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A Non-resonant Loudspeaker Enclosure Design

By A. R. BAILEY,* M.Sc.(Eng.), Ph.D., A.M.I.E.E.

—USING ACOUSTIC TRANSMISSION LINE WITH LOW-PASS FILTER CHARACTERISTICS

OVER the years, the design of loudspeaker units has progressed steadily until some are now available with very good performance capabilities. In particular, the advent of expanded polystyrene as a cone material has greatly reduced the distortions due to cone break-up.

Unfortunately, the design of loudspeaker cabinets has not kept pace with these developments, and there is little doubt that many enclosures now introduce more coloration than that produced by good loudspeakers. The loudspeaker enclosure to be described was developed to give as little coloration as possible, but to understand its evolution it is necessary to return to basic principles.

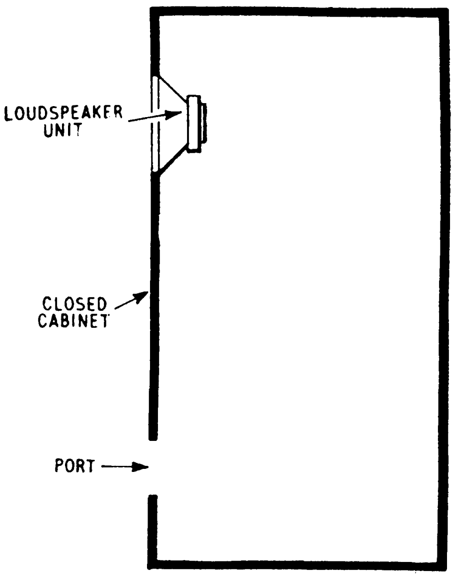

Fig. 1. Section through bass reflex cabinet.

By far the largest number of current loudspeaker cabinets are based on the "bass reflex" cabinet design[1]. This is shown in Fig. 1 as a sectional view. This cabinet appears to have only a relatively short path-length between the back and the front of the cone and would therefore be expected to give relatively poor l.f. response. In fact the response at low frequencies can be quite large, this being due to the cabinet having a Helmholz air-column resonance at about the lowest frequency being reproduced. In the reference given previously, the theory is well explained.

Unfortunately, this resonance in the cabinet causes coloration in the bass output of the system. This "ringing" on bass transients can be very noticeable, particularly on such instruments as string bass.

In addition the cabinet itself is frequently unlagged and consequently the sound is still emerging long after the original signal has stopped. Very heavy lagging is necessary to stop this effect and in so doing the cabinet "Q" is reduced so that the bass reflex action is lost.

Sine-wave testing does not necessarily show up the defects of a speaker system. Rapid cut-off at the edges of a flat response can make it sound far worse than a slower rate of fall at the edges of a system with apparently a poorer bandwidth. This is shown in Fig. 2.

The effect of the abrupt change in slope of the amplitude/frequency characteristic is to give 'ringing" at the frequency where the slope change takes place. This effect is unavoidable and is the necessary price to pay for the extension of bandwidth by the use of resonance effects. It is for this reason that loudspeaker systems can sound very "boomy" in the bass, even though the measured amplitude response shows no resonant peaks.

One method of testing that has not apparently been widely used is that of impulse-testing of loudspeaker cabinets. This method is very powerful and is described later on. For the moment it is sufficient to state that it confirmed that normal loudspeaker enclosures are not very good.

It is now apparent that it is the sound waves produced at the rear of the cone that have to be absorbed if delayed output and resonances are to be avoided.

Acoustic labyrinths[2] have been used in the past in an attempt to "lose" the sound down multiple paths. Such an enclosure is shown in Fig. 3, but the size needed is excessive. Unless there is adequate internal lagging, then these cabinets will also possess pronounced energy storage and the consequent lack of sound clarity.

Transmission line approach

The only safe method of removing the rear cone sound energy is by transmitting it down an infinite transmission line. This is obviously impracticable so the nearest approximation was examined.

If a transmission line for acoustic waves is filled with

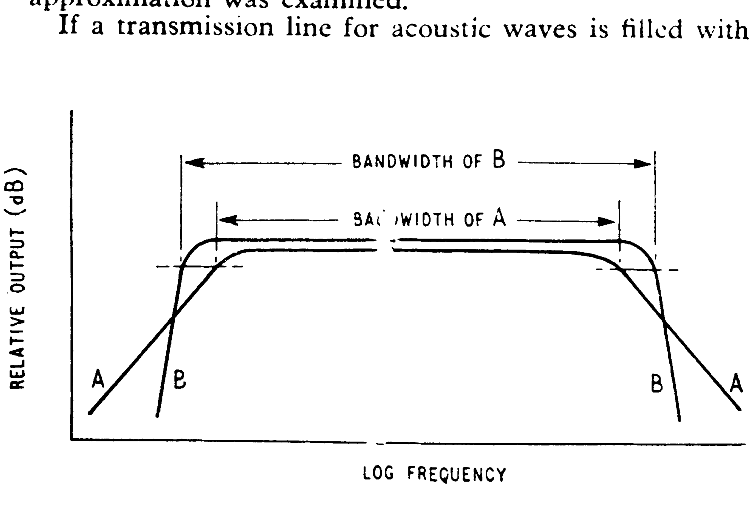

Fig. 2. Response curves having different transient responses.

