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HIGH EFFICIENCY WITH SMALL ENCLOSURES?

Why are modern hi-fi loudspeakers so inefficient that we need more amplifier power than ever before to drive them? Not so long ago ten watts per channel was ample for domestic sound reproduction but now a hundred watts is quite common; surely this is a retrograde development? And why, when "bookshelf" loudspeakers covering the full audio-frequency range have been around for years, are we still being invited to buy models ten times the size?

Both these questions, so often heard nowadays, are, of course, based on an over-simplified view of the situation. The lower efficiencies are not universal, but are mainly associated with loudspeakers designed to meet the demand for a frequency response that remains flat all the way down to the lower end of the working range. And the miniature models, though they may represent the best compromise for some purposes, are by no means equivalent to their larger cousins, for while they may have the same mid-band efficiency, the same bass cut-off frequency or the same power output capacity, they cannot have all three at the same time.

For any loudspeaker in which the diaphragm of the low-frequency drive unit acts directly on the air without the aid of a horn (a description that covers most types in common use), the three basic quantities, enclosure volume, bass response and efficiency, are interrelated in such a way that each can be traded against the others. The trade-off rates are governed by known physical laws, and for all the ingenious ideas that have been propounded over the years, these laws have not changed. What *has* changed, however, is that developments in amplifier design following the replacement of valves by transistors have made it possible to achieve much higher power ratings for the same size and cost; the requirement for maximum loudspeaker efficiency, previously imposed through the use of low-powered amplifiers, can now be relaxed, and designers can offer a choice of extreme compactness, extended bass response or a variety of intermediate combinations, each fulfilling a particular need.

The optimum design depends not only on the total cost allowed for the amplifier/loudspeaker combination, and the space available for the equipment, but also on the type of programme material to be reproduced, the maximum sound level required, the acoustics of the environment and the listening distance. It is clearly to the advantage of the prospective purchaser to consider all these factors and to understand the various ways in which the loudspeaker designer can balance the conflicting requirements against each other to produce the best possible solution in every case. This issue of KEFTOPICS is therefore devoted to a discussion of the fundamental relationships between enclosure volume, low-frequency response and efficiency, and of the exploitation of these relationships in practice.

Efficiency and Sensitivity

The simple concept of efficiency as "output power divided by input power" requires some qualification when applied to a loudspeaker. The process of electro-acoustic conversion takes place in two stages — the flow of power from the amplifier into the loudspeaker, and the transformation of some part of this power (in general, only a tiny percentage) into sound. If the impedance of the loudspeaker could be regarded as a constant resistance equal to the nominal value given in the specification, the power flowing into it could be easily calculated from the voltage at the input terminals. In fact this is not possible because a loudspeaker impedance varies widely over the working frequency range and so cannot provide a perfect match for the amplifier. For practical purposes therefore the input power is commonly defined as that which would be delivered to a resistor equal in numerical value to the nominal loudspeaker impedance; the two stages of electro-acoustic conversion are thereby treated as one, and the effect of mismatch on the amount of power actually flowing into the loudspeaker is automatically debited to the overall efficiency figure arrived at by measuring the acoustic output and comparing it with the input as defined.

The result of amplifier-loudspeaker mismatch depends on whether the loudspeaker impedance is higher or lower than the nominal value. A higher-than-nominal impedance in a particular frequency range represents a problem for the designer, who has had to achieve the required acoustic output with a reduced electrical input. A lower-than-nominal impedance, on the other hand, is a matter of concern to the user, for the increased current drawn by the loudspeaker may cause the amplifier to distort before its full rated output voltage is reached; in comparing the performance specifications of different models, it is therefore important to look carefully at their impedance/frequency characteristics.

Because the ear is a pressure-operated device, the output of a loudspeaker is generally specified as the resulting sound pressure level (spl) in decibels* at a certain point, rather than the acoustic power output in watts: the concept of efficiency is then expressed by a sensitivity figure, usually given as the spl produced at a distance of 1 m on the axis, for an input power (as defined earlier) of 1 watt. By convention, the sensitivity is averaged over the middle-frequency range, and is often referred to for brevity as the "mid-band" figure. Figure 1 curve (a) shows the relationship between mid-band efficiency and sensitivity rating for typical high-quality loudspeakers.

At first sight it might appear that a loudspeaker having a flat frequency response in terms of sound

**Sound pressure levels are given in dB above a reference pressure of 2 x 10^{-5} newton/square metre (in older textbooks, 0.0002 dyne/square centimetre).*

