With active design, i.e. the amplifier and speaker are designed as an integrated system, this limit does not hold. By supplying more power into the speaker at low frequencies the cut-off can be lowered while efficiency at higher frequencies is maintained. This often corresponds well with the spectral power contents in music. Servo or feedback loudspeaker systems are examples of such designs. However, since these techniques are only applicable to closed-box systems, requirements of high output levels at low cut-off frequencies lead to almost impossible demands for amplifier power and driver volume displacement. If bass-reflex systems could be used, the higher efficiency would decrease amplifier power requirements and the lower cone excursion could considerably decrease necessary driver volume displacements. Equalized bass reflex-systems are of course possible, but compared to feedback systems they do not decrease distortion and are sensitive to variations in natural frequency response.

A new method, for convenience called ACE-Bass (Amplifier Controlled Euphonic Bass), combining the best of the above techniques has been developed. ACE-Bass controls both frequency response and distortion and is applicable to bass-reflex systems as well as closed-box systems.

Most measurements in this paper were made on prototypes of the Audio Pro B2-50 ACE-Bass subwoofer. Its combination of deep and flat bass and high levels at low distortion is unique among moderately sized loudspeaker systems. ACE-Bass is patented in USA and Sweden and patents are pending in several other countries.

## 2 PARAMETER DEFINITION AND SOME THEORY REVIEW

Since this paper is principally about taming loudspeaker[1/] mechanical properties, a dissection of the loudspeaker into its elementary electrical and mechanical parameters is logical starting point, see fig 1.

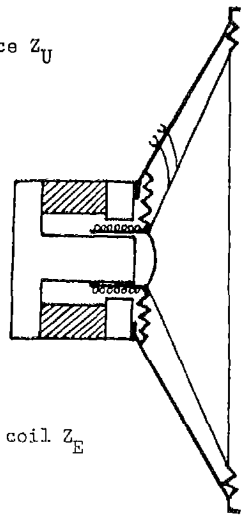
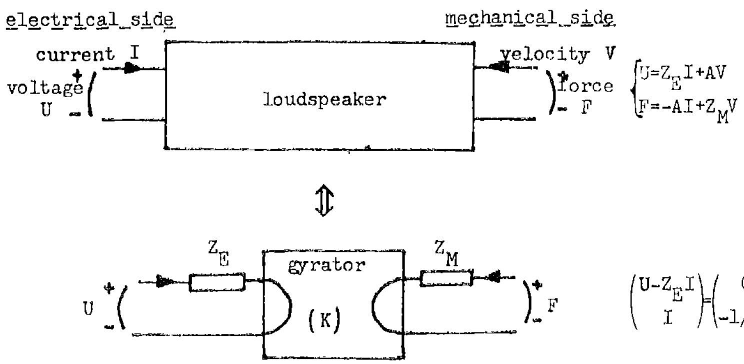



Fig 1. The loudspeaker defined by basic parameters.

A loudspeaker may be considered as a two-port network with the electrical terms on one side and the mechanical terms on the other. The relation between these are given by the equations, $\begin{cases} U = Z_E I + AV \\ F = -AI + Z_M V \end{cases}$, where $Z_M$ is the mechanical impedance consisting of mass, damping and compliance, $Z_M = sM_M + R_M + 1/sC_M$. These equations imply that a loudspeaker may be treated as a gyrator of chain-matrix form, $(K) = \begin{pmatrix} 0 & -A \\ -1/A & 0 \end{pmatrix}$, see figure 2. A gyrator has the characteristic that viewed from one side, the dual of the network on the opposite side is seen.

1/ In this paper the term loudspeaker or driver refers to the loudspeaker unit or chassis. Speaker or loudspeaker system is used to mean a loudspeaker mounted in an enclosure.




$$\begin{pmatrix} U - Z_E I \\ I \end{pmatrix} = \begin{pmatrix} 0 & -A \\ -1/A & 0 \end{pmatrix} \begin{pmatrix} F - Z_M V \\ -V \end{pmatrix}$$

Fig 2. The loudspeaker as a two-port network.

Normally a loudspeaker is fed from an amplifier with output impedance $Z_U$, and the mechanical side is loaded by a mechanical impedance $Z_B$, consisting of air and box components. Fig 3 shows the derived circuit, and fig 4 presents how it is seen from the electrical or mechanical sides respectively.