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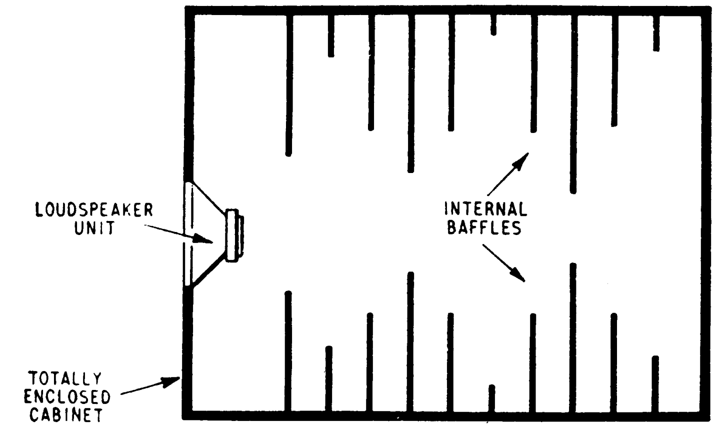


Fig. 3. Section through acoustic labyrinth cabinet.

a light acoustically-resistive medium, then the transmitted wave will be rapidly attenuated. After a certain distance the wave will be so weak that a blockage of the line will give only a minute reflected wave back to the speaker cone. The magnitude of the reflected wave can be determined by the standing-wave ratio immediately behind the speaker.

The choice of acoustic absorbing material will greatly affect the final performance so an initial investigation was made into the reflecting properties of various acoustic transmission line terminations. Many materials including glass fibre were tried, but the best results were obtained from long fibre wool. This gave a remarkably good absorption down to quite low frequencies. A typical set of the curves obtained is shown in Fig. 4.

For practical purposes a long pipe is not desirable so experiments were then made with a folded pipe of total length of about 8ft. This was built as shown in Fig. 5, the far end of the pipe having a pivoted flap so that characteristics could be taken with both open and short-circuit terminations. The results proved most interesting.

With the port closed the loudspeaker gave a very good performance with a slightly weak bass response. Sine-wave testing confirmed that the bass response fell by several dB below 60 c/s although the cone amplitude doubled for a halving of the input frequency. The trouble was finally traced to diffraction effects, the radiated wave-front changing its polar response at low frequencies. The effective bass response could be changed very markedly by positioning the cabinet away from a wall. The bass response then fell even further due to the increased diffraction at low frequencies. For test purposes a plain wall backing was used.

Opening the port had two effects. First, the bass response was improved to become approximately flat and secondly the cone excursion was greatly reduced between 30 and 50 c/s. The bass improvement was due to the line length being such that the delayed bass wave from the line was in phase with that radiated by the front of the cone. Also as the bass frequencies were radiated from two spaced sources, the diffraction effects would be reduced.

As the wool-filled line acts as a low-pass filter, the radiation from the vent cuts off before cancellation can occur at the higher frequencies. The rapid cut-off of this acoustic line is shown in Fig. 6. This shows the sound pressure at the port end of the line with the port closed.

Impulse response

As the performance so far appeared to be satisfactory it was decided to investigate the impulse response of the loudspeaker cabinet. The square-wave testing of loudspeaker units had previously shown that it was not possible to generate a good square-wave of sound pressure, let alone an impulse. Several mechanical methods were then tried but none proved to be really satisfactory. The author is therefore indebted to his colleague, R. V. Leedham, for suggesting the use of exploding wires as a standard impulse source.

Exploding wires proved to be a delightfully simple and accurate method of generating an acoustic impulse.