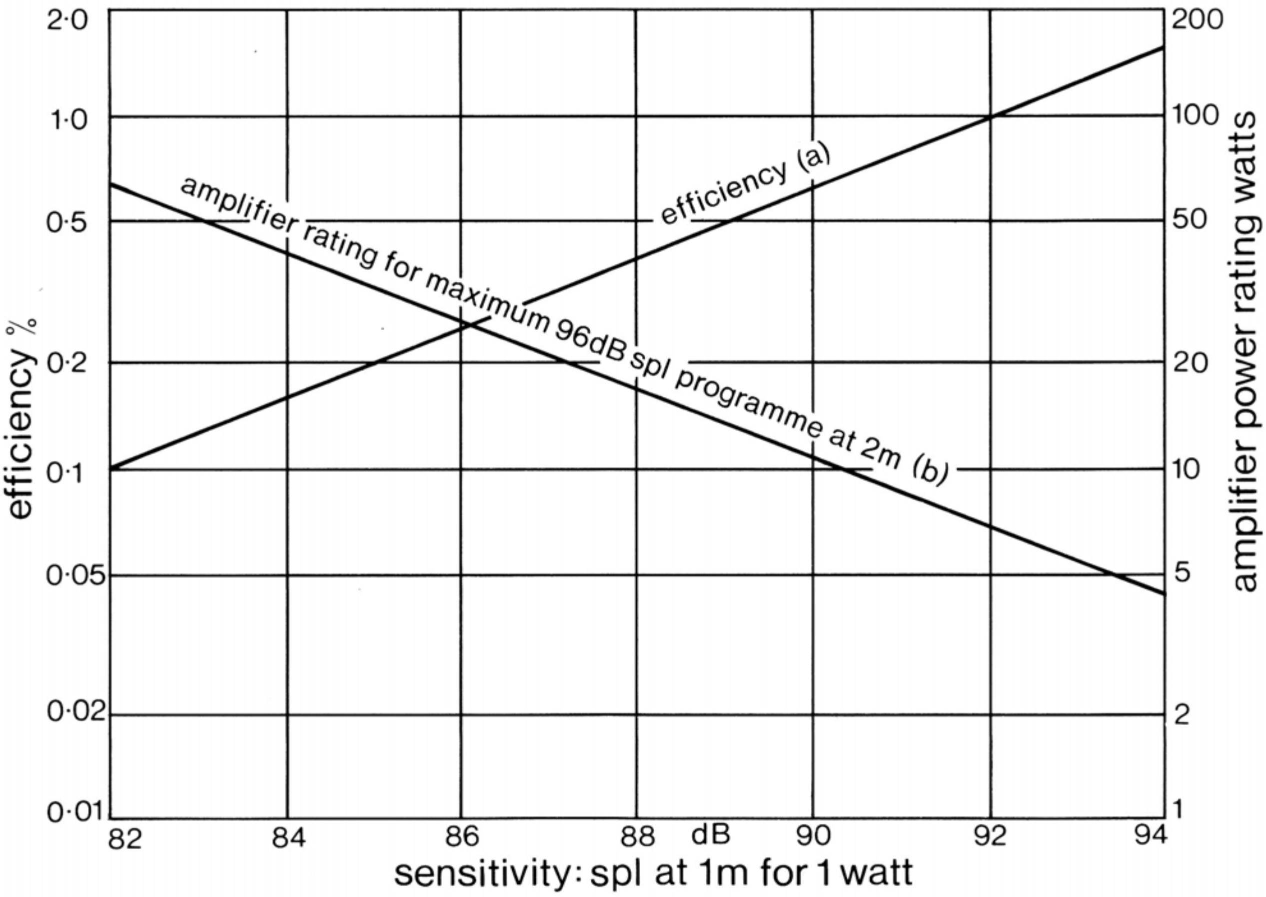

***Fig. 1.** Relationship between loudspeaker sensitivity and (a) mid-band efficiency (b) power rating of amplifier required to produce 96 dB spl at 2 m on programme in typical domestic environment.*

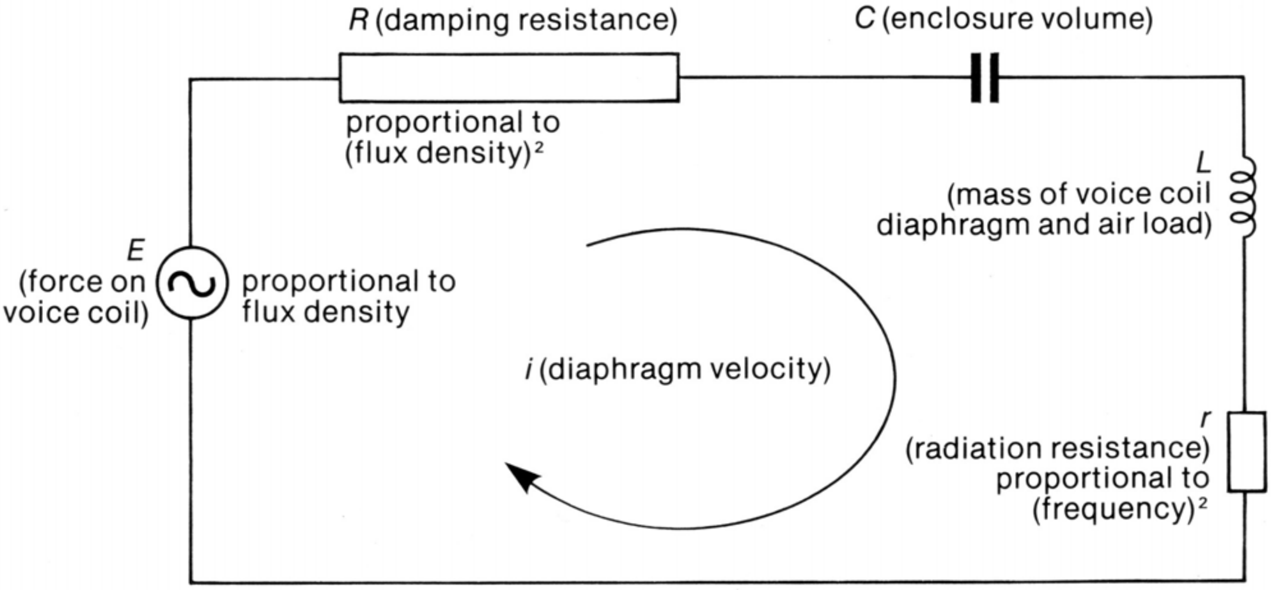

Fig. 2. *Equivalent electrical circuit representing mechanical system of an 'infinite baffle' loudspeaker.*

pressure would have uniform efficiency throughout its working range, but consideration of the spatial distribution of the acoustic output leads to a different conclusion. At the lower end of the frequency range, where the wavelength is much greater than the loudspeaker dimensions, sound is radiated with equal intensity in all directions†, in the middle-frequency range, however, the wavelength is comparable with the dimensions of the enclosure, which then acts as a baffle, increasing the radiation efficiency and concentrating most of the power in front. Unless these factors are taken into account in the loudspeaker design, the pressure response obtained in the middle-frequency range will not be maintained at the bass, but will fall to a lower level as the gradual transition to the condition of all-round radiation takes place. If a flat pressure response over the whole range is required, the efficiency of the system at low frequencies may need to be two or more times the figure obtained in the middle-frequency range, in order to compensate for the change of régime*.