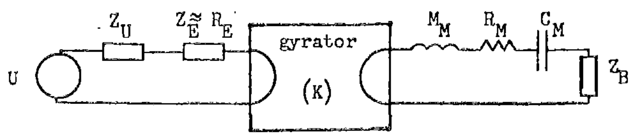



Fig 3. Equivalent diagram for a loudspeaker system under normal circumstances.

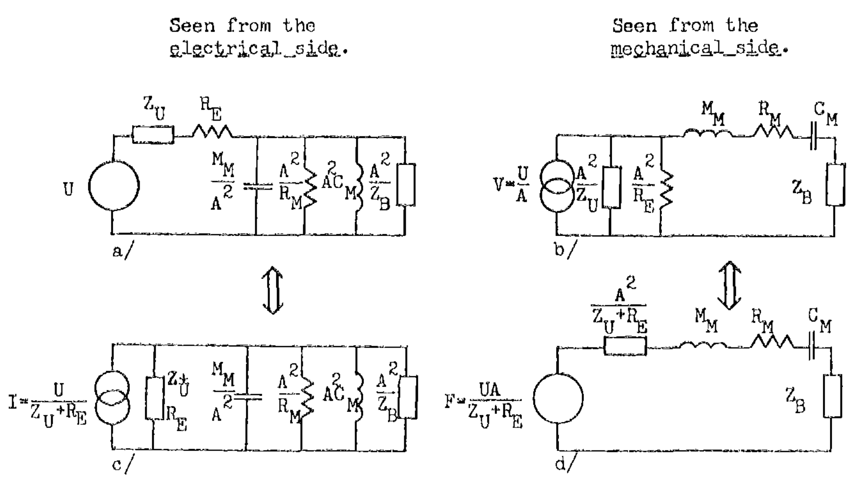



Fig 4. Equivalent diagrams; electrical and mechanical perspectives.

The transition from fig 4a/ to 4c/ and from 4b/ to 4d/ is accomplished by replacing a voltage generator with a current generator and vice versa.

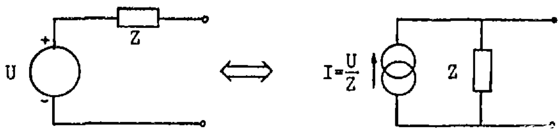



Fig 5. The transition from voltage to current source.

The circuit in fig 4d is the one usually seen in the relevant literature. In most applications the loudspeaker is fed by a constant voltage source, i.e. $Z_U = 0$; the loudspeaker's damping $R_M$ increases with $A^2/R_E$. By choosing a positive or negative resistive value for $Z_U$ the damping may be decreased or increased. This principle is well illustrated in the literature.

## 3 ACE-BASS OR TAMING $M_M$, $R_M$, AND $C_M$ BY ELECTRICAL MEANS

With the above electrical-mechanical interaction in mind it is easy to understand the new method. Consider the equivalent circuit seen from the electrical side in fig 4a. In the ACE-Bass configuration, the part which represents the amplifier is a current generator and a special impedance network, see fig 6.

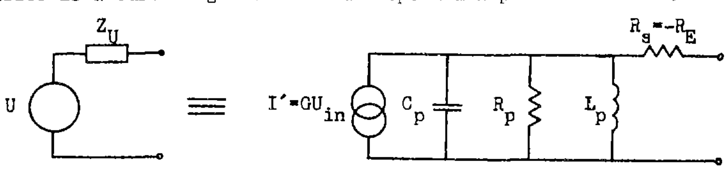



Fig 6. The ACE-Bass amplifier.

If the circuit is to be considered as a voltage generator instead of a current generator, the gain must be frequency dependent in the same way as the parallel impedance $Z_p$.

$$Z_p = \frac{1}{sC_p + 1/R_p + 1/sL_p}$$

$$U' = I'Z_p = GZ_pU_{in}$$

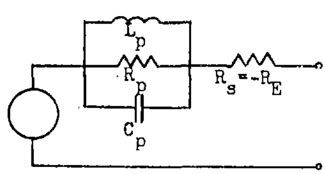



Fig 7. The ACE-Bass amplifier as a voltage source.

Thus deriving the complete circuit in fig 8, or seen from the mechanical side in fig 9, compare fig 4d.

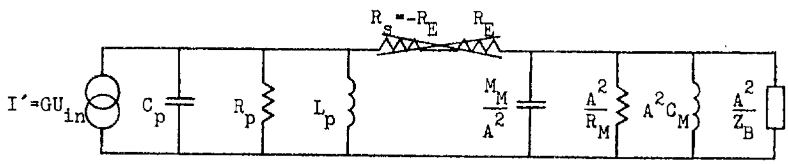



Fig 8. Equivalent diagram for ACE-Bass, seen from the electrical side.