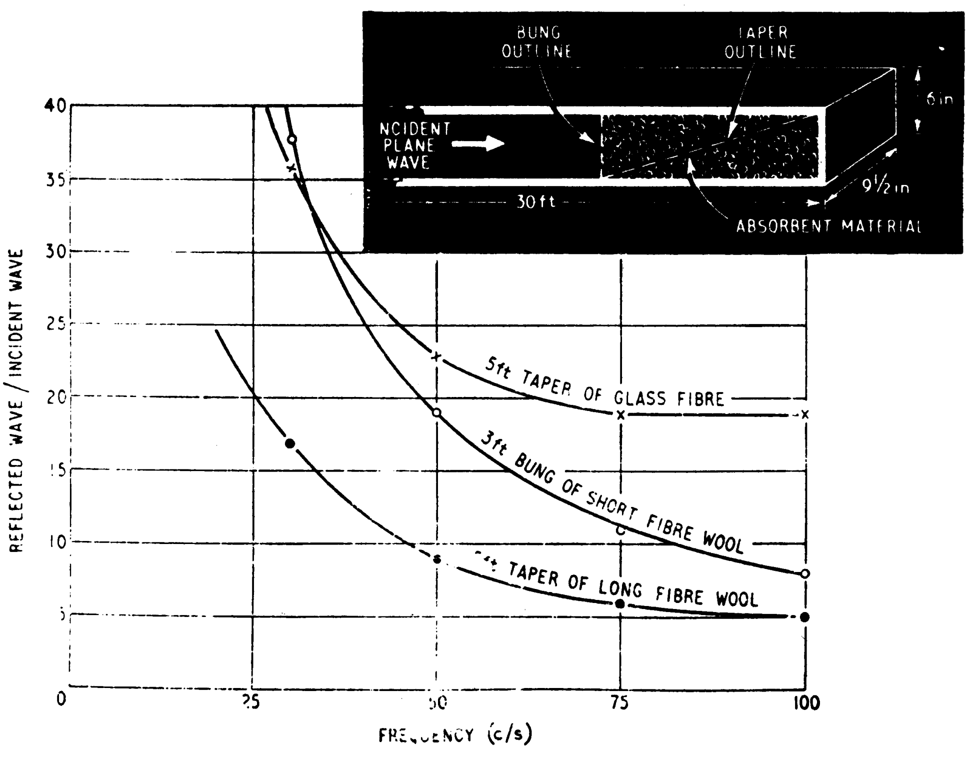


Fig. 4. Reflection characteristics of acoustic absorbents.

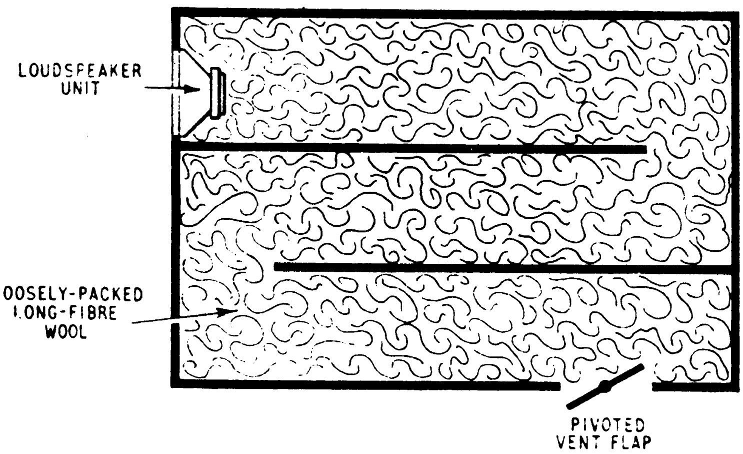


Fig. 5. Experimental acoustic transmission line cabinet.

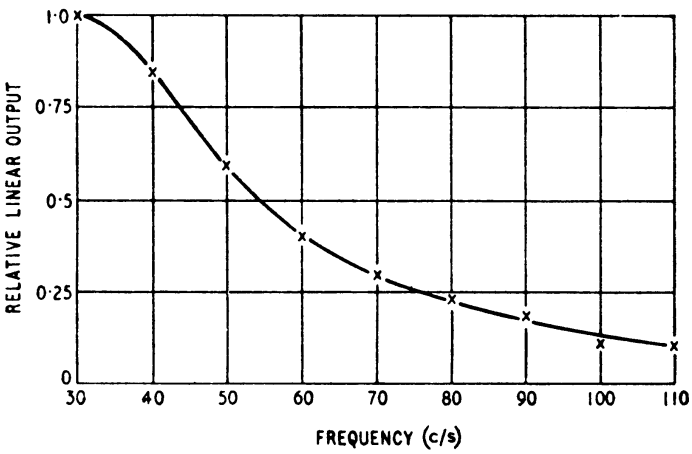


Fig. 6. Sound pressure in closed vent of experimental cabinet.

Basically the method involved discharging a low inductance capacitor of high value (1000 μF) charged to about 250 V through 1 cm of 40 s.w.g. tinned copper wire. The wire is vapourized almost instantaneously and the acoustic impulse produced had a rise time well into the supersonic region. Spark-generated impulses could have been used, but a high-voltage source is necessary of considerable stored energy if an adequate impulse is to be produced. As exploding wires were less lethal experimentally and only needed standard power supplies, the use of a spark source was not pursued.

The measuring microphone used had a working bandwidth of 30 to 10 kc/s and was used inside the cabinet at a distance of 18in from the exploding wire source. The exploding wire was operated at the position where the loudspeaker would be used, the loudspeaker opening being blanked off.

The results appear in Fig. 7a, the initial impulse being just discernible. The results were felt to be very creditable, the large damped oscillation being the flexure of the ¾in blockboard immediately behind the exploding wire. The experiment was then repeated with a bass-reflex cabinet of identical size having a port area of some 24in² and unlagged internally. The results were markedly dissimilar. Acoustically a much louder hollow explosion could be heard and the microphone pickup showed a far larger spurious output for a much longer time. This is shown in Fig. 7b, the sensitivity and time scales being identical with that of the previous test.

The cabinet was then lagged internally with sound absorbent and the test was repeated. The result is shown in Fig. 7c, the resonance obviously being better damped but still far worse than the line type of cabinet.