The sensitivity of a loudspeaker is measured, by convention, under free-air (anechoic) conditions, and for practical purposes it is necessary to relate this figure to the performance in a normal listening environment. The relationship is not, however, a constant one, but depends on the acoustics of the room. Although, as pointed out in previous issues of KEFTOPICS, the tonal quality of the reproduction and the sharpness of the stereo images are primarily determined by the sound that reaches the listener direct from the loudspeaker, the reverberant sound, which represents the total acoustic energy in the room, has a large and often predominant influence on the pressure level at the listening point, on which the sensation of loudness depends. To decide on the amplifier power required, not only the listening distance and maximum sound level but also the volume and sound absorption of the room have therefore to be taken into account. Figure 1 curve (b) shows the approximate amplifier rating required for a maximum spl of 96 dB on programme (which represents quite a loud sound) at a listening distance of 2 m in a typical domestic environment, plotted against the mid-band sensitivity of the loudspeaker. For rooms having a high degree of sound absorption, more power would be required, and vice versa. Small changes in sensitivity correspond to quite large changes in amplifier rating; 3 dB less sensitivity, for example, represents a halving of the loudspeaker efficiency and calls for double the power. With some miniature loudspeakers, the amplifier power indicated may be more than can be safely handled without distortion or damage; the user would then have to be content with a reduced listening distance and/or listening level.

Equivalent Circuit Analysis

For the reasons given earlier, the mid-band sensitivity of a loudspeaker is linked, albeit indirectly, to the efficiency in the bass region. Efficiency at the bass, in turn, is tied to the enclosure volume and lower cut-off frequency; this tripartite relationship, which follows the same basic pattern for all types of loudspeaker in common use, can be illustrated by analysing the behaviour of a sealed enclosure or 'infinite baffle' system.

Fortunately for designers, the efficiency and

†Open-baffle loudspeakers, which have a figure-of-eight polar characteristic at low frequencies, are outside the scope of the present discussion.

**An exception may be made in the case of some miniature loudspeakers of the "bookshelf" type, which are designed to be mounted flat against a wall.*

pressure response of a loudspeaker at the lower end of the frequency range, where all the dimensions are small compared with the wavelength of the sound, are not too difficult to calculate; the acoustic impedance of the enclosure can be represented by a single constant, while the diaphragm, moving as a whole on its suspension, can be treated as a combination of mass and compliance (the latter quantity being the inverse of stiffness) having the radiation characteristics of a rigid piston mounted at the end of a long tube.

To facilitate the analysis, it is usual to represent the loudspeaker system at low frequencies by an equivalent a.c. electrical circuit. There are several ways of doing this, but for the present purpose the most convenient form is an electrical analogue of the mechanical system, in which force is represented by voltage, velocity by current, mass by inductance, compliance by capacitance and damping by resistance. Figure 2 shows the essential features of an 'infinite baffle' system treated in this way. Here, the alternating voltage *E* represents the driving force produced by current flowing through the voice coil, and is therefore proportional to the flux density of the magnetic field in which the coil moves.

Resistor *R* takes account of the damping effect of the electrical circuit formed by the voice coil and the amplifier output; the amount of damping produced in the mechanical system depends on the degree of electromechanical coupling, and the value of *R* is in fact proportional to the square of the flux density. For simplicity, we will assume that the stiffness of the suspension has been made small enough to be negligible, leaving only the stiffness due to the air trapped in the enclosure. This latter quantity is inversely proportional to the enclosure volume; the corresponding compliance, represented in the equivalent circuit by the capacitor *C*, is therefore directly proportional to the enclosure volume.

Inductor *L* represents the mass of the voice coil and diaphragm, plus a small additional mass which is part of the load imposed by the outside air. This air load also includes a tiny resistive component — the radiation resistance, represented by *r*; the power dissipated in this resistor is equal to the acoustic power output of the loudspeaker. The value of *r*, unlike that of most resistors, is not constant, but is proportional to the square of the frequency — a fact that has to be allowed for in calculating the response of the system — but it is too small to affect the currents and voltages in the rest of the circuit. Finally, the current *i*, flowing through *R, C, L*, and *r*, represents the velocity with which the diaphragm moves.

Given the values of *E, R, C, L* and *r*, all of which can be derived from known physical constants, the low-frequency characteristics of the complete electro-acoustic system can be calculated; this process is simplified by the fact that when the variation of *r* with frequency is taken into account, the equivalent circuit turns out to be a second-order high-pass filter, which can be dealt with — as can the more complex filter systems referred to later — by the standard methods of circuit analysis and synthesis. For some purposes, however, it is more convenient to measure the response of an electrical simulator, such as that illustrated in Figure 3, to study the effect of varying different circuit constants. Figure 4 curve (a), obtained in this way, shows the response of a closed box loudspeaker of 30 litres internal volume, which has been designed to give a filter characteristic with a nominal cut-off frequency f_3 — at which the attenuation is 3 dB — of 50 Hz. The characteristic is of the form described in filter theory as "maximally flat", i.e. a smooth curve, without peaks or ripples, in which the attenuation within the pass-band is kept as small as possible up to f_3.

By changing the component values in the electrical analogue, we can now explore a number of alternative possibilities. Can we, for example, with the same diameter drive unit, achieve the same frequency response with only half the enclosure volume? *L* and *C* resonate at a frequency that is proportional to $\frac{1}{\sqrt{LC}}$, so simply halving *C* will increase this frequency $\sqrt{2}$ times. Figure 4 curve (b) shows the resulting response; f_3 is now 55 Hz and the resonance is under-damped, giving a broad peak in response at about 100 Hz.

To get back to our original frequency response, we shall have to restore the original resonance frequency by increasing the mass of the diaphragm and/or voice coil so that *L* is doubled. But this measure in itself is not enough; the resulting characteristic, shown in Figure 4 curve (c), has an even higher peak than before. Worse still, on the flat part of the curve, i.e. at frequencies at which *C* has no effect, doubling the value of *L* has halved the current i, so that the level in the pass-band of the filter has been reduced by 6 dB.