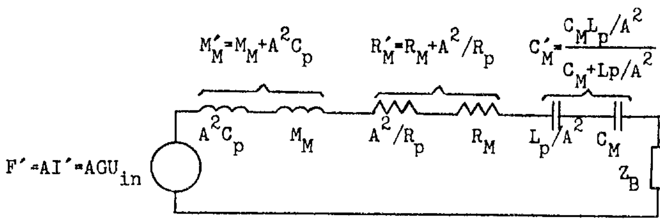



Fig 9. Equivalent diagram for ACE-Bass, seen from the mechanical side.

This implies that the apparent mass and damping have increased, and the compliance has decreased ($C'_M<C_M$). These apparent values are quite real. So real in fact that if a mechanical engineer were to measure these parameters with the amplifier connected, he would find the new values $M'_M$, $R'_M$ and $C'_M$.

Thus it is possible to change the loudspeaker's moving mass, damping and compliance by building the amplifier along the lines of fig 6. The output impedance consists of a negative series resistance which mainly cancels the voice coil's electrical impedance $Z_E \approx R_E$. In addition a capacitor, which provides control over the loudspeaker moving mass, is connected in parallel to a current source; a parallel resistance provides control over the damping and an inductance in parallel controls the compliance.

## 4 DESIGN OF ACE-BASS AMPLIFIER CIRCUITS

ACE-Bass amplifiers, as shown in fig 6 or 7, may be realized in various ways. The most straight forward solution uses a negative output resistance amplifier, which previously has been described in the litterature [2], with a parallel resonance circuit at the output and a bandpass filter at the input, compare fig 7 and 10.

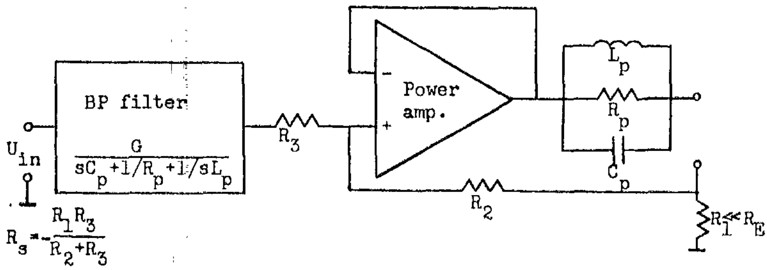
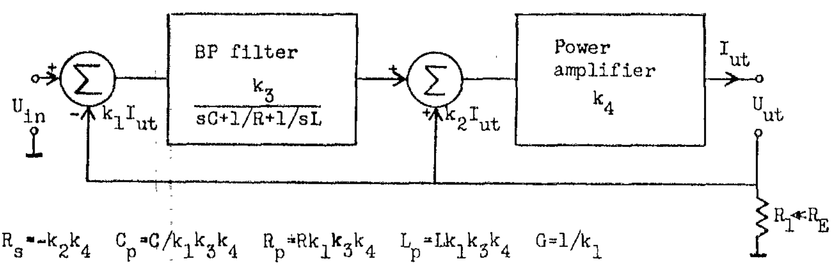



Fig 10. Direct synthesis of the ACE-Bass amplifier.

However, this synthesis has several disadvantages. $C_p$ is normally a few mF and $L_p$ some tens mH; both are quite difficult to realize in practice. There is also a power loss in $R_p$, and the bandpass filter must be congruent with $Z_p$.

The configuration in fig 11 is superior since it allows a completly active design. Apart from the power amplifier only a few operational amplifiers and some passive components are needed.