Listening tests proved that the cabinet had a "cleaner" sound than the bass reflex type, the effect of the line being very noticeable in its lack of coloration on speech. Transient response was definitely better on the line speaker, the sound being more "tight" and natural.

For obvious reasons it is preferable to have the long axis of the loudspeaker in the vertical plane. The cabinet ducting arrangement was therefore rearranged and one commercial form is as shown in Fig. 8. To make the most of the cabinet it is obvious that the loudspeaker units must not possess large colorations of their own. The units quoted give very good performance although other equally good units may be available. The cross-over frequency used is 1500 c/s.

The frequency-amplitude response of the complete loudspeaker system is shown in Fig. 9. The rate of fall at the low frequency end is creditably slow and far better than the majority of systems in use. It is not unknown for rates of cut-off to be as high as 18 dB per octave and to start very rapidly. This gives rise to a "heavy" bass effect that some people prefer; it is, however, not natural.

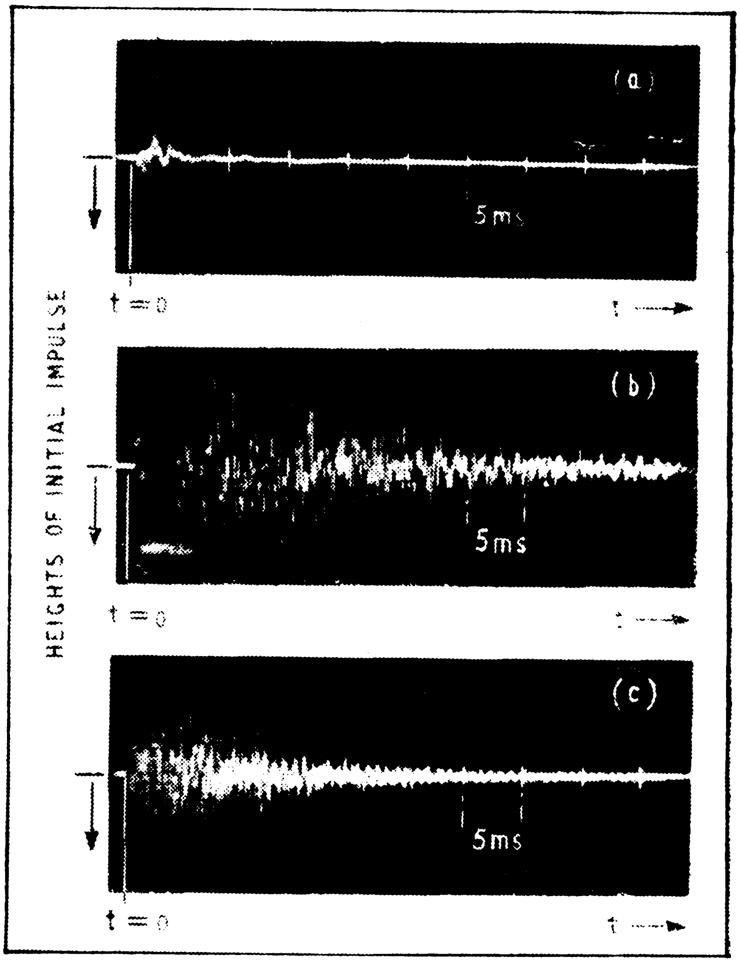


Fig. 7. (a) Impulse response of acoustic transmission line loudspeaker cabinet. (b) Impulse response of bass-reflex cabinet identical in volume to (a). (c) Impulse response of bass-reflex cabinet with internal lagging.

The bass resonant frequency of the speaker unit is below 15 c/s in the enclosure (about 30 c/s in free air) and quite well damped, so this will have no noticeable effect on the output. As the acoustic loading of the pipe