Since the reactive impedance of *L* and *C* have now been doubled, the only way to restore the

Fig. 3. *Electrical simulator for demonstrating effect of varying loudspeaker parameters.*

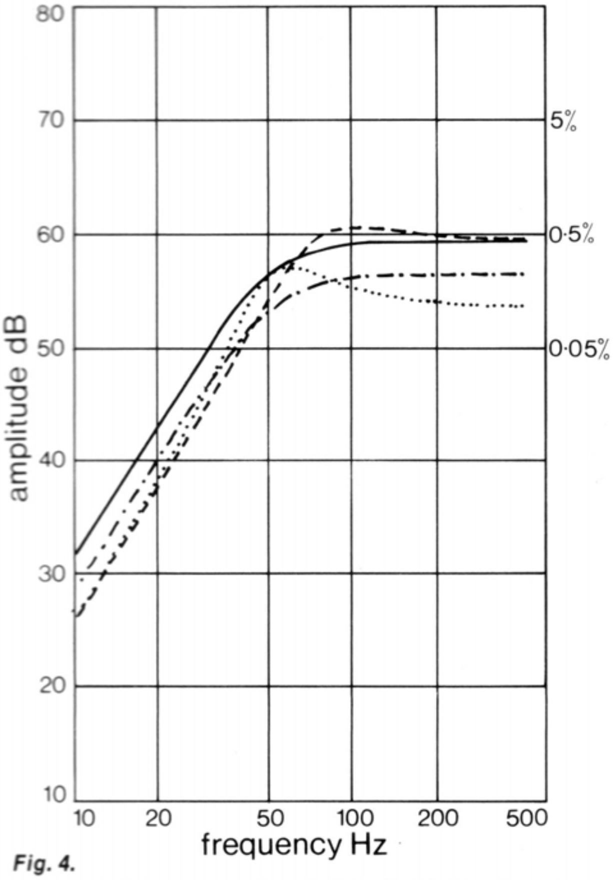

Fig. 4.

——— *(a) Response of an 'infinite baffle' loudspeaker designed as maximally flat 2nd order high-pass filter. Enclosure volume: 30 litres. Cut-off frequency f_3:50 Hz.*

— — — *(b) Enclosure volume halved, other parameters unchanged.*

········ *(c) Enclosure volume halved, moving mass doubled.*

—·—·—· *(d) Enclosure volume halved, moving mass doubled, flux density increased $\sqrt{2}$ times; original frequency response restored with 3 dB loss in pass-band level, i.e. efficiency halved.*

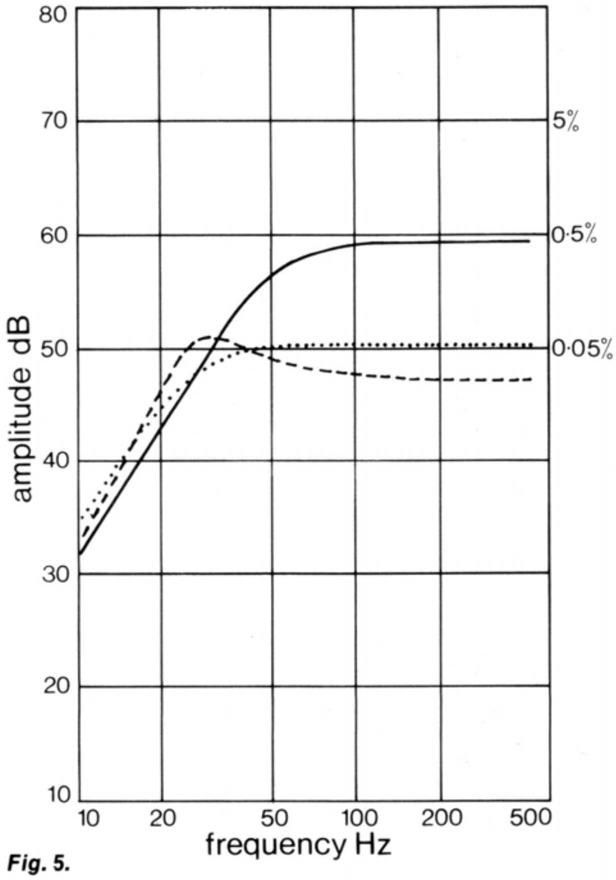

Fig. 5.

——— *(a) As for Figure 4, curve (a).*

— — — *(b) Moving mass increased 4 times, other parameters unchanged.*

········ *(c) Moving mass increased 4 times, flux density increased $\sqrt{2}$ times; cut-off frequency f_3 halved with 9 dB loss in pass-band level, i.e. efficiency reduced 8 times.*

frequency response curve to its original shape is to double the resistor *R* so as to preserve the proper reactance/resistance relationship. This can be done by increasing the flux density of the magnet by a factor of $\sqrt{2}$; the driving force, represented by *E*, will then be increased in the same proportion thus recovering 3 dB of the 6 dB loss in level. Figure 4 curve (d) shows the net result; the original frequency response has now been achieved with half the enclosure volume, but at the cost of a more expensive magnet and a loss of 3 dB in the pass-band level, i.e. the efficiency has been halved and the required amplifier power doubled.

Let us now return to the starting point represented by Figure 4 curve (a), which for convenience is reproduced in curve (a) of Figure 5, and see what happens if, while keeping the original enclosure volume and drive unit diameter, we want to shift the whole frequency response curve down by one octave, so that f_3 is halved. First, the frequency of resonance between *L* and *C* must be halved, and since *C* is unchanged, the value of *L* will have to be multiplied by four, thereby reducing the level on the flat part of the characteristic — Figure 5 curve (b) — by 12 dB. Again, this in itself is not enough; at resonance, the reactances in the circuit are now twice what they were, while the resistance is still the same, so that the system is under-damped and the response curve is peaked. To restore the original curve shape, the damping resistance will have to be doubled, just as in the previous example, by increasing the flux density $\sqrt{2}$ times, recovering in the process 3 dB of the 12 dB loss in level. Figure 5 curve (c) shows the end result; the price paid for halving the cut-off frequency for the same enclosure volume is a net reduction of 9 dB in level, in spite of the more expensive magnet. This means an eight-fold loss in efficiency, so that an amplifier of eight times the power is now required.