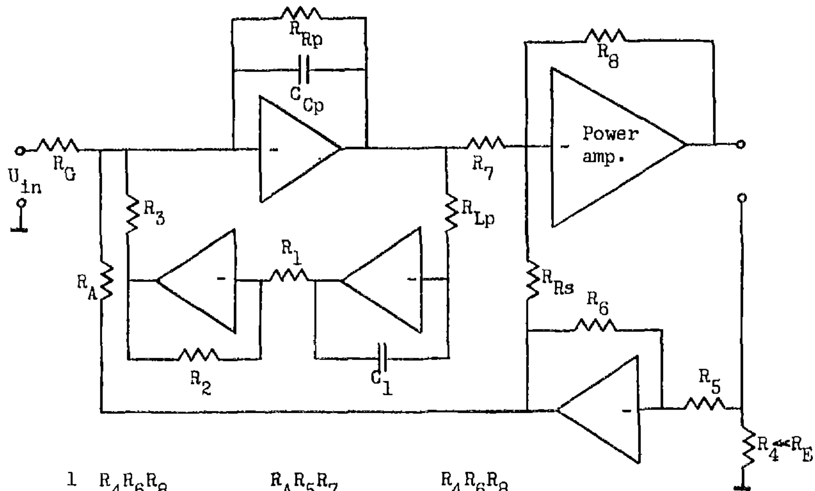
The output current is sensed through $R_1$ and the first positive feedback loop around the power amplifier gives the negative output resistance while the second negative feedback loop and the bandpass filter provides the parallel circuit (fig 6) on the output.




$R_s = -k_2k_4$   $C_p = C/k_1k_3k_4$   $R_p = Rk_1k_3k_4$   $L_p = Lk_1k_3k_4$   $G = 1/k_1$

Fig 11. Active synthesis of ACE-Bass amplifier.

If the bandpass section is realized as a DIG filter, as shown below, each parameter can be adjusted independently of the others by one component. This pleasent characteristic may be very convenient during the experimental and developmental phase.



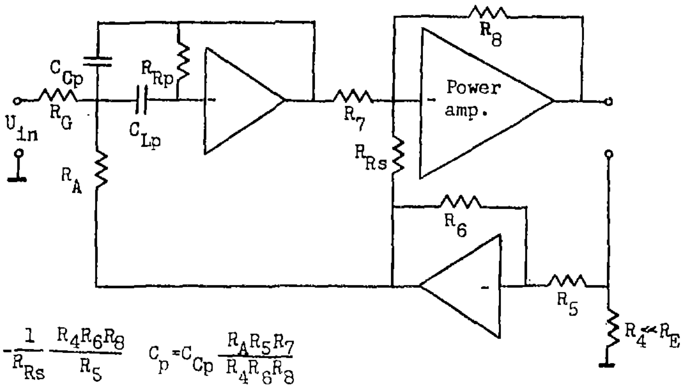

$$R_s = -\frac{1}{R_{Rs}}\,\frac{R_4R_6R_8}{R_5} \qquad C_p = C_{Cp}\,\frac{R_AR_5R_7}{R_4R_6R_8} \qquad R_p = R_{Rp}\,\frac{R_4R_6R_8}{R_AR_5R_7}$$

$$L_p = R_{Lp}\,\frac{R_1R_3C_1}{R_2}\,\frac{R_4R_6R_8}{R_AR_5R_7} \qquad G = \frac{1}{R_G}\,\frac{R_AR_5}{R_4R_6}$$

Fig 12. Realization of ACE-Bass amplifier useful for experiment purposes.

On the other hand, the circuit in fig 13 does the same job with fewer operational amplifiers, once the component values are determined through calculation.

Both these circuits are simplified if decreased compliance is not required. In a closed box, for example, it may be sufficient to increas mass and control damping.




$$R_s = -\frac{1}{R_{Rs}} \frac{R_4 R_6 R_8}{R_5} \qquad C_p = C_{Cp} \frac{R_A R_5 R_7}{R_4 R_6 R_8}$$

$$R_p = \frac{R_{Rp}}{1 + C_{Cp}/C_{Lp}} \frac{R_4 R_6 R_8}{R_A R_5 R_7} \qquad L_p = \frac{C_{Lp} R_A R_G R_{Rp}}{R_A + R_G} \frac{R_4 R_6 R_8}{R_A R_5 R_7} \qquad G = \frac{1}{R_G} \frac{R_A R_5}{R_4 R_6}$$

Fig 13. Simple realization of ACE-Bass amplifier.

## 5 UPPER FREQUENCY BOUND WITH ACE-BASS

So far the analysis has considered only low frequency performance. Since the voice-coil impedance is not purely resistive but also inductive, an upper frequency bound between 100 and 500 Hz occurs when ACE-Bass is used. Fig 14 shows the equivalent circuit seen from the electrical side, simplified for this frequency range.

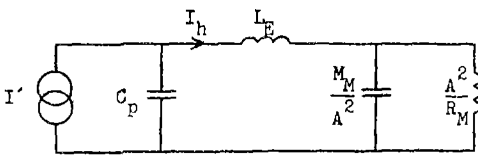



Fig 14. Simplified equivalent circuit relevant for upper frequency bound. $L_E$ is the inductance of the voice coil.