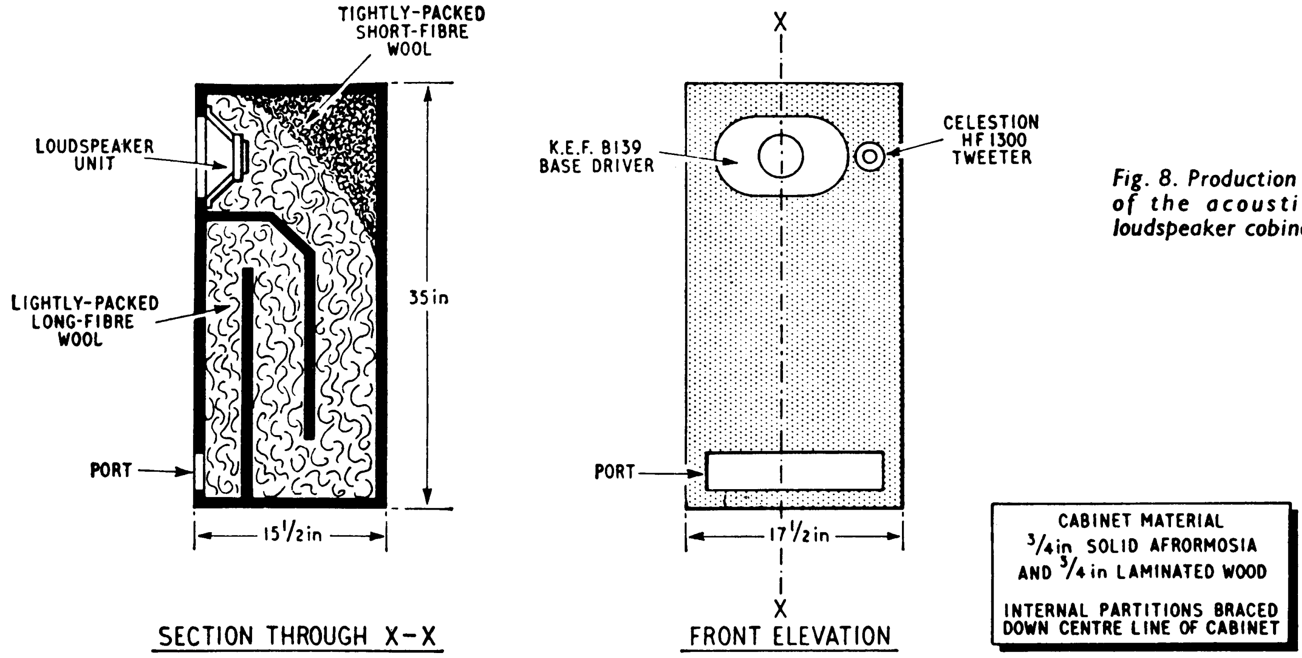


Fig. 8. Production version of the acoustic-line loudspeaker cobinet.

is, therefore, dominating the speaker unit, the low-frequency waveform will be better as the non-linearity in the loudspeaker unit suspension will be swamped by the linear acoustic loading.

The final subjective tests were very good. The sound quality is effortless and natural. At first hearing the bass sounds to be deficient but extended tests show that this is not so, it is merely that one has been conditioned to hearing resonant bass. The overall effect is surprisingly unexciting—only natural. In over a year's use of the system the author has noted, however, that musical listeners were very impressed with the result.

Practical Points

The cabinet design is not critical, and many variations are possible. The only cardinal point is that of keeping the pipe area above that of the cone. A rather strangled result can occur if an attempt is made to save space by restricting the pipe area much below that of the speaker cone. It must also be noted that a poor speaker does not usually sound much better in a good cabinet as the speaker deficiencies dwarf the improvement.

The application of the principle of the design is the subject of a Patent, but there is no restriction, of course, on private individuals making cabinets for their own use. For the amateur constructor the following points may be of use: —

(1) The cabinet should be made of thick acoustically dead material, chipboard being generally better than plywood. Due to the absence of high internal pressures and the absorbing effect of the wool, the cabinet thickness and bracing are not as important as in the case of the bass-reflex.

(2) Acute bends in the pipe should be arranged to occur as far from the loudspeaker cone as possible to reduce the magnitude of standing waves due to reflections.

(3) The wool should be of long fibre length and packed fairly loosely, about one pound to every two to three cubic feet. The grade of wool is still being investigated for the optimum specification.

(4) Either spray the wool with mothproofer or take other suitable action or the cabinet performance may suffer from an ageing process.

The author has constructed several different cabinets of totally different sizes and geometry, and apart from narrow pipes and badly angled bends the performance has been remarkably similar. In fact a low resonance 4in unit has been used effectively and gave a good output at 35 c/s. The power handling capacity was, however, limited.

Acknowledgements.—In conclusion the author would like to thank Radford Electronics Ltd. for permission to give the details shown in Fig. 8. Also thanks are due to R. V. Leedham and other colleagues for their help and criticism.

REFERENCES

1. "Sound Reproduction" G. A. Briggs, p. 62.
2. *Ibid*, p. 56.

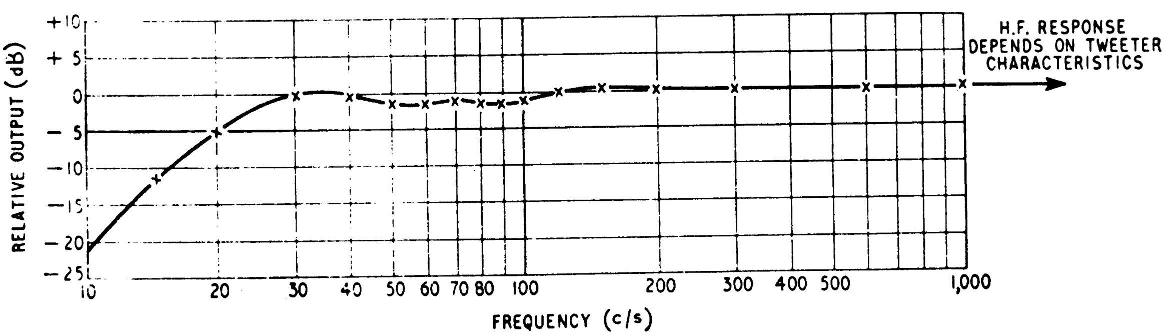


Fig. 9. Ove all sine-wave response of Fig. 8.