The Basic Formula

The results just arrived at by a step-by-step process could have been obtained more directly, for the two cases discussed are particular examples of a general rule applicable to loudspeakers which act as high-pass filters at low frequencies. It can be shown from first principles that the efficiency η of the system in the pass-band, i.e. on the flat part of

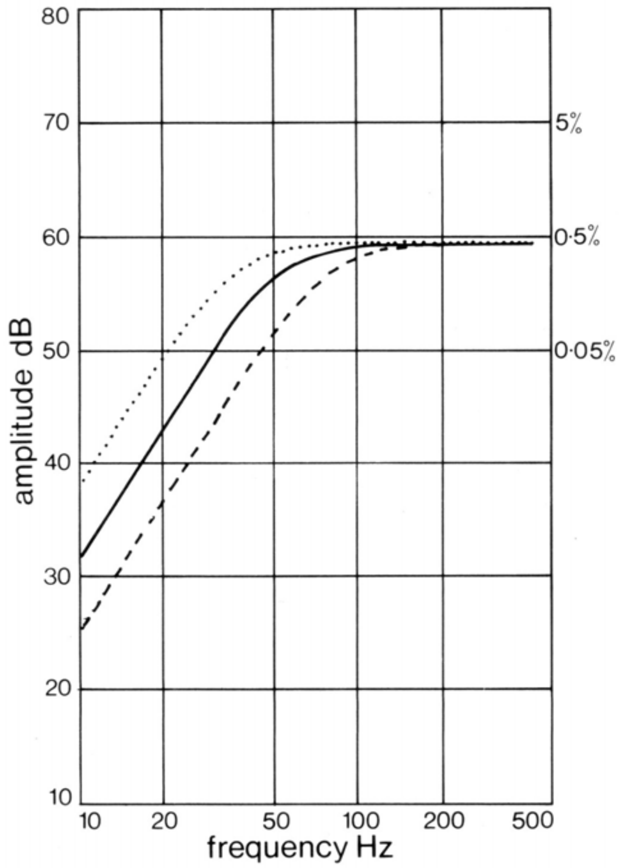

Fig. 6. *'Infinite baffle' loudspeaker: variation of cut-off frequency f_3 with box volume V_E: other parameters adjusted to maintain maximally flat characteristic with constant efficiency.*
——— *(a) V_E = 30 litres; f_3 = 50 Hz.*
— — — *(b) V_E = 10 litres; f_3 = 74.7 Hz.*
········ *(c) V_E = 100 litres; f_3 = 34.7 Hz.*

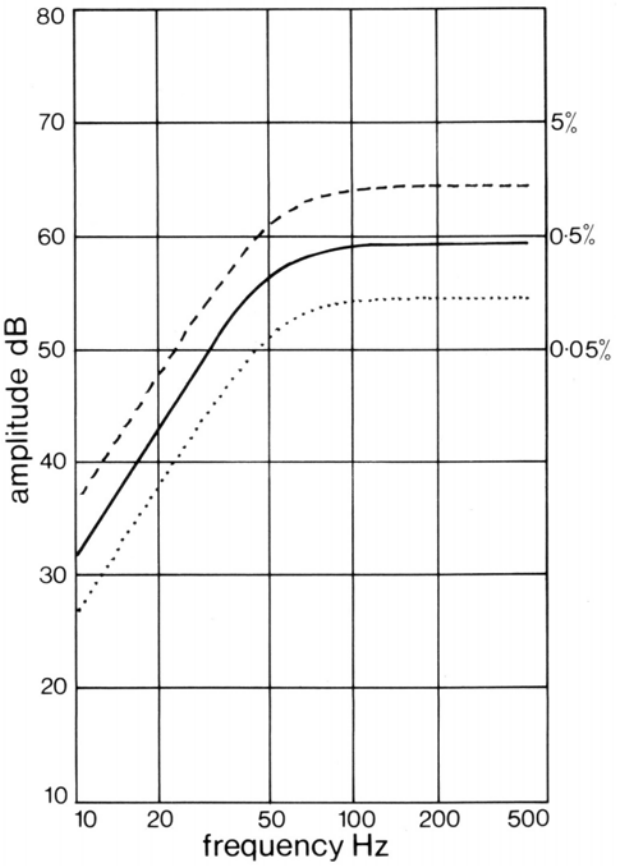

Fig. 7. *'Infinite baffle' loudspeaker; variation of efficiency with enclosure volume V_E; other parameters adjusted to maintain maximally flat characteristic with constant f_3 = 50 Hz.*
——— *(a) V_E = 30 litres.*
········ *(b) V_E = 10 litres.*
— — — *(c) V_E = 100 litres.*

the response curve, is proportional to the internal volume V_E of the enclosure and to the cube of the cut-off frequency f_3, so that:—

$$\eta = f_3^3 . V_E k$$

The factor *k* depends on the type of filter network. It also depends on whether the response, for example, takes the form of a gradual fall-off towards the bass, a maximally flat characteristic as in Figure 4 curve (a) or a peaked characteristic as in curve (b); in general, high values of *k*, i.e. high efficiencies, are achieved, other things being equal, at the cost of reduced bass.

These relationships are illustrated in systematic form by Figures 6, 7, 8 and 9; the starting point in each case is curve (a), which is the same as curve (a) in Figure 4, representing the maximally flat characteristics of an 'infinite baffle' system with V_E equal to 30 litres and f_3 equal to 50 Hz. Figure 6 curve (b) shows the effect of reducing the enclosure volume to 10 litres while altering the diaphragm/voice coil mass and the flux density in the magnet by the amounts necessary to give the same efficiency and the same type of frequency characteristic as before; f_3 has now gone up to 74.7 Hz. Curve (c) on the other hand shows the response with the enclosure volume increased to 100 litres, the drive unit parameters being again adjusted to give the same efficiency and curve shape; f_3 is now 34.7 Hz. Comparison of curves (b) and (c) shows, as expected, that the change in enclosure volume in the ratio 1:10 corresponds to a change in f_3^3 in the ratio $74.7^3:34.7^3$, i.e. 10:1.

In Figure 7, curves (b) and (c) show respectively the effect of reducing the enclosure volume to 10 litres and increasing it to 100 litres, while altering the drive unit parameters to give the same value of f_3 and the same curve shape; the two characteristics are separated in level by 10 dB, a ten-fold increase in enclosure volume. In Figure 8, the enclosure volume is kept at 30 litres, but the parameters of the drive unit are adjusted to give different values of f_3 while retaining the maximally flat form of characteristic. Curves (b) and (c) are for cut-off frequencies of 74.7 Hz and 34.7 Hz respectively; the 10 dB difference in level on the flat part of the curve in each case represents a ten-fold difference in efficiency — corresponding to the ratio $74.7^3:34.7^3$ — in favour of the higher value of f_3.