It is seen that the frequency response, which is proportional to the current $I_h$ has a lowpass character with a relatively high Q-value.

This built-in lowpass filter can be utilized as part of a crossover network. A useful crossover is obtained if the Q-value is decreased by reducing the value of the negative resistance $R_s$ at high frequencies, which creates a resistance in series with $L_E$, and combining this with a simple RC filter in the amplifier.

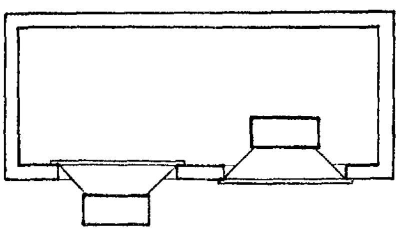
## 6 DISTORTION

No complete theoretical analysis of distortion has been made for the ACE-Bass method, but a few observations are worth mentioning. Measurements at low frequencies usually show considerable distortion reduction, and generally the more the apparent parameters dominate the real ones the less distortion.

In conventional loudspeakers some sources of distortion are nonlinearities in the force factor A and in the mechanichal parameters $Z_M$. With ACE-Bass $Z_M$ is often dominated by the apparent parameters $A^2/Z_p$. Cone velocity for conventional infinite baffle systems can be written $V_{MCON} = \frac{U_{in} A}{R_E Z_M}$,
while the velocity in ACE-Bass loudspeakers with dominating apparent parameters can be approximated $V_{MACE} = \frac{U_{in} G A}{A^2 / Z_p} = \frac{U_{in} G Z_p}{A}$.
The distortion improvements might then be explained by the elimination of $Z_M$ and by the placing of the force factor A in the denominator instead of the numerator.

As the upper frequency limit is approached, an increase of mainly second harmonic distortion can appear. Since the voice coil inductance has considerable influence at these frequencies, distortion is caused by the nonlinearity of the inductance which occurs during large cone excursion. This nonlinearity is due to the fact that the "iron core" of the inductance decreases (and consequenly its value) when the voice coil moves out of the magnet and increases when it moves into the magnet. This distortion can be reduced by using a loudspeaker with a copper ring around its center pole which short circuits the voice coil inductance. Another very effective method is to use two loudspeakers in series or parallel. If one of the loudspeakers is mounted back-side out (the polarity is naturally reversed in the electrical connection), then one voice coil moves towards the magnet as the other moves from the magnet. The result is that the second harmonic is decreased to negligible values throughout the complete frequency range.

Fig 15. Loudspeaker mounting for elimination of second harmonic distortion.



## 7 DESIGN APPLICATIONS

ACE-Bass has been tried with a number of loudspeakers in different types of enclosures. The best results were obtained in bass-reflex boxes with two loudspeakers push-pull mounted as in fig 15. To obtain large amounts of low bass, maximum cone amplitude has to be specially considered. A good way to keep it low is to use sixth-order Butterworth (B6) designs as given by Theile [2] and Small [4].

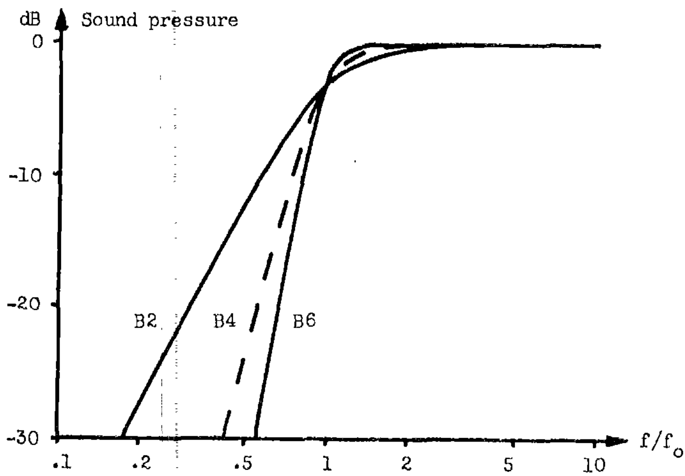



Fig 16. Frequency response for different Butterworth loudspeaker systems.