Letters to the Editor

Non-resonant Loudspeaker Enclosure

SINCE writing the article on the non-resonant loudspeaker, I have been examining further the performance of acoustic absorbents. Of those that are readily available, kapok is about the best but is not up to the performance of long wool. If the kapok is very well teased out then its properties are quite good. Unfortunately however it gradually compacts with use and the acoustic performance suffers accordingly. It may be possible to support it with wire netting, but this in turn can give resonance troubles.

The short fibre wool mentioned originally is very uncritical and cotton wool, kapok, or any usual cushion stuffing material is quite suitable. The purpose is only that of mid-frequency absorption and this is easily done by most textile materials.

ARTHUR R. BAILEY
Bradford

IT was particularly interesting to read Dr. A. R. Bailey's article describing a non-resonant loudspeaker enclosure, using a transmission line as a load. I would agree entirely with his contention that it is difficult to design a conventional reflex cabinet which is devoid of boom when reproducing the double bass or one which does not produce objectionable coloration of orchestral bass transients. However, I have established that it is possible to remove this defect from the conventional bass reflex cabinet by filling the interior of the cabinet with a fibrous material which provides a resistive load to the cone at low frequencies.

This system also becomes virtually non-resonant and was named a resistive reflex cabinet. The principle was used commercially early in 1962 and was the subject of a patent application on my behalf in May 1961. It is not unlikely that the subjective impression of music reproduced by means of a resistive reflex cabinet would compare favourably with Dr. Bailey's system, although their design concepts are clearly different.

Further research and development has established that reflex cabinets of only 1 ft^3 can be made virtually non-resonant in the frequency range above 30 c/s. The bass quality is life-like and there is an absence of boom or chestiness in speech. As a result of further research I have established that the amplifier stability margin at the bass resonance frequency is more satisfactory with such a loudspeaker, and that the transient response of the amplifier and loudspeaker in tandem is well damped. Undoubtedly Dr. Bailey's system possesses the same virtue. It is perhaps strange that speech should sound coloured when the main system resonance is around 40 to 50 c/s. This phenomenon appears to be due to the fact that the d.c. component of the distortion produced in the amplifier appears as a pulse when there is a rapid change of signal level unless the feedback loop is d.c. coupled throughout or has a very long time constant. This internally generated pulse excites the transient response of the amplifier speaker combination and gives rise not only to boomy speech and music, but to excitation of speaker cone resonances as well.

It would seem then that those people who maintain that no two amplifier-speaker combinations should alike are probably right after all.

The transient testing procedures adopted by Dr. Bailey undoubtedly show up the spurious coloration of an enclosure very well.

Another alternative method which I have found useful is to apply a step function to the speech coil from a lead-acid battery by means of a mercury switch. The latter produces very fast rise times without contact effects. Any spurious coloration is revealed outdoors or in an anechoic chamber. It is by the same process possible to identify whether the loudspeaker or room acoustics are producing unsatisfactory bass response.

J. R. OGILVIE
Sevenoaks, Kent.

The author replies:—

I was very interested to read Mr. Ogilvie's comments with regard to loudspeaker systems. There are, however, one or two points that I would like to comment on.

Firstly, there is the perennial problem of obtaining the best possible performance from small loudspeaker enclosures. This has always been a difficult requirement due to diffraction and other effects. I would agree with Mr. Ogilvie that it is possible to make a small bass reflex cabinet virtually non-resonant, but I have always found that the small port size necessary for a low Helmholz resonance gives very little benefit unless the cabinet is very resonant. If he has indeed solved the problem, then there will be many people grateful to him.

I would be interested to know the method of damping that Mr. Ogilvie uses, as all that I have tried in small systems either put up the effective stiffness of the enclosed air to an unacceptable value, or alternatively cause distortion due to the non-linear air friction effects. These same shortcomings exist in the damping materials used in the now popular closed-box systems. Too much stuffing in a bookshelf speaker can make it sound terrible.

Regarding the effect of resonant speaker systems on their driving amplifiers; I will agree that the speaker impedance can rise steeply at resonance peaks, but this should not upset any reasonable amplifier except perhaps under overload conditions. A good amplifier should give a satisfactory transient response at the bass end even with an open-circuit as a load. Overloads on output voltage levels should also not be capable of seriously upsetting the amplifier, irrespective of the output load conditions. Any high-fidelity amplifier worthy of that name should not be upset by load conditions to an audible degree, but then I would agree that there are some amplifiers that are not as good as their title suggests.

Regarding the coloration of speech by resonant speaker systems. I feel that Mr. Ogilvie is being confused between the lowest continuous tone that can be sung and the complex components of speech. The explosive components of speech have constituents that extend below the audible spectrum, these being easily isolated by a third-octave band filter. It is these components that are subjected to the bass resonance frequency of cabinets and speakers and cause the resulting coloration.