Finally, Figure 9 demonstrates the importance of the magnet flux density, both in relation to the efficiency and to the frequency response of the system. Curve (a) represents the condition in which the flux density has precisely the right value to give a maximally flat characteristic. Curve (b) shows the effect of increasing this value $\sqrt{2}$ times; the response flattens out at a 3 dB higher level, which

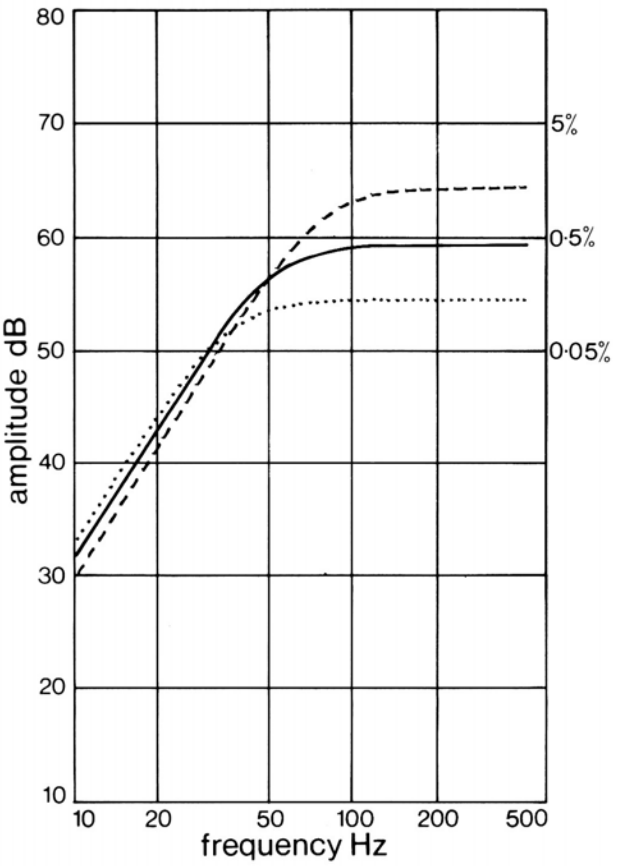

***Fig. 8.** 'Infinite baffle' loudspeaker: variation of efficiency with f_3; V_E constant at 30 litres and other parameters adjusted to give maximally flat characteristic.*

——— *(a) f_3 = 50 Hz.*

— — — *(b) f_3 = 74.7 Hz.*

········ *(c) f_3 = 34.7 Hz.*

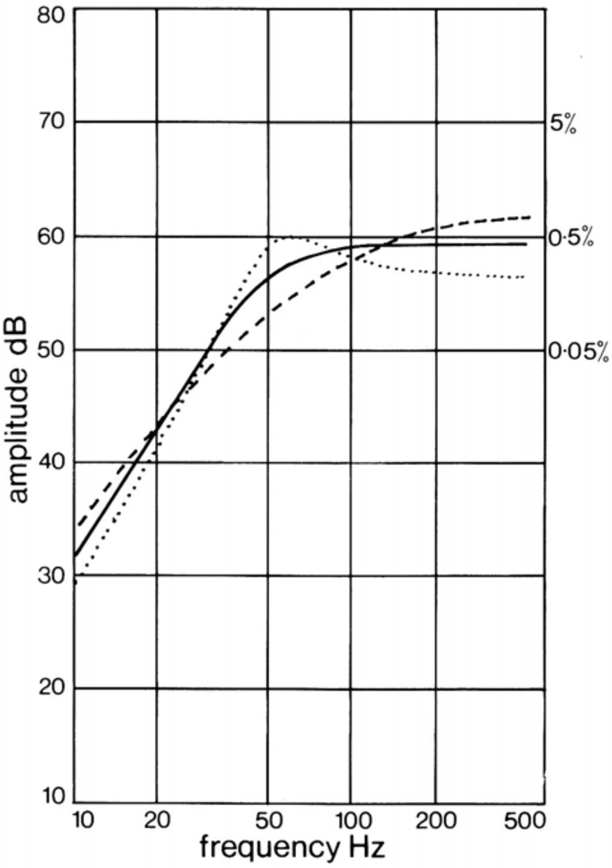

***Fig. 9.** 'Infinite baffle' loudspeaker: variation of response with flux density of drive unit, leaving other parameters unchanged; V_E = 30 litres.*

——— *(a) Optimum flux density for maximum efficiency obtainable with maximally flat characteristic.*

— — — *(b) Flux density x $\sqrt{2}$*

········ *(c) Flux density x $\frac{1}{\sqrt{2}}$*

corresponds to a doubling of the efficiency, but droops badly at the bass. Curve (c) illustrates the contrary effect of reducing the flux density to $\frac{1}{\sqrt{2}}$ of its original value; the efficiency is now halved, the system is under-damped and the frequency characteristic has a peak at 58 Hz.

Vented Enclosures

The basic efficiency formula applies also to the vented type of enclosure, which can be shown to act as a fourth-order high-pass filter. In this case, however, the value of *k* is higher, because the losses incurred through electrical impedance mismatch at the bass can be made less than with the usual type of 'infinite baffle' system so that, other things being equal, the efficiency is greater.

The difference in the performance obtainable with the two types is illustrated in Figure 10. Curve (a) again represents the response of the 30 litre 'infinite baffle' system with a nominal cut-off frequency of 50 Hz, while curve (b) shows the result that can be achieved with a vented enclosure of the same volume, when the parameters of the drive unit — including in this case the compliance of the suspension, which forms an essential filter element — are optimised in relation to the rest of the system. Each curve represents a maximally flat characteristic for the type of filter concerned; each has the same nominal cut-off frequency — though the response outside the pass-band falls off more rapidly with the fourth-order filter [curve (b)]. But the vented system has a 5 dB higher output level in the pass-band, corresponding to just over three times the efficiency.