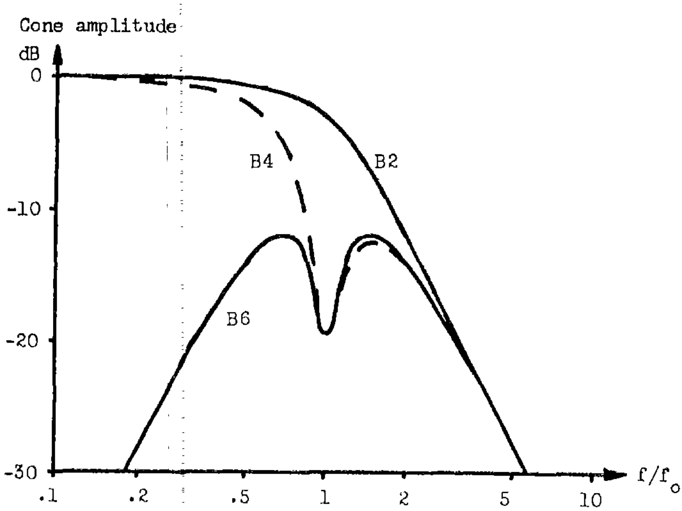



Fig 17. Cone amplitude for different Butterworth loudspeaker systems.

This is illustrated in fig 16 and 17 which show differences in frequency response and cone amplitude for second-, fourth- and sixth-order Butterworth alignments, representing closed systems, bass-reflex systems and bass-reflex systems with a 12 dB/octave highpass filter. It is seen that a B6 system requires only one fourth of the volume displacement compared to a closed box system, for the same output and cut-off frequency. By exploiting this possibility, small bass systems with very impressive data can be made. One system which works very well produces bass with less than 3% distortion down to 30 Hz (-3 dB) at 96 dB in half space ($2\pi$) at one meter. This is accomplished with a B6 ACE-Bass system consisting of two standard 5" woofers with 4 mm peak cone travel in a 12 liter (!) box. Maximum required amplifier output power is 40 W.

The characteristics of ACE-Bass is best described by showing how a subwoofer system was designed. The following specification was set up:

—flat frequency response down to 20 Hz (-3 dB)
—minimum 100 dBspl output at 1 meter in half space
—low distortion, less than 5% in worst case
—moderate size, about 50 liter net volume and
—moderate input power, maximum 80 W.

Analysis shows that this can be accomplished with two 6.5" loudspeakers with high force factor and extra long excursion capability in a sixth order Butterworth system. Special woofers were made to meet the requirements and the important data of these are:

—cone area $S=140\ cm^2$
—maximum cone excursion $x=\pm 9$ mm (=voice coil overhang) 1/
—force factor $A=8.8$ N/A
—voice coil resistance $R_E=6.7$ ohm
—moving mass 19 g
—damping 1.6 kg/s and
—compliance .9 mm/N.

1/ The reason for not choosing a larger cone area and a more moderate cone excursion is that the force factor has to increase in proportion to the cone area in order to achieve the specified output with the same input power. A much larger magnet would then be needed.

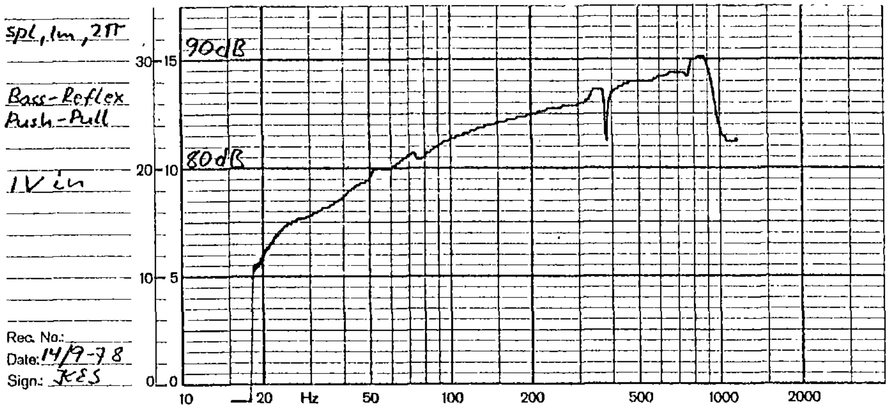



Fig 18. Frequency response in anechoic chamber for the subwoofer system when driven with a conventional amplifier.