I am rather puzzled by the reference to

d.c. components of distortion producing coloration effects. This is contrary to my own experience, where tone-burst testing an amplifier with bandwidth-limited waves gave no measurable d.c. components whatever. With a low-distortion amplifier I would not expect that any distortion products could produce audible colouring from resonances, due to their extremely low level.

When deciding on how to impulse-test loudspeaker enclosures, step waveforms were applied to loudspeakers and their acoustic outputs examined. Unfortunately no loudspeaker was found with a sufficiently good performance for the purpose. Even the best tested had far more coloration than that of the acoustic line cabinet to be tested. Certainly there is still useful work to be done before loudspeakers can be classed as giving true reproduction.

ARTHUR R. BAILEY

Loudspeaker Enclosures

DR. BAILEY'S loudspeaker design which he described in the October issue of *Wireless World*, is a resurrection of the almost forgotten labyrinth enclosure which was popular many years ago, and is still regarded in some quarters as being potentially superior in performance to bass reflex types. It bears no direct relationship to the labyrinth enclosure to which Dr. Bailey attaches the name, and in its usual form its chief disadvantage is the monstrous size required to attain the low frequency performance demanded by modern standards.

It is surprising at first sight, that the excellent bass response, shown by the curve Dr. Bailey gives us, can be produced by a phase inverting line only some 7ft. long. This will have its "free air," half-wave resonance, necessary to achieve the phase inversion required between the rear of the loudspeaker cone and the port opening, at 80 c/s. Below 40 c/s this results in the output from the port containing a component which is in antiphase with that from the loudspeaker cone, decreasing the total output and increasing the rate of fall off.

This is not the case with Dr. Bailey's enclosure, the output being well maintained to frequencies appreciably below 30 c/s, and it must be inferred that the phase inversion occurs by some means other than the free air resonance. There is a retarding effect on the waves within the enclosure, decreasing the frequency of its resonance, and thereby lowering the frequency at which phase inversion occurs. As the wool filling is the only difference between this enclosure and the simple labyrinth, it would appear that this is responsible for this effect, and there is a simple, if perhaps incomplete, explanation which indicates that this is the case.

If we consider two waves of the same frequency, but having different velocities, then:—

$$\frac{\lambda_0}{\lambda_0} = \frac{v_0}{v_1},$$ where λ_0 and λ_1 are the wavelengths corresponding to v_0 and v_1.

But $v = \frac{E}{\rho}$, where E is the elasticity of the propagating medium and ρ its density.

Hence $\frac{\lambda_0}{\lambda_1} = \sqrt{\frac{E_0}{E_1}}\sqrt{\frac{\rho_1}{\rho_0}}$, where λ_0, E_0 and ρ_0 correspond to free air conditions and E_1 and ρ_1 correspond to those in the filled enclosure.

With two assumptions, we can simplify this expression and relate it approximately to the amount of material added to the enclosure.

Firstly, it appears reasonable to assume that with a loosely packed filling, little air will be displaced. Also the fibres are themselves relatively incompressible compared with the remaining air. We can therefore say that $\frac{E_0}{E_1} = 1$ approximately since we can expect little change in the elasticity due to the filling.

Secondly, it seems quite probable that, for frequencies where there is little attenuation in the filled line, the filling, being highly compliant, will respond to the air movement, and its mass will effectively add to that of the air. Thus the density of the propagating medium will be higher than that of air, and to a fairly close approximation, can be assumed to be the density of air plus the filling rate.

The expression given above now reduces to

$$\frac{\lambda_0}{\lambda_1} \simeq \sqrt{\frac{\rho_1}{\rho_0}} \simeq \sqrt{\frac{\rho_0 \times r}{\rho_0}}$$

where r is the filling rate.

It would appear that the half wavelength resonance of Dr. Bailey's enclosure occurs at 30 c/s corresponding to a free air wavelength of 36ft. But the wavelength corresponding to the unfilled enclosure is 2 × 7 = 14ft.

Hence $\lambda_0 = 36$ft., $\lambda_1 = 14$ft.,

and $\rho_1 = 6{\cdot}6$ $\rho_0 = 0{\cdot}5$ lb/ft^3, taking $\rho_0 = 0{\cdot}075$ lb/ft^3 at room temperature.

This means that the filling must be added at a rate of 0·425 lb/ft³ or 1 lb to every 2·3ft³ of enclosure, which is within the range recommended by Dr. Bailey.

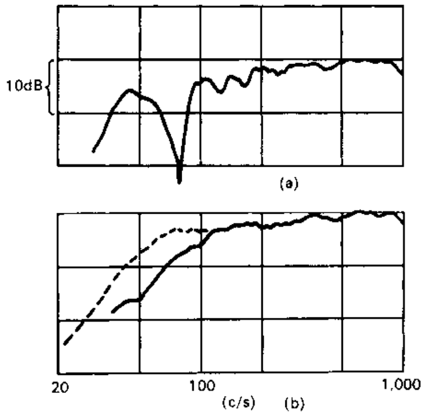
It is interesting to note that the line can be tuned to the required resonance by addition or subtraction of filling; this was always a difficulty with the simple labyrinth, since the fundamental resonance of the system changes with a change of line length, and "cut and try" could be expensive on timber. Furthermore, the use of other media is indicated since it is the weight added which is important. Provided that the low-pass characteristic can be correctly maintained, higher packing densities could be used to reduce still further the enclosure size.