It must be emphasised that the potentially high efficiency of the vented enclosure cannot be realised by simply adding a vent to a system already optimised for operation as an 'infinite baffle'. This fact is demonstrated in Figure 11, in which the response of the 'infinite baffle' loudspeaker used in the previous examples is reproduced in curve (a), while curves (b) and (c) show some of the effects obtainable by introducing vents of different areas. Curve (b), for which the resonance frequency of the vent and enclosure together was made equal to the resonance frequency of the drive unit in free air, approximates to a maximally flat characteristic with f_3 about 10% lower than in the original condition; however, there is no increase in efficiency in the pass-band. Doubling the vent area produces curve (c), which shows the beginnings of a peak in response, but still no improvement in efficiency; clearly, nothing is to be gained by moving further in this direction,

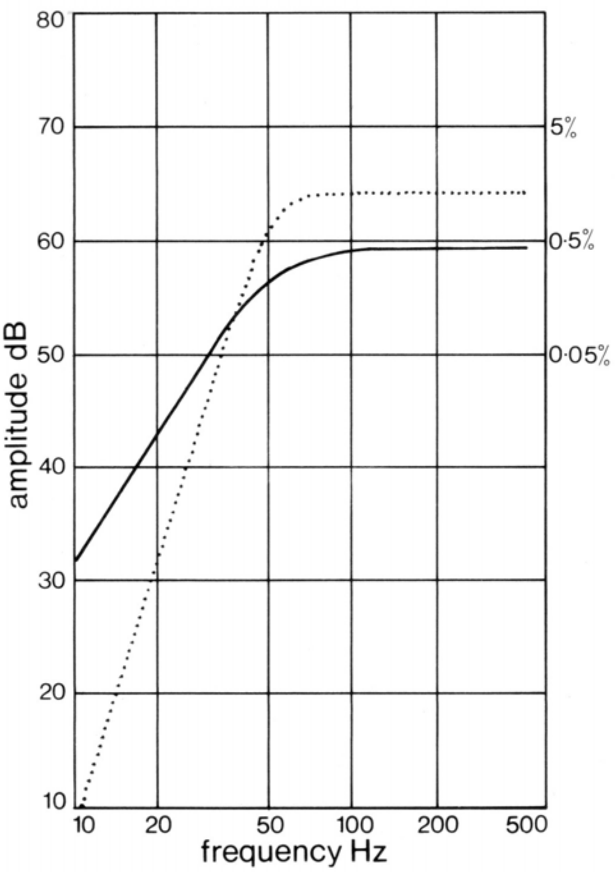

***Fig. 10.** Comparison between 'infinite baffle' and vented loudspeaker of equal volume, each designed for maximum efficiency with maximally flat characteristic (2nd order and 4th order respectively).*
——— (a) 'Infinite baffle'
········ (b) Vented enclosure of same volume.

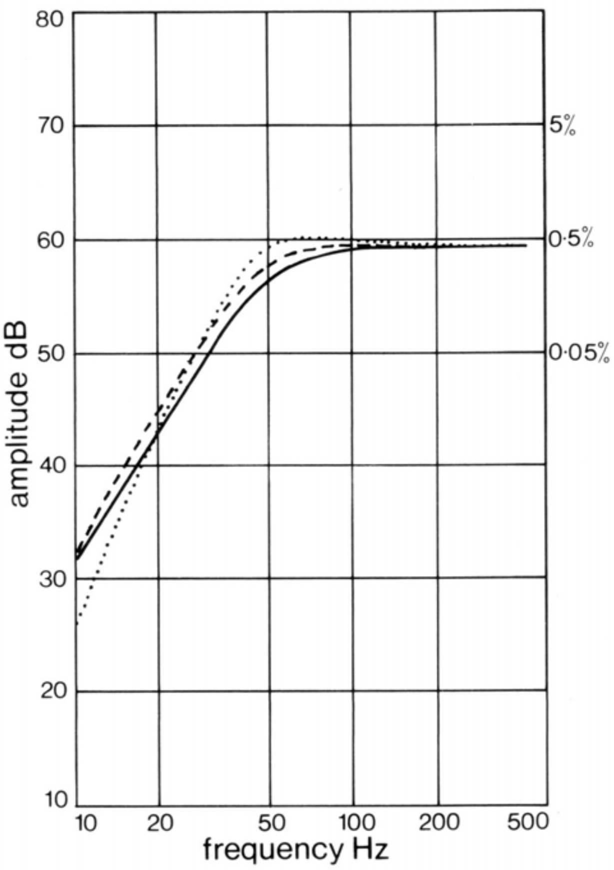

***Fig. 11.** Effect of adding a vent to a correctly designed 'infinite baffle' loudspeaker.*
——— (a) 'Infinite baffle'.
— — — (b) Vent added; resonance frequency of vent with enclosure equal to resonance frequency of drive unit in free air.
········ (c) Vent area doubled.

and to get any more out of the system, a radical re-design is necessary.

Passive Radiators

All that has been said so far about vented enclosures applies in practice to the variant of the system in which a passive radiator or "drone" diaphragm takes the place of an open port. The passive radiator has the additional advantage of avoiding air turbulence effects (and in the case of piped vents, resonant tube noises), which can be particularly troublesome in the smaller enclosures at high sound levels; it also provides a barrier to middle-frequency sound coming from the rear of the diaphragm and subject to colouration through residual internal reflections.

Labyrinth Enclosures

Enclosures constructed as a folded transmission line or "labyrinth" rather than a filter system have some features in common with the vented type. In both cases, radiation from the back of the diaphragm is used to create a second sound source operating at the lower end of the frequency range, where the vented enclosure acts as a Helmholtz resonator and the labyrinth as an organ pipe in the quarter-wave mode. In both cases, the increased acoustic load on the back of the diaphragm at the bass reduces the amount of movement required to produce a given sound output. But whereas the sound emanating from a vent or passive radiator at frequencies above cut-off remains in phase with the sound coming from the front of the diaphragm, the output from the transmission line changes phase rapidly with frequency and has to be heavily attenuated by acoustic absorbent material to avoid destructive interference at the full-wave and higher modes. This attenuation, together with the mass loading imposed on the diaphragm by the transmission line, makes the efficiency of the system less than that obtainable from a vented enclosure having the same volume and cut-off frequency; the principal application of the labyrinth is therefore in cases where the effect of pipe resonance in augmenting the extreme bass is considered to outweigh other factors.