Frequency response for these drivers mounted in a 50 liter bass-reflex enclosure tuned to 20 Hz is shown above. To achieve the specified response (sixth-order Butterworth, 20 Hz cut-off), both different mechanical parameters modified by ACE-Bass as well as a second-order highpass filter are required. A sixth-order transfer function can be split into three second-order functions, each mathematically represented by a pole-pair. There are thus three different alternatives to devide the pole-pairs between the second-order filter and the fourth-order system consisting of the loudspeaker system in combination with ACE-Bass. All three alternatives give the same frequency and transient response, but different distortion figures. Measurements showed that the lowest distortion occured when the pole-pair with the lowest Q was assigned to the filter and the other two pole-pairs were synthesized in the loudspeaker by ACE-Bass. This behaviour is typical for ACE-Bass and implies that the lowest distortion is achieved when the apparent mechanical parameters dominate the real parameters by the greatest magnitude.

To obtain the desired transfer function a 12 dB/octave filter with resonance at 20 Hz and Q of .52 was included in the amplifier and ACE-Bass was used to modify the mechanical parameters of both drivers combined as follows:

- increased moving mass from 38 to 260 g
- increased damping from 26 (electrical damping included) to 58 kg/s and
- decreased compliance from .45 to .25 mm/N.

These parameters would be almost impossible to realize by mechanical means, or if they were, the efficiency would be extremely low. However, with ACE-Bass this is no problem and the efficiency is the same as depicted in fig 18; there is no need to sacrifice efficiency at higher frequencies. Frequency response and distortion at different output levels for the complete subwoofer system is shown in fig 19.

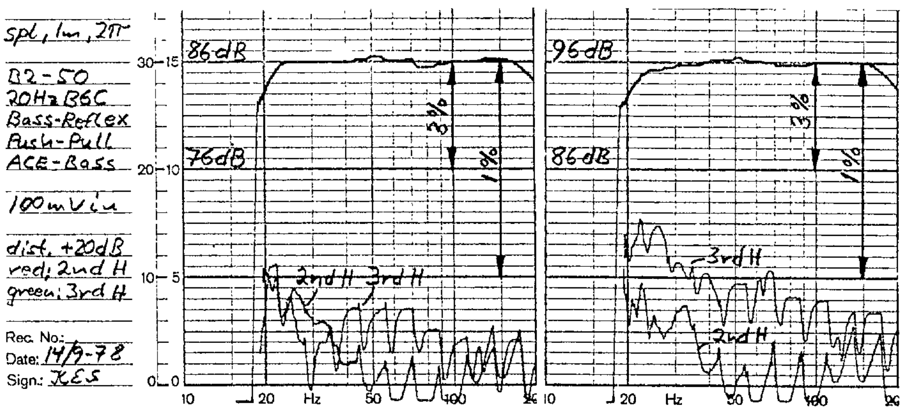
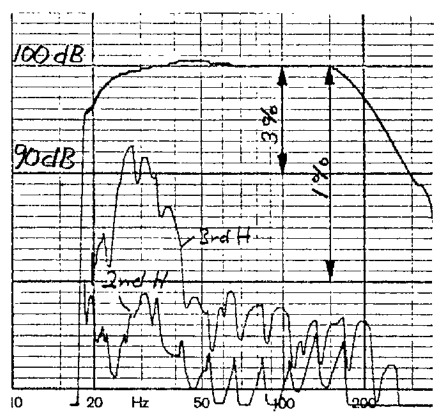



Fig 19. Frequency response and distortion for the complete ACE-Bass subwoofer measured with pure sine-wave in anechoic chamber. Paper speed was 3 mm/s and writing speed 100 mm/s. Second and third harmonics were measured with switched 1/3-octave filters and amplified 20 dB compared to the frequency response.




To illustrate how the different design characteristics contribute to the reduction of distortion, the system above, still with push-pull mounted drivers in the same bass-reflex box, was measured without ACE-Bass, i.e. driven with a conventional amplifier, see fig 20. To achieve flat frequency response the Brüel&Kjaer test equipment was operated in the compressor mode.

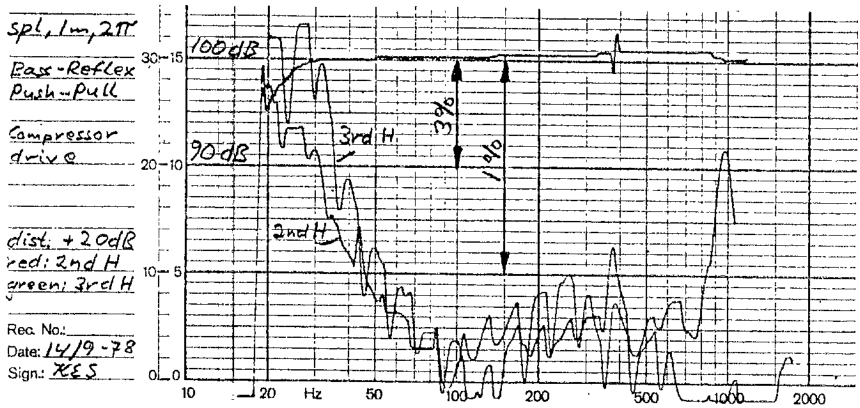



Fig 20. Distortion for the same system as in fig 19 but without ACE-Bass. The frequency response is kept flat by feeding back the amplitude level.