So far as the reduction of spurious resonances is concerned, many of the small airtight enclosures currently available are filled with a fibrous damping medium. But it is doubtful if any of them use the velocity retardation effect at undamped frequencies other than by accident. Certainly none could use it to better effect than the labyrinth, where not only does it in this case provide a reduction of 2·6 times in the line length, but also in the other dimensions. The required volume has been shrunk from a gargantuan 100ft³ to a domesticated 5·5ft³.

This is a remarkable achievement and with its possibilities for further improvement and application is of far greater importance than the other, coincidental, properties of Dr. Bailey's enclosure.

E. A. HARMAN
Chorley, Lancs.

SIX years ago, the writer tested a labyrinth cabinet almost identical to that described as an acoustic transmission line cabinet by Dr. Bailey in the October issue. Response curves taken under free-field conditions are shown in the Figure. Variations of cabinet and absorbent gave the same result of numerous resonances, as also did a folded horn. The curve for a totally enclosed cabinet of less than half the volume is included for comparison; provided the cabinet is not long and narrow, only the fundamental is present. These results were given in a lecture to the (then) Brit.I.R.E. on January 24th, 1962. Similar results were obtained many years ago by H. J. Leak and J. Bolingbroke. The original labyrinth was essentially a



Mr. Barlow's response curves. (a) labyrinth lined with ½in thick cotton wool; impedance peaks: 87, 140, 180, 230, 330, 460, 720 and 870 c/s (fundamental 44 c/s): (b) labyrinth completely filled with cotton wool; impedance peaks: 74, 100 and 340 c/s (fundamental 23 c/s). The dotted curve is for a totally enclosed cabinet half filled with cotton wool; impedance peaks: fundamental only 65 c/s.

resonant device, in which the resonances and anti-resonances were used to equalize the speaker output. It will be noted that the rate of cut off of the totally enclosed cabinet is similar to that of the absorbent-filled labyrinth, and can be varied if need be by design. When measured standing against a wall, as is done by Dr. Bailey, the response of the labyrinth may tail off more gradually, but this would apply also to the totally enclosed cabinet. If it is desired to tail off the bass gradually from a relatively high frequency, there are simpler and less resonant devices than the labyrinth for doing this.

D. A. BARLOW
*H. J. Leak & Co.,
London, W.3*

The author replies:—I read Mr. Harman's letter with great interest as his theory is borne out in practice. The velocity of sound in wool is considerably slower than in free-air, and is also slower than can be accounted for by the difference between isothermal and adiabatic compression of the air. The wool mass is definitely slowing down the wave front, but as there cannot be perfect coupling between the wool and the air the effect will be somewhat less than given by Mr. Harman's calculation. On the other hand the wave will be slowed by the isothermal effects of the wool as well, so the error in assuming perfect coupling will be reduced.

As Mr. Harman surmises, the velocity of sound can be slowed down very greatly in a high packing density, but unfortunately this gives rise to high back pressure on the loudspeaker cone due to the very restricted air passages. There is therefore a maximum packing density that can be used without giving a strangled effect to the sound. The maximum density varies with speaker design and cabinet design, but is far greater than the density used in the cabinet described.

Regarding Mr. Barlow's letter, I feel that he must have misunderstood the article. This may have been my fault, but the cabinet design is based on a transmission line (which should have no reflections) having energy absorbing properties at all but the lowest frequencies. There is no desire to form a labyrinth (dictionary definition—with many turnings) at all. In fact every turning tends to cause reflections and these are contrary to what is required.

Without knowing what design of cabinet Mr. Barlow used, it is difficult to be analytical of his results. It may be of interest, however, to note that cotton wool has not proved to be a suitable material from the tests that I carried out. I would disagree that the rates of cut-off are the same in the second figure, my constructed asymptotes on the mean rate of cut-off give the labyrinth a 5 dB per actave slower rate of fall.

Incidentally my own response curve was taken with B. & K. equipment with the speaker back to the wall of a 60 ft long laboratory, the microphone being 1 ft in front of the speaker midway between the speaker and vent axes. A free-field response was not given as this is intolerably bass-heavy if a flat characteristic is obtained. A floor and a wall were felt necessary to simulate the effect of normal domestic listening conditions.

If Mr. Barlow is still convinced that a closed cabinet gives better performance, then I will be only too happy to give him a demonstration of the system's capabilities. A 25 c/s pure sine wave can be generated acoustically by the system. A very large enclosed cabinet would be needed for this as the cone resonance is increased by the enclosed air. Incidentally, the effective system resonance of the transmission line speaker is below 15 c/s for the design given. The cone resonance as such may be above or below its free-space figure depending on the sign of the reflected reactance of the transmission line. This factor, however, has little significance as line loads the cone resistively to such a degree that reactive effects are negligible within the audible range.

ARTHUR R. BAILEY