Limitations of the Vented Enclosure

Because of the high efficiency obtainable with vented and passive radiator systems, one might expect these devices to be universally adopted. For the smaller enclosures, however, the effectiveness of an open vent is reduced by frictional losses, and there are practical obstacles to the use of "drones"; most bookshelf loudspeakers are therefore of the 'infinite baffle' type.

With the larger models, too, a closed box is sometimes preferred, because at subsonic frequencies the constraint imposed on the diaphragm by the enclosed air reduces the extent of any displacement which might be caused by record warp or amplifier d.c. offset, and, if excessive, could produce intermodulation distortion or even damage to the drive unit. Moreover, it is possible in some cases to raise the efficiency of an 'infinite baffle' system to equal that of the corresponding vented enclosure by introducing additional electrical components at the input to the loudspeaker. Because of the close electro-magnetic coupling in the drive unit, these components become, in effect, an integral part of the mechanical system, converting the simple second-order filter circuit to a more complex form that can be designed to give better matching at the bass; this artifice has been applied in the KEF Model 105*.

Power Output

To meet the demand for high sound levels, it is not sufficient to design the loudspeaker for maximum efficiency; the system must be capable of delivering a prescribed acoustic output without suffering damage or introducing distortion.

The maximum continuous sound output that can be safely obtained is limited by the need to avoid overheating of the voice coil. A further limitation is imposed by the allowable displacement of the coil and diaphragm; excessive movement can produce both damage and distortion, the latter arising from non-linearity of the suspension or non-uniformity of the magnetic field.

Because of the way in which the radiation resistance *r* varies with frequency, the volume of air that must be displaced to produce a given sound increases rapidly towards the bass. Allowing for the fact that the spectrum of most programme material falls off at the lower end of the scale, this means that for an 'infinite baffle' loudspeaker, the maximum diaphragm movement occurs round about f_3 and for a vented system (in which the vent takes over some of the work in the cut-off region), a little above this. It follows that if the designer wishes to extend the frequency range at the bass — thus increasing the maximum air displacement for a given sound level — he must allow for a greater amplitude of diaphragm movement or use a diaphragm having a larger area.

It may seem surprising that the efficiency formula given earlier contains no reference to diaphragm area. This comes about because the formula is derived by analysis of the "small-signal" working conditions, for which the question of damage or distortion in the loudspeaker does not arise. In these circumstances, the sound output obtained from a large diaphragm moving a given distance could equally well be obtained from a smaller diaphragm moving a correspondingly greater distance so as to displace the same volume of air; the mechanical constants and magnetic flux density of the drive unit could, in principle, be chosen in each case to produce the same frequency response and efficiency.

The situation is different when the diaphragm movement must not exceed a prescribed amplitude. In this case the large diaphragm has a clear advantage in that, for a given movement, the volume of air that it displaces — and hence the sound output — is correspondingly greater. With small enclosures, however, the maximum size of drive unit that can be used is limited, not only because of the lack of space, but because the effect of the enclosed air on the mechanical system of the loudspeaker depends on the diaphragm area. In mechanical terms, this air is equivalent to a compliance — represented by capacitor *C* in Figure 2 — that is not only proportional to the enclosure volume, but inversely proportional to the square of the diaphragm area. If then we attempt to use the largest diaphragm that the enclosure will accommodate, the air compliance may well be too low to allow the desired bass response to be achieved.

This difficulty could be overcome, at the expense of efficiency, by the process illustrated in Figure 4, in which the moving mass and the flux density are increased. In designing drive units for miniature loudspeakers having an extended bass response, it is more usual however to make the diaphragm area small enough to give the required value of compliance, and to provide a suspension that remains linear over a wide range of movement. To minimise distortion arising through non-uniformity of the magnetic field, the voice coil is made long enough to overhang the magnet gap at both ends; since however some of the turns on the coil are then dissipating power without doing useful work, the application of this artifice is limited by the resulting loss of efficiency.

In the design of loudspeakers capable of producing the high sound levels frequently demanded at the present time, the maximum acoustic power output must clearly be regarded as an additional factor in the trade-off process between enclosure volume, low-frequency range and efficiency.

Conclusion

To meet the demand for a response characteristic that remains substantially flat down to the nominal bass cut-off frequency, the enclosure volume for a given mid-band efficiency has to be greater — or the efficiency for a given enclosure volume less — than with a system in which the response is allowed to droop at the bass. Enclosure volume and efficiency are critically dependent on the cut-off frequency; thus, an extension of the working range by as little as a third of an octave — for example, the four semitones from A_{iii} (55 Hz) to F_{iii} (43.6 Hz) — would require either the volume to be doubled, the efficiency to be halved (necessitating the use of an amplifier of twice the power), or some intermediate condition. Even if adequate amplifier power is available, extending the low-frequency range at the expense of efficiency may not be practicable with the smaller models unless the maximum sound output is restricted to avoid distortion or damage. It is therefore no more than common sense to consider the type of programme material to be reproduced, and thence to decide whether the frequency range demanded is musically justified, rather than to increase the size

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or cost of the equipment simply to provide a facility that may be rarely used or appreciated.

The impression of loudness produced by a loudspeaker depends on the acoustics of the listening room, and cannot be reliably assessed from considerations of efficiency alone; even a practical demonstration can be misleading if carried out under unrepresentative conditions. Whenever possible, therefore, subjective judgements should be made with the loudspeaker set up in the intended location, reproducing programme material of the relevant kind.

Finally, to achieve the most favourable combination of efficiency, enclosure volume, bass response and power handling capacity requires an overall design approach, in which drive units, enclosures and, in some cases, associated electrical components, are developed together. However, contrary to the impression sometimes conveyed by the literature, there is no magic involved in the process, and in this connection, the following words from a technical paper[5] published 20 years ago, are still apposite:— "Trade journals tell of 'all new enclosures', 'revolutionary concepts', and 'totally new principles of acoustics' when in reality there is a close identity with enclosure systems described long ago in well-known classics on acoustics."

In this issue of KEFTOPICS we have discussed the interrelated physical factors to which practical loudspeaker designs are subject, together with the options open to the designer in meeting a specified combination of requirements. The purchaser who takes the trouble to consider these factors in formulating his own needs will find his efforts well rewarded.

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