Fig 21 shows how second harmonic distortion increases when the loudspeakers are mounted in a normal manner instead of the push-pull fashion. This would thus represent a good equalized bass-reflex system.

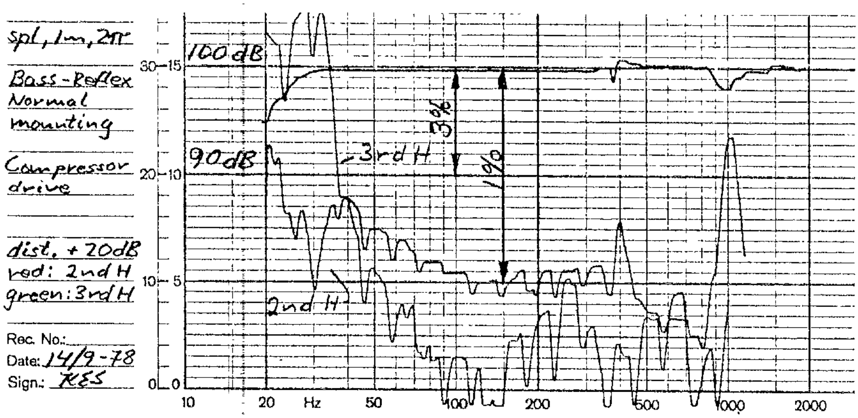



Fig 21. Same as in fig 20 but with normal mounting of the drivers.

Finally the system was converted to a closed box, fig 22. Full output below 40 Hz was no longer possible since maximum cone travel was reached, and distortion increased considerably at low frequencies.

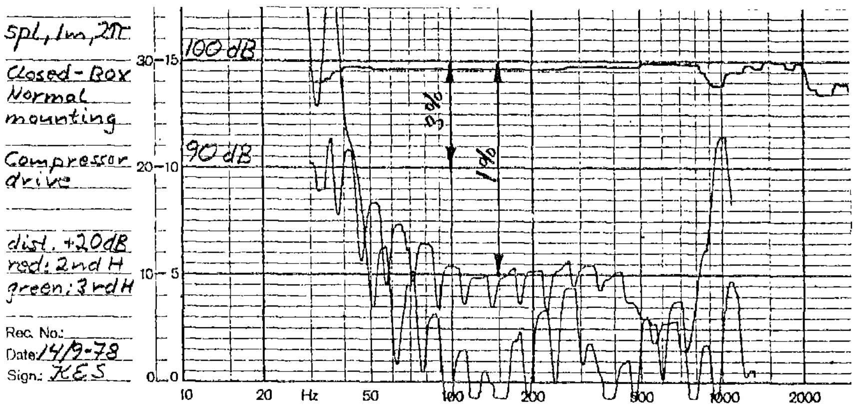



Fig 22. Distortion under same conditions as in fig 21 but with a closed enclosure instead of a bass-reflex enclosure.

To achieve the specified output level in a closed box using a normal driver with a cone travel limit of ±4 mm, a 24" driver would be necessary. It would require an enormous magnet and in spite of that 80 watts in the 50 liter box would not produce full output. The distortion could surely be made lower than in fig 22, but it is not likely that it should be as low as in fig 19 even if some type of feedback would be used.

## CONCLUSION

ACE-Bass is an effective method to achieve extremely accurate bass reproduction. The price is that the loudspeaker system must be made active, i.e. the amplifier must be specially designed for the speaker.

A great advantage over servo or feedback systems is that ACE-Bass allows the use of bass-reflex enclosures. Since the cone amplitude is not directly related to the output of a bass-reflex system, motional feedback is not applicable and in general fourth-order systems are almost impossible to control with feedback.

When compared to equalized systems, ACE-Bass provides lower distortion. In addition, ACE-Bass systems are insensitive to variations in the real mechanical loudspeaker parameters. Variations in voice coil resistance $R_E$ and force factor A do affect frequency response, but can be neatly trimmed out in the ACE-Bass amplifier.

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